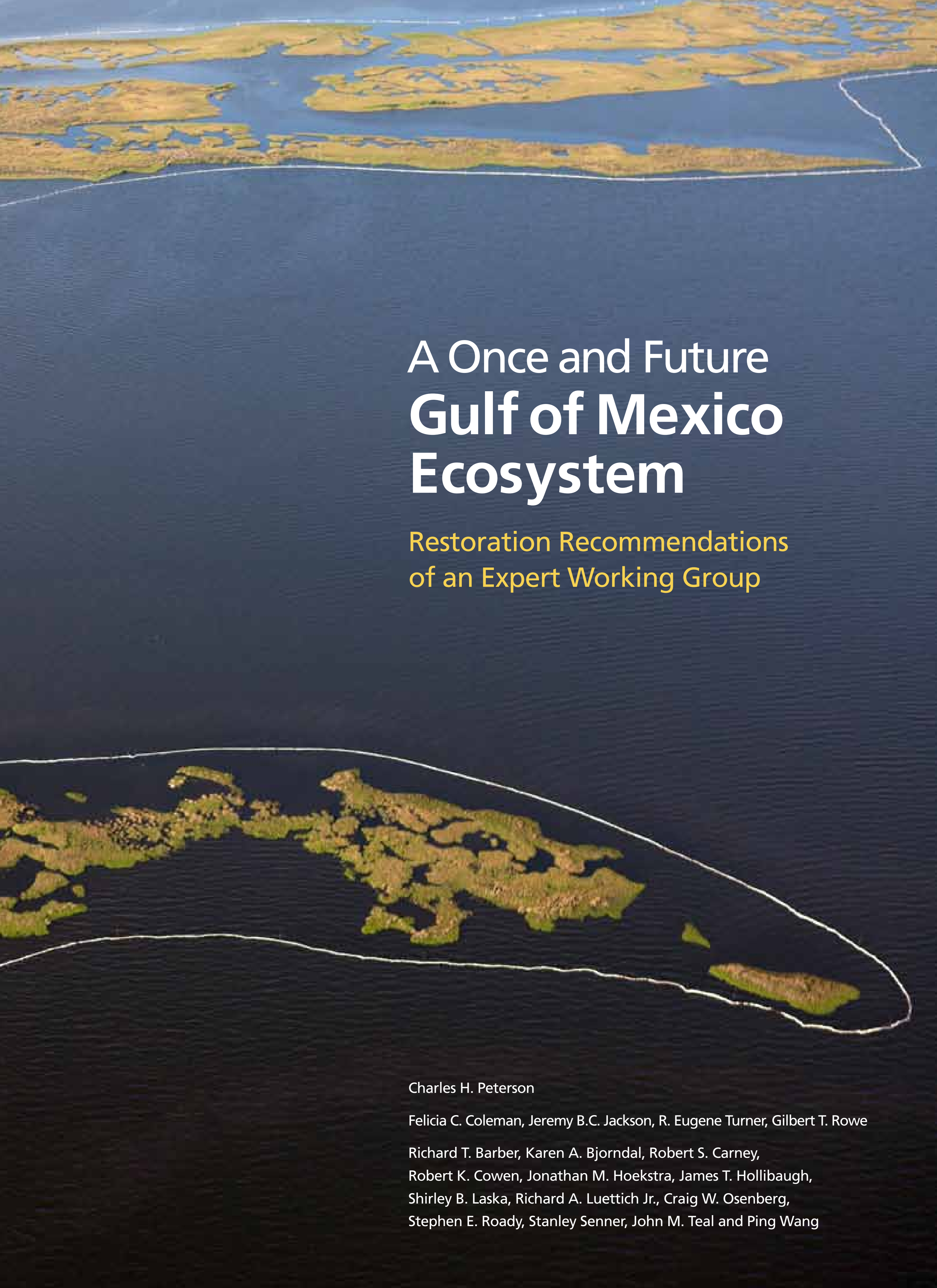


A Once and Future
Gulf of Mexico Ecosystem

Restoration Recommendations of an Expert Working Group

Charles H. Peterson

Felicia C. Coleman, Jeremy B.C. Jackson, R. Eugene Turner, Gilbert T. Rowe

Richard T. Barber, Karen A. Bjorndal, Robert S. Carney, Robert K. Cowen, Jonathan M. Hoekstra, James T. Hollibaugh, Shirley B. Laska, Richard A. Luettich Jr., Craig W. Osenberg, Stephen E. Roady, Stanley Senner, John M. Teal and Ping Wang

Acknowledgments

Pete Peterson wishes to thank his co-authors, in particular Gene Turner, Felicia Coleman, Gil Rowe and Jeremy Jackson, for their insights and assistance in producing this report. The authors thank the Pew Environment Group for financial support for this project and the three peer reviewers, whose comments helped to improve the manuscript. We appreciate the many helpful discussions that we each had with interested colleagues.

Suggested citation:
Peterson, C. H. *et al.* 2011. A Once and Future Gulf of Mexico Ecosystem: Restoration Recommendations of an Expert Working Group. Pew Environment Group. Washington, DC. 112 pp.

A Once and Future Gulf of Mexico Ecosystem

Restoration Recommendations of an Expert Working Group

Contents

THE PEW ENVIRONMENT GROUP

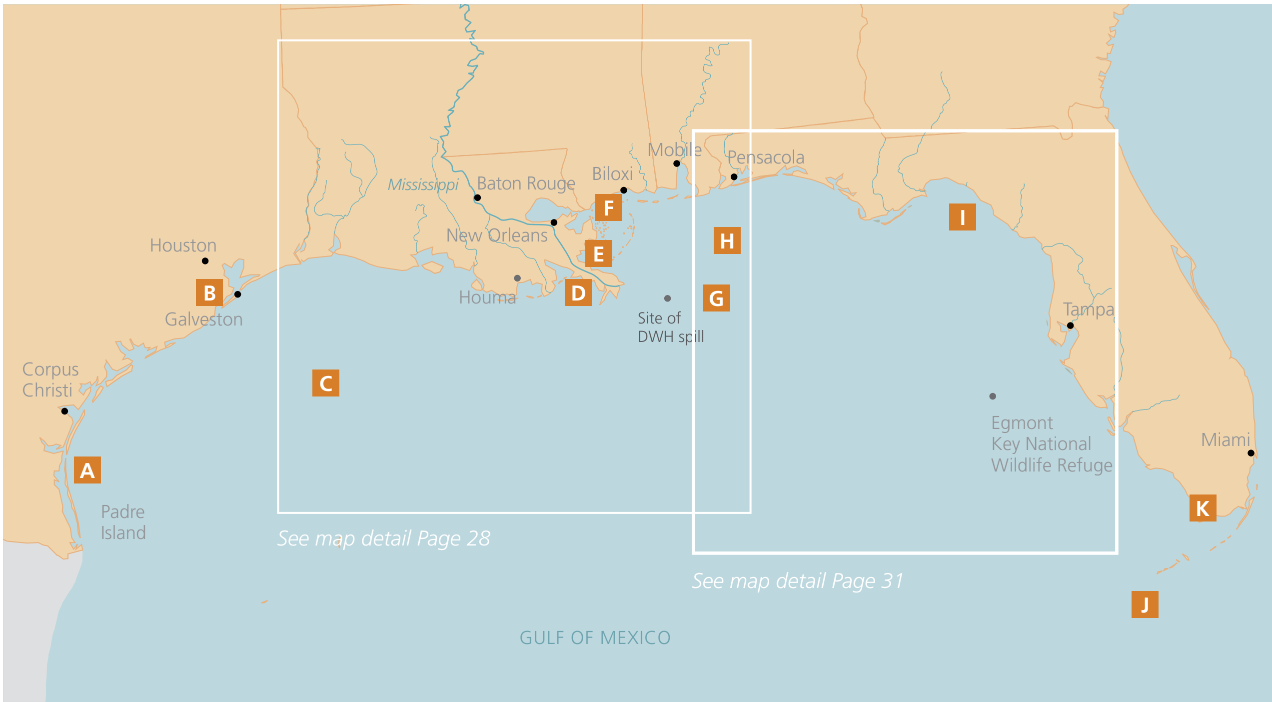
The Pew Environment Group is the conservation arm of The Pew Charitable Trusts, a nongovernment organization that works globally to establish pragmatic, science-based policies that protect our oceans, preserve our wildlands and promote clean energy.

www.PewEnvironment.org

Figure 1

The Gulf of Mexico Region

Featured sites mentioned in the report



A Padre Island National Seashore, TX

B Galveston, TX

C Flower Garden Banks National Marine Sanctuary

D Grand Isle, LA

E Chandeleur Islands, LA (Breton National Wildlife Refuge)

F Pascagoula River, LA

G Green Canyon area (near the DWH spill site)

H De Soto Canyon

I Big Bend coastal region, FL, includes Apalachicola Bay, St. Joe Bay and the Fenholloway, Suwanee and Ochlockonee Rivers

J Florida Keys National Marine Sanctuary

K Everglades National Park

Abstract

The Deepwater Horizon (DWH) well blowout released more petroleum hydrocarbons into the marine environment than any previous U.S. oil spill (4.9 million barrels), fouling marine life, damaging deep sea and shoreline habitats and causing closures of economically valuable fisheries in the Gulf of Mexico. A suite of pollutants—liquid and gaseous petroleum compounds plus chemical dispersants—poured into ecosystems that had already been stressed by overfishing, development and global climate change. Beyond the direct effects that were captured in dramatic photographs of oiled birds in the media, it is likely that there are subtle, delayed, indirect and potentially synergistic impacts of these widely dispersed, highly bioavailable and toxic hydrocarbons and chemical dispersants on marine life from pelicans to salt marsh grasses and to deep-sea animals.

As tragic as the DWH blowout was, it has stimulated public interest in protecting this economically, socially and environmentally critical region. The 2010 Mabus Report, commissioned by President Barack Obama and written by the secretary of the Navy, provides a blueprint for restoring the Gulf that is bold, visionary and strategic. It is clear that we need not only to repair the damage left behind by the oil but also to go well beyond that to restore the anthropogenically stressed and declining Gulf ecosystems to prosperity-sustaining levels of historic productivity. For this report, we assembled a team of leading scientists with expertise in coastal and marine ecosystems and with experience in their restoration to identify strategies and specific actions that will revitalize and sustain the Gulf coastal economy.

Because the DWH spill intervened in ecosystems that are intimately interconnected and already under stress, and will remain stressed from global climate change, we argue that restoration of the Gulf must go beyond the traditional "in-place, in-kind" restoration approach that targets specific damaged habitats or species. A sustainable restoration of the Gulf of Mexico after DWH must:

1. **Recognize** that ecosystem resilience has been compromised by multiple human interventions predating the DWH spill;
2. **Acknowledge** that significant future environmental change is inevitable and must be factored into restoration plans and actions for them to be durable;
3. **Treat** the Gulf as a complex and interconnected network of ecosystems from shoreline to deep sea; and
4. **Recognize** that human and ecosystem productivity in the Gulf are interdependent, and that human needs from and effects on the Gulf must be integral to restoration planning.

With these principles in mind, we provide the scientific basis for a sustainable restoration program along three themes:

1. **Assess and repair** damage from DWH and other stresses on the Gulf;
2. **Protect** existing habitats and populations; and
3. **Integrate** sustainable human use with ecological processes in the Gulf of Mexico.

Under these themes, 15 historically informed, adaptive, ecosystem-based restoration actions are presented to recover Gulf resources and rebuild the resilience of its ecosystem. The vision that guides our recommendations fundamentally imbeds the restoration actions within the context of the changing environment so as to achieve resilience of resources, human communities and the economy into the indefinite future.

Introduction

The blowout and spill released more oil into U.S. waters than any other oil spill incident in history. This tragedy, however, is but one of many historic, recent and ongoing stresses degrading the Gulf environment.

On April 20, 2010, the eyes of the nation and the world focused on the northern Gulf of Mexico and witnessed the beginning of a human and natural disaster. On that day, a BP oil well blew out on the Macondo Prospect 1,500 m below the ocean's surface and began gushing crude oil into the sea. Eleven men died from the explosions accompanying the blowout and subsequent fire on the drilling rig, Deepwater Horizon. The great depth of the well—almost a mile beneath the ocean's surface—complicated efforts to stanch the torrential flow of oil and natural gas. During the next 85 days, an estimated 4.9 million barrels of crude oil flowed into the sea as BP and the U.S. government tried chemicals, concrete, physical material and other desperate measures to plug the wellhead. The environmental tragedy was dramatized in a continuous, mesmerizing video stream of the turbulent flow of oil and gas at the seafloor wellhead and in the satellite and television imagery of oil covering the sea surface, seabirds and shorelines. This blowout and spill released more oil into U.S. waters than any other spill in history. In terms of human welfare, this single event severely damaged the Gulf's natural resources, harming the economy and costing lives and jobs in a region dependent on fishing, tourism and oil-and-gas extraction.

This tragedy, however, is but one of many environmental perturbations that have degraded or are still degrading the Gulf environment. Over the previous five years alone, for example, hurricanes Katrina, Rita and Ike struck the Louisiana, Mississippi and Texas coasts, causing extensive loss of life and property. Chronic stressors on the Gulf ecosystem include overfishing and overharvesting of marine life; pollution from agricultural runoff and industry; global climate change and rising sea level; and alterations of terrain and rivers for oil exploration and real estate development. Coastal marsh acreage, riparian wetlands, and forests in the drainage basins of the Mississippi and smaller rivers have declined dramatically, reducing fish and wildlife habitat and removing natural water-purifying functions. These changes, in turn, have reduced the Gulf ecosystem's ability to provide the services and resources on which coastal communities depend.

The success and durability of actions taken to restore damage caused by the oil release will depend upon the way Gulf restoration addresses the impacts of historical ecosystem degradation and anticipates future changes by creating both social and natural resilience. Even narrowly focused restoration actions are unlikely to be sustainable if they fail to consider the complex and interconnected human and natural ecosystem of the Gulf. Restoration plans must also compensate for prior impacts to individual resources and to human economic enterprises and must consider the full scope of relationships to historical baseline conditions. Finally, the ability of restoration plans to anticipate future dynamic change will determine the success of those plans over the long term. Some of these environmental changes, such as sea level rise and severe weather events, are occurring faster and having larger consequences along the Gulf Coast than anywhere else in the country. Therefore, the Gulf ecosystem could be a model for how

Oil burns during a controlled fire after the Gulf oil spill. Photo: Justin Stumberg/U.S. Navy/Marine Photobank to solve multiple social and natural challenges to achieve sustainability in the face of dramatic environmental change.

To assess restoration opportunities in the Gulf, we assembled a team of leading scientists with expertise and experience in coastal and marine ecosystems and their restoration. Together we identify strategies and specific actions that will help revitalize the Gulf Coast ecosystem and economy. Our scientific approach is based upon spatially explicit and ecosystem-based insights derived by inferring the baseline conditions and controlling functions of the Gulf coastal ecosystem as they were before major human modifications were made. Previous use of this approach to guide ecological restorations of estuarine (Lotze *et al.* 2006), marine (Jackson *et al.* 2001) and freshwater (Scheffer *et al.* 2001) aquatic ecosystems have revealed how human-induced modifications, such as overfishing apex predators and historically dominant filter feeders, have led to the loss of ecosystem resilience when subsequent perturbations occurred, such as nutrient overloading. Such interactions among multiple stressors can propel the ecosystem across a threshold and into an alternative persistent state from which recovery to baseline conditions is difficult. For example, the overharvest of suspension-feeding oysters from Chesapeake Bay and Pamlico Sound estuaries in the decades around 1900 disabled the capacity of the ecosystem to exert top-down grazing controls on phytoplankton blooms. When nutrient overloading occurred decades later, the suspension-feeders were no longer functionally capable of grazing down the microalgae and helping to suppress bloom development (Jackson *et al.* 2001). Therefore, our restoration recommendations address a range of modifications to the Gulf ecosystem. Using historical baselines to guide restoration does not mean that we advocate the impossible, such as rebuilding coastlines to match the locations and elevations of previous times before substantial subsidence occurred. Instead, historical ecology guides us toward restoring previously critical processes that serve to organize the ecosystem and trigger compensatory internal dynamics that strengthen resilience.

The DWH well blowout is an obvious tragedy, but it appears to have made at least two positive contributions to the region. The publicity generated by the oil spill put a spotlight on the immense value of the natural resources and communities of the Gulf Coast. It also drew attention to how little public or private investment has been made in restoring the Gulf ecosystem after past injuries or in creating the natural and social resiliency required for this unique region to sustain itself in the face of a dramatically changing natural environment. Although government promises of funding for hurricane rehabilitation and restoration have proved overly optimistic, funds for Gulf restoration derived from environmental fines for ocean pollution and natural resource damage will be more substantial. Some of the funds are restricted to direct compensation for damage done by the DWH oil spill to the Gulf ecosystem, its natural resources and the Gulf coastal economy; however, the potential uses for the rest of the funds range broadly.

The federal Oil Pollution Act of 1990 (OPA) dictates criteria for compensatory restoration projects that can be supported by monies given in settlement of natural resource damage claims or awarded by the court system. OPA then has general jurisdiction over Gulf restoration funds derived from legal settlements with BP. Under the provisions of OPA, compensatory restoration projects must be explicitly tied to the natural resource injuries, either damage to specific resources, such as the loggerhead turtle, or damages to specific habitats, such as coastal marsh. Consequently, restoration that draws upon this source of funding must be justified by linkage to one or more injured resources or habitats, such as those listed in Table 1.

The Gulf ecosystem has been buffeted and so deeply modified by such a wide variety of anthropogenic and natural stressors that merely following traditional government guidelines for "in-place, in-kind" compensatory restoration under OPA or other statutes is unlikely to provide sustainable benefits. For example, the combination of subsidence, global sea level rise, shoreline erosion by major hurricanes, and erosion and flooding facilitated by numerous navigation channels cut through the wetlands could easily lead to submersion and drowning of *Spartina* marsh constructed at most or all sites where the DWH oil spill

1900 Overharvesting of oysters from the Chesapeake Bay and other estuaries contributed to dramatic changes in their ecosystems. Above, the oyster fleet in Baltimore Harbor, circa 1885. Photo: Collection of Marion Doss

The ability of restoration plans to anticipate future dynamic change will determine the success of those plans over the long term.

1970s Passage of the Clean Water Act provided the framework for regulating environmental stressors on the Gulf ecosystem. Above, oil and natural gas spew from a broken cap in Bayou St. Denis in Louisiana. Photo: Carrie Vonderhaar/Ocean Futures Society/National Geographic Stock

destroyed previous marsh habitat. Consequently, at a minimum, compensatory restoration of injuries caused by DWH oil and collateral damage from emergency response actions should contemplate expected dynamic change to ensure durability of restoration projects. At best, the long-term Gulf restoration plan would redress past insults and restore a resilient Gulf ecosystem similar in functioning to its historic baseline condition, within which compensatory restoration of habitat and natural resources injured by the DWH oil release could be self-sustaining. President Obama's mandate to address historical and immediate ecological damage in the Gulf provides an opportunity for this ideal restoration strategy; the Mabus Report, commissioned by President Obama and written by Secretary of the Navy Ray Mabus, provides a broad and bold vision for how to proceed with important aspects of fulfilling this mandate.

Fortunately, the compensatory damages funds do not represent the only source of support for DWH oil spill and broader Gulf restoration, so the limiting criteria laid out in OPA need not apply to all restoration actions that are taken in the wake of the Deepwater Horizon incident. For example, under the federal Clean Water Act of 1972 (CWA), the uses of monies from water pollution penalties for illegal discharge of oil into the ocean are not similarly constrained. CWA penalties are based on volume discharged with an additional multiplier for negligence. Particularly if negligence is established as a significant factor to the blowout, CWA penalties may represent the bulk of the DWH restoration funds. The $500 million transferred from BP to the Gulf Coast Alliance does not appear to be controlled by provisions tying the use of those funds to injured resources. Finally, it is likely that other major grantors will emerge as the restoration process takes shape; these grantors may help to multiply the synergistic benefits from related restoration projects.

Our restoration guidance is therefore intended to target administrators of several funding sources. Funding institutions will value aspects of the Gulf of Mexico variously; for this reason, we have not prioritized the restoration actions that we develop. Nor have we made detailed estimates of the costs of these 15 restoration actions. Costs of compensatory restoration actions will vary with the scale of injuries from the oil spill that require compensation. The multiple funding sources will have different goals and constraints. Many of our suggested actions address long-standing modifications of the Gulf ecosystem that fit well into the strategies articulated in initial expert responses to the spill (e.g., the Mabus Report). Others are directly related to oil spill damage and compensatory restoration. We offer these recommendations to help guide allocation of resources while plans are still being developed. Guidelines for use of the funds provided by BP as an initial payment to jump-start restoration are now vague and will be developed by the administrators. Details of how water pollution fines will be allocated are likely to be determined by Congress. Consequently, our strategy is to offer what we conclude are the most influential and justifiable actions to take, while emphasizing the principles of restoration that must guide all expenditures so as to maximize likelihood of success, achieve synergies of integration based upon ecosystem connections, re-create lost ecosystem processes associated with historical ecological baselines, and enhance resilience through knowledge of ongoing and inevitable environmental change.

Precedents and Principles for Restoring the Gulf of Mexico Ecosystem

The interdisciplinary fields of restoration ecology, conservation biology, and community and ecosystem ecology all offer scientific guidance for restoration projects. Basic research in community and ecosystem ecology sheds light on the mechanistic functions of habitats and the roles of direct and indirect interactions between species in organizing communities. Conservation biology offers strategies for protecting habitats, species and their interactions in ecosystems. Restoration ecology tends to move ahead through practice, rather than via elaboration and subsequent testing of theory (Allen *et al.* 1997, Palmer *et al.* 1997, Peterson and Lipcius 2003). These fields offer related approaches to restoration, but no overarching theory of restoration has emerged. The absence of a compelling theory that could be applied to species or habitat restoration implies that empirical assessment of successes and failures of previous restoration actions should guide new decision-making and that small-scale tests of restoration concepts should be conducted before deciding on larger-scale projects (Bernhardt *et al.* 2005). Because so much was done under the banner of restoration after the Exxon Valdez oil spill, learning from that history seems prudent before restoration decisions are made to compensate for DWH injuries to natural resources of the Gulf and to restore its ecosystem services (see box, Page 11).

Because so much was done under the banner of restoration after the Exxon Valdez oil spill, learning from that history seems prudent before restoration decisions are made to compensate for DWH injuries to natural resources of the Gulf and to restore its ecosystem services.

Oyster reefs and mangroves (shown on Sanibel Island, FL) serve important functions in the Gulf ecosystem. Photo: Brian Kingzett

Learning from the Exxon Valdez restoration efforts

In response to the DWH oil spill, Dennis Takahashi-Kelso, executive vice president of Ocean Conservancy, wrote a letter in August 2010 to the government trustees of the DWH case, offering practical guidance based upon experiences from the Exxon Valdez restoration process. Addressed to Deputy Secretary of the Interior David Hayes and Under Secretary of Commerce Jane Lubchenco, this letter drew upon a panel of scientific experts that included two of us, Senner as panel lead and Peterson as participant, each with extensive experience in habitat and species restoration after the Alaskan oil spill. In this letter, Dr. Takahashi-Kelso quotes President Obama's June 15, 2010 charge to Navy Secretary Ray Mabus and pledge to develop a long-term Gulf Coast restoration plan. Dr. Takahashi-Kelso offered support for a plan that acknowledges the importance of the National Resources Damage Assessment (NRDA) restoration process, which is the process used for OPA's "in-place, in-kind" approach. But he stressed that restoration must also go beyond those constraints. We agree that recognition of the dual mandate of the president's wider plan and the narrower compensatory restoration process driven by OPA is critically important to achieving sustainable restoration. We build upon this overarching concept to design and advocate our specific restoration suggestions.

Based in part on his own Exxon Valdez experiences and those of Senner, Peterson and others, Dr. Takahashi-Kelso makes several fundamental points about the process of restoration after natural resource damage that should be applied to the DWH oil spill restoration process. We modify and expand upon these points to formulate our suggested ecosystem-based restoration guidance (Appendix I). A summary of the most relevant points from the Takahashi-Kelso letter follows:

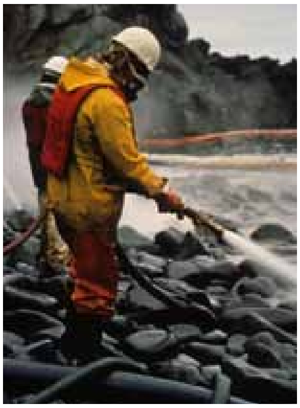
- The restoration process should be transparent to the public and should engage the public in meaningful dialogue over potential actions from an early point.
- Quick settlement of damage claims without a legal mechanism to achieve compensatory funding for restoration of unexpected, delayed injuries is not in the public interest. The legal settlement language is critical because it dictates the scope of restoration possibilities.
- Restoration should be broad to allow enhancement of injured resources over and beyond their status and condition at the time of the oil spill so as to be responsive to the need to account for past degradation and, in the process, create a self-sustaining system more similar to historic baselines.
- The scope of possibilities to be considered for restoration should be clearly defined and, for the compensatory restoration fund, limited to resources, habitats and systems that were injured by the hydrocarbon releases. Otherwise, public expectations can be misguided and overly expansive, which unnecessarily causes disappointment and bitterness.
- Care must be taken to avoid harming the ecosystem and its services by implementing untested projects that could result in negative rather than positive net impacts on resources.
- The restoration program or programs, separating the Gulf ecosystem restoration from compensatory restoration for spill injuries, should be ecosystem-based, integrating component projects into a comprehensive restoration plan across the northern Gulf.
- Division of restoration funds into state "block grants" would not achieve the synergies possible, resiliency needed and scope required to address the most critical challenges in sustaining Gulf ecosystems and their services, because those bigger challenges tend to be regional in scope and require coordinated responses.

Restoration must also be based upon science and developed using peer review by independent scientists without conflicts of interest. Some of the science needed to conduct successful restoration of important natural resources in the Gulf ecosystem, including the injuries caused by the Deepwater Horizon disaster, is not complete and needs further development before restoration can be confidently achieved (Bjorndal *et al.* 2011).

The Mabus Report

In addition to the Takahashi-Kelso letter, we take guidance from the Mabus Report (2010), which was prepared by the secretary of the Navy in response to the President's charge. Fundamentally, we endorse the recommendation of the Mabus Report that an informed and independent funding structure is necessary "to lead to long-term ecosystem, economic, and health recovery in the Gulf" (Mabus, Page 5).

Specifically, the Mabus report recommended the establishment of a Gulf Coast Recovery Council that "should work with existing federal and state advisory committees, as appropriate, to ensure that relevant scientific and technical knowledge underpins recovery planning and decision making, and that research, monitoring, and assessment efforts are organized. The Council should also provide oversight and accountability into Gulf of Mexico recovery efforts by developing quantifiable performance measures that can be used to track progress towards recovery goals" (Mabus, Page 8). However, we recommend that the (perhaps inadvertently) restricted focus on state and federal agencies be broadened to include academics and nongovernmental agencies. We enthusiastically concur with the five guiding principles for restoration (see box, Page 12) presented in the Mabus report, though we offer several cautions. We note that sediment management issues are complex, and some suggested interventions may be so narrowly focused as to be counterproductive. Additionally, monitoring conditions and processes is necessary, and the metrics of success must be identified and used to adapt the restoration actions as needed to achieve their goals.



1989 A worker operates respirator hoses during an oil dispersant application test on Smith Island in Prince William Sound after the Exxon Valdez oil spill. Photo: Alaska Resources Library and Information Service

Cormorants sit on stakes placed by researchers next to newly planted sea grass in the Florida Keys. The birds' droppings serve as fertilizer for the plants. Photo: Florida Fish and Wildlife Commission

Ecosystem Services

Natural ecosystems and their constituent organisms engage in a wide variety of processes. Some of these processes serve needs of other organisms, communities of organisms, and ecosystems; these clusters of beneficial processes are known as ecosystem services. Valuable ecosystem services have historically been taken for granted and therefore not properly considered in the process of permitting development projects. One example is the pollination of crops by honeybees. If farmers had to pay for the services of pollination instead, the costs of producing crops would be much higher. The recent decline of honeybee populations highlights our need to protect valuable ecosystem services as we modify natural systems.

Coastal wetlands have for decades been recognized for the high value of their many ecosystem services, and the importance of this delivery of goods and services has been reflected in federal and state legislation for the protection of coastal wetlands. The mantra of "no net loss of wetlands" has guided approaches to estuarine management for decades. Tidal marshes are valued, protected and restored in recognition of their ecosystem services (MEA 2005), which include:

- high primary productivity of emergent vascular plants as well as single-celled benthic microalgae and habitat provision supporting the food webs leading to fish and wildlife;
- serving as a buffer against storm wave damage to the adjoining vegetation and human development on higher ground;
- shoreline stabilization and erosion protection;
- flood water storage;
- water quality maintenance, including filtering out sediments, nutrients and pathogens;
- biodiversity preservation, especially of a suite of endemic, often threatened or endangered vertebrates;
- carbon storage as peat is accumulated, buried and stored, thus buffering greenhouse gas emissions; and
- socioeconomic benefits, such as sustaining the aesthetics of coastlines, maintaining a heritage and historical culture, supporting ecotourism, serving as a living laboratory for nature education, and promoting psychological health and supporting fishing and waterfowl hunting.

A Foundation for Durable Restoration

With guidance from Dr. Takahashi-Kelso's letter to government leaders, from published papers on ecosystem-based restoration, and from our own experience, we feel that restoration in the Gulf must rest on a solid foundation that acknowledges the past, is realistic about the future, and recognizes the interdependence of habitat, species, and human beings in the ecosystem. Therefore, durable and successful restoration in the Gulf of Mexico must:

1. **Recognize** that ecosystem resilience has been compromised by multiple human interventions predating the DWH spill;
2. **Acknowledge** that significant future environmental change is inevitable and must be factored into restoration plans and actions for them to be durable;
3. **Treat** the Gulf as a complex and interconnected network of ecosystems from shoreline to deep sea; and
4. **Recognize** that human and ecosystem productivity in the Gulf are co-dependent, and that human needs from and effects on the Gulf must be integral to restoration planning.

Mabus Principles (2010)

Our committee's reactions are in italics; details appear later. The following serve as ideal and guiding principles to restoration toward states to which the Gulf can realistically aspire. The Mabus Report asserts that they "serve as the drivers for achieving the vision of resilient and healthy Gulf of Mexico ecosystems" (Mabus, Pages 38-39).

Principle 1: Coastal Wetland and Barrier Shoreline Habitats are Healthy and Resilient. In order to sustain the many ecosystem services upon which humans rely, coastal habitats must be healthy and resilient. Reversing ongoing habitat degradation and preserving the remaining healthy habitats is a key principle. It must be recognized that even the healthiest ecosystems are dynamic, so a restoration effort should not focus entirely on a fixed "footprint." A key objective of this principle is to bring greater balance to managing the Mississippi River and other rivers for flood control, navigation, and ecosystem restoration. Another objective is to retain sediments in coastal wetlands, before they leave the river channel to the Gulf (Mabus, Page 38).

We concur with this guidance, although we express serious concern about whether the Mississippi River, with all its channelization and engineering constraints such as levees and dams, brings enough sediment to sustain wetland elevations beyond the immediate footprint of the river-mouth delta. We suggest that the organic soils of the inter-levee area can be harmed by the high concentration of nutrients in the river. We also suggest that filling dredged channels and preventing new wetland losses will be much more effective and less expensive than alternative restoration approaches.

Principle 2: Fisheries are Healthy, Diverse and Sustainable. The Gulf is home to the largest commercial fishery in the contiguous United States. The total trip expenditures for recreational fishing in the Gulf states in 2008 were nearly $1.5 billion. Key objectives of this principle may include incorporating testing and other mechanisms for seafood safety to ensure that fish and shellfish are safe for human consumption, and working through regulatory and other conservation mechanisms to restore populations of fish and shellfish (Mabus, Page 38).

We concur that conservation regulation will be required to render fishing sustainable in the Gulf, but we also identify habitat protection as a major additional process needed to develop the ecosystem support for resilient fish and shellfish populations.

Principle 3: Coastal Communities are Adaptive and Resilient. The needs and interests of Gulf communities vary and the most effective solutions will be based on local conditions. Given that much of the land affected by the oil spill is privately held, full restoration will rely on local citizen support. The impacts of climate change, including sea level rise and more frequent and intense storms, will likely alter the landscape significantly, forcing communities to reassess their priorities. Key objectives of this principle may include providing coastal managers with information and tools to make better land use and public health decisions, and increasing awareness of the connection between ecosystem and community resilience (Mabus, Page 38).

We concur and go further to add that a long-term process of social engagement with local communities to encourage understanding of the scope of unavoidable future change is required to support development of community resilience.

Principle 4: A More Sustainable Storm Buffer Exists. Persistent coastal land loss, compounded by sea level rise, is deteriorating natural lines of defense, leaving coastal communities vulnerable to tropical storms. Natural and engineered systems are necessary to reduce exposure and ensure protection. Key objectives of this principle may include maintaining and expanding natural storm buffers such as wetland and barrier islands and improving decision-making with regard to structural protection and navigation interests so that these complement and enhance restoration of natural systems. Another objective is the reduction of risk posed to people and private property through effective planning, mitigation, and balancing of interests (Mabus, Pages 38-39).

We concur while recognizing that hardened erosion protection structures and beach nourishment degrade barrier island ecosystem services and require compensatory restoration of impacts to natural resources.

Principle 5: Inland Habitats, Watersheds and Offshore Waters are Healthy and Well Managed. Communities across the nation rely on our ability to maintain healthy, resilient, and sustainable ocean, coasts, and Great Lakes resources for the benefit of present and future generations. Additional stressors on the health of these systems and the resources they support include overfishing, pollution, and coastal development. Further, ocean and coastal resources are directly and indirectly impacted by land management and use decisions in the watersheds that drain into the Gulf of Mexico. Key elements of this principle include improving management of agricultural and forest lands; restoring floodplains and wetlands to improve water quality by uptake of nutrients, reduce flood risks, and enhance wildlife habitat; reducing erosion and nutrient runoff from agricultural and developed land; and using state-of-the-art planning tools to deliver comprehensive, integrated ecosystem-based management of resources (Mabus, Page 39).

We concur with every point.

Acute and Chronic Stressors on the Gulf of Mexico Before and After the DWH Oil Spill

The DWH Oil Spill in the Gulf of Mexico

The state of the Gulf and its coastal zone immediately before the DWH incident was far from pristine, with countless stressors having already altered and degraded the ecosystem.

The Deepwater Horizon well blowout occurred April 20, 2010, resulting in explosions and fires on the drilling rig that killed 11 men, injured many more and led two days later (ironically on Earth Day, April 22) to sinking of the rig to the seafloor about 1,500 m below the surface. On April 22, substantial amounts of orange-brown crude oil appeared at the surface, confirming that a well blowout had occurred at the drill site. As the oil continued to flow for 85 days, totaling an estimated 4.9 million barrels, the nonprofit organization SkyTruth assembled and posted satellite images from infrared and radar sources depicting the location of the surface oil slick. By June 25 and 26, the slick had covered more than 24,000 square miles of the sea surface in the northern Gulf of Mexico (Norse and Amos 2010). By July 16, the day after all oil flow from the stricken well had ended, an area of about 68,000 square miles of the Gulf surface had been covered by oil (Norse and Amos 2010).

In late April, winds in the Gulf typically switch to the seasonally characteristic, southwesterly onshore direction, which would have brought the oil quickly and heavily onto shore and into shoreline habitats. Fortuitously, the spring of 2010 was not typical and lacked the spring period of onshore winds. In addition, much of the surface oil was caught up in an eddy that helped keep it at sea and prevent its transport via the Loop Current southward to the Florida Keys and then into the Gulf Stream and Atlantic Ocean. As a consequence, oil was not detected reaching shore until June 3 in Alabama. Oil ultimately grounded on hundreds of miles of beaches, marshes, sea grass beds, tidal flats and oyster reefs, despite intensive response efforts to prevent and minimize this outcome. These efforts included massive applications of dispersants both on the sea surface and injected into the plume emerging from the seafloor, skimming floating oil from the sea surface, burning it at sea, installing booms along marshes and other sensitive shorelines, diverting freshwater river discharges into marshes in an attempt to prevent intrusion of oil slicks, and dredging and filling to construct artificial berms on the coastline. Although no damage assessment test data are available, field observations suggest that these response actions caused some level of collateral injuries to wildlife and habitats, which therefore represent indirect damage attributable to the Deepwater Horizon blowout (Table 1).

Despite the emergency response efforts, the oil fouled many acres of the most valuable marsh edge habitat, fouled ocean beaches, forced closures of shellfisheries and finfisheries and decimated the economically vital Gulf tourism industry, extending at least as far as southwest Florida (Table 1). Many birds of several species were killed along shore, including brown pelicans and other species that were nesting during that spring-summer season, and marsh residents like rails. Lesser amounts of oil entered low-energy muddy habitats of marshes and mud flats, where it can persist without complete weathering for years. Consequently, the Deepwater Horizon oil release also

The skyscrapers of New Orleans are visible behind houses flooded by Hurricane Katrina. Photo: Tyrone Turner/National Geographic Stock resembled earlier shallow-water oil spills by affecting shoreline habitats of value to wildlife and to human enterprise.

Differences between DWH and other oil spills

As anticipated, the Deepwater Horizon blowout led to the oiling of sea-surface and shoreline habitats and to consequent damage to natural resources. In contrast to previous spills, however, the majority of the oil and gas released at the well-head remained far below the sea surface. An estimated 500,000 tons of gaseous hydrocarbons—perhaps half of all hydrocarbons released by the blowout (Joye *et al.* 2011)—entered the ocean yet were metabolized by heterotrophic bacteria in the deep ocean, and only 0.01 percent was vented into the atmosphere (Kessler *et al.* 2011). A large fraction of the oil was also retained beneath the sea surface because of the unique physical chemistry created by the deepwater blowout conditions. Under conditions of high-pressure deepwater discharge of hot oil and gas, the entrainment of cold seawater, caused by violent and turbulent flows at the wellhead, created a variety of dispersed phases, including fine-scale oil droplets, gas bubbles, dissolved gas, oil-water emulsions and gas hydrates. The collective buoyancy of this mixture of oil and gas created a rising plume, from which much of the oil and gas separated and was trapped by ocean stratification at depths of 800 to 1,200 m and subsequently deflected and transported by ambient currents (Joye *et al.* 2011). Massive production of methanotrophic bacteria was associated with the oil and gas in this depth stratum, causing a detectable depression of oxygen levels, but it did not approach anoxia (Joye *et al.* 2011).

The natural dispersal of oil induced by processes at the wellhead may have rendered the application of 1.8 million gallons of toxic Corexit dispersant unnecessary, but the net effect was the novel dispersal of the oil in very fine droplets and retention of a large percentage of the oil droplets in the mesopelagic and bathypelagic depths of the deep sea. Such dispersal and retention of oil in the water column as finely dispersed droplets exposes organisms living there or passing through to bioavailable, toxic oil, affecting copepods, salps, invertebrate larvae and other particle-consuming, mesopelagic zooplankters. Subsequent agglomeration of oil particles, sediments and marine snow, possibly mediated by release of muds from the well and by sticky bacterial exudates (Hazen *et al.* 2010), facilitated the transport of this oil to the seafloor, where observations of dead, soft corals and crinoids on hard bottom and polychaetes and brittle stars on soft bottom were associated with dark deposits of hydrocarbon-enriched sediments (Fisher 2010). Consequently, the process of dispersing the oil led to widespread exposures of particle-feeding organisms of the deep pelagic and seafloor realms. This oil stimulated massive production of microbes, with unknown consequences to deep-ocean food webs, in part because of the likely mortality and feeding incapacitation of the particle feeders that might consume these microbes (Table 1).

Clearly, the Deepwater Horizon oil release differs so dramatically from all previous, well-studied crude oil spills that it requires development of a completely new conceptual model, applicable not only to this spill but also to all future deepwater releases (Peterson *et al.* in press). Elaboration of this emerging model for deepwater well blowouts, including rigorous ecotoxicological models, is urgently needed to document and understand the deep-ocean impacts of this oil spill, and especially to allow for the effective compensatory restoration of lost ecosystem services.

The DWH oil release differs so dramatically from all previous, well-studied crude oil spills that it requires development of a completely new conceptual model.

What DWH indicates about failures in the deep-sea oil drilling program

The National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling (Graham *et al.* 2011a) provides an insightful and comprehensive account of the many factors over multiple time scales that led to the well blowout on the Macondo Prospect and the resulting loss of life, environmental contamination, and impacts to human enterprise along the northern Gulf Coast. The commission concluded that the spill was preventable. According to the commission, the immediate causes of the calamity were failures in management by BP, Halliburton, and Transocean on the Deepwater Horizon rig at the end of the drilling process. Communications failures among

Table 1

Major Natural Resource Damage From DWH Well Blowout

Damage from surface oil at sea

An oiled pelican stands on a rock jetty at Grand Isle, LA, after the Deepwater Horizon spill. Photo: Eileen Romero/ Marine Photobank

Resource	Damage
Seabirds	Tens to hundreds of northern gannets, brown pelicans, laughing gulls, terns, black skimmers and many others were killed and experienced fitness losses that reduced reproductive capacity.
Sea turtles	Hundreds of loggerhead, Kemp's ridley, green and leatherback turtles (all threatened or endangered species) experienced fitness loss or were killed.
Marine mammals	Bottlenose dolphins were killed.
Sargassum community	Plants were soaked with oil, hatchling sea turtles oiled, juvenile game fish exposed, forage fish and invertebrate prey exposed, resulting in community mortalities and fitness losses.
Fish and crabs	Blue crab in early life stages took up oil and dispersant with likely effects on fitness; fish in early life stages were similarly exposed.
Cannonball jellyfish and smaller gelatinous zooplankton	Physical fouling likely resulting in loss of life and fitness.

Damage from oiling of shoreline habitats

Oil from the spill is visible on a marsh. Photo: NOAA

Resource	Damage
Coastal marsh habitat	Loss of ecosystem services from hundreds of acres of heavily, moderately and lightly oiled marsh
Ocean beach habitat	Some mortality from fouling of feeding apparatus of mole crabs, bean clams, amphipods and polychaetes (prey for surf fish and shorebirds, reducing their productivity)
Sea grass bed habitat	Some mortality of sea grass with loss of its ecosystem services and mortality of sensitive species such as crustaceans and echinoderms
Tidal flat habitat	Many areas of partial loss of ecosystem services of producing fish, crabs and shrimp
Oyster reef habitat	Polycyclic aromatic hydocarbon contamination of oysters and likely slower growth and production; probable deaths of some resident crustaceans such as amphipods, shrimp and crabs.
Nearshore species	More bird deaths, including rails, pelicans, terns, black skimmers, shorebirds, gulls, wading birds; reptile deaths including terrapins and alligators; deaths of marsh mammals such as river otters

Damage from subsurface dispersed oil and gas

Dying corals have been found near the Deepwater Horizon site. Photo: NOAA OER and Bureau of Ocean Energy Management, Regulation and Enforcement

Resource	Damage
Pelagic suspension feeders	Ingestion of particulate oil and fouling of feeding apparatus caused widespread mortality of deep-sea, mesopelagic and benthopelagic guilds of particle feeders (e.g., salps, appendicularians, jellies, zooplankton), altering energy transfer through the food web
Benthic suspension feeders on hard bottoms and suspension and deposit feeders on soft bottoms	Ingestion of particulate oil and fouling of feeding apparatus caused widespread mortality of soft corals, crinoids, bryozoans, brittle stars, polychaetes—the benthos of both hard and soft bottoms
Heterotrophic microbial production throughout the water column, especially in 800–1,200m of water	Massive organic carbon enrichment resulted in localized oxygen reductions and disruptions in the food web.

Collateral damage caused by response actions

Two fishing vessels drag an oil boom after trapped oil is set ablaze in the Gulf. Controlled burns were conducted to prevent the spread of spilled oil. Photo: Jeffery Tilghman Williams, U.S. Navy/Marine Photobank

Activity	Damage
Soot releases into the atmosphere and deposition on the seafloor from burning oil	Wildlife health effects of respiring soot and possible benthic effects of its ocean deposition
Use of mechanical skimmers to remove surface oil	Contact with skimmers resulted in wildlife injuries and fatalities
Dredging and filling to create berms offshore in attempts to block oil from grounding on natural habitats	Mortality of benthic invertebrates, which serve as key prey for shrimp, crabs and demersal fish, and mortality of seabird and sea turtle eggs
Intensive repeated beach excavations and raking to remove tarballs	Simultaneous mortality of benthic invertebrates such as mole crabs and bean clams—important prey for surf fishers and shorebirds—plus removal of wrack, which serves as habitat for small crustaceans and insects consumed by plovers and other shorebirds
Sea turtle nest relocations from Gulf Coast to eastern Florida beaches	Risks of imprinting survivors to return to live along and nest on a different coast
Boom deployment offshore of marsh shorelines	Direct physical damage to marsh plants as booms break loose and are driven by waves into the marsh; occasional trapping of oil and waterbirds together, resulting in oiling and enhanced mortality of the birds
Use of 1.8 million gallons of Corexit	There is uncertainty about Corexit-generated chronic exposures to pelagic organisms, and likely fitness losses and direct mortality of particle feeders.

Ships clean up oil in the Gulf of Mexico using the same crude tools that were used after the Exxon Valdez spill 21 years earlier. Photo: James Davidson

separate specialists and failure to recognize the seriousness of inherent risks were part of a complex sequence of multiple failures that facilitated an improbable event. Although the blowout may have been improbable, an underlying and long-standing culture of indifference within both the petroleum industry and the federal regulatory agency (the former Minerals Management Service) set the stage for the blowout and made such an event inevitable (Graham *et al.* 2011a).

As the most accessible oil reservoirs are being depleted while the demand for oil increases, the petroleum industry has extended exploration and production into progressively deeper waters. This process has required remarkable engineering innovation for successful drilling in ocean waters over a mile deep and extraction of oil several miles deeper below the seafloor. Oil at such depths exists under far greater pressures than oil extracted from shallow depths, thereby increasing the need to control pressure in the well. Despite remarkable advances in engineering for oil exploration and production in deep water, corresponding progress has not occurred in blowout prevention, emergency response, clean-up and mitigation technologies. Some of the same crude tools used to respond to the oil release at the surface of the ocean by the grounded Exxon Valdez tanker in 1989—skimming and surface booming—were applied again 21 years later. Neither the industry nor government regulators had developed effective new technology for shutting down a deepwater, high-pressure blowout, as evidenced by the well-publicized and remarkably rapid conceptual development, construction and testing of tools and approaches by the industry in the weeks after April 20, 2010.

Despite remarkable advances in engineering for oil exploration and production in deep water, corresponding progress has not occurred in blowout prevention, emergency response, clean-up and mitigation technologies.

Industry complacency, failure to recognize risk and the differences between deep and shallow oil releases, and the conflicted mission of the federal regulatory agency charged with promoting development and production of oil and gas while simultaneously acting as regulator meant that appropriate advances were not made in environmental safeguards to match the heightened risks and challenges of deepwater drilling. The development and testing of effective and reliable technologies to cap a runaway blowout of a deep or ultra-deep well should have preceded the emergency need for them. Application of dispersant at the wellhead should at least have been tested in mesocosms under conditions mimicking a deepwater blowout before the decision to use it for the DWH. Toxicity tests using the unique deep-sea particle feeders at risk to finely dispersed oil should have been conducted in advance of the decision to use dispersants. In addition, scientific advances needed to understand the biological communities of the deep pelagic and benthic oceans and the physical transport regime that carries oil after release into the environment in deep water had also stalled. As a consequence, assessment of oil spill impacts from deepwater blowouts was seriously compromised.

As tragic as the DWH blowout was, it offers an opportunity. As with the 1969 blowout in the Santa Barbara Channel,[1] which led to passage of the National Environmental Policy Act (NEPA), and the moratorium on oil drilling off the California coast and other states, the DWH blowout could stimulate interest in protecting the economically, socially and environmentally critical Gulf region of the United States.

Ecosystem and natural resource impacts of oil and gas release

Before the Deepwater Horizon blowout, the prevailing paradigm of maritime oil behavior, biological exposure pathways fate, and consequent impacts to natural resources was based upon syntheses of past shallow-water, largely nearshore oil spills (e.g., NRC 2003). In such spills, crude oil remains at the surface, unless mixed into the water column by strong surface waves. If discharged below the sea surface, the oil rises rapidly to the surface because of its buoyancy. Gaseous hydrocarbons such as methane also rise to the sea surface, primarily as bubble plumes, and disperse rapidly into the atmosphere. The crude oil on the sea surface is viscous and sticky; it fouls the feathers of seabirds and the coats of fur-bearing marine mammals, causing high rates of mortality by disrupting thermoregulation and through ingestion of toxins as these birds and mammals preen feathers or fur (Rice *et al.* 1996). Other organisms that use the ocean surface, such as sea turtles, are exposed to physical fouling, potentially resulting in death. Smooth-skinned marine mammals, such as killer whales and harbor seals, risk mortality and sublethal effects on growth, reproduction and behavior from inhalation of oil globules while breathing through their blowholes and from inhaling the more volatile toxic hydrocarbons in the atmosphere. The floating oil is transported by winds and surface currents and can end up grounded on shores, where it exposes, fouls and kills intertidal and shallow subtidal organisms, including salt marsh plants, sea grasses, macroalgae and oysters that provide important biogenic habitat (Teal and Howarth 1984). Oil that penetrates into the sediments sufficiently, so that sunlight does not reach it and oxygen cannot be readily resupplied from the atmosphere, can persist for many decades without degradation (Boufadel *et al.* 2010), exposing animals that excavate those sediments to form burrows (Culbertson *et al.* 2007) or to uncover infaunal prey. This exposure can cause sublethal losses of fitness that can have population-level consequences for several years (Peterson *et al.* 2003b).

The DWH well blowout indeed led to substantial coverage of the sea surface and consequent fouling and killing of seabirds, sea turtles, bottlenose dolphins and perhaps other marine mammals, as expected from traditional shallow-water spills (Table 1). The seabirds that experienced the most loss of life include northern gannet, brown pelican, gulls, terns and the black skimmer. Aborted bottlenose dolphin fetuses were observed. Surface oil also collected in the floating *Sargassum*, a large brown alga that forms a unique floating nursery habitat in the Gulf and other seas. *Sargassum* supports large numbers of small fishes, including

Oil that penetrates into the sediments sufficiently, so that sunlight does not reach it and oxygen cannot be readily resupplied from the atmosphere, can persist for many decades without degradation.

The Menhaden Fishery in the Gulf of Mexico

The Gulf menhaden fishery dates to the late 1800s and remains economically important today. With landings of 468,736 tons in 2004, the Gulf menhaden landings comprise 11 percent of all U.S. fishery landings, and Gulf menhaden support the second-largest commercial fishery in the United States (Pritchard 2005). The menhaden catch records for years before World War II are incomplete, but annual landings from 1918 to 1944 probably ranged from 2,000 to 12,000 tons (Nicholson 1978). Landings appeared to increase from the late 1940s through 1970, with a peak of 521,500 tons landed in 1969 (Chapoton 1970, 1971). Landings continued to increase through the 1970s and 1980s, exceeding 800,000 tons for six consecutive years (1982 to 1987) and peaking at 982,800 tons in 1984 (Smith 1991). Since 1988, the landings have ranged from 421,400 tons in 1992 to 761,600 tons in 1994, showing no apparent trend. Although the menhaden landings do not appear to be declining further from the 1982–1987 levels, the potential for overfishing is still a concern and must be considered in the future management of this important fishery. Because menhaden is a forage fish for many predatory pelagic fishes, seabirds and marine mammals, reductions in stock levels by fishing may have consequences for the health and viability of populations of higher trophic-level predators (Botsford *et al.* 1997). To the extent that these higher-order predators are protected by law, these indirect ecosystem-based issues associated with menhaden harvest are likely to represent a critical management concern. The menhaden fishery's history indicates limited consideration for ecosystem-based impacts, yet as the ocean environment continues to change, management of this highly productive fish stock will need to take into account a broader range of factors that drive menhaden dynamics, including DWH oil spill impacts, and a wider range of consequences of fishing, including impacts on threatened and endangered species and on species injured by the oil spill. Menhaden represent one of many fish stocks for which ecosystem consequences of fishing need to be considered in a context of the changing Gulf environment so that sustainability is incorporated into management.

A menhaden fishing boat in Empire, LA. Photo: Louisiana Sea Grant College Program/ Louisiana State University juvenile bluefin tuna, cobia and wahoo, as well as crustaceans and other invertebrates that help feed juvenile predatory pelagic fishes. In addition, this is the critical habitat for juvenile loggerhead, Kemp's ridley and other sea turtles from the time of leaving the nest until they return to coastal waters. Large numbers of sea turtle hatchlings were recovered dead and dying from the *Sargassum*.

Damage to the Gulf of Mexico Prior to the DWH Oil Spill

1890s Green turtles are prepared for shipping to New York from Key West, FL, in 1898. The Gulf sea turtle fishery peaked in the late 1800s and then declined sharply because of overexploitation. Photo: Florida Keys Public Libraries

The state of the Gulf and its coastal zone immediately before the DWH incident was far from pristine, with countless anthropogenic stressors having already altered and degraded the ecosystem. In the Gulf and other ocean ecosystems, anthropogenic degradation is a historically cumulative process (Jackson 1997, 2010, Jackson *et al.* 2001, 2011), and an understanding of that degradation process is critical to successful restoration. Stressors can synergistically intensify their impacts over time and across systems and species in ways that may result in alternative and less desirable ecosystem states (Scheffer *et al.* 2001). Thus, attempts to repair the consequences of more recent disturbances in any ecosystem will necessarily fail unless restoration addresses all of the drivers of degradation both present and past. Consequently, the restoration should incorporate an understanding of the baseline natural processes of the ecosystem, the historical degradation of those processes, and the way in which progressive environmental changes in the ecosystem might affect restorative actions. The durability of restoration depends upon consideration of these factors. This section outlines some of the major historical and anthropogenic stressors on the Gulf ecosystem.

Humans have been active in the Gulf ecosystem for thousands of years, ranging from centuries of subsistence fishing and harvesting of nearshore resources by Native Americans to oil and gas extraction in the 20th and 21st centuries. The impacts of human activities include bottom habitat modification and population reductions in targeted fish and shellfish stocks and in species killed as bycatch from large-scale commercial and recreational fishing; channelization and damming of major rivers flowing into the Gulf; widespread and rapidly accelerating coastal development with its attendant modification of hydrology, increases in impermeable surface area, and dredge-and-fill activities in wetlands; extractions of subsurface fluids such as oil, gas and groundwater, which induce subsidence; water quality degradation from agricultural, urban, and industrial runoff of nutrients; and the burgeoning impacts of anthropogenically induced global climate change. The Gulf has endured the consequences of uncontrolled nutrient runoff and eutrophication because of agriculture upstream (Rabalais *et al.* 2002, 2007); overfishing and associated habitat destruction from trawling; and loss of habitat because of coastal development, land subsidence, channelization of wetlands, intensification of severe storms, and sea level rise. The historical context of each of these human modifications of the ecosystem is presented below.

Centuries of fishing in the Gulf of Mexico

The first significant human impact on the Gulf ecosystem was probably caused by fishing in coastal estuaries by Native Americans. Although no recorded evidence exists, Native American fishing may have particularly affected accessible species such as oysters near shore (Jackson *et al.* 2001, Lotze *et al.* 2006). This effect may have been minimal: From the time of Columbus's landing through the early 1600s, there were accounts of large abundances of fish, oysters, sea turtles and marine mammals found in the Gulf and the Caribbean. However, by the early 1800s, many of these organisms were already being overfished (Jackson 1997, Jackson *et al.* 2001), and exploitation increased through the 19th century. The sea turtle fishery peaked in 1890, when turtles ranked 10th among fishery products from Gulf states and fifth in Texas, and declined sharply after 1892 due to overexploitation (Doughty 1984).

Advances in fishing technology affected the Gulf as vessels and catching devices improved the efficiency of fishing. The transitions from sailing vessels in the late 1800s to steamers in the early 1900s and then to diesel-powered vessels in the 1930s each increased the impact that fishing had on marine populations. The introduction of purse seines and longlines in the late 1800s, otter trawls for groundfish and shrimp in the early 1900s, and more recent advances such as durable nylon fibers for nets, Loran-C, and GPS navigation systems dramatically increased efficiency, the ability to target specific sites, and the size of catches. Refrigeration also helped increase demand by creating globalization of markets.

These technological advances in the commercial and recreational fishing industry have contributed to overfishing and the subsequent decline of major fisheries in the Gulf, including Spanish and king mackerel, red snapper, several species of grouper, red drum and many pelagic shark species (UN FAO 2005, Coleman *et al.* 2004a, Baum and Myers 2004). The U.S. National Marine Fisheries Service reported that in 2002, the five Gulf Coast states landed a total of more than 1.7 billion pounds (771,800,000 kg) of fish, including Gulf menhaden (see box, Page 20) and shellfish, worth more than $705 million. These landings, however, do not include the many pounds of bycatch (including juvenile commercial fishes, forage fishes, birds, sea turtles and marine mammals) that are associated with many fisheries (Moore *et al.* 2009), making the total extraction of fish and wildlife from fisheries much greater.

Gulf landings of shrimps and oysters account for about 68 and 70 percent, respectively, of total U.S. landings. Although impacts of fishing on populations of these animals are not well documented in the Gulf, the indirect effects of their harvest on the benthic habitats and the communities of invertebrates and fish that they support have been well studied in recent decades. Trawling for shrimp and groundfish disturbs bottom habitat and reduces the species diversity, abundance and biomass of bottom-dwelling organisms that serve as a food source for many demersal fish and crustaceans (Collie *et al.* 1997). Different assemblages of fish and crustaceans can also be associated with habitats frequently disturbed by trawling, indicating shifts in community structure at multiple trophic levels (Wells *et al.* 2008). Such bottom disturbance resets the benthic invertebrate community to an early successional stage of small, short-lived invertebrates. When combined with the loss and degradation of coastal habitats induced by other stressors, continued intense fishing pressure and bottom disturbance associated with trawling and dredging may cause even more habitat modifications and reductions in fish stocks.

Fishing is a major pillar of the contemporary Gulf coastal economy. Achieving sustainable harvest levels at higher stock abundances would result in millions of dollars' worth of enhancement to Gulf state economies. Our Gulf restoration actions under Theme 3 (see Page 75) include suggestions for achieving sustainable levels of extraction of fish and shellfish at high yields while also minimizing impacts on wildlife.

Late 1800s Sailing vessels were replaced by steam vessels. Credit: NOAA

Pollution in the Gulf

Trends in nutrient loading and pollution
Nutrient loading, sedimentation and discharges of other pollutants into the Gulf has increased over the past 200 years as a consequence of more intense human occupation, development and use of land in the Mississippi River watershed and other rivers entering the Gulf (Turner 2009). The concentration of nitrate and phosphorus in river systems that feed into the Gulf, such as the Mississippi, increased three- to fivefold between the early 1900s and the 1990s and may continue to rise with increasing demands for food and, more recently, for corn and other crops used in ethanol production in the Midwest (Figure 2; Turner *et al.* 2007). The concentrations of pollutants such as heavy metals have increased in the sediments, and these increases are probably associated with oil drilling activities in the Gulf (Vazquez *et al.* 2002). Increased levels of mercury and some other toxic contaminants in the Mississippi River and other rivers leading into the Gulf can be linked to settlement of the Midwest by European immigrants in the mid-1800s. Contaminant concentrations of heavy metals peaked in the 1960s and have since declined, primarily in response to environmental laws enacted in the 1970s such as the Clean Water Act (Wiener and Sandheinrich 2010).

The concentration of nitrate and phosphorus in river systems, such as the Mississippi, that feed into the Gulf increased three- to fivefold between the early 1900s and the 1990s.

Despite regulatory protections, mercury and organic pollutants, such as DDT and PCBs, which were released into the Gulf watersheds before effective regulation, have gradually biomagnified to concentrations adversely affecting apex predators (Wiener and Sandheinrich 2010).

Impacts of nutrient loading and pollution

Salt marshes, sea grass meadows and oyster reefs act as filters for nutrients and other pollutants, but the process of trapping excess nutrients, heavy metals and toxic organic chemicals has ecological consequences (Dame *et al.* 1984). Although nutrient enrichment is not the primary cause of wetland loss in the Gulf, it appears to contribute to it. From 1998 to 2004, 370,760 of the 3,508,600 acres of saltwater wetlands along the Gulf Coast were lost, more than along any other U.S. coastline (Stedman and Dahl 2008).

1920s–present Widespread application of pesticides and fertilizers occurred on agricultural lands beginning in the 1920s and continuing today. Photo: Willard Culver/National Geographic Stock

In general, nutrient enrichment of wetlands results in higher aboveground standing biomass (Morris 1991). However, belowground production is more critical than aboveground production to sustaining marshes as sea level rises. The production of roots and rhizomes elevates the marsh surface at rates that can help compensate for relative sea level rise. Results from a 30-year experiment in salt marshes in Massachusetts show that eutrophication does not increase organic matter accumulation belowground but instead weakens soil strength and may cause a significant loss in marsh elevation equivalent to about half the average global sea level rise rates (Turner *et al.* 2009). Therefore, sustaining and restoring coastal emergent marshes is more likely if they receive fewer, not more, nutrients.

Like wetlands, other biogenic shoreline habitats have suffered significant degradation and loss from nutrient enrichment in the decades before the DWH oil spill. Nutrient loading can cause massive blooms of phytoplankton, microalgae and macroalgae, which can compete with benthic sea grasses (Hughes *et al.* 2004, Burkholder *et al.* 2007) and corals (Anthony *et al.* 2011) for light and oxygen and can interfere with oyster spat settlement on reefs (Thomsen and McGlathery 2006). Orth and van Montfrans (1990) estimated that sea grass covered 2.47 million acres (nearly one million hectares) of the Gulf; sea grass habitat losses over the past 50 years, however, have been estimated at 20 to 100 percent for most northern Gulf estuaries (Duke and Kruczynski 1992). Similarly, losses of 50 to 89 percent are estimated for oysters in the Gulf from baselines ranging from 20 to 130 years ago to the present (Beck *et al.* 2011). Coral reefs in the Gulf have experienced coral bleaching and disease outbreaks attributed to anthropogenic stressors in the past few decades, resulting in losses in total coral cover on some reefs (Knowlton and Jackson 2008). Because of the known stress of excess nutrients on these organisms, we can attribute some aspect of these losses to nutrient loading. Nutrient loading is likely to continue to increase in the coming decades and could interfere with successful restoration of coastal wetlands and subtidal biogenic habitats of the Gulf if it continues unabated.

Dead zones in the Gulf of Mexico: The consequences of hypoxia

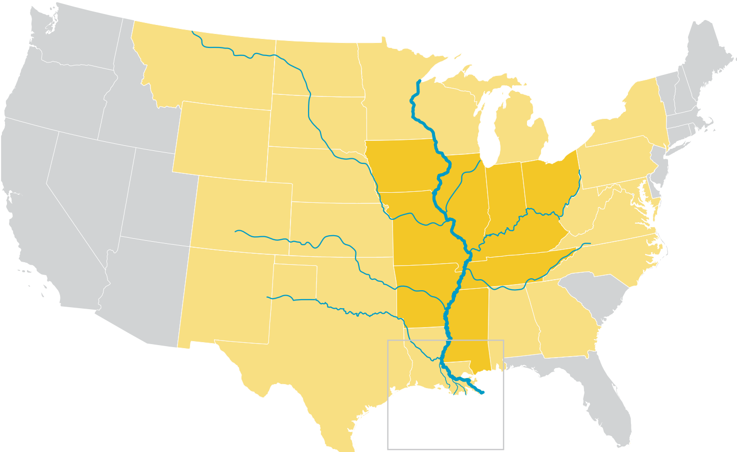
In large part because of nutrient loading, hypoxia (dissolved oxygen < 2 mg l^{-1}) is a growing problem worldwide in estuaries and coastal oceans (Rabalais 2002, Diaz and Rosenberg 2008). The extent and persistence of hypoxia on the continental shelf of the northern Gulf make the Gulf's "dead zone" the second-largest manifestation of anthropogenic coastal eutrophication in the world (Figure 2). Systematic mapping and monitoring of the area of hypoxia in bottom waters began in 1985 (Rabalais 2002). The dead zone size, as measured each year in July, has ranged between 40 to 22,000 km² and averaged 16,700 km² from 2000 to 2007 (excluding two years when strong storms occurred just before the hypoxia survey).

An Action Plan for Reducing, Mitigating, and Controlling Hypoxia in the Northern Gulf of Mexico (Mississippi River/Gulf of Mexico Watershed Nutrient Task Force 2001) endorsed by federal agencies, states and tribal governments calls for a long-term adaptive strategy coupling management actions with enhanced monitoring, modeling and research, and reassessment of accomplishments and environmental indicators at five-year intervals. Several models summarize the relationship between the nutrient loading of nitrogen and phosphorus and the severity of the hypoxic zone (Figure 2; Rabalais *et al.* 2007) and support

Figure 2

Mississippi River Basin

Rivers, estuaries and tributaries from the 48 contiguous states run off into the Gulf via the Mississippi River basin. Source: USDOI and USGS 2008



States that run off into the Gulf

More than 75% of nitrogen and phosphorus runoff comes from Illinois, Iowa, Indiana, Missouri, Arkansas, Kentucky, Tennessee, Ohio and Mississippi

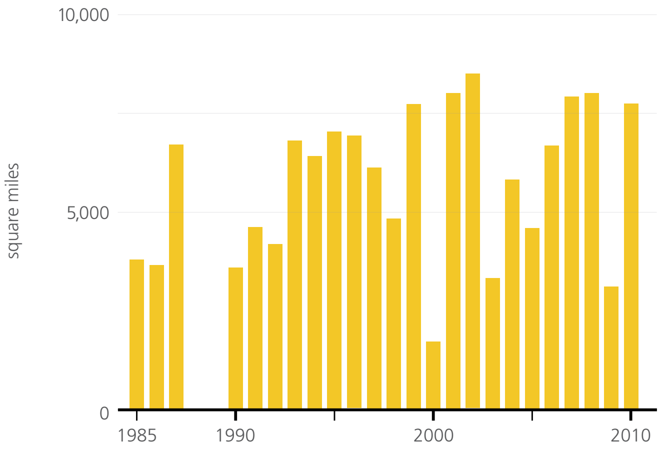
Hypoxic "Dead" Zone

When dissolved oxygen levels reach two milligrams per liter or less—a condition called hypoxia—most slow-moving or attached animals suffocate, creating areas known as dead zones in the bottom waters. The dead zone in the northern Gulf of Mexico is nearly the largest in the world, averaging 6,700 square miles (17,300 square kilometers) over the past five years; it is second only to the hypoxic zone in the Baltic Sea.

The maximum area of this dead zone was measured at 8,481 square miles (22,000 square kilometers) during the summer of 2002; this is equivalent to the size of Massachusetts.

Year-to-year area of Gulf of Mexico hypoxia, shown in square miles

No data available for 1988 and 1989.
Source: Rabalais et al. 2010



Agricultural sources contribute more than 70% of the nitrogen and phosphorus delivered to the Gulf, versus only 9 to 12% from urban sources.

Nitrogen

66% comes from growing crops, especially corn and soy. Other sources include atmospheric deposition (16%), urban and population sources (9%), pasture and range (5%), and natural land (4%).

Phosphorus

43% comes from crops, especially corn and soy, and 37% comes from range and pasture, particularly animal manure. Other sources include urban and population sources (12%) and natural land (8%).

Source: Alexander *et al.* 2008

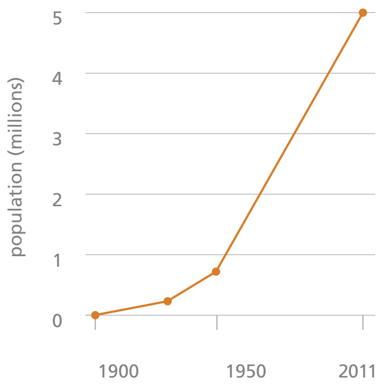


Figure 3

South Florida Population Growth Since 1900 South Florida's population has grown from 5,000 in 1900 to a current population over five million. Source: Walker *et al.* 1997

Coastal Development in South Florida

South Florida, consisting of seven counties, supported a population of only 5,000 people in 1900. By 1930, after Henry Flagler, a principal in Standard Oil, completed the Miami railway, the population had grown to more than 230,000. With this population surge came large increases in agriculture in the first half of the 20th century, with more than 55,000 hectares of farmland by 1943, accompanied by the destruction of coastal mangrove forests and the Everglades wetlands, and then large increases in residential and urban development in the latter half of the 20th century. Massive flooding in the late 1940s with burgeoning mosquito populations caused the federal government to build dikes around Lake Okeechobee to provide flood protection for the growing urban areas to the south and to build mosquito abatement ponds throughout the area. By 1950, the South Florida population reached 720,000, primarily associated with migration of retirees into suburban single-family residences surrounded by golf courses, pools and urban centers (Walker *et al*. 1997). Today the population is over five million, representing one of the highest growth rates in the United States from 1900 to the present.

Because of the high rate of development, many of the functions of the ecosystems in South Florida are no longer being performed. Erosion has become a major problem on the coast, largely as a result of severed water and sediment transport pathways from upstate down through the Everglades and to Miami, loss of mangroves on shore, consequences of channel dredging, and impacts of subsidence caused by groundwater extraction. With sea level rise now threatening to flood all of South Florida (Figure 8), restoration efforts in this region must address a suite of ecological issues to restore long-term sustainability and resilience of ecosystems and human communities.

1980–2008 The population of the five Gulf Coast states increased by 45 percent. Above is Panama City, FL. Photo: Ray Devlin

the key component of the management action, which is to reduce nutrient loading to the Gulf of Mexico so that the average hypoxic area in summer is 5,000 km² or less by 2015. Turner *et al.* (2008) suggested that there was an increase in the oxygen demand of marine sediments arising from the accumulation of organic matter and that the accumulation in one year made the system more sensitive to nitrogen loading the next year. Remedial actions meant to reduce the size of the hypoxic zone must address these future increases in nutrient loading and today's legacy of eutrophication.

Land loss along the Gulf Coast

Coastal development

The population of the five Gulf Coast states increased by 45 percent between 1980 and 2008. More than 20 million people are now living on the Gulf Coast, with coastal counties in Texas and Florida (see box above) experiencing the largest population increases (Crossett *et al.* 2004). Increases in residential, commercial, industrial and agricultural development have accompanied this population increase, resulting in the loss of coastal forests and wetlands and increases in storm water runoff and transport of nutrients and sediments into the Gulf.

Channelization, levee construction and damming have limited floodwater flows onto the flood plains, thereby suppressing the transport, deposition and retention of sediments to enrich the soils and vegetation. Motivated by a desire to create more waterfront real estate with riparian access for large boats, aggressive construction of "finger channels" (see photos, Page 26) took place in the mid-1950s to late 1960s along much of the coast of south Florida. The dredge-and-fill operations were often conducted directly over mangrove forests or oyster reefs, as illustrated in these photos. In addition to destroying critical fish habitats, aggressive construction in the estuaries

1950s–1960s Finger channels were constructed over mangrove and oyster reef habitats in South Florida. The reduction in bay size from filling also had a substantial impact on the tidal inlets and on sediment supply to adjacent beaches. Photos: Courtesy of Ping Wang

reduced the bay size and altered the sediment dynamics of the tidal inlets and the nearby ocean beaches (Wang *et al.* 2011).

Compounding the rapid residential development, dredging for oil and gas extraction has been causally linked to coastal wetland loss in the Gulf. More than 90 percent of U.S. offshore oil and gas reserves, past production and present yields are in the coastal waters of the Gulf of Mexico, but the inshore recovery peaked more than a decade ago. Large-scale efforts to slow or reverse wetland losses along the Gulf began in the early 1990s, focused on construction of river diversions. Such projects make up the largest and most expensive strategy for addressing wetland loss in the Louisiana coastal area, with future costs possibly reaching several billion dollars. Dredging navigation routes through Gulf coastal wetlands began at least 200 years ago (Davis 1973), but it was the canals dredged for oil and gas recovery efforts beginning in the 1930s and peaking in the 1960s (Figure 4) that had demonstrable and coastwide influences on wetlands. The direct impact of dredging on wetlands amounted to 1,017 km^2 of canals in 1990 (Britsch and Dunbar 1993), with an equal area of spoil banks stacked on the adjacent wetlands (Baumann and Turner 1990). There is a much larger indirect impact from canals and the dredged spoil deposits that is demonstrable at several temporal and spatial scales. For example, 1) land loss rates in the deltaic plain, in similar geological substrates, are directly related to dredging; 2) the amount of land loss where dredging is low is near zero; and, 3) the land loss rates accelerated and slowed when dredging rose and slowed in the Barataria basin (Turner *et al.* 2007b).

The rise and fall in dredging is coincidental with the rise and fall of wetland loss (Figure 4). Other plausible explanations for wetland loss are related to the loss of the accumulated organic matter and plant stress accompanying an altered hydrology (Swenson and Turner 1987, Turner 1997, 2004). But the fact that sea level rise, soil subsidence and the concentration of suspended sediment in the river have remained about the same from the 1960s to the present (Turner 1997, Turner and Rabalais 2003) supports the conclusion that the current dominant cause of Gulf wetland loss is dredging.

Dredging is regulated and authorized through permits issued by state and federal agencies, and the permitting process does not appear to reflect the foreseeable consequences for wetland loss. Damage that is now evident was largely completed before critical analyses of wetland impacts of canal dredging were completed. But even today there is no coastwide restoration program that specifically targets compensating for the direct and indirect impacts of canals and spoil banks on wetland loss. Existing canals and any future dredging and canal construction could compromise DWH restoration efforts if they occur within areas targeted for restoration.

The rise and fall in dredging is coincidental with the rise and fall of wetland loss.

1918 A canal is dredged in New Orleans. Photo: Team New Orleans/U.S. Army Corps of Engineers

Figure 4

Relationship between land loss and canal density in the Louisiana coastal zone The study measures land loss over five time periods between 1930 and 2000. Source: Adapted from Turner *et al.* 2007b

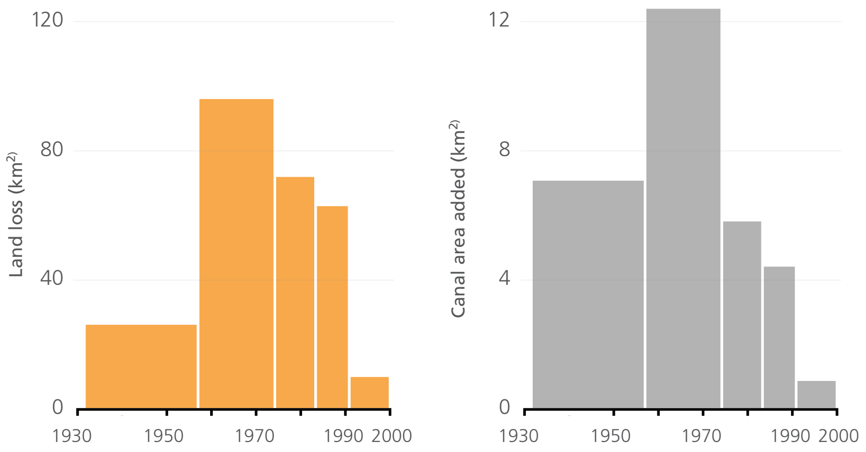
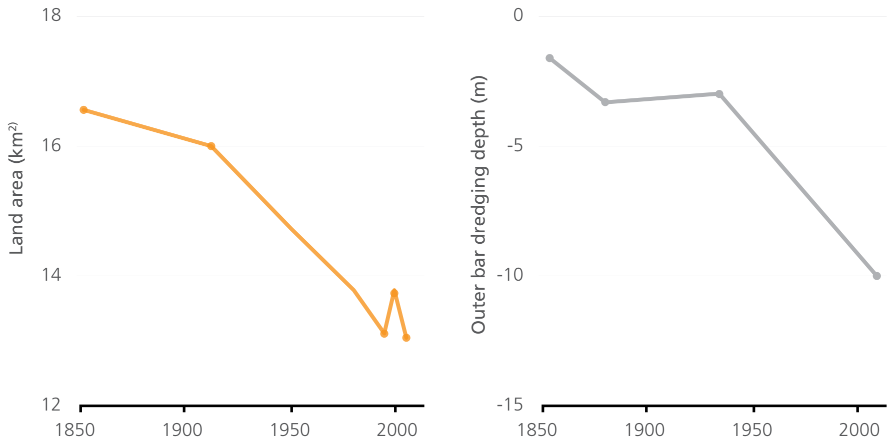


Figure 5

Land loss trends for Horn Island, a Mississippi-Alabama barrier island (left), compared with depths of shipping channels dredged through the outer bars at the Horn Island Pass. Source: Adapted from Morton 2008



The sinking coastline: unsustainable oil, gas and groundwater extraction

Although natural subsidence processes, such as sediment compaction and downwarping of underlying crust (e.g., in the Mississippi River Delta plain, Barataria Basin, and Atchafalaya Basin) are occurring along the coast, the withdrawals of subsurface oil and gas are also major contributors to Gulf wetland loss in some places (Kennish 2002). For example, the rates of soil compaction and eustatic sea level rise along the upper Texas coast can exceed 13 millimeters per year (mm yr^{-1}), while human-induced subsidence rates can be as high as 120 mm yr^{-1} (White and Tremblay 1995). In the Houston-Galveston area, withdrawal of groundwater has caused up to three meters of land surface subsidence, with the rate of subsidence ranging from 10 mm yr^{-1} to more than 60 mm yr^{-1} (Gabrysch and Coplin 1990).

Beach nourishment to compensate for land loss

As sea level rises and hurricanes and other storms subject barrier beaches to high wave run-up and beach erosion, the land forms can change dramatically. With rising sea level, barrier islands commonly roll over through the process of over-wash and become reestablished in a new location displaced landward (Figures 9, 10). This process represents a natural dynamic of sandy shorelines, although the greenhouse gas-driven high rates of present and future sea level rise are abnormal. So long as barrier islands and coastal barrier beaches are not developed and residents do not attempt to draw permanent property lines, the roll-over of coastal barriers does not represent a problem (Figures 9, 10). However, when houses, roads and other infrastructure and businesses are constructed on these mobile

Figure 6

Detail of northern coast of Gulf of Mexico

See Gulf overview map Page 2. See Barrier Island detail maps on Pages 34–35 (Isles Dernieres and Chandeleur Islands).

lands, then engineered hard structures such as seawalls and jetties or soft solutions such as beach nourishment are typically pursued to protect the investments. Stabilizing costal barriers under the emerging context of accelerating rates of sea level rise and enhanced frequency of intense tropical storms will make occupation of coastal barriers along the Gulf Coast increasingly expensive, environmentally damaging and potentially too costly to maintain, especially on the rapidly subsiding Mississippi Delta.

Beach excavations to locate and remove buried oil and tarballs also represent physical habitat disturbances that can bury and kill the invertebrate prey for shorebirds and surf fish, but this is a brief pulse disturbance from which recovery should occur within a year. Removal of plant wrack composed of marsh macrophytic and sea grass materials takes away a resource that nurtures insects, amphipods, isopods and other invertebrates that serve as prey for shorebirds, especially plovers. Consequently, this intervention into sandy beach habitats also represents degradation of ecosystem services. Potential impacts on the threatened piping plover are especially critical to assess.

Alterations of river systems that lead into the Gulf of Mexico

The watersheds in the Gulf contain a range of habitats that support biologically diverse and productive ecosystems with both nursery and feeding grounds for ecologically and economically important species (Livingston 1997, MCWMP 2007). Although representative bays have a number of morphologic and hydrologic similarities, they differ in the extent to which they have been affected by anthropogenic changes and in their loss of ecological integrity over the past few decades (NOAA 2009). For example, the Mississippi Sound, near metropolitan New Orleans, is heavily affected by sewage outflows, agricultural drainage and intensive development, while the Apalachicola Bay system is still relatively pristine and is the last bay of that quality in the northern Gulf of Mexico. A tremendous advantage in the scientific study of these systems is that each contains established National Estuarine Research Reserves (NERRs), thus providing investigators with access to significant stores of existing data, new or recently developed numerical

A sign warns of a pipeline crossing in Louisiana. Because of coastal erosion, many pipelines are closer to the surface and in open water. Photo: Paul Goyette

The Pearl darter, a rare small fish, is one of the threatened or endangered species in the Gulf region. Photo: Joel Sartore/ National Geographic Stock

Environmental Concerns Related to Petroleum Storage in Salt Domes

The practice of storing oil in salt domes throughout the Gulf of Mexico has gone on for more than 40 years, with active storage sites in Louisiana and Texas (DOE 2011). Domes are considered ideal storage receptacles because the salt forms a seal around contained substances, creating a stable reservoir. But leakages in similar domes off Weeks Island, LA., have proven problematic, resulting in the removal of petroleum stores and abandonment of the site (Neal 1997, Neal *et al.* 1998, Kurlansky 2002). Undoubtedly, heterotrophic microbes exist in the continental shelf that can degrade petroleum hydrocarbons relatively rapidly, but if the oil leakage creates significant patches of floating oil or contaminates oysters or other shellfish, then leakage is clearly unacceptable.

A proposal from the DOE to create a petroleum reserve site in Mississippi salt domes, which was recently withdrawn, threatened the Pascagoula River basin. The process for preparing the Mississippi site for oil storage would involve inundating the dome each day with millions of gallons of freshwater drawn from the river to dissolve the salt and then pumping out the resulting hypersaline (264 parts per thousand) solution into a pipeline constructed over 1,500 acres of wetlands to transport it 80 miles to the Gulf of Mexico. The activity would take five to six years to complete, severely reduce flow in the Pascagoula and discharge millions of gallons of salt brine just south of Horn Island, a 2,763-acre barrier island that is part of a group of islands along the Mississippi coast that the federal government has spent millions of dollars to protect. Other anticipated damage includes saltwater intrusion from the Mississippi Sound up the river, with potentially devastating outcomes (if the damage caused by Hurricane Katrina is any indication) and development of a dead zone near the outfall from the pipeline. Although the proposal was withdrawn in March 2011, it still looms over the river's future.

models, and guidance of NERR managers with tremendous expertise in the needs of coastal and environmental decision-makers. Research conducted in these reserves can help to restore unimpeded water flows, improve water quality and restore and protect riparian in-stream habitats of high value. Below are short descriptions of several Gulf waterways and their known historic stresses.

The Mississippi Sound System

The Mississippi Sound (drainage area, 69,700 km^2) is a shallow estuarine system that extends from Lake Borgne, Louisiana, to Mobile Bay, Alabama. It receives freshwater through marsh habitat runoff and seven watersheds (from west to east, the Pearl, Escatawpa, Pascagoula, Tchoutacabouffa, Biloxi, Wolf and Jourdan Rivers) and occasionally receives large freshwater inputs via Mississippi River flood control releases that can cause low-salinity anomalies that last for months. It exchanges water with the Mississippi-Alabama-Florida (MAFLA) Shelf through barrier island passes involving seven primary islands, including Grand Island, Cat Island, West Ship Island, East Ship Island, Horn Island, Petit Bois Island and Dauphin Island. The shelf-scale hydrography is dominated by seasonally shifting winds that influence salinity patterns, creating offshore-directed salinity gradients driven by river discharge. Seasonal differences result in westward-directed transport over the shelf during fall and winter, reducing the local influence from the Mississippi River, while low-salinity water spreads over the shelf during the spring and summer, resulting in a strong halocline (Morey *et al.* 2003a, b).

The Pascagoula River (drainage area, 23,310 km^2), the second-largest basin in Mississippi, is the last unimpeded river system in the continental United States and the largest contributor of freshwater to Mississippi Sound. Unobstructed flow and natural fire regimes are critically important in maintaining the high productivity of bottomland forests, marshes, savannas and aquatic habitats that support an enormously diverse biota, including 22 threatened or endangered species. Among these are species found only in Mississippi, including the Pearl darter (*Percina aurora*), a rare small fish found only in the Pascagoula and Pearl River drainages, the Mississippi sandhill crane *(Grus canadensis pulla*), critically endangered nonmigratory birds, the yellow-blotched map turtle *(Graptemys flavimaculata*) and the Louisiana black bear. The river basin also provides habitat to other species endangered throughout their range, such as the red-cockaded woodpecker, swallow-tailed kite (*Elanoides forficatus*) and Gulf sturgeon (*Acipenser oxyrhynchus desotoi*), among others. Stresses to the Pascagoula River ecosystem include invasive plant species; sedimentation from mining and other activities; water withdrawal for use in agriculture, industry and domestic purposes; and direct discharge of pollutants, especially nutrients, from industrial or municipal wastewater treatment facilities, mining and waste management. Although these stresses take their toll, another concern is a proposal from the U. S. Department of Energy (DOE) to create a petroleum reserve site in Mississippi salt domes (see box, Page 29).

The Perdido River (drainage area 2,937 km²) provides the primary freshwater source for Perdido Bay, a relatively small, shallow estuary at the Alabama-Florida border. The bay is affected by two interwoven problems: artificial widening of its mouth in the 1970s and nutrient loading that started as early as the 1940s. The widening of the bay mouth to help retain sediment led to the unanticipated consequence of saltwater intrusion into the bay. This contributed significantly to salinity stratification, the development of hypoxia and ultimately serious declines in benthic invertebrates and fish assemblages in the deeper waters of the bay. The overall effect was disruption of local food webs. Nutrient loading created a different set of trophic problems. The nutrients entered the bay from multiple sources, including effluents from a paper mill (operated by International Paper; effluent enters Eleven Mile Creek), urban storm water and sewage runoff (the area around the bay is highly developed), and agricultural runoff from Alabama (Livingston 2000, 2001, 2007). The introduction of different nutrients at various times of the year stimulates a series of phytoplankton blooms, with diatoms predominating in the spring, raphidophytes in summer and dinoflagellates in winter. When these become coupled with high concentrations of orthophosphate and ammonia from the mill, the outcome is characterized by the loss of planktivorous infaunal invertebrates. Teasing apart these multiple effects is quite difficult without intensive food web modeling that takes into account benthic conditions, planktonic responses to nutrient loading, and climate change. Clearly, both top-down and bottom-up processes act on this system (Livingston 2007).

The pulp mill adopted some strategies to reduce nutrient input, and these resulted in some improvement in the complex of infaunal species. Although much remains to be done, the only solution proffered by the industry (and approved by Florida's Department of Environmental Protection [DEP]) was to build a pipeline that would move the effluent discharge site from the upper stretches of Eleven Mile Creek to the mouth of creek. This would help clean up Eleven Mile Creek, but it would do nothing to stop the arrival of pollutants in Perdido Bay. Within months of approving this plan, DEP Director David Struhs retired to become vice president for environmental affairs at International Paper. This plan illustrates one of the many challenges of large-scale restoration projects: the intertwining of industry and government interests in the use of natural resources.

The Pascagoula River is the largest contributor of freshwater to Mississippi Sound. Photo: Jennifer Cowley/Plan for Opportunity

The Apalachicola System

Apalachicola Bay (drainage area, 50,674 km²) (Figure 7) consists of a large estuary with extensive wetlands that receive water from the Apalachicola, Chattahoochee and Flint Rivers (the ACF watershed). The Apalachicola River, the largest river in Florida and among the largest entering the Gulf of Mexico, provides 35 percent of the freshwater input to the northeast Gulf (Richter *et al.* 2003). Apalachicola Bay, covering approximately 1,012 km², is one of the more productive estuaries in North America, supplying approximately 90 percent of the oyster landings (*Crassostrea virginica*) in Florida and 10 percent nationally It also provides nursery habitat for

Apalachicola Bay is one of the more productive estuaries in North America, supplying approximately 90% of the oyster landings (*Crassostrea virginica*) in Florida and 10% nationally.

Figure 7

Detail of northeast coast of Gulf of Mexico

See Gulf overview map, Page 2

The Big Bend coastal region in Florida includes Apalachicola Bay, St. Joe Bay and the Fenholloway, Suwanee and Ochlockonee Rivers.

A blue crab prepares to fend off an intruder among the rocks in the Florida Keys. Photo Courtesy of 1stPix

numerous economically important fish and invertebrate species (Livingston *et al.* 1974, Livingston *et al.* 1997). The adjacent west Florida shelf, extending along the length of the Florida peninsula and the panhandle, makes up 75 percent of the total U.S. Gulf continental shelf and contains some of the most diverse and economically important marine habitats (e.g., salt marsh, sea grass meadows, coral reefs) and fisheries (e.g., snappers, groupers) in the nation (Coleman *et al.* 2000, Koenig *et al.* 2005). Despite its great importance to Gulf state economies, this system remains relatively unstudied in terms of defining its influence on ecologically and economically important species in inshore and nearshore environments.

The major water bodies of the estuary are East Bay, Apalachicola Bay and St. George Sound. A series of inlets (one of which is man-made) allows sediment and seawater exchange with the Gulf. The Apalachicola River is the principal source of sediment for the development of the barrier islands, despite the presence of a dam approximately 115 km upstream from its mouth, with beach sand dispersion having a net westward transport. Circulation in the bay is dominated by local winds and tides, whereas hydrography and salinity are dominated by river flow on multiple time scales (Conner *et al.* 1982), although salinity is also influenced secondarily by freshwater drainage from Tate's Hell Swamp. Tides in this multiple inlet estuary form a complicated pattern of mixed semi-diurnal/diurnal tides and have small amplitudes (Huang and Spaulding 2002).

Like the Pascagoula River, the Apalachicola River is one of the last free-flowing alluvial rivers in the continental United States, but river channelization and damming of its upstream distributaries affect its flow. The natural flow of the river provides a seasonally varying supply of nutrients (e.g., nitrogen and phosphorus) that enhance primary productivity from Apalachicola Bay (Mortazavi *et al.* 2000a, 2000b, 2001). Sustained declines in river flow, the result of drought or upstream diversion, could lead to fundamental shifts in both trophic structure and the capacity of the system to support overall productivity (Livingston 1997). Indeed, ocean color images from satellite radiometry show an extended plume of river water emanating from the watershed southward over the west Florida shelf during periods of peak river discharge. This conspicuous biological event, known as the Green River Phenomenon (Gilbes *et al.* 1996, 2002), occurs during late winter and early spring and persists for weeks to months, overlapping in time and space with the spawning season and locations of a

Figure 8

Lands vulnerable to sea level rise

This map displays land below an elevation of 1.5 m. The IPCC estimates that sea level will rise 75 to 190 cm by 2100, resulting in tidal inundation in the areas pictured here. Source: Adapted from Titus and Richman 2001

number of important fish species (Koenig *et al.* 2000). Its inter-annual variability is in part explained by climatic variability over the ACF drainage basin that influences freshwater flow (Morey *et al.* 2009). Although dedicated investigations are lacking, we suspect that this plays a key role in supplying nutrients and fixed organic carbon that influences the general structure and function of estuarine and offshore oceanic food webs in the northeast Gulf (Mortazavi *et al.* 2000a, 2000b, 2001, Putland and Iverson 2007a, b).

Recent national attention focused on the management of the ACF drainage system because of extended drought conditions over the southeastern United States and regional conflicts over water use. Georgia and Alabama have drawn an increasingly larger volume of water for municipal and agricultural needs over the years that in concert with regional drought has resulted in severe declines of floodplain forests (Darst and Light 2008) and possibly overall estuary health. The fact that this conflict remains unresolved despite years of debate highlights the need for effective science that can inform policy decisions by addressing human needs while sustaining key ecosystem services. There is concern that the continued alteration of historical pathways of energy flow will precipitate significant declines in fisheries production (currently valued at billions of dollars per year) and potentially undermine the entire food web in this portion of the Gulf of Mexico. Given the enormous economic value of these fisheries, such a disruption would be devastating, and even more so when considered in light of anticipated growth in coastal development and the effects of climate change.

Effects of flood control efforts on the Gulf Coast

The flooding regime, freshwater volume and routes of the major U.S. rivers flowing into the Gulf have been significantly altered through levee construction, damming and channel rerouting to accommodate increases in coastal populations, agriculture, shipping and industry over the past century. The reduction in the sediment supply to many Gulf barrier islands has affected their morphology (Figure 5, Morton 2008), and drainage of wetlands for urban development has led to increased soil subsidence (e.g., much of New Orleans is now below sea level). Explosive breaks in flood protection levees, called crevasses, are recognized by geomorphologists as being vastly different from the overbank flooding that occurred before levees were built. Before the construction of levees, sediment overflowing river banks accumulated near the river to form a levee parallel to the river channel not much wider than the river itself (Frazier 1967). The dramatic release of floodwater through flood protection levees sends sediments farther from the river levee and sometimes forms a mini-delta or "splay." Kesel (1988) estimated that the amount of sediment flowing over-bank in an unconfined river and through the flood protection levees was equal to 2.3 and 0.86 percent of the river's sediments, respectively. This compares with 12 percent returned from offshore from hurricane

Barrier islands in the Gulf are threatened by increasing rates of sea level rise. Houses on Dauphin Island in Alabama are protected by sand berms. Photo: Joel Sartore/National Geographic Stock

deposition, primarily within a few kilometers of the seashore.

Hurricane protection levees, increasingly needed to protect people settled in the Gulf, will both impound wetlands behind them and restrict sediment deposition—each reducing the resiliency of the wetlands seaward that should function to reduce storm surge heights. These changes in how sediments, nutrients and water are redistributed must be quantified and considered for each proposed wetland restoration project to ensure long-term sustainability of restored areas.

Effects of global climate change on Gulf ecosystems

Large parts of Louisiana and southern Florida, as well as other smaller sections of the Gulf Coast, will be submerged even under moderate estimates of sea level rise.

Global climate change, occurring as a direct result of anthropogenic increases in levels of carbon dioxide and other greenhouse gases in the atmosphere, is predicted to continue to increase atmospheric and sea surface temperatures, acidification of the oceans, rate of sea level rise and frequency of intense storm events, in addition to numerous other changes over the next several decades (IPCC 2007). The long-term impacts of these changes on the ecosystems will be wide-ranging and potentially irreversible (Scavia *et al.* 2002). Although the rate of eustatic, or global, sea level rise projected by IPCC (2007) is rapid, we now know that these projections actually underestimated the rate of change by substantial amounts because the IPCC was unable to include estimates of increasing melt rates for the Greenland ice sheets and polar ice caps. Vermeer and Rahmstorf (2009) show that under the future global temperature scenarios of the IPCC (2007) report, predictions of eustatic sea level rise from 1990 to 2100 range from 75 to 190 cm.

The most alarming expected consequences of climate change for the Gulf Coast are the combined effects of relative sea level rise at an already high and escalating rate and more frequent severe hurricanes. Using a projection that accounts only for flooding of low-lying land without including impacts of storm erosion, large parts of Louisiana and southern Florida, as well as other smaller sections of the Gulf Coast, will be submerged even under moderate estimates of sea level rise (Figure 8). In addition to the loss of human settlements, rising sea levels are likely to result in the "drowning" of wetlands, some barrier islands, sea grass meadows, oyster reefs and coral reefs if they are unable to achieve increases in their vertical elevation equal to sea level rise. Mangroves have greater ability to move inland as seas rise, provided the uplands are undeveloped and not bulkheaded or armored in some other way, but the uneven ability of organisms to adapt to rising sea levels will shift the balance of the ecosystem in unpredictable ways. It seems highly unlikely that accretion rates in these critical coastal habitats will keep pace with sea

Figure 9

Shoreline Changes of the Isles Dernieres Barrier Island Arc, Louisiana, 1887–2005

Source: Adapted from Lee *et al.* 2006

level rise if it increases by a factor of two or more in the next 50 to 100 years, as expected (Vermeer and Rahmsdorf 2009). Indeed, many Gulf wetlands are already being submerged and subsequently lost (Day *et al.* 1995).

Increased water depth will result in decreased light availability to sea grasses and hermatypic corals and increased turbidity for oysters, probably resulting in increased mortality and decreased growth rate. Loss of shoreline habitat destroys its capacity to buffer the shoreline from wave-driven erosion. Under higher ambient sea level and more frequent intense storms, storm-surge flooding of the Gulf Coast will be more extensive and damaging to infrastructure, threatening massive loss of property and life. Effects of hurricanes on shoreline erosion, damage to structures, and risk of loss of life interact with rising sea level and human modifications to hydrodynamic regimes. For example, the loss in area of Gulf coastal barriers from multiple states is clearly related to hurricane activity and also to depth of shipping channels excavated through the barriers (Figure 5).

Ocean acidification and increased sea surface temperature are stressors that interact to affect calcification in marine organisms, such as corals, oysters and a host of other taxa with external or internal skeletons of calcium carbonate. For example, models developed by Anthony *et al.* (2011) based on the IPCC A1F1 scenario (fossil-fuel intensive) demonstrated that severe ocean acidification and sea surface warming could decrease coral reef resilience even under otherwise favorable conditions of high grazing intensity and low nutrients. These results indicate that coral reefs already subjected to overfishing of herbivorous fishes and to nutrient loading are likely to be even more vulnerable to increasing carbon dioxide Impacts on larval fishes could be profound as they struggle to form internal skeletons that are needed for locomotory ability when full grown. The thin larval shells of oysters and other bivalve mollusks may be unable to form; several studies have demonstrated increased mortality rates of juvenile clams and other bivalves during early development. Shell additions to estuarine environments, which would augment the ability of the mollusks to grow their shells, may be necessary as a management adaptation to acidification in estuaries to provide chemical buffers for growing acidity and to allow sensitive calcifying organisms to persist.

The effects of climate change on the Gulf ecosystem extend beyond those discussed here and it is impossible to outline every possibility. However, restoration efforts must address the inevitable environmental changes to achieve restoration that is resilient.

Figure 10

Shoreline Changes of the North Chandeleur Islands, Louisiana, 1855–2005

The area of the islands has decreased from 6,827.5 acres in 1855 to 913.9 acres in 2005. Source: Adapted from Lee *et al.* 2006

Scale

5 miles

Area of islands 2005

Area of islands 1855

Recommendations for Resilient Restoration of the Gulf of Mexico

To treat an ecosystem holistically—including the lives and processes and futures of marine animals, vegetation, microbes and humans—is difficult but essential for resilient restoration.

Grass is planted on a newly created embankment on Dauphin Island, AL. Photo: Joel Sartore/National Geographic Stock

In this chapter, we provide 15 recommendations that can work together to produce comprehensive and long-term restoration of the Gulf. Our understanding of historical and contemporary stresses on the ecosystem, as described in the previous chapter, informs these recommended actions. Restoration of an anthropogenically damaged ecosystem such as the Gulf must include not only an understanding of its basic history and natural processes but also a realistic and scientific assessment of damage, well-defined goals and policies that accurately reflect these realities, and open communication of all decisions to educate the public and earn the trust of local communities. Our recommended actions, then, reflect this exigency for rigorous assessment, defined goals and cooperation with human communities. Taken alone, each action may be no more effective than the traditional "in-place, in-kind" approach to environmental restoration. However, we have designed our recommended actions to work in concert, treating the Gulf as a holistic ecosystem that must accommodate multivalent, intersecting and sometimes competing uses by plants, wildlife, microscopic organisms and humans. To treat an ecosystem holistically—including the lives, processes and futures of marine animals, vegetation, microbes and humans—is difficult but essential for resilient restoration.

Our recommendations stress the need for rigorous scientific research, goals that reflect that research, and open communication and involvement with human communities in the Gulf. Below, we provide more detail on these characteristics that we find so fundamental to restoration:

Understand the past.
We need to account for historical baselines, expected future dynamics and ecosystem interactions to develop a responsible and effective restoration program. We need to recognize the historically pristine condition and functions of Gulf ecosystems and the nature of their degradation as the basis for defining realistic restoration goals. The purpose is not to return the Gulf to some idealized pristine condition, but to recognize that restoration will be unsustainable unless all of the necessary components and functions of the ecosystem are in place. We also need to be realistic about the time frames required to achieve goals in the light of extreme variations in recruitment and growth rates of different essential species, the necessarily enormous spatial scale of intervention and protection that may be needed, as evidenced by the recent rezoning and protection of one-third of the entire Great Barrier Reef (Pandolfi *et al.* 2005), and the inevitable future consequences of climate change, sea level rise and intensification of hurricanes (Rahmstorf *et al.* 2007, Vermeer and Rahmstorf 2009, Jackson 2010).

Acknowledge the future and restore resilience.
Restoration will require a comprehensive and integrated plan focused on rebuilding the functional integrity and services of entire ecosystems that have been harmed as a consequence of the DWH oil spill, in addition to responding to the systematic degradation that has progressively compromised Gulf ecosystems. To ensure sustainability, restoration should be defined to include enhancement of natural resources

Recommendation Themes

THEME 1	THEME 2	THEME 3
Assess and repair damage from DWH and other stresses on the Gulf of Mexico.	**Protect** existing Gulf of Mexico habitats and populations.	**Integrate** sustainable human use with ecological processes in the Gulf of Mexico.

over and above pre-DWH levels and should take explicit account of the highly dynamic nature of the Gulf environment that will require adaptive management as conditions change. The institutional mantra of "in-place, in-kind" restoration is inappropriate without including analysis of sustainability and would probably lead to longer-term failures without planning for future changing conditions. Efforts to achieve durable restoration should not be diluted by calls for economic and community development.

Recognize the interconnection between human prosperity and ecosystem health.

The experience of the Exxon Valdez spill and some harmful consequences of so-called restoration actions demand that the goals for restoration in the Gulf, plans for their implementation and subsequent assessment of progress be fully transparent to the scientific community and public at large. The public must be aware of the time frames and geographic scope of intended restoration actions as they compare to the pace of environmental change. It is critically important to acknowledge, celebrate and foster meaningful and timely public participation in the restoration process, especially because increasing sea levels and increased frequencies of intense storms will ultimately require retreat from the Mississippi River delta. Resilience of human communities and ecological resources are intimately connected; therefore, the ecosystem must be understood as a coupled human-natural system. A robust model for restoring ecosystem resiliency holistically combines environmental with human approaches—for instance, compensatory habitat restoration combined with a project that redresses historical anthropogenic injuries that now jeopardize the sustainability of shoreline habitats.

Such a wide-ranging restoration program calls for structuring the recommendations around general goals. Therefore, we have organized our 15 recommendations along three themes:

1. Assess and repair damage from DWH and other stresses;
2. Protect existing habitats and populations; and
3. Integrate sustainable human use with ecological processes in the Gulf of Mexico.

Each recommendation stresses the need for rigorous scientific research, goals that reflect that research, and open communication and involvement with human communities in the Gulf.

Marshes are replanted near Lake Pontchartrain near New Orleans. Photo: Scott Eustis

Examples of Ecosystem-Based Approaches to Restoration

Example 1: Coastal Marsh

Shoreline margins damaged by the DWH spill should be replanted only if we can be reasonably confident that this planting will be sustainable over time. Therefore, planting should be combined with filling of navigation channels in the vicinity and possibly also construction of a living oyster reef breakwater to reduce erosion rates and induce sediment deposition, as predicted by application of locally relevant hydrodynamic models. Additionally, restoring marsh habitat in locations subject to high rates of relative sea level rise should proceed only where public ownership or publicly owned development rights exist up-slope so that transgression can occur and produce resilience of the marsh habitat and its ecosystem services.

Example 2: Sea Turtle and Shorebird Nesting Habitat

Attempts to restore or protect nesting habitat for sea turtles and ground-nesting shorebirds and seabirds on coastal barrier islands must rely on a broader scientific understanding of inexorable environmental change to be resilient. Use of hardened structures such as seawalls, jetties and groins that are designed to combat shoreline erosion can have serious negative effects on barrier island habitat. The intertidal sand beach is lost to erosion seaward of seawalls, which removes invertebrate prey for shorebirds. The seawall structure can prevent female sea turtles from reaching the back beach for egg laying, and thus reduce reproductive success. If terminal groins serve their designed purpose near inlets, they limit the movement and dynamic changes of shoreline locations around the inlet. Inlet stabilization by groins inhibits over-wash, thereby allowing denser growth of vegetation, which suppresses nesting of some shorebirds such as piping plovers and American oystercatchers. Beach nourishment, sometimes justified by contentions that it enhances habitat for sea turtles and ground-nesting birds, can actually have negative impacts. Sediments that do not match natural beach sands can be rejected as unsuitable by female turtles seeking to lay eggs. The filling that defines beach nourishment covers and kills prey invertebrates on the intertidal beach. Beach invertebrate populations recover within about a year if sediments match the grain sizes of natural beach sands but may require years if coarse shelly or rocky materials are included (Peterson *et al.* 2006). Beach nourishment lasts on average only about five years before requiring repetition (Leonard *et al.* 1990). Costs of beach nourishment are likely to increase as sea level rises further because of the need to elevate the beach even more to avoid flooding. Consequently, the best way to sustain nesting habitat for sea turtles and shorebirds is to leave uninhabited barrier islands alone to roll over and migrate landward in their natural response to sea level rise. Where subaerial habitat has disappeared and the barrier sand mass has been lost in critical locations, then island reconstruction by dredging and filling (nourishment) may be necessary to replace lost nesting and foraging grounds for sea turtles and shorebirds, but this process should be done in collaboration with sedimentary geologists, engineers and ecologists to maximize sustainability of the project in light of sea level rise and storm risks.

THEME 1

Assess and Repair Damage from DWH and Other Stresses on the Gulf

To respond to the damage that has resulted from the DWH oil spill as well as prior and compounding stressors, we must first know the extent of the damage to the ecosystem. Monitoring damage from the oil spill is challenging because there is a paucity of ecological baseline data on the Gulf. This lack of information is due in some cases to inaccessibility, for example, the deep ocean. But in many other cases, we lack data because there has not been enough funding and support to monitor and assess changes in the environment. The recommendations under this theme are directed toward the assessment and repair of damage related to the DWH oil spill, as well as other stressors in the Gulf. We address important shoreline, marine and deep-sea habitats and describe ways to improve water quality and habitat for critical ecosystem species. Our focus is not on quick fixes, but rather on innovative restoration actions that will be sustainable over the long term.

RECOMMENDATION 1

Restore shoreline habitats directly and indirectly damaged by the oil release.

- » Restore critical foundation habitats such as coastal marsh, sea grass and oyster reef using proven methods and consideration of sustainability under climate change.
- » Allow natural recovery to restore ocean beach and estuarine mud flats.

Habitat restoration promises cost-effective restoration of natural resources harmed by the spill because a restoration of even a single type of foundation (bioengineered) habitat can serve multiple injured species simultaneously. Moreover, habitat is often the limiting resource for many marine and estuarine species, and so an improvement or expansion of habitat can have a greater effect than other measures on population health. Habitat restoration can allow natural reestablishment of appropriate flora and fauna to an enormous extent at relatively low cost and with great capacity for the system to sustain itself (Coats *et al.* 1995, Reed 2002, Teal and Weishar 2005).

The coastal habitats in the Gulf are the most vulnerable and at the same time are extraordinarily important to the ecological and economic productivity of the region. The foundation species that provide the architectural structure—oysters, salt marsh macrophytes, sea grasses, mangroves, corals and sponge—also provide critical habitat for additional species, including many juvenile and forage fish that support fishery production. Many of these habitats also play a vital biogeochemical role as filters of pollutants (Grabowski and Peterson 2007). We recommend restoration projects targeting biodiverse, accessible shoreline habitats such as coastal marsh,

Dead cypress trees resulting from saltwater intrusion near Houma, LA. Photo: Paul Goyette

The oil spill damaged important habitat, such as Louisiana's Breton Island, which is home to as many as 2,000 brown pelican nests. Photo: U.S. Fish and Wildlife Service/Southeast

Many restoration programs presume that human intervention can accelerate the process of habitat recovery without further injury and therefore undertake activities with insufficient planning, inadequate baseline data, no monitoring and unrealistic expectations.

sea grass meadows and oyster reefs. In this section, we first provide an introduction to habitat restoration and then detail specific measures to restore these critical habitats in the Gulf.

Proper habitat restoration

Proper habitat restoration, as described by Teal and Peterson (2009), takes into account the life cycles of the animals in the habitat, potential shifts in the habitat resulting from environmental change, and human concerns and management of the habitat (see box, Page 43). Although excellent examples of restoration using these principles can be found in salt marsh projects (Broome *et al.* 1986, Teal and Weishar 2005) and oyster reefs (Schulte *et al.* 2009), the principles cannot guarantee success in restoration (NRC 2001a). Each habitat is unique and requires careful and specific scientific study to achieve the best results.

Habitats cannot be considered in isolation: Restoration projects should account for the pathways that organisms travel through their life cycles and seasons. Corridors permit important movement of fish and mobile crustaceans among different types of habitat. Such connectivity enhances feeding opportunities, which vary with tidal stage, and survival rates, which may be improved by accessing rich but risky habitats during protection of night while moving to structured habitats for protection in daylight.

Habitat restoration projects must also include systematic monitoring and adaptive management, and be sufficient for as long as is necessary to reach restoration goals. Unfortunately, many restoration programs presume that human intervention can accelerate the process of habitat recovery without further injury and therefore undertake activities with insufficient planning, inadequate baseline data, no monitoring and unrealistic expectations. This naivete illustrates that we have not learned enough from the history of problematic restoration approaches (Bernhardt *et al.* 2005).

Marsh habitat restoration

Restoration of marsh habitats damaged by the DWH oil spill and other prior stresses would involve replanting native marsh vegetation. But any marsh restoration in the Gulf must also take into account the travel corridors for marsh organisms, prevailing water currents, earlier stresses on the marsh, such as channel excavation, and future risk of marsh edge drowning from sea level rise.

Early work in marsh restoration developed critical horticultural principles for success (e.g., Broome *et al.* 1986). Subsequent advances have further demonstrated the importance of allowing normal water flows to develop with meandering channels penetrating into the marsh or, if necessary, to engineer inundation and water delivery regimes that mimic naturally productive marsh habitat. These channels enhance connectivity between the marsh and the estuary, allowing tidal transport of sediments, plant propagules, larvae of fish and invertebrates, and nutrients into the marsh. The channels also provide corridors for larger fish and mobile crustaceans to access the marsh for feeding, spawning and escaping predation under protection of plant cover (Able *et al.* 2002, Weishar *et al.* 2005). Allowing distributaries, or parts of the river that flow away from the main channel, to penetrate into the marsh can create substantially more ecologically valuable edge habitat for a variety of fish and wildlife (Peterson and Turner 1994, Minello and Rozas 2002).

The history of successful restoration of *Spartina alterniflora* (smooth cord grass) marshes is sufficiently reassuring for us to recommend direct restoration to compensate for DWH injuries to Gulf coastal *Spartina* marshes. However, several cautions and conditions require attention beyond adherence to the principles of proper habitat restoration presented in the box on the next page. First, because *Spartina alterniflora* plants are available commercially and the horticultural guidelines are well known, there is some risk of restorers planting it in locations that are more appropriate for other marsh macrophytes. For example, *Juncus romerianus* (black needle rush) is appropriate for higher marsh elevations and for areas subjected to irregular flooding by meteorological tides instead of regular astronomic tides. *Spartina alterniflora* is not well adapted to such conditions, and if planted there, it would not have the intrinsic resilience of a natural marsh.

Second, the traditional guidelines for compensatory restoration that promote "in-place, in-kind" replacement would appear to be an ineffective action in much of the marshland affected by the DWH oil, especially in the Mississippi Delta region, where most coastal marsh injury occurred. Most of the loss of coastal marsh, whether from oiling or from unintended physical impacts by emergency response actions, occurred at the marsh edges. These are the locations at highest risk of ongoing marsh drowning and loss caused by sea level rise. Consequently, restoration of the marsh edge has little likelihood of persistence. An important management adaptation to climate change is to pursue marsh restorations in the Mississippi Delta and elsewhere that incorporate realistic projections of relative sea level rise and opportunity for transgression landward to maximize the likelihood of persistence under dynamic future conditions (Peterson *et al.* 2008). Marsh restoration can be accompanied by filling in erosion-inducing channels cut through the marsh and by erecting oyster reefs as living breakwaters so as to reduce wave energy and induce sedimentation on the planted marsh to enhance its ability to persist as sea levels rise.

Proper habitat restoration, as described by Teal and Peterson 2009, takes into account the lifecycles of the animals in the habitat, potential shifts in the habitat due to environmental change, and human concerns and management of the habitat.

The Louisiana Sea Grant College Program deployed shell bags along eroded shore at its Sea Grant Oyster Hatchery in Grand Isle. Photo: Louisiana Sea Grant College Program/Louisiana State University

A mollusk in sea grass in the Florida Keys. Photo: Sean Nash

Sea grass habitat restoration
Sea grass, or submerged aquatic vegetation (SAV), provides nursery habitat for many economically important species in the Gulf of Mexico. It is most abundant off the west coast of Florida, which contains the largest expanse of sea grass in the United States. Sea grass has experienced alarming global declines over the past 50 years because of a variety of perturbations, including propeller damage from commercial and recreational boats, industrial pollution, eutrophication, sedimentation and coastal development (Waycott *et al.* 2009). Sea grass also suffered injury from the DWH oil and emergency response activities, although the west coast of Florida was least affected by the DWH spill. Restorations of sea grass have been successful (Fonseca *et al.* 2000), although the success rate is not as high as it is with marsh grasses. Many sea grass meadows experience dynamic seasonal and yearly changes, more so in aboveground (shoots and leaves) biomass than in belowground (roots and rhizomes). This dynamism can present a challenge to habitat restoration because habitat persistence is often identified as a metric of successful habitat restoration. Late-succession species of sea grass may represent preferred targets for restoration because they are less ephemeral and more likely to persist long term. In the Gulf of Mexico, this would mean that species such as turtle grass (*Thallassia testudinum*) may be more desirable long-term targets of restoration than species such as shoal grass (*Halodule wrightii*). Sea grasses differ among themselves in optimal habitat conditions; some sea grasses occupy shallower and even intertidal elevations, whereas others cannot tolerate aerial exposure. Thus choice of the proper species for the restoration site can be important to success.

Although a climax species of sea grass may be the desired endpoint of restoration, clever methods have been devised to allow natural processes to contribute to restoration success. For example, planting an early-succession species with a typically fast growth rate can stabilize soils and mitigate erosion at sites that might prove otherwise inhospitable to slow-growth climax species (Fonseca *et al.* 1998). Fertilization of newly transplanted sea grasses has also been provided "naturally" by inserting stakes in and around the planted area, which are then used as perches by terns and cormorants. Guano produced by these birds is rich in nutrients, thereby providing fertilizer to speed growth and recovery of the newly planted sea grass. Stakes can be removed and bird defecation discouraged

Principles for Proper Habitat Restoration

(modified from Teal and Peterson 2009)

- Set goals for the restored habitat system, including establishing structural and functional characteristics of the biogenic habitat needed for success. Have an acceptable timeline with allowable variability. State how these were chosen.
- Incorporate ecological engineering (self design) into the planning. Consider the larger surrounding landscape in which the restoration will occur. Plan for sustainability and response to long-term changes, especially in sea level.
- Develop a plan for how propagules, larvae, etc., can become established, including natural and artificial methods.
- Plan, design and model how extensive water circulation similar to that which characterizes natural wetlands will be achieved, using engineered and natural processes.
- Establish criteria for and choose reference sites, develop methods for data collection and monitoring and plan for adaptive management
- Plan for management oversight such as independent advisory groups, regulators and stakeholders.

after sea grasses have become established so as to avoid impacts of over-fertilization that transform sea grass habitat into algal-dominated systems (Valiella and Cole 2002). We recommend SAV restoration actions to replace DWH oil spill losses in the Gulf. Restoration of injured sea grass is particularly critical in areas such as protected sites around the Chandeleur Islands, where sea grass beds serve as a nursery for many commercially and recreationally important fish, including several depleted reef fish, blue crabs and penaeid shrimps (Fodrie and Heck 2011).

Oyster reef habitat restoration
Oyster reefs provide habitat and ecosystem services, such as water filtration, throughout East, Gulf and West Coast estuaries (Grabowski and Peterson 2007, Beck *et al.* 2011). Although oyster reefs in the Gulf suffered damage from the DWH spill and prior disturbances, evidence indicates that they can be recovered through restoration (e.g., Lenihan and Peterson 1998, Lenihan *et al.* 2001, Schulte *et al.* 2009). Oyster mortalities extended over hundreds of acres after the DWH oil release, mostly as collateral damage from emergency response efforts. To keep floating oil from entering sensitive marshes, the freshwater was diverted through the Mississippi Delta and provided out-welling water flows. The resulting reduction in salinity around existing oyster reef habitat induced oyster mortality.

Beyond the impacts of the DWH spill, causes of oyster declines are complex. Stresses include overharvesting of live oysters for food, overharvesting of oyster shell substrate for industrial use, sedimentation on reefs, mismanagement of freshwater flows causing either excessively high (e.g., Apalachicola River) or excessively low (e.g., Mississippi Delta) salinities and the impacts of the protozoan parasite *Perkinsus marinus*, commonly known as "Dermo" (MacKenzie 1996). Although Dermo affects Gulf of Mexico oysters, longer growing seasons and faster oyster growth have typically allowed oysters in the Gulf to reach marketable size before dying from its effects. However, extended drought and restricted flow of freshwater lead to increased infection rates that in turn lead to increased mortality (Carnegie 2009).

Despite these stresses, the oyster fisheries of the Gulf, especially in Louisiana, Texas and the Florida Panhandle, have persisted, while mid-Atlantic oyster fisheries have suffered near-economic extinction. The success of the oyster fishery in the Gulf may have diverted attention from assessing, restoring and sustaining the natural habitat structure of oyster reefs, which plays an important role in providing ecosystem services (Lenihan 1999, Grabowski and Peterson 2007). In subtidal environments, tall reefs expose oysters to faster water flows, which prevent sedimentation, can induce faster growth, suppress parasite impacts and create better physiological condition. In addition, tall reefs provide more oyster reef habitat for fish, crabs and shrimp, and allow oyster filtration to clarify estuarine waters over a larger fraction of the water column.

Oyster bed restoration should be motivated by the need to restore injuries from the DWH incident in the estuaries of the northern Gulf of Mexico but should be focused on providing ecosystem services of the oysters and their reefs. Restorations should include establishing oyster reef sanctuaries and assessing whether re-creating tall subtidal reefs, probably characteristic of pristine Gulf estuaries, make this habitat more naturally sustainable and improve its ability to provide ecosystem services. Furthermore, linear oyster reefs parallel to estuarine shorelines can be built to serve as natural breakwaters, protecting the shoreline habitats and development from wave erosion and inducing local sedimentation to help counteract subsidence and global (eustatic) sea level rise. These oyster reefs can substitute for ecologically damaging bulkheads and other engineered shoreline protection devices (Peterson *et al.* 2008).

Some of the Gulf oyster reef restoration should be designed to test the effectiveness of this shoreline habitat protection function. In relatively quiescent environments along estuarine shorelines that are exposed to modest wind fetch, naturally sustaining oyster reefs have the potential to act as an ecologically beneficial alternative to bulkheads and revetments on the shore itself. The presence of a fixed shoreline protection structure, even if constructed landward of the marsh, guarantees ultimate loss of marsh habitat and its ecosystem services

The success of the oyster fishery in the Gulf may have diverted attention away from assessing, restoring and sustaining the natural habitat structure of oyster reefs, which play an important role in providing the ecosystem services.

Commercial fishermen use dredgers to scrape the seafloor of oysters, damaging habitat as well as species populations. Photo: Kristi Durazo

A temporary "burrito levee" was put in place at Grand Isle, LA, in 2008 while Hurricane Ike approached. After the hurricane, the Army Corps of Engineers installed geotubes to create an artificial dune to reduce the impact of storm surge on the island. Photo: Team New Orleans/U.S. Army Corps of Engineers

The dredging necessary for beach nourishment vacuums up and kills the sessile bottom invertebrates at the source sites, depriving bottom-feeding fishes, crabs such as blue crabs, and penaeid shrimps of their food resources.

as sea level rises and the structure prevents transgression of the marsh up-slope to higher land (Peterson *et al.* 2008). Oyster reefs grow upward, maintaining a peak elevation at the same level relative to the water surface. Therefore, using oyster reefs as natural breakwaters takes advantage of natural physical-biological feedbacks to provide resilience of both shoreline protection and also of habitat ecosystem services (Beck *et al.* 2011).

Beach and mud flat habitat restoration

Beach nourishment—the process of dredging sediments from source sites on the seafloor and filling ocean beaches—needs to be viewed cautiously within Gulf restoration plans (Peterson and Bishop 2005). Although beach nourishment has been an accepted practice for shoring up coastlines and protecting beach residences and infrastructure from erosion, the process has negative consequences for coastal ecosystems. For instance, the dredging necessary for beach nourishment vacuums up and kills the sessile bottom invertebrates at the source sites, depriving bottom-feeding fishes, crabs such as blue crabs, and penaeid shrimps of their food resources. Consequently, beach nourishment represents habitat degradation, not restoration, and should be viewed as such during planning for Gulf coastal restoration.

Recovery of the benthic invertebrates—clams, polychaete worms and crustaceans—at the source sites can be rapid, taking about a year, if the excavation pits are shallow. However, deeper excavation pits serve as sedimentation basins and fill with fine, organic-rich sediments. The oxygen demand arising from the microbial degradation of the organic materials collecting in deeper pits, where bottom water flows are suppressed, can lead to anoxic seafloor habitat where benthic invertebrates cannot survive (Rakocinski *et al.* 1996).

Similarly, the process of filling the beach with these dredged sediments is a "pulse disturbance" (a quick perturbation), killing the benthic invertebrates that provide the prey of shorebirds such as sanderlings and several species of plovers, and surf fish such as pompano. Recovery of the beach habitat and its service of providing food for these shorebirds and surf fish depends on how well the dredged sediments match natural sands of the beach. Adding muddy sediments induces periodically elevated turbidity for as long as the dredged materials remain on the beach as natural wave action erodes and transports the sediments away (Peterson and Bishop 2005). This turbidity degrades coastal water quality, interfering with the ability of visually orienting predatory seabirds such as pelicans and of pelagic fish such as mackerel from detecting and capturing their prey. The addition of sediments that are unnaturally coarse also causes longer-term stress to the sandy beach ecosystem (Peterson *et al.* 2006). These disturbances may last for years because coarse sand, gravel and cobble-size materials, commonly including shell and shell hash, are unacceptable habitat for some critically important invertebrates, such as bean clams, which are of value as prey for pompano, juvenile flounders and shorebirds (Peterson *et al.* 2006). These larger sediments are retained on sandy beaches indefinitely because they are heavier and less readily transported than finer particles. The natural abrasion and wave action on ocean beaches takes decades or centuries to break up some of the shell and other coarse materials.

Where beach nourishment is conducted in response to the DWH incident, the habitat damage (loss of prey for surf fish and shorebirds) should be quantified empirically and this collateral damage mitigated by an appropriate compensatory restoration project. Injury caused by beach nourishment to threatened or endangered species would require special attention, intensive monitoring and adaptive management (Peterson and Bishop 2005). We recommend that benthic invertebrates suitable as prey for shorebirds and surf fish be supplemented wherever beach filling has occurred to restore the injured prey resources. In addition, on any beach that has received shell, rocky gravel or cobbles in excess of its natural abundance on similar unmodified beaches, the coarse materials should be sorted immediately after filling and removed from the beach environment to prevent multiyear inhibition of recovery of benthic invertebrate prey.

Although they do not serve as recreational sites to nearly the same degree as ocean beaches, mud flats are also important for the Gulf ecosystem. Technologies for restoration of mud flats and other unvegetated shallow sedimentary bottoms along shore, and of the deeper seafloor, are not well developed. Because natural recovery rates of unvegetated sedimentary bottom after physical disturbance can be rapid, taking only months to a year, natural recovery is the preferred option for these habitats with compensatory restoration for the temporary loss of mud flat ecosystem services being provided by restoration of more structured estuarine habitats that have been in decline. Where sedimentary bottoms have been contaminated by oil deposition, some cleanup may be required. Bioremediation through the addition of nutrients to speed up microbial degradation of oil has the negative consequence of enhancing eutrophication in an environment where excess nutrient loading is already a huge problem. Where oil may lie buried in conditions of anoxia and thus pose long-term risks of remobilization and exposure of vertebrate consumers that excavate prey, then some engineering interventions, such as oxygen injection (Boufadel *et al.* 2010), may be justifiable as restoration actions on high-value shores. Nevertheless, pilot studies should be conducted to demonstrate levels of benefit and potential harm and to guide adaptive changes of methodology before any large-scale application of this technology. In addition, oxygen injection may not be feasible over the wide spatial scales typical of oil exposures to intertidal mudflat shorelines. In general, relying on natural chemical, biological and light-induced degradation of oil grounded on soft sediments, with regular monitoring of progress toward recovery is the wisest approach. Perceived opportunity generates numerous proposals offering application of untested technology, which should be treated with skepticism and pursued only after cautious testing indicates promising outcomes.

Cleanup proposals using untested technology should be treated with skepticism and pursued only after cautious testing indicates promising outcomes.

RECOMMENDATION 2

Investigate effects of dispersed oil and dissolved natural gas on deep-sea ecosystems and test capacity for restoration of ecosystem services.

An orange brisingid basket star rests on a coral reef at a depth of 450 meters in the Gulf. At the top of the image is a school of Beryx fish swimming over the reef. Photo: NOAA-OER/BOEMRE

» Conduct field observations and novel mesocosm experiments to infer toxicological impacts of oil on deep-sea particle feeders to provide quantitative estimates of damage.

» Test and implement restoration strategies, such as *Sargassum* enhancement, to stimulate recovery of particle feeder populations.

» Through field observations and laboratory mesocosm experiments, evaluate the fate of the heterotrophic microbes produced in such massive amounts as they degraded dissolved hydrocarbon gases and dispersed oil droplets.

Although public perception persists that microbes rapidly degraded most of the natural gas and much of the oil from the DWH spill, the biogeochemical consequences of greatly enhanced microbial production and the toxicological effects of finely dispersed oil droplets on deep-sea food webs are likely complex and largely unknown. The flux of organic matter that typically fuels deep-sea food webs is derived from photosynthesis at the surface of the ocean. This primary production supports a downward flux of sinking cells and detrital organic matter that is consumed by many different groups of protists and zooplankton as it falls through the water column. This rain of particles also supports heterotrophic microbial production throughout the water column. The magnitude of the particle flux decreases with depth, because particles slowly dissolve as a result of bacterial activity and as the carbon consumed is respired. Fluxes are variable in space and time, but it is believed that on average, only one percent to at most 10 percent of the carbon fixed by phytoplankton at the surface of the ocean reaches a depth of 1,000 m. Additional macroinvertebrate consumers, varying in nature as a function of bottom geology and carbon flux, are found on the bottom of the deep ocean. Rocky, hard bottoms support deep-water corals such as *Lophelia*, crinoids and other sessile invertebrates.

The blowout and subsequent BP response have multiple, but largely undetermined, ecological implications for deep-sea organisms.

Sedimentary bottoms are characterized by motile organisms such as polychaetes, brittle stars and other echinoderms, protozoa and small meiofaunal organisms, with infauna dominated by polychaetes and bivalves. Because the seafloor serves as a final destination for the downward rain of organic particles, they become concentrated there, leading to higher concentrations of animals on the ocean floor than are found in the overlying water column. Heterotrophic bacterial production continues to occur in the sediment surface of the deep-sea floor. This biological setting provides the backdrop for the injection and multi-month retention of massive amounts of organic carbon as a result of the DWH blowout.

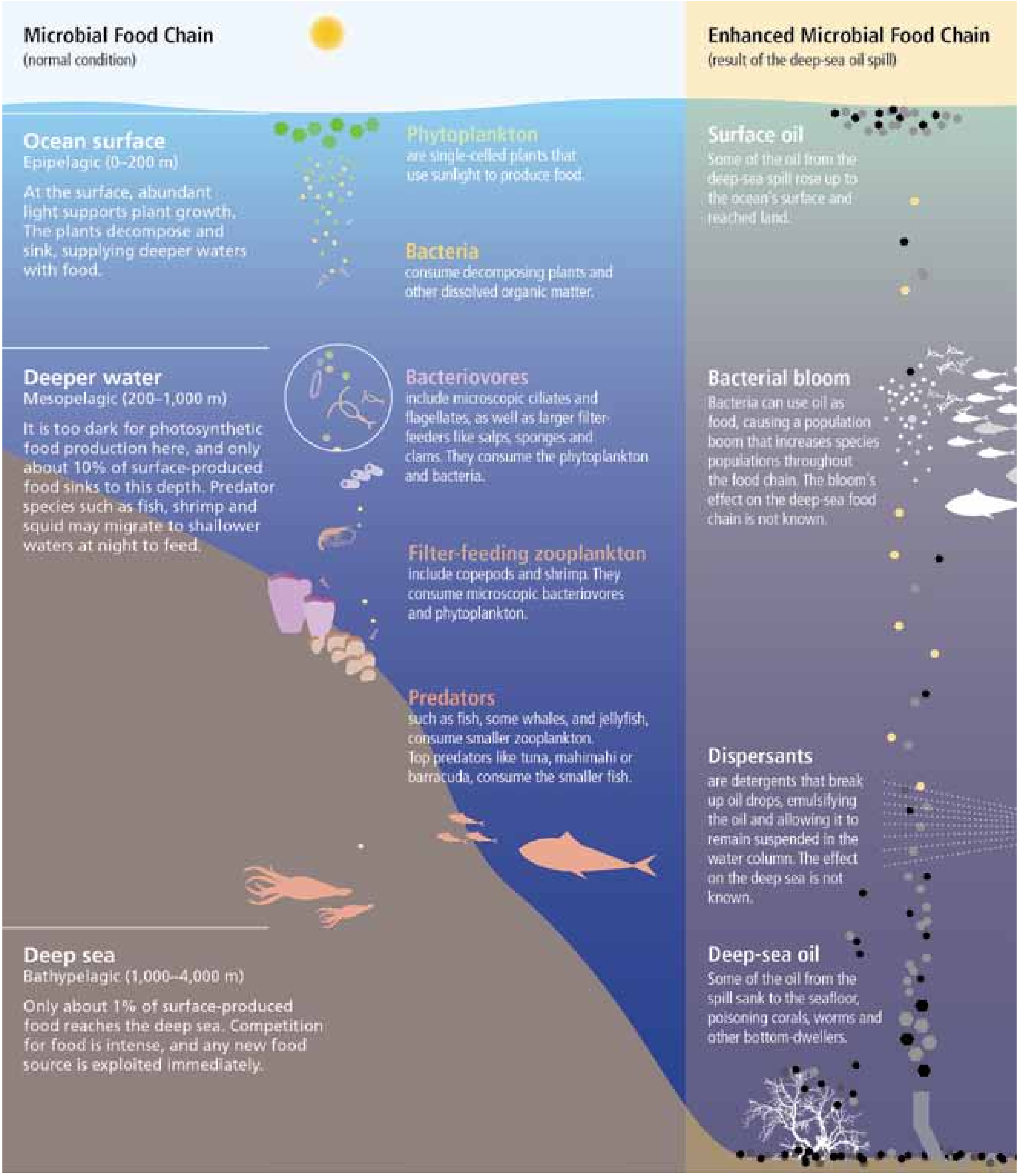
Deep-sea changes triggered by the DWH oil and gas discharge

Virtually all of the gaseous hydrocarbons and a large fraction of the oil released by the Deepwater Horizon well blowout were retained in the water column deep beneath the sea surface, concentrated in one or more plumes of dispersed hydrocarbons at depths of 800 to 1,200 m (Camilli *et al.* 2010, Joye *et al.* 2011). Our knowledge of the specific biota and understanding of ecosystem processes at this depth in the pelagic water column is limited because the ecosystem is not readily observable or amenable to experimentation. In contrast, surface waters are easily sampled from ships, and even deep benthic communities can be catalogued from remotely operated vehicles (ROVs) or submarines. The observations that scientists have been able to make indicate that these pelagic communities (Kessler *et al.* 2011), as well as the deep-sea benthic environments (Fisher 2010) of the northern Gulf were, and probably still are, affected by the massive injections of organic matter in the form of methane and other natural gases, oil droplets and emulsions from the blowout. Much of the methane seems to have been processed by microbes (Kessler *et al.* 2011), resulting in an increase in the biomass of microbes able to grow using the energy from methane. These bacteria are

Figure 11

How the Oil Spill Affects the Micobial Food Chain

The deep sea is already difficult for scientists to access, but there is little doubt that the microbial food chain in the Gulf has been affected by the oil spill. Impacts from the spill may be direct (i.e., poisoned bottom-dwelling organisms) or indirect (i.e., a bacterial and species population boom) with many unknowns, including how much oil rose to the surface and how much sank to the bottom. Without further research, the impacts on this region and the ocean as a whole may remain unknown. Source: T. Hollibaugh, pers. com.



A field of the soft coral *Callogorgia sp.* in the Gulf of Mexico. Photo: NOAA-OER/BOEMRE

The dispersed nature of the oil allowed it to encounter and probably foul and disable the feeding organs of many particle feeders of the oceanic water column and of the seafloor.

potential food for the grazing food chain. The emulsions that were formed by the physical processes unique to the deep-water blowout are in the same size range as the sinking cells and detrital particles that are the food of deep-sea protists and zooplankton. Oil in highly dispersed and partially degraded forms was highly available to and doubtless ingested directly by grazers (particle feeders) over a wide range of ocean depths.

The dispersed nature of the oil allowed it to encounter and probably foul and disable the feeding organs of many of these particle feeders of the oceanic water column and of the seafloor. Dead jellyfish, including salps (a grazer on fine particles), were commonly reported by biologists during the spill. It seems likely that the oil effects on particle feeders throughout the water column caused major disruption of the food web leading to higher trophic levels, including several marine mammals and large fish. Even pelagic consumers at higher trophic levels may have been directly harmed by encounters with highly dispersed oil droplets. Did the toxicity of the oil intermixed with dispersants kill many of these higher-order consumers and modify the deep-sea pelagic food webs? Crustaceans (especially amphipods) and echinoderms are known to be especially sensitive to toxicants (Lenihan *et al.* 2003), so the disabling of the food webs may have been selective.

We have little information on the ultimate fate or effects of the Corexit dispersant added at depth to the escaping hydrocarbons, but we do know that Corexit is moderately toxic to test organisms, that it renders the oil more bioavailable and that components of the dispersant appear to be capable of persisting for months without substantial chemical degradation (Kujawinski *et al.* 2011). Petroleum hydrocarbons have also been found on the seafloor, and there are indications of mortality among benthic organisms coming into contact with them (Fisher 2010). Thus the blowout and subsequent BP response have multiple, but largely undetermined, ecological implications for deep-sea organisms.

Outstanding questions concerning the effects of the DWH oil spill on deep-sea food webs

We can hypothesize these impacts of the DWH spill on pelagic and deep-sea benthic communities, as described above; however, we currently lack the knowledge to evaluate their significance. One of the most obvious, and perhaps easily assessed, processes is the effect of direct toxicity on benthic organisms. Oil on the bottom is likely to have other consequences besides direct toxicity. Possible additional effects include smothering benthic organisms and stimulating blooms of benthic hydrocarbon-degrading microbes, respiration with possible local anoxia and the production of toxic sulfide as a consequence of alternative respiration pathways (sulfate reduction). The toxicity and lability of the hydrocarbons reaching the bottom are likely to be different depending on whether they come directly from the discharge plume, indirectly from surface sedimentation or are mixed with the blowout muds. The relative contribution to benthic deposits of weathered oil sinking from the surface slick, of microbially processed oil from the dispersed plume, or of oil mixed with drilling fluid that was expelled during the initial blowout and in subsequent efforts to stop flow from the well is not yet known. We do know that the oil from the spill has entered into the pelagic food chain in shallower coastal waters of the Gulf (Graham *et al.* 2010), but we do not know whether hydrocarbon-degrading microbes entered deep-sea food webs to any appreciable degree through consumption by particle feeders, many of which were probably killed or disabled by fouling of feeding and respiratory apparatus.

The hydrocarbons dispersed in the deep-water plume represented a massive organic subsidy to the pelagic and deep benthic communities (Joye *et al.* 2011), but we do not know exactly what the communities did with this carbon infusion. Many possible disruptions or shifts in the food web may be occurring as a result of the oil. Was this huge bacterial biomass simply respired in a series of microbial loops? Did it enter macro food chains of the sea leading to fish and other organisms of the pelagic and benthic realms? Or is much of it recalcitrant organic matter that resists degradation? Hydrocarbons are not a "balanced meal" for microbes, so this growth of heterotrophs would then increase demand for nitrogen, phosphorus, iron, copper and other micronutrients needed to produce more bacterial biomass. Such increased demand on resources might then limit further growth of bacteria or other deep-sea microbes. The resulting microbial production in the deep sea is not likely to support greatly increased production of the higher trophic levels that feed on bacteria (e.g., Pomeroy 1974, 1979, Ducklow *et al.* 1986). Nevertheless, bacterial growth on hydrocarbons dispersed in the plume appears to have resulted in the production of flocculent material and microcolonies that are more available to higher trophic levels for consumption by particle feeders than typically small, free-living bacterial cells in the ocean (Hazen *et al.* 2010). This may have resulted in enhanced trophic transfer of both bacterial biomass and of any toxic hydrocarbons associated with the flocs.

Respiration of hydrocarbons in the water column uses oxygen and, in the case of the plume resulting from the DWH blowout, resulted in an area of lower oxygen that could be detected 500 km from the wellhead a month after the well had been capped (Kessler *et al.* 2011). Although oxygen depletion associated with this feature was not great enough to be life-threatening to most organisms, it may have caused altered behavior of vertically migrating fish and invertebrates. Also, respiration produces carbon dioxide that reacts with water to form carbonic acid, which then dissociates to cause ocean acidification. Calculations (W.-J. Cai, pers. com.) indicate that respiration associated with microbial oxidation of methane sufficient to decrease the dissolved oxygen concentrations at depth by 50 percent of saturation would result in an approximately 0.1 unit decrease in pH. Decreases of this magnitude affect biogeochemical processes (Beman *et al.* 2011) as well as calcification and probably also speciation and bioavailability of trace metals. This decrease in pH may be particularly significant in the deep sea because of the relationship between pressure and calcium carbonate solubility (i.e., carbonate is more soluble at depth). This is particularly in the northern Gulf, where subsurface waters are already excessively acidified because of heterotrophy associated with the seasonal dead zone underlying the Mississippi River plume (Cai *et al.* in review). The acidification associated with a mesopelagic plume could affect calcified benthic organisms such as foraminifera, echinoderms, mollusks or stony corals such as *Lophelia* where the plume intersected the bottom.

The boundaries and interactions of deep-sea communities also remain unclear. The shelf break of the Gulf of Mexico is a prime habitat for sperm whales, which are especially concentrated in the canyons, where they feed largely on squid. Do deep-sea squid benefit from microbial production if one traces back the origins of their diets? Alternatively, did mortality

Bluefin tuna swim in the Gulf. Photo: NOAA/Marine Photobank

Many possible disruptions or shifts in the food web may be occurring as a result of the oil.

The spill provides an opportunity to enhance scientific understanding because it represented a massive intervention on a scale wide enough for responses to emerge despite background variability.

of particle feeders at various trophic levels result in depletion of squid prey and thus have bottom-up impacts on even higher-order predators? Post-spill surveys of the benthic communities in the vicinity of the Deepwater Horizon wellhead have revealed some locations containing dead *Lophelia* and crinoids on hard bottoms, covered by dark, as yet unanalyzed, material (Fisher 2010) and large areas without living polychaetes and with recently killed brittle stars, also accompanied by dark surface deposits high in polyaromatic hydrocarbons (S.B. Joye, pers. com.). Analyses that might allow causation to be inferred are incomplete as of this writing. Thus, we are far from an adequate understanding of "oil spill oceanography" for the deep sea based upon microbial processes and toxicological effects. Yet the spill provides an opportunity to enhance scientific understanding because it represented a massive intervention on a scale wide enough for responses to emerge despite background variability. Research that answers these questions is an essential part of the restoration process: Without information on damages, no restoration will follow. Legitimate concern over long-term, delayed impacts will persist if the science remains incomplete and the deep-sea processes continue to be a black box of unknowns. Furthermore, oil exploration and extraction continue in the deep waters of the Gulf and its intensity is growing.

Restoration of deep-sea ecosystem despite uncertainty

Because of the probable mortality of particle feeders in the water column from exposure to fine particulate oil and of suspension and deposit feeders of the deep-sea floor from fouling by adhesive oil deposits, the most important deep-sea injury is likely to be disruption of energy flow and production in both pelagic and benthic food chains. Thus, restoration planning needs to address both restoration of deep-sea pelagic and benthic food-web production. One direct method of restoring this food web production relies on enhancement of the floating *Sargassum*-associated community. Enhancement of *Sargassum*, and thereby its community of associated invertebrates and fish, could generate a meaningful downward flux of natural organic materials. These materials, in turn, would serve as nutrition for the particle feeders of the ocean from shallow waters through the mesopelagic (i.e., middle of the water column) and then the benthopelagic zones on down to the benthos.

In the following section describing the restoration of *Sargassum* ecosystem services, we outline a feasible culturing method for enhancing *Sargassum* and its ecosystem services. Because *Sargassum* and associated organisms that use it as habitat suffered injury from the DWH oil spill, and therefore require compensatory restoration, *Sargassum* enhancement as a means of restoring lost deep-sea production must involve enhancement of this surface system beyond what is required to compensate for direct *Sargassum* community damage itself to avoid giving double credit.

Restoring lost pelagic and benthic production over wide areas of the coastal ocean is feasible, based on our understanding of how the deep-sea food webs are subsidized by surface ocean production. Nevertheless, the concepts require testing and the processes require quantification. This should be done on a small scale as proof of concept and then scaled up accordingly to compensate for estimated losses to the oceanic resources.

RECOMMENDATION 3

Determine effects of the DWH oil spill on the *Sargassum* community and restore its lost habitat services to fish and wildlife.

- Conduct realistic mesocosm experiments to complement field observations made during the spill to assess acute and chronic mortality of *Sargassum* and its animal associates by floating oil and dispersants.
- Restore *Sargassum* by prohibiting commercial harvest, and by culturing it in lab settings to test whether *Sargassum* augmentation increases survival or production of its animal associates and, if it does, scaling up augmentation to match expected benefits with estimated damages.

Unlike most biogenic habitats created by macroorganisms, oceanic *Sargassum* is not rooted in place. It is concentrated at the sea surface by localized downwellings at frontal zones, such as commonly characterize the western wall of the Gulf Stream and other boundary currents such as the Loop Current of the Gulf of Mexico, and in windrows created by Langmuir circulations cells. *Sargassum* thus exists at the boundary between the atmosphere and the sea surface. It serves as structural habitat, providing physical refuges for juvenile and small fish, crustaceans and other invertebrates such as nudibranchs. Many of the associated organisms graze directly on *Sargassum* or consume epiphytes growing on the seaweed surface. These associated invertebrates and small fish are preyed upon by seabirds, larger fish and sea turtles. Consequently, an entire food web is centered on the floating plants and travels with them.

More than half of the oil released by the DWH well blowout reached the sea surface and then remained at sea for weeks to months, trapped in eddies spun off the Loop Current. As a result, the floating *Sargassum* habitat, which is entrained and transported by the same surface currents, was heavily exposed to oil. Although brown algae are not particularly sensitive to oil toxicity, oiling is likely to have had negative effects on many of their associated animal assemblages, including early life stages of loggerhead and other sea turtles (hatchlings), as well as bluefin tuna, cobia, wahoo, mahimahi and juvenile stages of other fish of commercial and recreational value. Oil interacts with UV light to aggravate phototoxicity, putting many of these surface organisms at relatively high risk. Fouling by the sticky oil mousse that represents the floating form is likely to have been the cause of much mortality among *Sargassum*-associated animals.

Given the large area of coincidence between *Sargassum* and the surface slick of mousse, impacts to this community could be highly significant. We recommend analysis of damage assessment data for the *Sargassum* community in combination with mesocosm studies to assess the sensitivity of *Sargassum* and associated organisms to oiling and to establish (if possible) the contribution of Gulf of Mexico *Sargassum* to the Gulf Stream population.

As an initial restoration action, commercial harvesting of *Sargassum* should be prohibited in U.S. territorial waters of the Gulf. The benefits of a harvest prohibition would need to be quantified and compared with the estimated damage to the *Sargassum*-associated community to assess whether this prohibition alone would match the scale of oil spill damage to the *Sargassum* community. It is likely that prohibition of harvest would fall short of providing full quantitative compensation. Hence, the phycological horticulture of healthy live *Sargassum* should be tested for technological feasibility at reasonable cost to provide biomass of plants for supplementation to replace any remaining uncompensated damage.

In adopting some combination of culture or ending commercial harvest of *Sargassum* as a vehicle for restoring injury, tests would be necessary to determine how associated animals responded to added *Sargassum* biomass. The most likely contributions of augmented *Sargassum* biomass to its associated animals are structural

Oiled *Sargassum* in Louisiana. Photo: Carolyn Cole/Los Angeles Times

Oiling is likely to have had negative effects on many of *Sargassum*'s associated animal assemblages, including sea turtle hatchlings, bluefin tuna, cobia, wahoo, mahimahi, and juvenile stages of other fish of commercial and recreational value.

protection against predation and stimulation of bottom-up production of consumer species in the food web. The quantitative relationships between *Sargassum* biomass and production of associated animals could be tested by experiments in the field. For example, experiments could be conducted in which differing amounts of *Sargassum* are maintained inside floating enclosures, open at the top and bottom to allow predation but with enclosing mesh of a size that prevents exchange of associated animals among *Sargassum* patches. These patches, differing in biomass, would then be seeded with different densities of the associated fish and invertebrate community. Following their survival and growth as a function of plant biomass could provide the quantitative basis for scaling the restoration of *Sargassum*-associated animals. Additional resource-specific restoration would probably still be necessary for the large numbers of hatchling sea turtles killed in oiled *Sargassum* because of their special status under the Endangered Species Act. It is possible that provision of more *Sargassum* habitat could enhance hatchling survival sufficiently to compensate for estimated oiling mortality, but if experiments fail to demonstrate compensation then additional means of replacing lost sea turtles would be needed, probably based upon actions already developed in the species-specific recovery plans.

Crop dusting near Ripley, MS, contributes to water pollution through chemical runoff.
Photo: Roger Smith

RECOMMENDATION 4

Modify farming practices in the Mississippi River basin to reduce nutrient loading in the Gulf of Mexico.

» Establish demonstration watersheds upstream in the Mississippi River basin that would test the economic benefits to farmers and the nutrient runoff reductions achievable by transforming and locally managing regional farm policy.

» Adjust U.S. farm policy to allow regionally tailored crop diversification and reduction of subsidies in the Farm Bill without loss of income to the farmers because of reductions in fertilizer costs.

Improvements in coastal water quality in the northern Gulf of Mexico could help achieve two major restoration goals: conserving and restoring coastal Louisiana wetlands and reducing the size of the Gulf hypoxic zone, the dead zone. Coastal wetland restoration is thwarted by the high nutrient concentrations in river water diverted into wetlands (Kearney *et al.* 2011,Turner 2010, Howes *et al.* 2010). Spring nutrient loading of the northern Gulf induces formation of the dead zone each summer (Figure 2, Rabalais *et al.* 2007, USEPA Science Advisory Board 2007). The increase in nutrient loading from the Mississippi-Atchafalaya River in the past 60 years is principally a result of more intense agricultural land use in the upper basin (Figure 2, Crumpton *et al.* 2006, Alexander *et al.* 2008, Turner and Rabalais 2003). Reducing nutrient delivery from the Mississippi River watershed would have benefits for local communities (USEPA 2006, 2010) and improve the fisheries in the Gulf.

Water quality improvements to the coastal waters of the Gulf near the Mississippi River delta must be made at the source. Because much of the excess nutrients in the Gulf can be traced upstream to the Midwest—the Corn Belt (Figure 2)—we recommend focusing on this area to help solve nutrient loading problems. To this end, we propose two general actions: 1) establish demonstration watersheds upstream in the Mississippi River basin that would test the economic benefits to farmers and the nutrient runoff reductions achievable by transforming and locally managing regional farm policy; and 2) adjust U.S. farm policy accordingly to allow regionally tailored crop diversification and reduction of subsidies in the Farm Bill without loss of income to the farmers because of reductions in fertilizer costs. Demonstration watersheds would shift farm control to the regional level, allowing each region to make decisions that reflect its unique crop priorities and growing conditions. Crops tailored to each farming region could lead to a reduction in nutrient export from the landscape, improved soil quality and sequestered carbon while sustaining the working lands and economies of local communities. Second, changes should be made to subsidies and policies under the U.S. Farm Bill. Farming regions should be released from national constraints on cropping priorities so that regional priorities can be developed in each watershed. Incentives to optimize environmental and economic outcomes could be included in new federal farm policies.

Background on U.S. Farm Policy

The predominant factor affecting land use in the Corn Belt is the federal farm policy. This set of policies drives land use practices that ultimately affect riverine nitrogen concentrations. For example, agricultural landscapes receiving higher government payments per area of farmland exhibit (Broussard *et al.* submitted): 1) a higher concentration of specialized crops; 2) a larger proportion of fertilized farmland (Crumpton *et al.* 2006); 3) farmland with lower cropland diversity; and 4) surface waters with relatively high concentrations of nitrate. Several other factors potentially contribute to the observed changes in production agriculture and surface water quality, e.g., climatic variability, soil type, urban expansion, wastewater treatment facilities and confined animal feedlot operations. The transition to current agricultural practices, however, probably would have been more gradual without federal support, because government programs are intended to reduce the risk in farming operations (Key and Roberts 2006) and favor the survival of larger operations with the resources to pursue land and capital acquisition (Key and Roberts 2007, Roberts and Key 2008).

Farm Bill subsidies vary depending on crops and region, but here are some illustrative points. Federal government farm payments authorized by the Farm Bill accounted for 32 percent of the total U.S. net farm income in 2005 (Broussard *et al.* submitted). Farm subsidies in 2002 were $22 billion. Some states average more in farm subsidies than their net income. In other words, without the subsidies, the net farm income would often be negative. The total subsidies amount to about $417 per capita for the Mississippi River watershed. Conservation programs and commodity programs are working at cross purposes where commodity program payments influence landowner decisions to convert grasslands to croplands (Claassen *et al.* 2004). Farm payments, therefore, are a potent policy instrument that could be used to influence alternative environmental and economic outcomes that protect soil and water resources while

A "crop cover" riparian buffer in Iowa reduces polluted runoff from fields. Photo: University of Maryland Press Releases promoting local food security and jobs and maintaining farm profitability.

Optimizing for these multiple goals is known as capitalizing on the potential of "multi-functional" agriculture (Jordan *et al.* 2007). It is distinct from the valuable but spatially restricted current federal programs that subsidize the retirement of land from active production. These programs have produced substantial environmental benefits (Sullivan *et al.* 2004) but public investment in these programs is unlikely to increase in the foreseeable future. There is evidence that major additional benefits may be gained from a "working landscape" approach that improves the performance of active farmland by rewarding farmers for delivering environmental benefits as well as food and biomass (Jordan *et al.* 2007). A variety of strong political constituencies now expects a very different set of outputs from agriculture, and the U.S. farm sector could meet many of these expectations by harnessing the capacities of multi-functional agriculture. Here we recommend capitalizing on the potential of multi-functional agriculture through the specific actions outlined below.

Establish "demonstration" watersheds

We propose the creation of a network of research and demonstration watersheds that will establish and evaluate new bio-economic enterprises based on multi-functional production systems. These demonstration watersheds would be authorized as regional management units to develop farm policies that more closely reflect regional growing conditions and crop priorities. Regional demonstration watersheds could improve relationships between farm policies and on-the-ground crop outcomes and lead to environmental benefits suggested by this report as well as by others (Jordan *et al.* 2007, Batie 2009). They could explore alternative uses of federal farm funds at sufficiently large temporal and spatial scales to match the needs of the agricultural communities living in them. A portion of the DWH oil spill restoration funds would be the catalyst for this change.

These demonstration watersheds must be sufficiently scaled (ca. 5,000 km²) to address the complexity of natural, human and social factors. They should be managed by groups that encompass multiple levels of government and include multiple stakeholders to determine the societal worth of ecological services produced by these multi-functional production systems and to establish mechanisms that appropriately compensate farmers for production of these services. Administrative bodies that integrate across political, economic and social boundaries (Roux *et al.* 2008) are required to successfully apply management practices in ecological units stretching from small upland watersheds to coastal waters. A consortium of state and federal interests that embrace positive changes is required: Land grant colleges and universities are critical potential members, for example. It is also critical to involve the local communities that drink the water, swim and fish in the streams and eat the food from the local farms. Such an effort to integrate land management across a wide spectrum of interests and authorities is underway in a larger sub-basin of the Chippewa River in Minnesota (Boody *et al.* 2005), where the focus is on development of grasslands for biofuel and meat and dairy food production. The multi-stakeholder processes of learning, deliberation, negotiation and experimentation that are essential to developing new production systems under the demonstration watersheds will not occur without organizational mandates, resources and policies supporting participation.

Adjust U.S. farm policy to encourage crop diversification and regional farming priorities

We suggest that government commodity programs can be used to support a wider variety of crop types, particularly on smaller farms (Roberts and Key 2008), can decrease the risks of diversifying crops in impaired agricultural landscapes (Dimitri *et al.* 2005) and can stimulate economic markets for other crops (Jordan *et al.* 2007). Additionally government farm programs for soil conservation could protect valuable soil resources (Claassen *et al.* 2007) by encouraging investment in long-term soil fertility and agricultural sustainability.

One way to encourage sustainable conservation and the development of ecological services is to require that farms implement conservation practices in order to receive government-issued commodity payments. Examples of conservation management practices that could reduce nitrogen

One way to encourage sustainable conservation and the development of ecological services is to require that farms implement conservation practices in order to receive government-issued commodity payments.

leaching and coastal hypoxia include adoption of traditional and innovative conservation practices (Nassauer *et al.* 2007), maintaining living plant cover on the soil for the majority of the growing season (Jordan *et al.* 2007), reduced dependency on field drainage systems (Nassauer *et al.* 2007), and increased production of perennial field crops—all of which could support a market-driven economy (Cox *et al.* 2006, Glover *et al.* 2007, Jordan *et al.* 2007, Nassauer *et al.* 2007).

Each region has its own set of circumstances, its unique soil fertility, drainage, transportation and culture. It is best, therefore, if agricultural management includes and reflects these regional factors by empowering local decision-making. The outcomes anticipated from freeing farmers to establish locally appropriate crops rather than planting corn to receive incentive payments under the Farm Bill will be: 1) a 50 percent reduction in the nitrogen loading from the watersheds within 25 years; 2) more diverse crop choices; 3) a landscape with more than 15 percent perennial crops; 4) the creation of region-specific solutions that result in new opportunities for the emerging bio-economy; and 5) *in toto* and in parts, models of sustainable ecosystem management that incorporate democratic participation at the community level and a legacy of guidance for future generations.

We conclude that farm subsidies can be used to provide the infrastructure and incentives to become a basis for a sustainable agricultural bio-economy. These subsidies could be released from national constraints on cropping priorities and assigned regional priorities by the watershed governing entities (in a process that is determined in a competitive review), whose goal is to protect and enhance environmental and economic outcomes over 50 years. But funding is needed to support the transition. Through initiatives proposed above, we judge that this can be done with relatively modest public investments (ca. $10 million annually for five sites over 25 years).

RECOMMENDATION 5

Reduce fish and wildlife casualties resulting from aquatic debris.

» Conduct field programs to remove and simultaneously determine types, locations and sources of debris.

» Develop programs to limit and prevent debris discards at the source and to regularly remove debris at hot spots where it collects.

Marine debris in many forms is now ubiquitous around the planet (UNEP 2009), and, notwithstanding many laws, regulations and programs targeting marine debris, this problem is likely to increase in the 21st century (NRC 2008). Marine debris comes from many sources, including several that are ocean based, such as cargo ships, commercial fishing boats and recreational craft. In the Gulf, the offshore oil and gas industry is a significant source of debris (NRC 1995, 2008). Up to 10 percent of all debris on Padre Island National Seashore has been attributed to oil and gas operations (Miller and Jones 2003). We recommend funding projects to systematically survey and remove marine, estuarine and riverine debris in all Gulf states affected by the DWH oil spill. These projects have the potential to garner significant public support in part because they would improve the aesthetics of the shoreline.

Removal of debris from the seafloor and surface, shoreline habitats, estuaries and other waterways is motivated not merely by aesthetics but also by wildlife and habitat protection. The emergency responses to the DWH oil spill generated tons of debris, which persists as collateral injury to habitat and to fish and wildlife of the northern Gulf. Furthermore, removal of preexisting debris is critical to the effectiveness of species recovery plans and improved management more generally. For example,

Seabirds and sea turtles can become entangled in discarded gillnets and other netting. Sea turtles mistake plastic bags for jellyfish and consume them, often resulting in death.

Derelict traps abandoned by fishermen are harmful to coral reefs. Photo: Amy Uhrin/NOAA/ Marine Photobank

Debris removal should target not only materials left behind after emergency response to the DWH oil spill but also those generated by ongoing human activities.

a removal program for Louisiana stream debris was designed to avoid stream flow blockage and resultant flooding (S. Laska pers. com.). Marine debris removal programs are funded by various nongovernmental organizations (NGOs), industry and government agencies. NOAA programs, for example, target disused, discarded and lost fishing gear such as crab pots, longlines and fishnets that can persist for years, trapping, entangling and killing wildlife.

Support for existing marine debris programs and mobilization of new ones for the northern Gulf could help restore Gulf resources, including sea turtles, seabirds, marine mammals and other wildlife harmed by DWH oil. For example, many clapper rails were among the birds killed by the oil. Crab pots cast up onto marshes trap and kill rails and other marsh birds, and removal of discarded crab pots can speed recovery of rail populations. In addition, crab pots abandoned or lost on the estuarine bottom trap and kill a wide range of fish and crustaceans that were injured by DWH oil. In the five Gulf states, volunteers with the 2009 International Coastal Cleanup picked up 728 discarded or lost crab, lobster or fish traps, which represent only what was found on a single day in relatively accessible locations (Ocean Conservancy 2010).

Seabirds and sea turtles can become entangled in discarded gillnets and other netting. Sea turtles mistake plastic bags for jellyfish and consume them, often resulting in death. Bottlenose dolphin and other marine mammals suffer death and injury from entanglements with nets, and pygmy sperm whales and sperm whales, both found in the Gulf, are vulnerable to the ingestion of plastic bags and plastic sheets. Although it is difficult to establish the ultimate impact of entanglement and ingestion at the population level (NRC 2008), the deaths of marine mammals, sea turtles and other wildlife caused by marine debris are largely avoidable and fall within the scope of necessary Gulf restoration to enable other recovery actions to be effective.

Many marine debris programs engage the public as volunteers and hence pay dividends in education that may reduce future debris introduction. Public participation can impart useful feelings of ownership and responsibility for stewardship of the publicly owned resources of the Gulf. Field debris removal teams must be trained to minimize unintended habitat damage, however. For example, landing small boats on marsh shorelines and walking through soft sediments of coastal marshes can reduce their habitat value. The potential for injury to, contamination of and removal of artifacts from archaeological sites is sufficiently high that standardized training for teams removing shoreline debris is necessary.

Debris removal should target not only materials left behind after emergency response to the DWH oil spill but also those generated by ongoing human activities. Debris generated during emergency response activities includes unretrieved boom, mostly present in marshes, and trash discarded by response workers and from the fleet of boats. Debris that has been generated over longer time frames is important to distinguish from that generated during spill response, because organizing the search for and removal of debris in a spatially explicit fashion is important to targeting future efforts in regular debris removal projects.

Debris removal projects should require standardized data recording to characterize all debris by type and location; effort should also be recorded (e.g., number of participants, area searched, etc.). Survey designs should be based upon knowledge of locations and types of fishing and other activities. They should be combined with understanding of physics of transport and deposition to construct, empirically test and refine evidence-based models of debris accumulation. This allows future removal projects to be more efficient and effective and may even serve to help identify appropriate education or regulatory programs to limit generation of debris. This quantitative information and these models of debris generation should also be employed to mount successful educational or regulatory programs to prevent discard of marine debris.

RECOMMENDATION 6

Restore water flows, riparian habitats and water quality to reduce nutrient loading and enhance ecosystem services of smaller rivers.

- » Survey the smaller rivers of the Gulf to determine their water and habitat quality and their flow challenges.
- » Assess potential effects of environmental change on the ecosystem services of these river networks.
- » Preserve the more pristine rivers and restore damaged rivers using plans adapted to progressive environmental changes.

Natural resource managers and planners in states along the Gulf of Mexico are scrambling to develop management plans that take into account anthropogenic impacts on freshwater flow, water quality, fisheries and other services of watersheds in a realistic fashion, following the provisions of the U.S. Coastal Zone Management Act, the Magnuson-Stevens Fishery Conservation and Management Act and other important legislation. Contributing to the urgency is the ecological and economic damage caused by the series of hurricanes striking the region from 2004 to 2008 and then the DWH oil spill. A particular concern is the disconnect between science and management, resulting in freshwater use plans that lack sufficient scientific input (Brewer and Stern 2005, Tribbia and Moser 2008). A major scientific challenge is determining where, when and to what degree marine systems are likely to be affected by global climate change (IPCC 2007), including regional precipitation and hydrologic alterations arising from climate change. One can expect significant changes in species' distribution and abundance, as well as reshuffling of their trophic interactions as organisms respond to their changing environment (Parmesan and Yohe 2003, Coleman and Petes 2010). The question is: How can we predict and manage the responses?

Alteration of river flow regimes is a major threat to aquatic species (Richter *et al.* 2003). To date, research on its effects has focused primarily on freshwater species within river basins, while the effect of riverine flow on estuarine and marine productivity and ecosystems is less well understood (Baron *et al.* 2002, Fitzhugh and Richter 2004). The effects are not isolated but interact with anthropogenic stressors such as fishing, habitat loss and eutrophication. Furthermore, they are embedded within larger regional and global changes, such as atmospheric pollutant deposition and sea level rise, that are expected to further alter hydrologic cycles and the nature of interactions at the land-sea interface (Jackson *et al.* 2001, Pringle 2001, Milly *et al.* 2008, Breitburg *et al.* 2009).

A related and equally important effect of altered river flow on aquatic organisms relates to nutrient delivery—both the minimum requirements to support the ecosystem and the maximum threshold that precipitates over-enrichment. The high productivity of coastal ecosystems associated with major river systems is generally attributed to the addition of land-derived nutrients to otherwise nutrient-limited marine waters, and the resulting trophic transfer of enhanced primary production up marine food webs to harvested species (Caddy 2000, Grimes 2001). This bottom-up effect of nutrients is evident in studies that show higher fishery yields in ecosystems with higher nutrient inputs originating upstream (Caddy 1993, Nixon and Buckley 2002, Breitburg *et al.* 2009). Excessive nutrient loading can lead to a variety of secondary phenomena, such as harmful algal blooms and hypoxia (Paerl *et al.* 1998, Diaz 2001, Landsberg 2002), with negative consequences for fishery production. The ecological mechanisms that mediate these dual effects of nutrient loading are not well known, but river flow, which fundamentally affects the timing and magnitude of nutrient delivery to estuarine and offshore waters, is clearly important (Paerl *et al.* 2006). Human alterations of river flow and nutrient loading associated with industrial and agricultural development are implicated in some of the world's most spectacular downstream fishery and ecosystem

The Old River Auxiliary Control Structure on the Mississippi and Atchafalaya rivers in Louisiana. Photo: Team New Orleans/U.S. Army Corps of Engineers

Human alterations of river flow and nutrient loading associated with industrial and agricultural development are implicated in some of the world's most spectacular downstream fishery and ecosystem collapses, including Florida Bay, the Nile River and San Francisco Bay.

Reduction of nutrients helps recovery of sea grass. Photo: Sean Nash

Successful Nutrient Remediation

Examples of successful nutrient remediation are rare. Two are available, however, from the Gulf: Tampa Bay, FL, and Bayou Texar, near Pensacola, FL.

When a nutrient-reduction plan was implemented in Tampa Bay in 1984, sea grasses had been reduced to 20 percent of the area covered 100 years earlier (Johansson and Lewis 1992). The sea grass cover in Hillsborough Bay and Middle Tampa Bay doubled from 1986 to 1989 and was continuing to improve into the late 1990s.

By the early 1970s, the nutrient over-enrichment of Bayou Texar appeared to be causing extensive fish kills, noxious algal blooms, high algal biomass and closures to recreational use (Moshiri *et al.* 1981). A retention reservoir and weirs in the upstream channels were built in 1974, and sewage plants were repaired. The authors reported an almost total reduction in fish kills and the elimination of algal blooms. Wide public uses of the estuary then resumed.

collapses, including Florida Bay (Fourqurean and Robblee 1999), the Nile River (Nixon and Buckley 2002), the Black Sea (Kideys 2002) and San Francisco Bay (Sommer *et al.* 2007).

Nutrient over-enrichment has long been viewed as a general threat to estuarine and coastal water health. Sixty-seven percent of the surface area of U.S. estuaries exhibits moderate to high degrees of nutrient over-enrichment (Boesch 2002), and the condition is well documented in the Gulf of Mexico (e.g., Diaz and Rosenberg 2008). Poor water quality may enhance the likelihood of harmful algal blooms, which threaten fisheries (Hegaret *et al.* 2007) and contaminate shellfish beds, requiring them to be closed to harvest. Sewage (identified by the presence of fecal coliform bacteria) is a major contributor to poor water quality. Indeed, it is the density of fecal coliform bacteria that triggers the closing of oyster beds to harvest. Overall, increased nitrogen loading is directly related to the loss of submerged grass beds, a key fisheries habitat.

The restoration path of overnourished estuaries, however, may not mirror the trajectory of degradation (Duarte *et al.* 2009). This is because nutrient over-enrichment is not merely the result of higher loading of one or more nutrients to a water body but is embedded in a set of cultural and geomorphological modifications affecting ecosystems in diverse and interdependent ways (see box above).

The data on variation in nutrient loading among Gulf estuaries have not been updated for more than a decade (Turner 2001). The variability in loading is directly related to human population density and land use. This information needs to be updated to: (1) identify the less modified estuaries so that protective measures can be put in place; (2) document systems in transition toward nutrient degradation so that remedies can be implemented before any irreversible threshold is passed; and (3) restore highly degraded estuaries through development of locally relevant management plans. We recommend establishing and implementing a comprehensive research plan to evaluate critical watersheds in the northeastern Gulf of Mexico, from the Mississippi Sound to the Apalachicola Bay. This evaluation of smaller Gulf rivers would benefit several riverine restoration projects, including those that target farming practices upstream (Recommendation 4) and those that focus on habitat restoration sustainability by coupling wetland restoration with filling of dredged channels. We also recommend that these reviews be used to establish protections of pristine and highly functional rivers and to implement restorations to control problems identified in other rivers.

THEME 2

Protect Existing Gulf Habitats and Populations

Although restoration of injured habitats, described in our recommendations under Theme 1, clearly represents an important responsibility of the DWH natural resources trustees, protection of habitat supporting sensitive life stages and critical processes such as spawning, nesting and overwintering of fish, birds and other wildlife also has exceptional long-term benefits. Habitat protection represents a less risky action than direct restoration, which may fail or not endure. On an acre-for-acre basis, habitat protection is typically much less expensive than direct restoration. Moreover, organizations and resources are already actively focused on preserving habitats in the Gulf, and DWH funds can be used to augment existing programs or improve enforcement of current legislation that protects habitat. The following four recommendations are focused on preserving valuable habitat in the Gulf and enforcing existing legislation designed to protect wildlife and resources.

RECOMMENDATION 7

Preserve functionally valuable habitat for fish and wildlife sanctuaries to enhance injured species recovery.

» Conduct a systematic review of available large parcels of prime habitat, rating them by the importance of uses by injured species.

» Purchase land and/or development rights for habitat of highest rated value to injured species.

» Establish permanent stewardship for these habitat protections by merging them with national parks, wildlife sanctuaries or other responsible public land management programs.

Wildlife sanctuaries established for the benefit of species injured by oil spills and other anthropogenic stresses have proven to be effective at aiding the recovery of those species. After the Exxon Valdez oil spill, the natural resources trustees (the federal and state agencies legally responsible for carrying out natural resource damage assessment and compensatory restoration) reasoned that recovery of fish and wildlife required sustained protection of their habitats, including those in adjacent uplands, and chose habitat protection as a principal tool for restoration. Extensive efforts were made to consult with federal and state resource agencies, NGOs, private landowners, municipalities and others to identify and evaluate alternative parcels in the spill area as habitat for injured species of fish and wildlife (EVOSTC 1994). In some cases, additional fieldwork was undertaken specifically for that purpose (e.g., Kuletz *et al.* 1994). These evaluations also took into account the potential for incorporation of the habitat parcels into various conservation systems (e.g., parks, and refuges) to ensure

An osprey presides over a nest on the Pascagoula River in Mississippi. Photo: Jennifer Cowley/The Constituency for a Sustainable Coast

Recovery of an injured species may best be assisted by action to protect vital habitats *outside* the spill area. Northern gannets, for example, nest in the maritime provinces of Canada.

Brown pelicans fly over St. Vincent National Wildlife Refuge in Apalachicola, FL. Photo: Nicole Rankin/USFWS Southeast

management and long-term stewardship for recovery of injured species.

This concept and process provide a model for restoration after the DWH oil spill. Several NGOs, including The Nature Conservancy and local and regional land conservancies, already invest effort in identifying significant parcels of undeveloped or relatively intact land in private hands that provide vital habitats for sustaining ecosystem services and fish and wildlife populations. To help with recovery from the DWH spill, efforts should focus on the northern Gulf of Mexico spill area but also take into account a wider geographic area in response to the habitat requirements of injured species. In other words, recovery of an injured species may best be assisted by action to protect vital habitats *outside* the spill area. In the cases of injured species of migratory birds, many of which range widely, there may be need and opportunity for actions even more distant than the spill area. Northern gannets, for example, nest in the maritime provinces of Canada, while pelagic species such as Audubon's shearwater nest in the Greater Antilles.

A major difference between habitat protection programs after the Exxon Valdez oil spill and the current situation in the northern Gulf of Mexico is the present need to compare and rank alternative potential habitat purchases in the context of anticipated impacts of climate change, which may threaten some otherwise suitable habitats. For example, purchase of rapidly subsiding or low-lying lands cannot be justified by assuming perpetual provision of their ecosystem services as dry land habitats. Nevertheless, as coastal lands become flooded, they may still deliver valuable ecosystem services as submerged lands and still be worth purchasing. Expert judgment should prevail in choosing land parcels to ensure that future generations of people and wildlife continue to benefit.

We recommend that a broad program of habitat protection (including, as appropriate, fee-simple purchase or purchase of development rights) be organized. This program would first solicit local and regional knowledge about available privately owned lands and their habitat values for species of concern. Purchase of land parcels could be prioritized by available ecological data and economic considerations. This would ensure that funds are most effectively spent on habitats that will yield the highest benefit for their cost. Finally, permanent stewardship for these lands should be arranged to ensure their long-term delivery of ecosystem services. State and federal agencies, NGOs and networks of protected areas could serve as stewards of newly purchased habitats, including the U.S. Fish and Wildlife Service's National Wildlife Refuge System and NOAA's National Marine Sanctuaries Program.

Two large shrimp prowl the coral bottom in the Flower Garden Banks National Marine Sanctuary, Gulf of Mexico. Photo: G.P. Schmahl/NOAA

RECOMMENDATION 8

Implement and augment existing recovery actions for species of management concern injured by the DWH oil spill.

- » Use metrics established in prior population status reviews to help assess damage to injured species of concern.
- » Implement restoration actions identified and detailed in preexisting recovery plans for species of concern.

Many of the species that suffered population losses from the DWH oil spill and from collateral damage caused by response actions can be considered species of concern from population declines that predate the DWH incident and from special status granted by federal legislation or state declarations. These include threatened and endangered species protected by the Endangered Species Act (ESA), marine mammals protected under the Marine Mammal Protection Act (MMPA), and a number of severely depleted fish populations managed under the Magnuson-Stevens Fishery Conservation and Management Act (MSA). These laws mandate development and implementation of recovery or rebuilding plans for these species of high value, interest, and concern. The plans are drafted by groups of experts and are regularly updated. They include specific recommended restoration actions that are well founded in existing science and tend to be detailed. The recovery or rebuilding plans also include information on available metrics of abundance and historical records of change in abundance. Consequently, the restoration planning to redress damage caused by the DWH incident can be facilitated and made immediately up-to-date scientifically by making direct use of these intensive species status evaluations and the detailed set of restoration actions they contain.

Restoration activities must be based on quantitative estimates of the injury to each resource and quantitative estimates of the benefits of the enhancement actions to achieve truly compensatory restoration. As it applies to a specific resource, such as the brown pelican, or a habitat, such as a salt marsh, the process of determining the quantitative balance between injury and restoration is termed restoration scaling. The scale of compensatory restoration is computed by Resource Equivalency Analysis when applied to a species, or Habitat Equivalency Analysis, when applied to loss of ecosystem services from an injured habitat (NOAA 1995, English *et al.* 2009). Computations produce an estimate of how extensive a project must be to replace the losses attributable to the oil spill.

For an injured species that is also federally listed under the ESA, the federal agencies will have available a formal Species Recovery Plan. These plans include prioritized recommendations for recovery actions, which can greatly facilitate effective restoration for such species. For example, after the North Cape oil spill near Point Judith, Rhode Island, restoration of injuries to the federally listed piping plover included protection from people and dogs on potential nesting grounds around coastal barrier inlets. Sufficient data had been collected from monitoring previous interventions at other locations to provide a basis for scaling of this restoration approach and moving ahead with some confidence in success (Donlan *et al.* 2003). For many species not included in ESA listings, concern at the state level has led to development of formal recovery or management plans for species of state concern, which also provide well-informed and professionally developed guidance to restoration actions likely to be successful. Many ecologically similar species also share the same suite of stressors and have sufficient similarity in ecology so that plans developed for endangered and threatened species can apply more broadly. For example, the black skimmer, which suffered relatively high mortality after the DWH oil spill, exhibits a declining population in many states. Like the piping plover, the black skimmer also requires undisturbed coastal barrier habitat for nesting, yet development of coastal barriers and increased human uses such as off-road driving have greatly reduced suitable nesting areas. Consequently, compensatory

A bottlenose dolphin swims in the heavily polluted Galveston Bay off Texas. Photo: Flip Nicklin/Minden Pictures/ National Geographic Stock

Three-hour-old Kemp's ridley turtles are released into the Gulf at South Padre Island, TX, in 2008. Photo: Jeromy Gregg

Preservation of Habitat for the Kemp's Ridley Sea Turtle

The ongoing recovery of the Kemp's ridley sea turtle has led to expansion of its nesting range beyond Rancho Nuevo in Mexico to include regular nesting on southern Texas beaches, a region beyond substantial direct spill impacts of the DWH spill. The Texas Department of Parks and Wildlife has identified a key privately owned parcel that is now an inholding in the Laguna Atascosa National Wildlife Refuge. Acquisition of this area would protect nesting areas for three species of endangered sea turtles, including Kemp's ridley, and help maintain water quality in the adjacent Laguna Madre, which provides critical turtle feeding and resting habitat.

The Kemp's ridley sea turtle is the most seriously endangered of all Gulf sea turtles and comprises a relatively high proportion of observed sea turtle deaths after the DWH oil release.

restoration for black skimmer mortalities caused by oil and likely collateral damage by beach cleanups that disrupted breeding should contemplate making use of restoration actions identified for the piping plover by protecting coastal barrier nesting sites for both species.

Because all the sea turtles of the Gulf and Atlantic coasts are listed as either threatened or endangered, species recovery plans also exist that will facilitate identification of appropriate compensatory restoration actions for injured sea turtles (see box above). The Kemp's ridley sea turtle is the most seriously endangered of all Gulf sea turtles and comprises a relatively high proportion of observed sea turtle deaths after the DWH oil release, many of which may be related to the oil. NOAA and the U.S. Fish and Wildlife Service are jointly considering listing some geographically and evolutionary distinct subpopulations of the now-threatened loggerhead sea turtle as endangered, so the information on spill impacts on the loggerhead may contribute to a status change for the Gulf subpopulation. The green and leatherback sea turtles may also have suffered injury from the DWH oil and/or emergency response actions, and their Species Recovery Plans may serve to guide restoration.

The MMPA has also focused the attention of wildlife biologists on protection, enhancement and recovery of marine mammal populations, thereby serving to guide potential compensatory restoration actions. The DWH oil spill appears to have led to deaths of bottlenose dolphins in the Gulf, so compensatory restoration will be needed. One potential restoration action could be to properly shut down and seal so-called orphan wells in the Gulf coastal zone, of which there are many—in the low hundreds in Louisiana waters alone. To the extent that these abandoned wells are releasing oil and possibly other pollutants on a chronic basis, they are polluting the sea surface where marine mammals come to breathe and fouling coastal and estuarine habitats frequented by bottlenose dolphins. Shutting these abandoned wells would contribute to the enhancement of environmental quality, supporting healthier populations of multiple species, including dolphins. Management plans for bottlenose dolphin under the MMPA could help guide the necessary conversion of reduction of surface oil from well plugging to enhanced survivorship of the dolphins so as to convert benefits to the same units as spill damages.

Before implementing any untested restoration action, pilot projects may need to be conducted to serve as proof-of-principle and to allow credit to be estimated quantitatively based on accepted metrics of population increase. This is especially true for species that lack an existing, shovel-ready restoration plan, but even for those that do, the site-specific aspects of how a restoration action may function require confirmation and quantification. Similarly, monitoring needs to be included for all restoration actions so that adaptive management can be applied to achieve the restoration targets.

A Coast Guard member examines a turtle exclusion device at the Gulf Regional Fisheries Training Center in New Orleans. Photo: Petty Officer 3rd Class Casey J. Ranel/U.S. Coast Guard

RECOMMENDATION 9

Maintain and enforce existing legislative protections for water, habitat, fish and wildlife to preserve public health and provide valued resources.

- » Enforce existing federal and state laws designed to protect air, habitat and water quality and to sustain natural resources.
- » Develop state-level environmental legislation that is tailored to specific needs of Gulf states and is adaptive to changing environmental conditions.
- » Promote more holistic interpretations of environmental legislation by encompassing indirect impacts and targeting non-point pollution sources.

In the late 1960s and early 1970s, Congress reacted to decades of increasingly unhealthy air and water pollution and unsustainable exploitation of natural resources by enacting a set of environmental statutes designed to protect, restore and maintain the country's natural resources and to manage those resources in a sustainable manner. These laws include NEPA (1969), CAA (1970), the MMPA of 1972 (the first time the term "best available science" was invoked), the Federal Water Pollution Control Act Amendments of 1972 (CWA), the Marine Protection, Research and Sanctuaries Act (the Ocean Dumping Act), ESA and the Fishery Conservation and Management Act of 1976 (later renamed the Magnuson-Stevens Fishery Conservation and Management Act). These major federal statutes provide needed protections to sustain public health and to perpetuate the valuable services that ocean ecosystems provide naturally to the public: fish production, opportunities for wildlife watching and water sports, and more. Restoration of the Gulf ecosystems in the aftermath of the DWH tragedy will depend on maintenance of and improved compliance with these laws.

These statutes and others have contributed to the protection of our country's oceans, but degradation of ocean resources has not been halted. NEPA requires federal agencies to analyze the environmental impacts of major federal actions that will significantly affect the quality of the human environment. Over the years, however, the scope and quality of those analyses appear to have declined. The MMPA sets ambitious goals for minimizing mortality of ocean mammals, but those goals have not been achieved. The success of the CWA is evident in data records of the National Status and Trends Program on metals and

Street runoff in adjoining states affects the Gulf. Photo: Link Roberts/Marine Photobank

Non-point source nutrient pollution is the single most devastating source of impacts on coastal waters and habitat (e.g., the hypoxic zone off Louisiana), yet because the sources are diffused throughout many states, regulation of this pollution is difficult.

organic contaminants at more than 300 sites around the U.S. coast (Kimbrough *et al.* 2008). The CWA is also responsible for tremendous enhancement of sewage treatment and improvements nationally in quality of wastewater discharge. Nevertheless, levels of pathogens are still increasing in shellfish waters of estuaries and at ocean beaches. Although gratifying in their intent and in some cases far-reaching in their effect, these laws placed the burden of proof of harm and defining the metric of that harm on the government and the public. The outcome, especially in arenas where there is considerable uncertainty, is risk-prone decision making. But when considered from an ecosystem services perspective, the greater the uncertainty, the greater the precaution required (Dayton 1998, NRC 2004).

Yet there also has been increasing recognition of the importance of precaution when facing uncertainty in ecosystem management. The U.N.'s 1992 Rio Declaration addressed the problem of scientific uncertainty about the use of environmental resources. It stated that when "there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation." This approach recognizes that lack of information does not mean lack of an impact, and that activities need to proceed with due caution when data are lacking. To assess the full impact of an immediate target activity (e.g., effect of fishing on a fished population), all collateral ecological effects must be included to be truly precautionary (Gerrodette *et al.* 2002). Although NEPA requires analysis of cumulative impacts, this provision does not appear to be practiced consistently in the United States (NRC 2004). Craig (2002) suggested that the political forces at play to block legislation that would enact truly precautionary policies have been considerable. Gerrodette *et al.* (2002) stated that federal regulatory bodies tend to pursue easier, short-term regulatory problems (e.g., protection for marine mammals) rather than long-term, complex issues (e.g., marine pollution from land-based runoff, sustainable fishing practices or protection of wetlands).

Federal legislation provides important measures of protection for coastal habitats under the MSA and the CWA. The essential fish habitat provisions in the 1996 reauthorization of the MSA (16 U.S.C. §§ 1801-1882) placed habitat at the center of NOAA's goals to restore and preserve ecosystems and develop sustainable fisheries. These provisions defined essential fish habitat as "those waters and substrate necessary to fish for spawning, breeding, feeding or growth to maturity" and required fishery management plans to "minimize to the extent practicable adverse effects on such habitat caused by fishing." Some have asserted that these provisions encouraged adoption of an ecosystem-based approach to fishery management (Koenig *et al.* 2000). At a minimum, they recognized the profound importance of healthy habitat to fishery production (Dayton *et al.* 1995). The focus on habitat damage caused by fishing gear (Jones 1992, Watling and Norse 1998, NRC 2002) and exploitation of commercial species (Goeden 1982, Estes and Duggins 1995, McClanahan *et al.* 1999, Graham *et al.* 2011b) is no surprise, given that the MSA focuses on fisheries-induced impacts. But the act's provisions do not address many land-based impacts, including point and non-point source pollution, that have a significant effect on coastal habitats. Those impacts are nominally subject to a different federal statute, the CWA.

The CWA (33 U.S.C. §§ 1251 *et seq.*), once considered among the most far-reaching pieces of environmental legislation in the country, provides the primary protection against water pollution with a goal of restoring and maintaining the chemical, physical and biological integrity of U.S. waters. CWA's coverage extends seaward for all purposes out to three miles offshore and out at least to the 200-mile limit of the nation's exclusive economic zone with respect to point source discharges and the establishment of ocean discharge criteria. Under the latest draft guidance (issued by the Environmental Protection Agency and the Army Corps of Engineers in April 2011) establishing the scope of inland waters covered by the act, the following are presumptively protected: 1) traditional navigable waters; 2) interstate waters; 3) wetlands adjacent to either traditional navigable waters or interstate waters; 4) non-navigable tributaries to traditional navigable waters so long as the tributaries contain water at least seasonally;

and 5) wetlands that directly abut relatively permanent waters. In addition, the draft guidance provides that certain other waters are protected under the act if a fact-specific analysis determines that they have a "significant nexus" (some sort of physical, chemical or biological connection) to either a traditional navigable water or an interstate water. Importantly, this nexus provision provides protection to tributaries to traditional navigable waters and interstate water, wetlands adjacent to these tributaries, and certain other waters, even if they are not geographically proximate to these tributaries.

Regulatory authority under the CWA can complicate its enforcement. The EPA has ultimate federal authority for regulation of point-source discharges (§ 402), while the Army Corps of Engineers has some authority, subject to ultimate review by EPA, for regulation of discharges of dredged or fill material (§ 404). The EPA can delegate its authority over pollution control to the states but can take back control if a state does not carry out the requirements of the law. However, non-point pollution issues defy this rather simple separation. Non-point source nutrient pollution is the single most devastating source of impacts on coastal waters and habitat (e.g., the hypoxic zone off Louisiana), yet because the sources are diffused throughout many states, regulation of this pollution is difficult. Another problematic issue for regulation is stormwater runoff, which is also generally non-point source pollution. Federal authority is generally restricted from interfering with state authority in these non-point pollution cases, and attempts to remove these restrictions on federal authority have been blocked by Congress, ostensibly because they pertain to land use management (Craig 2000). Other restrictions on the enforcement of the CWA came from two recent Supreme Court rulings, which devalued the ecosystem services certain lands provide and essentially changed the equation of enforcement.

The CAA (42 U.S.C. §§ 7401 *et seq.*) is designed to protect and enhance the quality of the nation's air resources. The act limits emissions of various air pollutants, including a number of hazardous substances such as nitrogen oxides. Like the CWA, the CAA vests ultimate authority in the EPA but allows the EPA to delegate implementation and enforcement authority to the states. Also like the CWA, the CAA allows states to enact more stringent emissions limits but prevents them from allowing greater levels of air pollution emission than allowed by federal law. Among the pollutants controlled by the act are emissions of nitrogen, which can enter water through atmospheric deposition and adversely affect water quality by enhancing acidity and contributing to nutrient-based eutrophication problems.

The ESA (16 U.S.C. §§ 1531–1544) is intended to provide for the conservation of species that are in danger of extinction throughout all or a significant portion of their range. Management is split between the U.S. Fish and Wildlife Service (terrestrial and freshwater species) and the National Marine Fisheries Service (marine and anadromous species). The overarching purposes of the ESA are to provide a means for conserving endangered and threatened species along with the ecosystems on which they depend (16 U.S.C. § 1531(b)). The ESA defines an endangered species as one that "is in danger of extinction throughout all or a significant portion of its range." (16 U.S.C. § 1532(6)). The ESA defines a threatened species as one that "is likely to become an endangered species within the foreseeable future" (*Id.* at 1532(20)). ESA-implementing regulations repeat these definitions without further elaboration (50 C.F.R. § 424.02(e), (m)). The determination of whether a species is threatened or endangered is governed by threats to its habitat, overutilization, natural stressors such as disease or predation, or any "other natural or manmade factors affecting its continued existence" (16 U.S.C. § 1533(a)(1); 50 C.F.R. § 424.11(c)). Determination of an endangered or threatened species under the ESA must be made based on scientific evidence and must exclude considerations of economic impacts (16 U.S.C. § 1533(b)(1)(A), 50 C.F.R. § 424.11(b)).

Under the terms of the ESA, the federal government must avoid actions that jeopardize the continued existence of listed species. Thus, for example, the federal government has required turtle excluder devices to be placed in shrimp trawl nets in the Gulf of Mexico and southeast Atlantic Ocean to protect several species of sea turtles that are listed as endangered under the ESA. Threats to enforcement of the

Factory smokestacks are a source of pollution in Florida. Photo: Monica McGivern

As global climate change is modifying the Gulf Coast, there is a pressing need for legislative adaptation at the federal and state levels to address emerging needs for protections of habitat, water quality, air quality, fish and wildlife.

Laws often do not take account of diffuse stressors and nonpoint sources of pollution, allowing continued habitat degradation from indirect stressors.

Endangered Species Act come from commercial interests, but more recently and bizarrely from the spending bill for FY 2011, which included a rider de-listing a species of wolf as endangered. Because this is the first time Congress has taken legislative action to remove ESA protections from a listed species, many conservation and environmental groups are concerned that members of Congress might attempt to de-list more targeted species via riders on future bills.

Challenges to the legislation that protects the environment, species and their ecosystems include enforcement, rapidly shifting needs for regulation because of climate change and narrow interpretations of laws. As global climate change is modifying the environment along the Gulf Coast, there is a pressing need for legislative adaptation at the federal and state levels to address emerging needs for protection of habitat, water quality, air quality, fish and wildlife (see box below). Laws often do not take account of diffuse stressors and non-point sources of pollution, allowing for continued habitat degradation from indirect stressors. An example of this insufficiently holistic view can be seen in the degradation of several Gulf habitats. Sedimentation from land erosion and non-point source pollution, especially as transferred by poorly controlled storm-water flows, is covering and killing oyster reef habitat. Nutrient loading from atmospheric nitrogen deposition and storm-water runoff from agricultural and developed lands is causing microalgal proliferation in coastal lagoons and estuaries at the expense of sea grass meadows. Mowing and burning of salt marsh macrophytes is commonly allowed simply to reveal water views. All of this damage to essential habitat for fish and wildlife production occurs despite federal protections. These loopholes in protections need to be closed to promote long-term environmental health and the delivery of economically valuable ecosystem services.

We urge that some of the restoration funds for Gulf coastal habitats and resources be used to review the current failures of these landmark environmental and natural resource protection laws and to develop precautionary modifications to sustain environmental quality, habitats, and fish and wildlife in the face of growing challenges posed by environmental change. We further suggest that information campaigns be supported in all the Gulf states to inform the public about the economic and societal value of this legislation.

A school of fish swims among mangrove trees in Florida. Photo: Bianca Lavies/National Geographic Stock

Protecting Mangroves

Mangroves have expanded their range in shoreline areas of the Gulf, often replacing salt marsh plants. This process is doubtless continuing as winter temperature minima continue to rise in the region. Mangroves represent one of the key foundation species that define certain shoreline habitats of tremendous importance as providers of ecosystem services, including support of fish and wildlife. Mangroves were afforded no protection under law until 1996, when the Mangrove Protection Act (Mangrove Trimming and Preservation Act) was passed in Florida. The intent of this law was to protect and preserve mangrove habitat from unregulated removal, defoliation, and destruction, while requiring private property owners to obtain permission before trimming any mangrove. Despite the intent of the law, the authority devolved to local governments with the result that corporate interests and private property rights determine the health and fate of this important coastal habitat in Florida (Ueland 2005). The distribution of mangroves in the continental United States is primarily on Gulf and Atlantic coasts of South Florida, although black mangroves are now appearing in Alabama and Louisiana, extending the need for their protection to other Gulf states.

RECOMMENDATION 10

Create networks of protected habitats to enhance fish stocks and other valuable species.

- » Establish marine protected areas on the inshore shelf to allow recovery of overexploited reef fish.
- » Protect connected series of habitats in the Big Bend coastal area of Florida from the estuary to the De Soto Canyon that are used sequentially in the development and migration of reef species.
- » Establish deep-sea biological preserves to protect organisms such as coral that provide habitat structure and install observing systems to monitor the mysterious and intriguing deep-sea system.

Gulf fisheries, as well as the overall ecosystem in which they occur, are seriously compromised by overfishing, habitat degradation, eutrophication and other anthropogenic influences (USEPA 2008). The failure to sustain such valuable fisheries, slow progress in restoring stocks and uncertainties about the multiple processes that cause the declines in yield imply that new approaches are needed. The establishment of marine protected areas (MPAs) is an important conservation approach that simultaneously protects biodiversity and promotes rebuilding of depleted fish stocks, especially demersal fishes of reefs (NRC 2001b, Gaines *et al.* 2010). Unfortunately, the amount of habitat currently protected in the ocean is far below that recommended by scientists.

MPAs can be unpopular with fishermen because of the initial closure of fishing grounds to form them. But the availability of restoration funding for the Gulf provides an opportunity to compensate fishermen for their temporarily decreased catch. After stocks rebuild within the MPAs and replenish areas outside them by spillover of juveniles and adults or by elevating larval abundances and recruitment into fished areas, fishery yields are expected to grow.

Critical questions remain about which habitats to protect, how much to set aside, and where to locate MPAs to be most effective. Progress in this area is impeded to some extent by three fundamental issues. First, restoration goals depend on historical baselines, but these are difficult to establish because systems have been degraded over many years. Second, the flux of materials and organisms connects systems in ways that do not map cleanly to property or government jurisdictional boundaries. Research is needed to identify connectivity among habitat patches and thereby allow creation of an array of MPAs and areas open to harvest that will function best. Finally, our rudimentary understanding of remote deep-sea ecosystems—a focal area for oil and gas exploration and extraction—limits our ability to design networks of deep-sea reserves that could serve to preserve important ecosystem functions. We highlight these issues with three specific examples.

Shrimp are processed at a facility in Dulac, LA. Photo: Paul Goyette

Shifting Baselines

Establishing goals for habitat recovery requires determining the pre-impact state we wish to achieve. Clearly, human effects on the marine environment have accumulated over hundreds and even thousands of years. As a result, our current view of human impacts is based on our perception of what constitutes a pristine system, rather than on historical data that predate our more recent dramatic influences on marine ecosystems. Indeed, appropriate baselines predate oil and gas production in the Gulf, which began in tidal lands of Texas and Louisiana around 1920, making historical data collected through programs supporting the oil and gas industry inadequate for many applications. Shrimp trawling in the Gulf, which began in the early 20th century, may prove to have been the most destructive to habitat (see Dayton *et al.* 1995) on a broad areal basis over a somewhat longer (more than 100 years) period of time. In its pre-trawled state, the soft-bottom shallow shelf habitat now trawled for penaeid shrimps contained substantial amounts of biogenic habitat provided by erect bryozoans, sponges and other epibiota, which are extremely sensitive to mortality from bottom disturbance caused by trawling. Yet we lack specific descriptions of the baseline conditions that would reveal the

Ernest Hemingway poses with sailfish in Key West, FL, in the 1940s. Photo: State Library and Archives of Florida

To assess the health of the bay scallop population, researchers conduct surveys at several sites along Florida's west coast each spring. Photo: Florida Fish and Wildlife Conservation Commission

Restoration goals depend on historical baselines, but these are difficult to establish because systems have been degraded over many years.

continental shelf habitat structure, biodiversity and biomass prior to intensified trawling. To what extent has trawl-induced habitat modification altered these communities and their contributions to ecosystem function, ecosystem services and resource production? How has their loss affected juvenile fish and fish recruitment?

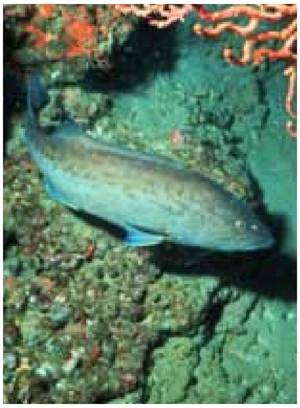
Clearly an assessment of the impact of that habitat modification is warranted. Two approaches seem reasonable to pursue: retrospective research of museum collections and historical cruise reports; and experimental studies using MPAs. We suspect that retrospective research will provide evidence that shrimp trawling has dramatically modified the soft-bottom benthic communities of the inshore shelf along large areas of the northern Gulf of Mexico. An empirical assessment of the benthic communities would require evaluating trawled grounds and neighboring, otherwise environmentally identical, areas closed to shrimp trawling. Research programs focusing on these sites should: 1) evaluate the magnitude and nature of indirect impacts of trawling and of restoration of habitat provided by the emergent epibiota as it recovers in areas closed to bottom trawling; 2) quantify changes in the habitat value, as measured in terms of use by fish, crustaceans (including shrimps) and other marine organisms; and 3) document how observed effects of protection spill over to influence production and ecosystem services, including augmentation of commercial fisheries, in nearby areas. If empirical tests reveal changes to the benthic soft-sediment communities that lead to enhanced production of fish, shrimp and crabs, then establishment of multiple trawl-exclusion refuges should be pursued. Research should also be conducted on spatially explicit ocean management options to minimize loss of shrimp catch arising from area closures while maximizing ecosystem services arising from the restoration of historic epibiotic habitat.

Connectivity through habitats and ontogeny

Marine habitats are connected both by the flow of nutrients and by the movement of organisms, especially as they grow from larval to adult stages. MPAs must be established in a coherent manner that recognizes how the reserve and non-reserve portions of the ecosystem are connected and how organisms change their habitat use through ontogeny (development) (St. Mary *et al.* 2000; see box, Page 70). This connectivity is nicely illustrated off the Florida Panhandle[2] and Big Bend,[3] areas that are relatively pristine, define a biodiversity hot spot and are home to a variety of important fisheries species. The area (Figure 7) is bathed by freshwater flowing from a number of rivers (the Apalachicola being the largest) and infused by groundwater and seepage from dozens of coastal springs (Rosenau *et al.* 1977, Taniguchi *et al.* 2002, Scott *et al.* 2004). This input of freshwater carrying nutrients together with the seasonally

Designing Marine Reserve Corridors with Ontogeny in Mind

Two related aspects of a species' ontogeny to take into account when designing corridors and reserves are the duration of the larval stage and the primary sites of settlement. Many species depend on currents to transport larvae from spawning sites over variable distances to reach suitable nursery habitat. For species in which larval duration is short and dispersal distances are minimal (e.g., approximately 10 km), a single reserve may suffice. For species in which larval duration is relatively protracted (more than 30 days) and transport distances long (e.g., tens to hundreds of kilometers), protecting the entire corridor is impractical because it may be impossible to pinpoint settlement sites with any degree of accuracy. In this case, it may be necessary to identify multiple reserves down current from one another to ensure that the larvae spawned from the protected spawning population are also protected when they recruit to nursery grounds. There is an exceptional case, however, for species for which juvenile abundance in geographic locations has been evaluated (e.g., see Koenig and Coleman 1998). Here, a reasonable approximation can be made about where the greatest level of recruitment occurs. For gag, this is clearly in the sea grass beds of the Big Bend.



A gag grouper swims off the Carolina coast. Photo: T. Potts/ NOAA

variable circulation patterns (He and Weisberg 2003) drive regional productivity and connectivity (Toner 2003, Zavala-Hidalgo *et al.* 2006, Morey *et al.* 2009, Walsh *et al.* 2009). This is particularly important to reef fish with complex life cycles that use very different habitats and change diets over the course of a lifetime. Unfortunately, most studies of MPAs have focused on productivity via larval transport without consideration of ontogeny or the effects of processes occurring in coastal watersheds (but see St. Mary *et al.* 2000).

Gag grouper (*Mycteroperca microlepis*) provides a clear example of a fish with a complex life cycle that needs multiple habitat protections. Adult gag live offshore on drowned patch reefs on the continental shelf edge at 60 to 100 m depths during most of the year. Females are scattered across the shelf while males remain along the shelf edge year-round. Adult females, in the months before the spawning season, move inshore to feed on fish emigrating from sea grass beds during the first cold periods of fall (Coleman *et al.* 1996), thereby building up their biomass for egg production (Nelson *et al.* in press). They then move to the shelf edge to join males on spawning sites in late winter. These spawning aggregations have been targeted by fishermen since the 1970s. As a result, the sex ratio became severely biased, with males making up only one percent of spawning populations (Coleman *et al.* 1996). To protect these populations, the Gulf of Mexico Fishery Management Council in 2000 established two year-round marine reserves, Madison Swanson Marine Reserve and Steamboat Lumps Marine Reserve (Coleman *et al.* 2004b, Coleman *et al.* in press). The reserves have effectively increased the percentage of spawning males in the population from the overfished condition of one percent to near historical levels of 15 percent (Koenig and Coleman in prep).

Although the marine reserves have resulted in a rebalancing of the sex ratio for gag, other habitats and life stages lack protection. For example, spawning of gag generally coincides with the development of a nutrient plume emanating from the Apalachicola River that can extend for hundreds of miles down the west Florida shelf and may be an important determinant of year class strength in this and other species (Morey *et al.* 2009). The buoyant fertilized eggs hatch in several days. The pelagic larval stage lasts 30 to 60 days, after which the larvae metamorphose into juveniles and settle into shallow sea grass beds. The juvenile stage persists for up to seven months, with immature fish leaving the sea grass beds and migrating to shallow-water (20 to 30 m) reefs dominated by sponge and soft coral, where they remain for several years before joining spawning populations offshore at the shelf edge. The complex life cycle of the gag grouper means that this species is affected by factors that impinge on freshwater watersheds, sea grasses, nearshore shallow reefs and deep offshore reefs, all of which experience anthropogenic stress.

Many other species show analogous linkage across vastly different types of habitats. Species with habitat needs that change through ontogeny are much more likely to spill over the boundaries of marine reserves (Ward *et al.* 2001). An organism that emigrates from one habitat to another faces the gantlet of getting from point A to point B without harm. Thus, in designing marine reserves and other spatial protection measures, managers must consider constructing networks of protected areas ranging across different habitats. Placing or managing MPAs incorrectly could result in no net increase in target fish populations, or worse, result in harm (Crowder *et al.* 2000). This is especially true when one part of a species' life history makes it vulnerable to capture by fishermen and managers leave the fish unprotected in those places (Farrow 1996, St. Mary *et al.* 2000). Juveniles may be fished out while en route to their offshore destination or females may be efficiently captured as they aggregate just prior to spawning. Dense aggregations and high fluxes of fish can facilitate ease of capture and these features often are associated with MPA boundaries (Ward *et al.* 2001).

An organism that travels from one habitat to another faces the gantlet of getting from point A to point B without harm. Thus, marine reserves and other spatial protection measures must consider constructing networks of protected areas.

Because gag grouper is seriously overexploited and its life cycle includes stages and places of especially high vulnerability to capture by fishermen as it moves sequentially among habitats, we suggest development of a protective cross-boundary corridor that following a relict Pleistocene river delta extending from the Apalachicola River to the shelf edge (deltas described in Gardner *et al.* 2005). This corridor would include swaths of critically important habitats, including oyster reefs, salt marshes and sea grass beds, from Apalachicola to Anclote Key. These architecturally complex habitats are inextricably linked inshore and offshore and across horizontal and vertical strata (Vetter and Dayton 1998, He and Weisberg 2003, Heck *et al.* 2008) and are essential to the propagation and, now, restoration of many Gulf species.

A special case can also be made for providing protection for a deep-sea area known as the De Soto Canyon (Figure 6). This region, off the Alabama-Florida coast, is a valley (800 to 1,000 m) that cuts through the broad continental shelf in the northeastern Gulf. The canyon is peculiarly shaped, probably formed by intrusion of the Loop Current and characterized by upwelling that bathes the continental shelf in nutrient-rich water (Gilbes *et al.* 1996). It has an offshore extension into deep water from the Florida Panhandle and thus has important connectivity with the outflow from the Apalachicola River. During the oil spill, it became clear that the geological structure of the canyon, coupled with local currents, served as a conduit for oil to reach the canyon at depth, raising concerns that it could intrude upon the shelf. That possibility remains and is of keen interest. The area is known to have lush planktivorous communities of sponges, soft corals and ahermatypic hard corals, including a black-coral habitat that is at least 2,000 years old (Prouty *et al.* 2011) and fairly extensive *Lophelia* coral banks. There are also abundant planktivorous fishes that support a rich fish fauna important to fisheries production, including abundant large demersal fishes and sharks. Sperm whales are regular users of the De Soto Canyon, where they forage for giant squid. The pristine nature of the canyon, its trophic support for many apex predators such as sharks and whales, and its role in harboring iconic species of deepwater corals and other habitat-providing benthic invertebrates compel us to recommend establishment of a large fraction of the De Soto Canyon as an MPA to protect its resources from degradation.

By connecting reserves with marine corridors that encompass a focus species' ontogenetic habitat range, the chances of species recovery are increased. But marine corridors have other advantages besides providing protection over the life history of a target animal. Corridors can protect heterogeneous habitat types (for example, from the marsh to the shelf break), which in turn means a more diverse species assemblage can be protected than if a large homogeneous area were protected (Carr *et al.* 2003). Small, interconnected or well-placed reserves may be good first steps in reserve creation. It is true that smaller reserves are more likely to garner political approval (Ward *et al.* 2001). In this case, creating a network of reserves that can complement and strengthen the resilience as a whole system may be more practically attainable than creating a single massive reserve. Corridors for large, pelagic animals, such as bluefin tuna (*Thunnus thynnus*), would be prohibitively large because of their extensive range. A network of smaller reserves, well chosen to protect critical nursery, feeding or breeding grounds, may be more feasible. Ballantine (1995, 1997) argues that individual characteristics of reserves and their connectivity are less important than designing a network that is comprehensive and representative of habitats, is redundant in habitats and is sufficiently large to ensure sustainability of resources.

The Deep Sea: The Challenge of the Remote and Thus Invisible

The deep northern Gulf and its continental margin have been studied intensively for half a century with support from federal agencies tasked with documenting living resources and predicting the effects of the oil and gas industry on the ecosystem. (See Appendix II for an abbreviated regional list of government documents generated by consulting firms and academic institutions under contracts with the Bureau of Land Management, the Minerals Management Service [MMS] and now the Bureau of Ocean Energy Management, Regulation and Enforcement [BOEMRE].) Based on these studies and associated peer-reviewed literature, we know that the deep-bottom assemblages of macroinvertebrate fauna and groups of bottom-associated demersal fishes are separated into four major depth zones stretching from Florida to Mexico (Pequegnat *et al.* 1990, Powell *et al.* 2003, Wei *et al.* 2010, Wei *et al.* in prep. a), whereas the smaller meiofaunal invertebrates can be found in a more patchy distribution pattern (Baguley *et al.* 2006). It is well established that biomass of benthic invertebrates and fish declines exponentially with depth across the northern Gulf at a regular and predictable rate. The greatest biomass occurs on the upper continental slope within two major canyons: the Mississippi Trough (Soliman and Rowe 2008) and the De Soto Canyon (Wei *et al.* in prep. b). The Deepwater Horizon site lies directly between these two canyons in an area with the highest surface primary production in the Gulf (Biggs *et al.* 2008). Biodiversity has a mid-depth maximum at approximately 1,200 m (based on data in Rowe and Kennicutt 2008), which is somewhat shallower than that encountered in the western Atlantic (Rex and Etter 2010). In general, the biomass of the fish, the larger invertebrates (megabenthos) and the sediment-dwelling invertebrates (the macrobenthos) are lower at any given depth in the Gulf than that in the North Atlantic and Pacific deep basins (Rowe 1971, Rowe 1983, Wei *et al.* in prep. b). The extensive databases that have resulted from historical baseline studies (Appendix II) may allow us to directly compare earlier values to post-spill values, if similar follow-up sampling can be conducted.

A CTD (conductivity, temperature, depth) device detects how the conductivity and temperature of the water column change relative to depth. Photo: NOAA

Incomplete knowledge of the fate of the oil released from the DWH wellhead greatly limits our ability to infer impacts on benthic and pelagic communities of the deep sea. Some of the oil almost certainly was deposited on the seafloor, but the NOAA oil fate calculator does not make any estimates of the quantity. The sinking of drilling muds released from the wellhead provides one mechanism of transport to the seafloor, while more widespread transport may have been provided by the fall of marine snow and bacterial agglomeration of finely dispersed oil into larger particles (Hazen *et al.* 2010, Joye *et al.* 2011). The ability to observe particles in the deep sea is limited to transmission from ROVs, and the number of remote sensors in the deep sea in the Gulf is low. Consequently, assessment of ecosystem injury and potential for restoration of deep-sea ecosystem services will require more extensive catch-up studies than were needed to stage the natural resource damage assessments in the more accessible sea-surface and shoreline habitats.

No comprehensive monitoring system exists for the whole northern Gulf, where oil and gas drilling is so intensely focused.

The oceanographic research community has been making strides toward installing instruments in the oceans to collect much more extensive information about physical, chemical and biological conditions and processes. This development in the field has extended to the deep sea, with pilot studies of the potential for deploying deep ocean-bottom observatories (DOBOs) to enhance understanding of what is currently invisible

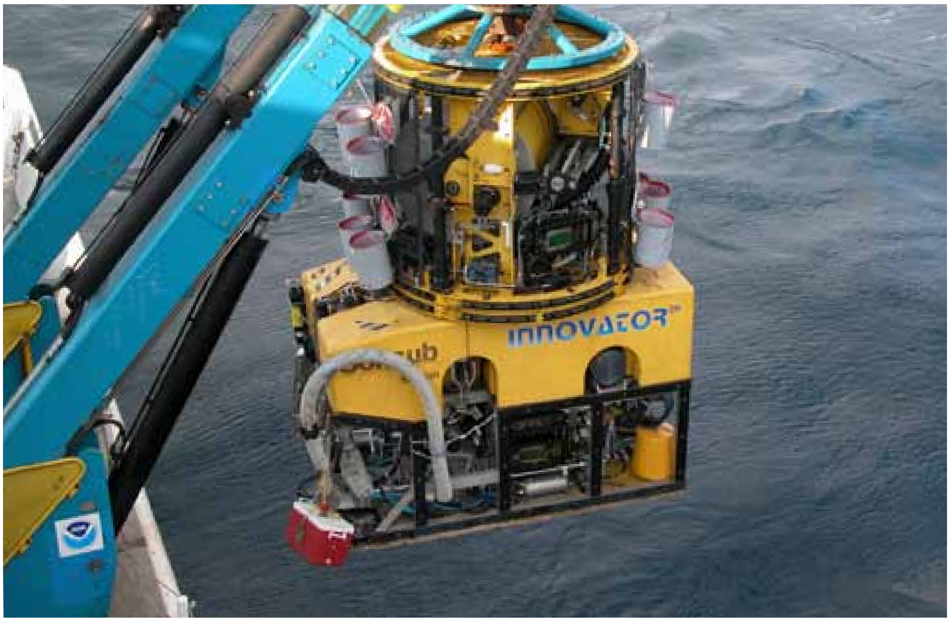
This scleractinian coral (*Lophelia pertusa*) lives about 450 m deep in the Gulf of Mexico. Photo: NOAA

Coral Formations Indicate Hydrocarbon Fluid Seeps

Scientific discoveries have accompanied the research associated with oil exploration. Two remarkable features of the deep Gulf seafloor that have been documented recently are the occurrence of extensive hydrocarbon fluid seeps along the continental slope (ca. 100 to more than 3,000 m deep) (Brooks *et al.* 1987 and others, see Appendix II) and intermittent coral heads (*Lophelia pertusa*, principally) and their associated invertebrates. The peculiar assemblages of the upper continental slope associated with oil and gas deposits known generally as seep communities and associated *Lophelia pertusa* coral assemblages are now given special consideration during exploratory drilling for oil and gas because of regulations developed by the MMS. This involves specifying minimal distances required between the wellhead and these communities.

The *Lophelia* heads and clumps are consistently encountered along the upper continental slope. They require solid substrate, and these are found at older seep sites with diminishing flows of hydrocarbons where carbonates have been deposited. Ironically, these remarkable assemblages are encountered where oil and gas prospects are also high, with, for example, numerous documented occurrences of *Lophelia* thickets at relatively small distances (a few km) from the DWH drill site on the Macondo Prospect. Both NOAA and BOEMRE have sponsored diverse field programs designed to construct predictive maps of these biologically iconic features, along with sampling to determine their physiological dependence on a food chain derived from seep hydrocarbons (Cordes *et al.* 2007, Roberts 2010). It is remarkable that these assemblages of high biomass lie among soft-bottom communities of relatively low biomass. Subsidy of edible organic materials from the seep sites to the surrounding macrofauna, based on stable isotope fractions (C del-13), appears to be limited (Carney 2010), raising the question of what supports the high coral community biomass. Increased understanding of the functioning of these unique assemblages continues to emerge from ongoing and recently completed studies (Roberts 2010, Cordes *et al.* 2007). But the DWH oil spill implies that current scientific knowledge of these intriguing systems and their habitat value is insufficient. A marine reserve protecting these communities might best be designed to encompass the range of environments and the scope of biological differences among *Lophelia* communities.

to science. Such bottom observatories can house an acoustic Doppler current profiler (ADCP), fluorometers, probes to monitor chemical and physical variables, side-scan sonar, fish finders, cameras looking up into the water and onto the bottom, heat flow sensors, seismometers and other instruments. An initial site at which to conduct manipulative experiments with pilot DOBOs has been established in the sub-Arctic (Soltwedel *et al.* 2005). BP has deployed two large bottom observatories (called DELOS, for deep environmental long-term observing systems) off Angola near a wellhead and at distance from a wellhead (Vardaro *et al.* in press). The initial motivation among deep-sea biologists for such observatories on abyssal plains was to evaluate long-term signals of climate change (Ruhl and Smith 2004). Now, after the DWH tragedy, there is a clear role for such instruments to monitor operations and perhaps through rapid reactions to signs of trouble prevent future safety failures during oil and gas exploration and production. The move of the oil and gas industry into deep oceans suggests that the industry should be engaged or even required to develop and deploy DOBOs at some wellheads. Open access in real time to data showing what is happening at deep-ocean habitats would also provide new avenues for informing and educating scientists and the public about these remarkable habitats. DOBOs would facilitate monitoring of conditions and processes, research and public education of an intriguing and remote environment.



A remotely operated vehicle is used to collect samples from the ocean floor. Photo: Gulf of Mexico Deep Sea Habitats Expedition/NOAA/OAR/OER

As a portion of the restoration of DWH injury to the deep-ocean benthic communities, including the *Lophelia* assemblages, we recommend establishment of an underwater monitoring system that is designed to uncover emerging degradation of valuable deep-ocean communities as it first appears so that adaptive management of oil and gas drilling could be practiced and further damage minimized. This would represent a method of sustaining the integrity of *Lophelia* and other deep-sea benthic communities. At present no comprehensive monitoring system exists for the whole northern Gulf, where oil and gas drilling is so intensely focused. We recommend that this monitoring provide open access across the entire northern Gulf shelf. A model for this monitoring system is the Texas Automated Buoy System (TABS), which has positioned buoys across the continental shelf of Texas, with funding from the Texas General Land Office, to monitor the fate of future offshore spills and provide open access to the resulting data. River system monitoring should be included to determine the success in revolutionizing farming practices miles upstream of the Gulf. Key hot spots of biological activity also deserve installation of real-time environmental monitoring packages. These include methane seep communities, *Lophelia* coral heads (see box, Page 73) and the Florida escarpment adjacent to and including the De Soto Canyon. A network of information on the physics and chemistry of the offshore environment could be established, perhaps through new BOEMRE regulation, by requiring offshore drilling and production operations to report water column physics (with in-place ADCPs), water column and seafloor video, and surface water chemical parameters to an open-access operator that would make such information available to the government, public, NGOs and environmental managers. Information on this remote ecosystem would be useful to managers, but the educational opportunities of such open-access, real-time information for schools and the general public is of paramount importance in building appreciation for and conservation of many now poorly known deep-sea systems.

THEME 3

Integrate Sustainable Human Use with Ecological Processes in the Gulf of Mexico

The astounding biodiversity of the Gulf ecosystems—in the shoreline habitats, the coastal systems and the deep sea—is tightly connected to local economic prosperity, culture and human welfare. The Gulf supports human communities and livelihoods as well as natural ecosystems. Successful restoration necessarily includes support for its human residents, especially because Gulf communities are increasingly vulnerable to the consequences of global climate change. In our final five recommendations, we argue that engagement with coastal communities is a critical component of the Gulf restoration program. These final recommendations outline plans for more sustainable fisheries, ways to inform Gulf populations about the effects of climate change and engage them in meaningful dialogues on how they might respond to it, and programs that will help monitor the Gulf ecosystems to sustain the delicate balance of human and natural uses.

RECOMMENDATION 11

Engage Gulf Coast communities to adapt to increasing coastal inundation while sustaining fish and wildlife.

2010 Sea turtle nests containing hatchlings are laid on Alabama's beaches. Photo: Bonnie Strawser/USFWS Southeast

- » Share with Gulf coastal communities spatially detailed information about the environmental changes expected from global climate change, including sea level rise, increased hurricane damage and flooding.
- » Develop science-based scenarios in collaboration with the community that depict the consequences and risks of maintaining residence in coastal hazard and flood zones.
- » Promote community engagement to encourage sound decisions that provide integrated resilience for people and the ecosystems upon which they depend.

We acknowledge a critical need to design and implement strategies for making the ecosystems, human communities and infrastructure along the Gulf Coast more resilient in the face of relative sea level rise, land loss and increased exposure to coastal hazards of intense storms and floods. The coastline of the Gulf of Mexico is being inexorably and rapidly redrawn as the combination of land subsidence and rising eustatic sea level (these two processes together are referred to as relative sea level rise) set the stage for more extensive flooding, erosion and damage to habitats and human structures during hurricanes. One indication of the scope of this geomorphological change is inundation of an average of about 65 km² of coastal marshes in Louisiana each year (Barras *et al.* 2003). Grounded oil from the DWH spill has enhanced loss of marsh habitat, and thus loss of storm buffering capacity, directly by suffocating marsh grasses and indirectly

Houseboat Row on South Roosevelt Boulevard in Key West, FL, after Hurricane Georges in September 1998. Photo: Monroe County Public Library/The Dale McDonald Collection

by physical damage of marsh edges from breakaway booms, leaving underlying soils highly vulnerable to further erosion.

All along the Gulf Coast, coastal development, oil and gas infrastructure, and navigation channels have degraded and destabilized oyster reefs, marshes, beaches and barrier islands, thereby diminishing the ecosystem services that these habitats should be providing. What habitat remains is more susceptible to further erosion by storm-generated waves, currents and winds, and changes in the hydrological framework in which they were created. In Louisiana, wetland loss is especially severe because of extensive dredging of oil and gas navigation canals through wetlands, which enhance erosion. At the same time, the land is subsiding, in some areas as fast as 20 to 30 mm per year, and the current rate of eustatic sea level rise of around 3 mm per year is increasing rapidly with global climate change. Losses of salt marsh, oyster reef and coastal barriers affect more than fish and wildlife. This habitat loss increases the vulnerability of coastal residents to loss of life and property during hurricanes because the biological barriers provided by these foundation organisms that should dissipate erosive and damaging storm-wave energy and help suppress movement of storm surge inland are no longer providing this service to Gulf coastal residents, particularly in the Mississippi Delta.

Economic costs of climate change and defenses against it in the Gulf

As a consequence of climate change, large areas along the Gulf Coast are being progressively inundated, leaving adjacent land, people and property considerably more vulnerable to flooding and storm damage (IPCC 2007). At risk are millions of Gulf coastal residents within many miles of the current coastline, and more than $2.4 trillion in property and coastal infrastructure (Entergy Corporation 2010). In the 48 contiguous counties from Galveston Bay in Texas to Mobile Bay in Alabama, there are more than 27,000 km of highways, four of the top-five-tonnage ports in the United States and more than 60 public-use airports. The region is one of only four places in the United States where railcars can be exchanged between the eastern and western halves of the country. Nearly two-thirds of all U.S. oil imports are brought through the Henry Hub on the Louisiana coast (Fayanju 2010). The ports at New Orleans and other lower Mississippi River cities are vital to the Midwest's agricultural enterprise and to local agriculture.

On average, the Gulf Coast suffers annual losses of $14 billion because of storm damage. Over the next 20 years, development and land subsidence could push cumulative losses to approximately $350 billion. Storm damage reconstruction would consume seven percent of total capital investment and three percent of regional

Storm wind damage insurance for homeowners and businesses is becoming prohibitively expensive if it is available at all, with many private insurers abandoning the high and uncertain risks associated with this Gulf Coast region.

1900 The hurricane that destroyed Galveston, TX, was the deadliest in U.S. history. Photo: Library of Congress

2005 Hurricanes Katrina and Rita cause massive flooding and destruction on the Gulf Coast. Photo: NOAA

GDP (Entergy Corp. 2010). The loss and degradation of coastal wetlands and other nursery habitats results in decreasing capacity to produce fish and wildlife, with consequent economic declines in commercial fishing, recreational fishing and tourism, which depend upon fish and wildlife abundance. Storm wind damage insurance for homeowners and businesses is becoming prohibitively expensive if it is available at all, with many private insurers abandoning the high and uncertain risks associated with the Gulf Coast region.

Options for managing these risks range from engineered defenses such as levees and bulkheads to protection and restoration of natural habitats that reduce the damaging effects of hurricanes on coastal communities by absorbing storm energy. Costs and benefits of these options vary. According to an economic analysis by McKinsey and Co. and Swiss Re, the cost-benefit ratio of levee systems ranges from 0.7 to 3.8 depending on the value of infrastructure being protected. Cost-benefit ratios for restoration of natural habitats varied comparably from 0.7 for beach nourishment to 3.3 for wetlands restoration (Entergy Corporation 2010). Planned retreat of human residence from high-risk areas can be the most cost-effective response that simultaneously prevents loss of life. Different choices of response to risk of storm damage have great consequences to the long-term ability of the Gulf Coast to sustain production of fish and wildlife, with rebuilding of natural marsh and coastal barrier habitats providing more protection for natural ecosystem processes and fish and wildlife than vertically engineered interventions (Houck 2006).

One possible advantage of protecting and restoring coastal habitat instead of engineering levees, seawalls and dikes has to do with maintenance costs. Restoration of oyster reefs can create living breakwaters that can build themselves up faster than predicted sea level rise rates and thus provide continued protection against shoreline erosion and land loss (Reed 2000, Zedler 2004). In contrast, concrete and other engineered structures deteriorate over time and become undermined so that must be maintained, repaired and built up to maintain needed protection levels. Operation and maintenance costs for these structures exceed $195 billion annually (CBO 2010). With likely increases in energy costs and rising sea levels, maintenance expenses are expected to become even more prohibitive (Day *et al.* 2005). Additional economic advantages of coastal habitat protection and restoration are co-benefits of production of shellfish and finfish, improvement of water quality, and contributions to tourism and recreational activities. For example, nursery habitats associated with oyster reef restoration are estimated to yield approximately one ton of finfish and large crustaceans per acre per year with landing values of approximately $40,000 (Grabowski and Peterson 2007).

Risks to Gulf communities from climate change

Challenges to the human communities that border the sea have always been present worldwide. Delta areas affected by river channelization, such as the Mississippi River Delta, have magnified risks of relative sea level rise with subsidence rates well in excess of present eustatic sea level rise and projections of dramatically greater water levels as the climate continues to warm. Given the place attachment experienced by natural resource harvesters and residents more broadly, a concerted effort to remain in the coastal areas is understandable among Delta inhabitants. The choice between engineered structures and ecosystem restoration for storm protection is largely directed by communities that desire to remain in place. Whereas people living in the most low-lying and vulnerable areas will eventually be forced to relocate as water levels and storms take their toll, many see themselves as exemplars of what will happen to coastal peoples worldwide with relative sea level rise. If they remain and can persist in sustaining and using coastal resources to make a living, they may see themselves as potential models of adaptation to areas of flood and storm risk.

If sea level rises as projected, hundreds of thousands of people could be put at extreme risk. We do not know when people will decide that it is time to move and where they will go, but significant economic, social and cultural costs should be expected. The complexity of human communities challenges our ability to accomplish socially, economically, politically and psychologically successful relocations. It is important to support coastal communities

Top Gulf Coast Executives in Pursuit of Resiliency

Scientists consider hurricanes, climate change, tornadoes, floods, ecosystem degradation and contamination often without the benefit of collaboration with the communities most affected by them. Technical experts have authority for information development and are often "stovepiped" into enforcement of the specific regulations for which they are responsible without interacting more broadly with other experts or the public. Such narrow compartmentalization of government leads to many problems. Among these can be failure to consider the big picture of resiliency.

Yet efforts have been made to engage with community leaders, and these efforts have become more urgent in the wake of Hurricane Katrina and the DWH tragedy. The Center for Hazards Assessment, Response and Technology (CHART) at the University of New Orleans has a decade of experience attempting to open the dialogue of environmental risk reduction to the entire community, from the engaged citizens to the highest government, business, NGO and faith-based organization leaders. A recent workshop titled "Executive Program in Resilience and Risk Management" inaugurated efforts to impress upon leaders that their participation and guidance is necessary to build resilient communities. Fifty leaders—parish (county) presidents, city and parish council members, bank officials, port commissioners, and other executives—co-mingled at circular tables to confront their respective challenges and to seek solutions. (www.chart.uno.edu)

A house near Cocodrie, LA, is elevated as a defense against storm surge flooding. Photo: Paul Goyette

along the Gulf Coast to achieve both successful adaptation in the near term and, when necessary, successful relocation in the longer term. Recognition of the value of the human communities and their residents and support for their way of life is important in forming the collaborative processes needed to achieve these goals of risk reduction.

Recommended approaches to help Gulf communities achieve resilience

More applied research, more pilot projects and greater commitment to the successful outcomes as described above are necessary to help Gulf communities achieve resilience in the face of their daunting challenges. These successful adaptations will not occur without support for and a commitment to a process of engagement between the scientific and local communities. We recommend that Gulf ecological restoration projects work with residents including community leaders to help spread recognition of the impacts of climate change on the Gulf's human communities. With this co-developed knowledge and shared experience, teams could present scenarios to communities that describe the risks associated with maintaining residence in coastal hazard, flood and inundation zones. With better understanding of these risks, communities might elect to migrate together and thereby preserve their social coherence and sense of place. A more resilient and coherent community could make sound decisions about how to reduce risk to life and property, maintain the services of natural ecosystems and their way of life without the establishment of damaging interventions into nature, such as seawall, jetty, groin and levee construction, that seriously degrade the production of fish and wildlife. Given the expectations for the number of coastal residents who will be similarly affected not only around the coast of the Gulf of Mexico but also worldwide, the achievement of paired human and ecosystem resilience here would be widely applicable to multiple at-risk coastal communities.

RECOMMENDATION 12

Manage Gulf fisheries sustainably by recognizing ecosystem processes.

A 364-pound Goliath grouper was caught in the Gulf of Mexico off Key West, FL, in 1984. The species is now critically endangered. Photo: Monroe County Public Library/ Collection of Don DeMaria

» Develop a suite of ecosystem models that will improve capacity to forecast fishery yields and the impacts of environmental changes.

» Apply these ecosystem-based models to fishery management in the Gulf.

Living marine resources extracted from the world's oceans provide critical and substantial ecosystem services to humans in the form of nutrition and livelihoods. Many communities throughout the Gulf of Mexico persist only because of these services. However, the factors that can improve the management and production of one resource may lead to impairment of another. As a result, management goals focused on single outcomes (such as maximization of short-term yield for one species of fish) often unintentionally lead to reductions in the quality of other services by decreasing ecosystem diversity over space and time (Peterson *et al.* 1998, Costanza *et al.* 2007). Such shifts in exploitation schemes not only reduce the overall value of services provided, but they also can create societal conflict, pitting one user group against another.

The poor status of fisheries worldwide bears this out, forcing us to move beyond simple catch trajectories and economic calculations of ex-vessel values and their multipliers to consider the intersection of ecology and economics at the scale at which fisheries operate, how they interact with other human activities, and how these in concert affect ecosystem services, broadly construed. Indeed, we now find that fisheries management is becoming more and more reliant on defining what those services are, from enhancing water quality, shoreline protection or tourism to the conservation of biological diversity at all levels while protecting the aesthetics of the natural world.

The concept of ecosystem-based management has emerged as a means to deal with these conflicts and reverse the more traditional management agenda. Ecosystem-based management aims to ensure long-term sustainable delivery of services and define an ecosystem's ability to recover from acute and chronic impacts (Rice and Rochet 2005, Leslie and Kinzig 2009). Although ecosystem-based management appears to be largely focused on direct effects of industrial fisheries (e.g., Pikitch *et al.* 2004), it is critically important that it address indirect effects (including species interactions), bycatch, environmental change and the full suite of sectors—commercial, recreational and artisanal fisheries (Crowder *et al.* 2008). In other words, truly resilient ecosystem-based management must include not only the animal ecosystem but also the human community that relies on it and the physical environmental system in which it is imbedded.

Table 2

National Coastal Condition Report (2008) for primary health indicators in the Gulf of Mexico coastal zone. All numbers are percentages. The overall rating for 2008 represents a slight decrease from the conditions observed in the previous report, released in 2005. Source: USEPA 2008

Resource Assessed	Good	Fair	Poor	Missing	Overall
Fish Tissue	81	11	8	0	Good
Water Quality	35	49	14	2	Fair
Dissolved Oxygen	—	—	5	—	Fair
Coastal Wetlands	—	82	18	—	Poor
Sediment	79	1	18	2	Poor
Benthos	35	17	45	3	Poor

Red snapper has been overfished for decades in the Gulf. Photo: Steve Harwood

Challenges to ecosystem-based fishery management in the Gulf

Fisheries are recognized as a major force shaping the structure and function of ecosystems (Botsford *et al.* 1997, Jackson *et al.* 2001) and are an important driving force acting on the ecosystem of the Gulf (USEPA 2008). We recognize, too, that there are other forces at work in this ecosystem, including introduced species, habitat loss and macroscopic environmental changes. These forces interact with fisheries and affect ecosystem processes by disrupting normal species interactions, altering foraging behaviors and changing distribution patterns that can dramatically increase species vulnerabilities.

Although most fisheries in the Gulf concentrate on top-level predators (see box, Page 81), others focus on important forage species, either for human consumption (e.g., vermilion snapper) or industrial and agricultural use (e.g., menhaden). This general focus of the largest species of fish is coupled with intensive pressure on the largest individuals within populations, which severely truncates the size and age structure of populations, thereby driving down overall fecundity and reproductive success as smaller, less experienced and less fecund fish make up the bulk of spawning populations. Thus, there are both top-down influences that ratchet down the food web, and bottom-up influences on productivity that limit food availability. This is coupled with destructive fishing practices that bring additional impacts to fisheries productivity by degrading habitats that are critical to many species' life cycles. Shrimp trawlers, for instance, have for more than a century raked the Gulf seafloor, removing the architectural complexity provided by bottom-dwelling filtering and photosynthesizing species, including sponges, bryozoans, ascidians, soft and hard corals, algae and sea grass. Yet no fundamental fisheries management plan has been enacted in the Gulf that incorporates habitat management or restoration.

Most important fisheries species spend some portion of their life cycles in coastal habitats. The productivity of these habitats is in part influenced by proximity to watersheds and thus is affected by freshwater management decisions (Sklar and Browder 1998) as well as by influx of land-based industrial and agricultural pollutants. All of these habitats have declined significantly over the past 50 years (Handley *et al.* 2007, Waycott *et al.* 2009, Beck *et al.* 2011). Indeed, the overall condition of the Gulf of Mexico ecosystem has declined, and its habitats are considered to be in fair to poor condition, based on the Environmental Protection Agency's most recent National Coastal Condition Report (2008) (Table 2).

Despite these conditions, there remains resistance to adopting an ecosystem-based management approach in the Gulf of Mexico. That resistance comes from fishermen, from those in charge of defining the

Sharks are caught on a fishing line off the coast of Florida. Photo: Flip Nicklin/Minden Pictures/National Geographic Stock

Overfishing of Apex Species Has Cascading Effects Down the Food Web

Fishing has targeted the largest species, depleting them preferentially and then moving down the food web (Pauly *et al.* 1998). Removal of apex consumers can have dramatic consequences on the abundances and dynamics of species lower on the trophic scale. Trophic cascades can be induced by depletion of top consumers in the ecosystem, resulting in release from predation of populations down the food chain, which may themselves be important predators (Myers *et al.* 2007). For example, increased fishing pressure on the 11 most abundant great sharks along the Atlantic seaboard during the past 35 years has resulted in declines in abundance ranging from 87 percent to more than 99 percent. In turn, 12 of the 14 most abundant elasmobranch prey (smaller sharks, rays and skates) of the great sharks exhibited simultaneous population explosions (Myers *et al.* 2007). One of these, the cownose ray, caused the loss of a century-long fishery for bay scallops in North Carolina by consuming scallops unsustainably during its seasonal migrations between wintering and summering grounds.

Other impacts of the loss of apex consumers acting through trophic cascades include historic overfishing of green sea turtles, leading to a lack of grazing on turtle grass, which in turn resulted in senescence of the older ungrazed blades that may have promoted the fungal disease that now afflicts turtle grass in the Caribbean (Jackson *et al.* 2001). Overfishing of great sharks has been epidemic in the Gulf of Mexico, in pelagic environments far from shore (Baum and Myers 2004) and in coastal embayments (O'Connell *et al.* 2007). In international waters, including those of the Gulf of Mexico, shark finning is still practiced, and the slaughter of great sharks continues to supply Asian markets for shark fin soup. To maintain the integrity of the pelagic and coastal ecosystems of the Gulf, targeted management actions to protect and restore the great sharks and other apex species are urgently needed.

For more than a century, shrimp trawlers have raked the Gulf seafloor, removing sponges, corals, algae and sea grass. Yet, no fundamental fisheries management plan has been enacted that incorporates habitat management or restoration.

status of fished stocks (the scientists at state and federal institutions), and those charged with implementing fishing regulations (managers at state natural resource agencies; and at the federal level, the Gulf of Mexico Fishery Management Council). Fishermen are generally suspicious of new management actions, particularly those that might limit fishing opportunities in the short term, while stock assessment scientists are often uncomfortable working outside their discipline. Disagreements on science and management aside, there is a lack of funding to make ecosystem-based management a reality.

Recommendations for sustainable, ecosystem-based fishery management in the Gulf

Our primary goals now are to move beyond the concept, bash the myths (Murawski 2007), define what managers need (Rosenberg and Sandifer 2009) and adopt a set of operational principles that will move ecosystem-based fisheries management forward (Francis *et al.* 2007).

The management of fisheries in the Gulf of Mexico has not resulted in sustaining fish populations or harvests. Even now, there are calls to open fisheries for species that are considered critically endangered throughout their range (e.g., goliath grouper [*Epinephelus itajara*]) and to increase quotas for others that have been overfished for decades and have severely truncated age and size structures (e.g., red snapper [*Lutjanus campechanus*]). A fundamental change in approach that includes proactive, precautionary management with long-term sustainability in mind is required. The focus should be on monitoring ecosystem indicators and management effectiveness, learning from applying adaptive management, ensuring that marine communities remain intact and avoiding those practices that degrade ecosystem functions. Cross-cultural, cross-jurisdictional and interagency collaboration is needed to develop an integrated approach to ecosystem assessment (Levin *et al.* 2009) using system models. These models include Atlantis—a complex dynamic ecosystem model to evaluate suites of management scenarios (Fulton *et al.* 2005)—and Ecopath with Ecosim (e.g., Okey *et al.* 2004) to evaluate a range of management options and to find emergent properties that help forecast risk of fisheries declines.

We advocate developing a suite of ecosystem models for the Gulf of Mexico to provide managers with adequate scenario-building capabilities that encompass all aspects of ecosystem management options. In concert, comprehensive survey and experimental (including adaptive management) approaches must be developed and implemented to improve data going into the models and, consequently, our ability to forecast change. Some aspects of data collection will be quite straightforward, such as developing spatially explicit habitat maps, catch statistics, and phytoplankton and environmental data surveys (GSMFC 2008). Others will be more complex, such as defining food web dynamics of exploited predators and prey and other interspecific interactions. The approach to management must be adaptive, particularly for actions that are novel and/or whose outcomes are highly uncertain. In essence, management actions serve as tests of the adequacy of the model if sufficient monitoring exists of key model components.

Although ultimately a full Gulf model may be ideal, regional models will be more tractable in the near term (e.g., Big Bend, north Gulf, west Florida shelf and Florida Keys.). Ideally, local dynamics can be nested within the more general regional models to address site-specific management issues. We especially advocate a focus on marine and coastal regions that are socioeconomically valuable (e.g., the Florida Keys) and among the least affected and most productive in the Gulf of Mexico (e.g., the Big Bend). For instance, the relatively pristine Big Bend region is particularly important for testing ecosystem-based management to achieve resilience and sustainability, because this system will require less effort to restore, freeing more resources for preservation of ecosystem integrity. In particular, the currently low level of coastal development allows preservation of critical fisheries-supporting habitats, a far easier and less expensive proposition than restoring degraded systems.

Specific recommendations for the Big Bend system, which can serve to facilitate model development and evaluation for other regions, include the following:

1. Map habitats of discrete and unique Gulf ecosystems, such as those extending from the De Soto Canyon to hard-bottom reefs across the west Florida shelf, especially including systems defined by foundation species.
2. Define trophic interactions of species using a diversity of approaches, such as the application of stable isotope and fatty acid analyses combined with intensive diet studies conducted at the finest taxonomic resolution possible.
3. Use marine reserves as experimental units to evaluate effects of trawling on habitat as well on as fish populations to protect spawning populations and restore sex ratios for protogynous species such as gag grouper and the age and size structure of all fish populations, including apex predators (e.g., grouper species, amberjack, sharks) and forage species (roughtongue bass [*Pronotogrammus martinicensis*] and red barbier [*Hemanthias vivanus*]).
4. Use models to evaluate the ecosystem-level effects of different management strategies. For example, evaluate how closure of the bottom longline fishery in the Gulf of Mexico would affect populations of sharks, red grouper (*Epinephelus morio*) and sea turtles, as well as the rest of the ecosystem to which these key species are dynamically linked.

The fishery management actions that we recommend as part of the ecosystem restoration of the Gulf will require innovative local and international cooperation and actions, a difficult but necessary task.

Even now, there are calls to open fisheries for species that are considered critically endangered throughout their range and to increase quotas for others that have been overfished for decades.

Of the severe impacts on Gulf habitats and fauna, shrimp trawling may have been the most destructive on a broad aereal basis over a long period of time.

A shrimper culls his catch, which consists mostly of bycatch, off the coast of Texas. Photo: Norbert Wu/Minden Pictures/National Geographic Stock

RECOMMENDATION 13

Assess damage from shrimp trawling and potential fishery benefits of no-trawling reserves.

» Conduct reviews of museum collections and other historical information on bottom communities of intensely trawled areas to infer the pre-trawling baseline.

» Find, and record video of, non-trawled areas that are similar to trawled areas to determine differences.

» Conduct small-scale, experimental tests of consequences of establishing no-trawling reserves to test capacity to restore habitat and habitat-dependent fisheries.

Of the severe impacts on Gulf habitats and fauna, shrimp trawling may have been the most destructive on a broad areal basis over a long period of time. Intense trawling removes large epibiotic animals such as sponges that provide three-dimensional structure, habitat and refuge for juvenile fish. Trawling also regularly and repeatedly disturbs the bottom sediments, thereby maintaining the invertebrate communities in a constant state of early succession dominated by opportunistic small organisms rather than the longer-lived bivalve mollusks, which provide water filtration services (Botsford *et al.* 1997, Dayton *et al.* 1995).

Bycatch from trawling has resulted in serious declines in populations of threatened and endangered sea turtles, taken a toll on juvenile fishes before they can recruit into the fisheries, and driven down populations of many other species not otherwise fished but important to food webs as forage species and scavengers.

The major problem with assessing the impacts of shrimp trawling is lack of an adequate historical baseline: What was the status of the continental shelf habitat, biodiversity (species composition) and biomass before the intensified trawling that began in the early 1900s? Several comprehensive global databases are being developed (GBIF, OBIS, etc.), but gleaning relevant information on species lists, mean sizes and distributions over time would be daunting, especially because the databases are not yet complete for the Gulf. Consequently, several less quantitative approaches may have to be developed to infer original conditions. Oral histories are subjective but useful, especially for finding ostensibly lost information. Photographic archives are also helpful; we can measure fish sizes when photographed at dock-side over time. Some documentation in the literature is available (Farley 2005). Perhaps the best approach is to enlist the assistance of museum curators at long-established institutions where original specimens, collected before trawling intensified, can be measured and weighed. These would include initially the Harvard Museum of Comparative Zoology in Cambridge, MA, the American Museum of Natural History in New York City, and the National Museum of Natural History in Washington, DC.

Coastal social anthropologists and archaeologists should be recruited to establish baselines, including, for example, surveys of the evolution of seafood menus over time (G. Jones pers. com.), regional economic archives in port cities (such as resources in the Rosenberg Library in Galveston, TX, dating to the early 19th century). Similar information may be available in small, regionally maintained historical archives across the northern Gulf, but assembling such information piece by piece would take time and perseverance by dedicated, funded scholars.

If retrospective research provides evidence that shrimp trawling has modified the soft-bottom benthic communities of the inshore shelf along large areas of the northern Gulf of Mexico, then a subsequent empirical assessment of the benthic communities on trawled and untrawled grounds should be conducted. To compare trawled areas to an untrawled state, we should look first for areas neighboring trawled areas that are environmentally identical except that they are closed to shrimp trawling. These areas may be untrawled because of obstructions or military bans on commercial fishing. Video to capture activities and visible life in both areas can serve to document and even quantify the effects of trawling on the ocean bottom. Comparisons of these areas should be undertaken as partial tests to determine how epibiotic benthos may be removed by repeated shrimp trawling and how that removal affects habitat use by fish, crustaceans and larger marine species, including those of economic value.

If such research reveals intriguing changes to the benthic soft-sediment communities and if empirical field comparisons imply consequent impacts on fish and crustaceans, then establishment of multiple trawl-exclusion refuges should be considered. DWH monies could fund research efforts to evaluate the magnitude and nature of indirect impacts of restoration of structural biogenic bottom habitat and to quantify any increases in ecosystem services that may follow, including augmentation of commercial fisheries. Research on spatially explicit ocean management should be done to help determine where to establish no-trawling reserves to minimize loss of shrimp catch arising from the closures and maximize the value of the restoration of historic epibiotic habitat.

1921 A woman with a 185-pound tarpon. Photo: State Library and Archives of Florida

The major problem with assessing the impacts of shrimp trawling is lack of an adequate historical baseline. Oral histories, photographic archives, museum specimens and economic archives can help provide information.

RECOMMENDATION 14

Endow Gulf capacity building in social-environmental monitoring and problem solving.

» Invest DWH monies to establish an endowed fund with earnings directed by a broad-based board of advisers to support a range of programs for Gulf restoration:

- A regionally distributed Long Term Ecological Research (LTER) site in the Gulf to compensate for the lack of representation of the region in the NSF-funded LTER network
- A Gulf Center for Ecological Analysis and Synthesis (GCEAS) modeled after the national center (NCEAS) in California.
- An annual scientific symposium on Gulf science intended to foster collaboration, information exchange and Gulf capacity building in ecosystem restoration.
- One or more NOAA National Estuarine Research Reserves to serve as models for monitoring and research in valuable estuaries.

Despite the existence of a national network of National Science Foundation-funded Long Term Ecological Research sites, not a single one is located along the Gulf of Mexico shores.

Sea grass recovery project in the Florida Keys. Photo: Florida Fish and Wildlife Conservation Commission

A major challenge in ecological research to support wise and adaptive management of marine and coastal resources is the absence of reliably available long-term funding for monitoring ecosystem condition, environmental drivers and multidisciplinary ecosystem processes that link changing conditions with changing environmental drivers. We urge that a substantial portion of the funds for Gulf coastal restoration be invested so that the interest can be used indefinitely to support ecosystem monitoring efforts (including natural and social variables), research on mechanisms of change (especially those associated directly and indirectly with global change) and adaptive management of valuable habitats and resources.

The coast along the Mississippi Delta has been identified by a recent U.S. Global Change Research Program report as the area in the coastal United States most at risk of negative ecological impacts of global change on estuarine ecosystem services (Titus and Richman 2001). Yet no institutions focused on long-term monitoring of Gulf coastal ecosystems exist. Despite existence of a national network of National Science Foundation-funded LTERs, not a single one is located along the Gulf of Mexico shores. Similarly, there is insufficient investment by NOAA in establishing National Estuarine Research Reserve System (NERRS) sites in the Gulf, where funding allows estuarine ecosystem monitoring and research. As a result, we have little long-term information on changing environmental drivers, biological components and human interventions in the Gulf. This lack of data harms the region because it is difficult to infer causation of ecosystem change, such as that following the Deepwater Horizon blowout, without baseline values. We urge that restoration funds be directed to fund research at a spatially distributed LTER site and one or more NERRS estuaries in the Gulf. No location exists at which Gulf ecosystem data are maintained and no institution exists to solicit proposals and fund the winners to conduct ecological data synthesis and analysis. This synthetic approach has been championed by NSF through the National Center for Ecological Analysis and Synthesis in Santa Barbara, CA. This center is reaching the end of its funding life as a national center. Its functions should be assumed by a Gulf counterpart, where growing computer power and regional databases can be combined to solve critical ecosystem problems to benefit Gulf restoration.

Regional Long-Term Ecological Research Network (R-LTERN)

The National Science Foundation's LTER program supports long-term scientific study of critical ecosystems and facilitates cross-system comparisons. The program includes 26 diverse sites (e.g., a coral reef, the South Pole, a temperate prairie, a tropical forest, a city) spread across the globe, yet only one of these (the Florida Coastal Everglades LTER) is near the Gulf of Mexico. We call for a Regional LTER Network consisting of three to 15 sites throughout the Gulf and modeled on the NSF program. Each site would: 1) generate long-term ecological and environmental data urgently needed to assess changes in the Gulf ecosystem; 2) provide infrastructure for additional (externally funded) process-oriented field studies; and 3) facilitate collaborative field research and student training.

With such a network, the Gulf could become an exemplar for the regional study of large complex ecosystems that are jointly driven by natural and anthropogenic factors. The R-LTERN would complement the developing network of data streams for the physical environment in the Gulf (e.g., through the various ocean observing systems—the Gulf of Mexico Coastal Ocean Observing System and those for Florida and the Southeast, FLCOOS and SECOOS, already in existence). It also would augment existing long-term biological monitoring programs such as the Florida Fish and Wildlife Conservation Commission's fisheries independent monitoring (FIM) of exploited fish populations. The physical and biological data are critical to understanding the Gulf ecosystem, its dynamics and the role played by various environmental phenomena.

Gulf Center for Ecological Analysis and Synthesis

The distinctness, high productivity and biodiversity of the coastal ecosystems of the Gulf that are simultaneously stressed by many anthropogenic perturbations underscore the need for a Gulf Center for Ecological Analysis and Synthesis (GCEAS). Such a center would promote and fund unbiased, rigorous analyses of major environmental issues of the Gulf ecosystem to guide

Specific Recommendations for a Gulf Center for Ecological Analysis and Synthesis

Resolving environmental problems requires synthesis of data, quantitative analysis and modeling (e.g., involving mathematics, statistics and computational informatics) and application that spans disciplines, including biology, chemistry, sociology, economics and engineering. Teams at the GCEAS should be highly integrative and transcend the boundaries of ecological and social sciences where appropriate, such as in the study of ecological-social dynamics of fisheries restoration. Because problems change, the expertise required to solve these issues also should be dynamic. Rather than create a center with defined personnel, the GCEAS would support dynamic collaborations established ad hoc to adaptively respond to emergent environmental and management issues important to the region. The center would use income from the endowment created by provision of restoration funds to create and support interdisciplinary, collaborative research teams consisting of faculty mentors, postdoctoral fellows, graduate students and undergraduates. These teams would use the data generated by the R-LTERN, as well as existing data assembled from federal and state monitoring programs and by scientists throughout the world. The intellectual heart of the program would be the interdisciplinary postdoctoral fellows, cross-mentored by faculty from different institutions. Research teams would have a specific and defined set of goals with an approximate two- to four-year time frame. For example, two to four groups, with staggered initiation dates, may address environmental problems defined in consultation with state and regional environmental institutions and agencies and an international advisory board.

To make sure new ideas are developed and considered and old assumptions rigorously reevaluated, the advisory board and research teams of the center should have national and international participation. By partnering with NCEAS and its Ecoinformatics program, the GCEAS could immediately build on the California center's years of experience in interdisciplinary working groups, postdoctoral mentorship and complex database compilation, management and distribution. Through NCEAS we also would gain immediate connections with DataONE (Data Observation Network for Earth), which is a new NSF initiative that currently has no Gulf Coast participants. DataONE is poised to become *the* central environmental distributed data network. This partnership would therefore jump-start the GCEAS and facilitate a focus on synthesis and propel the Gulf into this emerging research arena. Partnering with the Northern Gulf Institute's Ecosystems Data Assembly Center would enhance the ability to distribute data and facilitate collaborations with other Gulf institutions.

Bathymetric maps guide scientists as they explore the seafloor for coral and reef sites. Photo: NOAA-OER/BOEMRE

management and policy and build and sustain a resilient human-natural ecosystem into the indefinite future (see box above). A GCEAS, emphasizing the compilation, synthesis, analysis, integration and interpretation of ecological and environmental data and theory, would:

1. Advance understanding of the ecosystems of Florida and the broader Gulf of Mexico/Caribbean region;
2. Facilitate the management and conservation of biological resources and resolve pressing environmental issues;
3. Invigorate collaborative research within the Gulf region; and
4. Enhance the role of the Gulf universities in interacting with federal and state agencies to develop and apply ecosystem-based management policy central to breaking down traditional management compartmentalization and forging sustainable management of Gulf ecosystems and resources.

The partnerships created in the wake of the Exxon Valdez oil spill forged relationships that have paid great dividends in coordinating research, information analysis and synthesis, and agency management plans.

This center should be modeled on the transformative success of the National Center of Ecological Analysis and Synthesis, funded by NSF and the state of California.

An annual scientific symposium focused on Gulf restoration and sustainability

One major flaw in historical management of natural resources has been the partitioning of management authority among separate agencies and departments in federal and state governments. In addition, academic, environmental NGO and private scientists have historically not been integrated into the management processes. The trustee-driven damage assessment and restoration process that followed the Exxon Valdez oil spill imposed partnerships among agency scientists from federal and state agencies and included academic, NGO and private researchers in a way that broke down agency boundaries and took a major step toward development of holistic, ecosystem-based management. The partnerships created in the wake of the Exxon Valdez oil spill forged friendships and interactions on a personal level that have paid great dividends in coordinating research, information analysis and synthesis, and agency management plans. The process has endured for more than 20 years in large part by continuing support of an annual science symposium at which new results and scientific advances are shared openly and widely and where scientists, managers and policymakers interact in substantive and meaningful ways on issues of fundamental significance.

This beneficial aspect of the Exxon Valdez experience can be repeated in the Gulf if sufficient funds from the DWH payments are invested and the investment income is used in part to support a Gulf-wide annual scientific symposium. This symposium would serve to strengthen and expand the partnerships that break down boundaries among agencies and bring together people whose interests and responsibilities necessitate integrated, ecosystem-based research on rapidly shifting ecological processes. A symposium such as this represents a vital form of capacity building that will pay many dividends in enhancing science and management in the Gulf restoration process.

NOAA National Estuarine Research Reserves in the Gulf

Several existing federal programs can be enhanced to play an integral role in restoration of the Gulf region. The National Estuary Program (NEP), established by Congress in 1987 as part of the Clean Water Act, works to restore and maintain water quality and ecological integrity of estuaries of national significance. The NEP works with local communities to develop environmental goals and blueprints for achieving these goals. There are seven NEPs located in the Gulf, but none in Mississippi.

NERRS was established in 1972 with the Coastal Zone Management Act. There are 29 NERRS sites, including five in the Gulf, located in every coastal state except Louisiana. These reserve sites serve a variety of purposes but are primarily for community-based educational and long-term research. Federal funding comes with participation in the NERRS program, which requires matching funds once established. The governor officially initiates the nomination process, but support from the educational and research community is a necessary infrastructure requirement. Because of its critical role in the Gulf, Louisiana should be added to the NERRS program. Based on the area of coastal wetlands in the United States, Louisiana should have three NERRS sites, or even more if we consider its wetland loss and fisheries values. DWH oil spill-derived funds could be used to: 1) facilitate a successful Louisiana application for several NERRS sites and one NEP site in Mississippi; and 2) supplement funding at other Gulf NERRS and NEP sites to provide a long-term source of support for monitoring, research, education and community involvement.

Students participate in the Louisiana Sea Grant College Program's "Ocean Commotion" educational fair at Louisiana State University. Photo: Louisiana Sea Grant College Program/Louisiana State University

RECOMMENDATION 15

Communicate within Gulf communities to inspire informed environmental decisions.

» Develop and test novel and interactive processes, educational materials and creative information delivery methods to engage and inform Gulf residents of all ages about the value of natural ecosystems and the implications of climate change.

» Establish coalitions of knowledgeable, approachable and articulate scientific and social experts to engage with Gulf residents through educational programs and community meetings.

Effective communication about the ongoing and future challenges and risks of living in and making a living from Gulf ecosystems is essential to engaging communities in successful and resilient restoration efforts. Climate change is a particularly crucial and complex issue to address, and it will be done best with a range of communication approaches. Nowhere in the United States are the very underpinnings of the economy and culture so at risk from climate change, specifically rising sea level, enhanced frequency of major hurricanes and increased flooding. And yet the question of how to engage with communities on the issues of risks and opportunities posed by a changing natural and human environment is a daunting one. Coastal residents have utilized their surroundings with gusto and sometimes with little attention to their impact on those surroundings. Some residents report that the lushness of the coastal environment enabled them to believe that the resource was limitless; that no amount of use could make a dent in its ability to exist and to rebound. Corporate interest in extracting these initially robust coastal resources contributed to this belief. For instance, lumbering of cypress on the Louisiana coast occurred without the resistance of residents (Conner and Toliver 1990); later it became apparent that the removal of first-growth trees was detrimental to the swamps, reducing many of them to treeless open landscapes. But now that the damage is done, residents are uncertain about where to begin restoration and how to work toward achieving a robust, healthy environment. The DWH spill presents a new opportunity to focus on what it will take to continue to inhabit the Gulf Coast safely with a superb quality of life and perpetuation of the rich cultural traditions of the regions comprising the Gulf Coast.

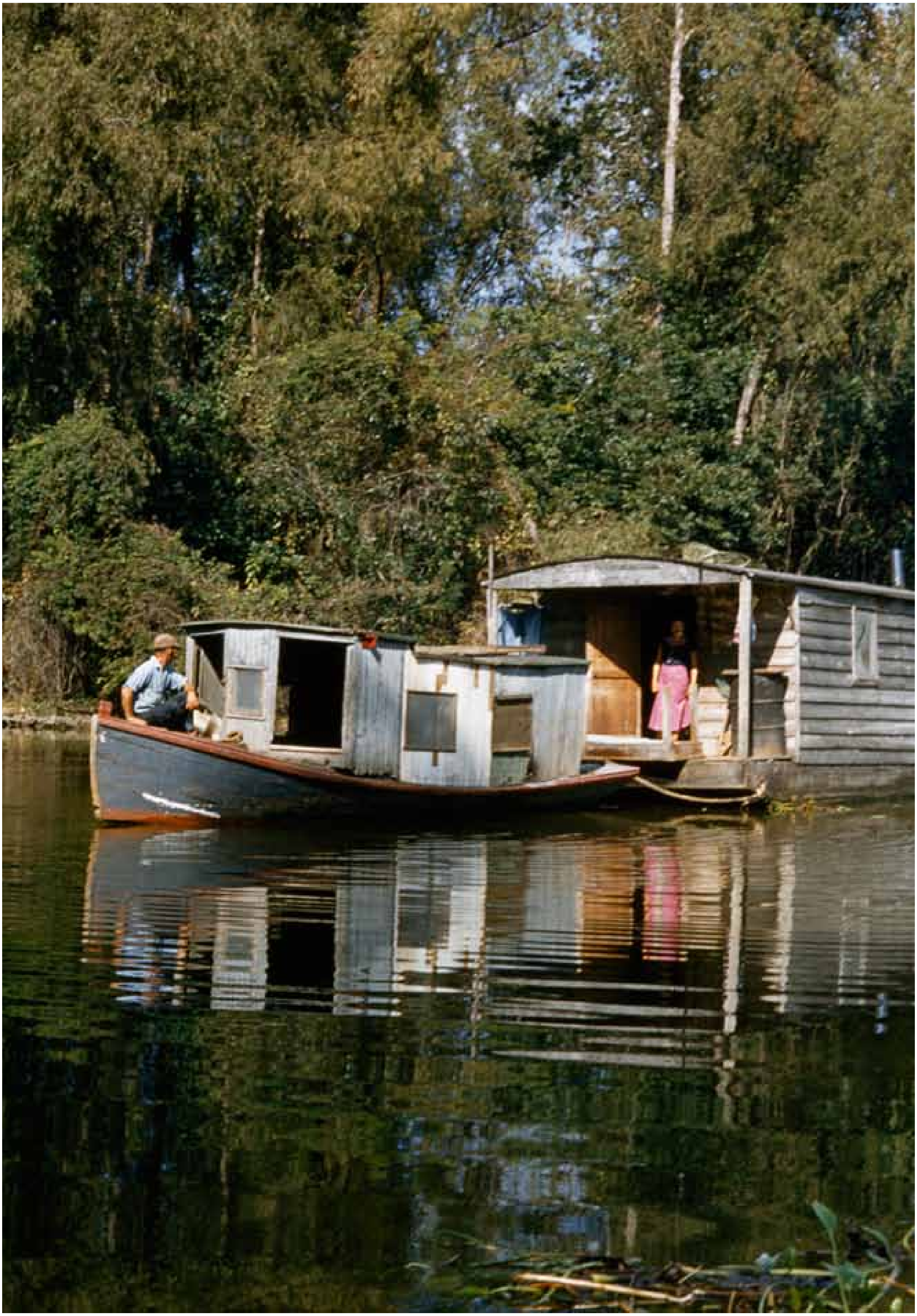
There is a growing realization that science can't do *to* people, it must do *with* people, who become 'engaged citizens' to be effective in the hoped-for restoration.

Volunteers learn to replant shoreline in New Orleans' City Park. Photo: Louisiana Sea Grant College Program/ Louisiana State University

Efforts within Louisiana and other Gulf states are now focused on developing programs and outreach materials on risks and impacts that are accessible to the public rather than just for technical audiences. Scientists in the area have become "citizen scientists" in their attempts to provide Gulf Coast risk assessments to the public (Rosa and Clarke in press). There is a growing realization that science can't do *to* people; it must do *with* people who become "engaged citizens" (Laska *et al.* 2010) to be effective in the hoped-for restoration. New, participatory approaches to community engagement are being developed for dealing with the climate change issues (Chambers 2009). The condescending "classroom" model where experts and government officials lecture an audience is being replaced by models of engagement and meetings where experts and communities talk together about issues. This community engagement model is a way of involving coastal residents in the decisions and actions necessary to protect their own interests and those of the Gulf ecosystem.

A successful engagement program will start with forging partnerships involving a wide range of stakeholders in the Gulf coastal region. Recent Gulf-wide research demonstrates the interest within the various stakeholder groups in acquiring information about climate change and outlines recommendations for how it could be provided (Vedlitz *et al.* 2007). Nevertheless, the effectiveness of these efforts will depend upon careful consideration of the characteristics and needs of the communities, including their perceptions of risks and underlying biases (Fischhoff 2007). Success probably depends on developing collaborative partnerships between biophysical scientists who understand and can communicate the natural science of climate change, and social scientists who study the dynamics of establishing community resilience and utilize effective methods of respectful public engagement and communication.

Education and outreach represent more formal components of the engagement process. Informing Gulf residents about the impacts of the DWH oil release is an obligation of the NRDAR process and should be accomplished through multiple media, including personal appearances of scientific experts within the Gulf communities, social media and websites. Educating Gulf residents and various stakeholders about the consequences of global climate change should be viewed as a generation-long process at minimum, in part because the accumulating evidence of the local degree of relative sea level rise and cumulative storm and flood damage will serve to refine the understanding and the message. A responsive problem-solving and adaptive approach to global change should be taught in the schools, beginning with K-12 curricula and continuing through college to create future generations of informed citizens equipped to meet the challenges of living in and managing a dynamic ecosystem. Adding educators to the collaboration between social scientists and biophysical scientists would help in the development of appropriate curriculum for classrooms.



Conclusion: Human and Ecosystem Prosperity are Intrinsically Linked in the Gulf of Mexico

Perhaps no other coastal economy in the U.S. is so closely tied to the health and productivity of the marine and estuarine ecosystem as that of the northern Gulf of Mexico coast.

A Louisiana fur trapper makes his way to work in the bayou. Photo: Willard Culver/National Geographic Stock

The past two decades have seen growing commitment among academics to the identification and quantification of the economic values of natural ecosystem services that tend to be taken for granted in many environmental management decisions. But despite this growing academic commitment to value ecosystem services, the socioeconomic benefits of ecosystem restoration are still rarely identified and even less often quantified despite the numerous connections among restoration, economic development and societal well-being (Aronson *et al.* 2010). We should not make this mistake in developing the restoration plan and actions for the Gulf of Mexico. It is especially critical that we value the multitude of ecosystem and human services provided by critical components of the Gulf ecosystem, because human prosperity and economic health of the Gulf depend on the restoration of its ecosystem services.

The fate of the oyster may mirror the fate of the Gulf of Mexico as a whole—its residential communities, its economic health, its flora and fauna, its water and land. We know much about the economically valuable ecosystem services provided by the oyster and the reefs it forms (e.g., Grabowski and Peterson 2007, Beck *et al.* 2011), and we know that the oyster is deeply embedded in the northern Gulf culture and economy. Of course, those outside the Gulf know the oyster primarily as a delicacy; for this reason, natural oyster populations have been decimated by intense demand and consequent overharvesting. But the ecosystem services provided by oysters are numerous and have economic value to other human enterprises, perhaps worth an order of magnitude more than the oyster's value as an exploited food (Grabowski and Peterson 2007). We now recognize that oyster filtration serves to clarify estuarine waters, promoting growth and expansion of sea grass habitat, which is, in turn, a critical nursery for shrimp, blue crabs and many finfish. The biodeposition of oyster feces and pseudofeces induces denitrification, which helps reverse destructive nutrient loading and eutrophication naturally, without the use of costly engineered wastewater treatment to remove inorganic nitrogen nutrients. The oyster reef with its diverse associated algal and invertebrate community serves as an important habitat for finfish such as redfish and sea trout as well as blue and stone crabs, which provide economic value to the region (Peterson *et al.* 2003a). Oyster reefs also act as natural breakwaters, protecting coastal marshes, shorelines and development along the shores from erosion and storm damage. Oyster shell is constructed largely of calcium carbonate and serves as a natural local buffer to rising ocean acidity, allowing larval and juvenile shellfish to develop and retain their developing shells, thereby surviving this component of changing climate. The very creation of shell mounds (reefs) of oysters reveals how oysters sequester carbon and bury it so that it does not contribute to atmospheric carbon dioxide. Consequently, restoring and sustaining oyster reef habitat feeds directly into human enterprise and welfare in the northern Gulf of Mexico.

The oyster and oyster reef habitat example represents a single illustration of how human welfare can be served by sustaining healthy coastal ecosystems, and similar stories can be told for other Gulf habitats and natural resources. Perhaps no other coastal economy in the United States is so closely tied to the health and productivity of the marine and estuarine ecosystem as that of the northern Gulf of Mexico. Commercial and recreational fishing businesses of the Gulf Coast are important not only to the local economy but also to the national economy. The combined value of the region's commercial and recreational fisheries is the largest in the nation (NMFS 2010). Hunting and trapping provide income and define traditional Gulf Coast cultures. Tourism in the region depends on unpolluted waters, clean beaches and a healthy aquatic environment. A vibrant and growing retirement industry likewise flourishes only so long as the environmental quality is sustained: Retirees can choose to resettle elsewhere. The northern Gulf Coast contains a wealth of wildlife sanctuaries for flourishing populations of water birds of many types, many of which redistribute themselves seasonally across the entire country while attracting bird watchers in droves to places such as Dauphin Island.

Because humans and human enterprise are an integral component of the Gulf ecosystem, we must treat it as a coupled natural-human system to achieve sustainable prosperity in this region. Balancing the preservation of ecosystem services with industrial development will be necessary in the Gulf of Mexico to restore a vibrant coastal economy and culture that may remain resilient to the many serious environmental perturbations ahead.

Appendix I

Recommended restoration principles for the northern Gulf of Mexico

based on experiences of the Exxon Valdez oil spill restoration process, knowledge of restoration ecology, evidence of Gulf degradation, and an August 26, 2010, letter from Dennis Kelso of the Ocean Conservancy to David Hayes and Jane Lubchenco

1. The overarching goal of the Gulf restoration is to bring back a robust and resilient northern Gulf ecosystem that sustains fish and wildlife and coastal economies indefinitely.
2. Although the NRDA-based compensatory restoration has certain legally mandated constraints, a broader Gulf Coast Restoration Plan should be pursued using other funds, such as fines for pollutant discharges, as called for in President Obama's directive June 15, 2010.
3. In part because historical baseline levels of most important natural resources and shoreline habitats reflect substantial human-caused degradation over decades and centuries, as in implementing the Exxon Valdez oil spill settlement, restoration at the Gulf should be defined to include enhancement of natural resources over and above pre-DWH levels.
4. Restoration should focus on natural resources that have been harmed and lost as a consequence of the spill and the systematic degradation that has progressively compromised, and continues to challenge, the Gulf ecosystem. The limits to what is appropriate use of restoration funds should be clearly set under this principle so as to avoid public disillusionment and lose support and collaboration.
5. Care should be taken to ensure that restoration projects cause no harm. This principle implies use of pilot demonstration projects in some cases and rigorous scientific reviews before implementation.
6. Projects that favor one set of resources over another should only be supported after confident determination of overwhelming net benefits.
7. Adopt an ecological, ecosystems-based approach to the broad restoration plan, as well as to individual projects, so as to promote synergistic benefits across multiple species and habitats and avoid counterproductive conflicts among separate projects.
8. Create a comprehensive restoration plan with integrated components that is approved and implemented jointly by trustees across the Gulf coastal region. Avoid partitioning of restoration funds into state-by-state "block grants," which could impair efforts to achieve a coordinated set of restoration actions.
9. Resist the pressures to fund "economic or community development" projects, which do not achieve restoration of the base of sustainable natural resources, and normal agency management, which would lead to public disillusionment with the restoration motivation.
10. Think creatively ("rethink possible") about restoration options while benefitting from insights and effort reflected in existing plans for species and habitat restoration. Here comes opportunity for an unprecedented scope of coordinated actions – a one-time chance that should not be squandered.
11. Seek opportunities to leverage restoration funds by collaborations with partners, but maintain strict guidelines set by the other restoration principles, including especially the ecosystem-based coordination with other projects and the clean relevance to natural resource restoration targets.
12. Take special and explicit account of the dynamic nature of the Gulf ecosystem and shorelines such that restoration actions are compatible with, adaptive to, and sustainable in the face of dynamic change. The institutional mantra of "in-place, in-kind" restoration preference may lead to longer term failures without thorough consideration of the future conditions.
13. Where appropriate and consistent with the other principles for restoration, choose projects that enhance regional expertise and institutional capacity, thereby leaving a legacy of improved potential for achieving societal as well as ecological resilience.
14. Use restoration funding to ensure that the whole story of spill impact and recovery is told. This principle is most critical as it applies to solving the mysteries of novel impacts of the hydrocarbons to the deep-sea pelagic and benthic resources and ocean ecosystem processes.
15. Contemplate the legacy of restoration that will persist long after the formal restoration process has been concluded so as to incorporate projects and goals that insure that the ecosystem receives support indefinitely. Such enduring support from the Exxon Valdez restoration included public acquisition of important, ultimately threatened, parcels of critical fish and wildlife habitat and investment in science of understanding how the natural ecosystem functions so that management and conservation of natural resources and ecosystem services are enhanced.
16. Acknowledge, celebrate, and foster public ownership of the restoration process so that public participation is routine and meaningful, restoration decisions are transparent, and information on ecosystem injury and recovery is regularly shared in multiple fashions.

Appendix II

Selected relevant published studies for background on deepwater biology in the Gulf of Mexico

from the Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE), formerly Minerals Management Service (MMS)

Chemo I First dedicated Gulf of Mexico chemosynthetic community study, primarily above 1,000 meters (3,280 feet) depth

MacDonald, I.R., W.W. Schroeder and J.M. Brooks. 1995. *Chemosynthetic Ecosystems Study, Final Report*. Prepared by Geochemical and Environmental Research Group. U.S. Department of the Interior, Minerals Management Service, Gulf of Mexico OCS Region, New Orleans. OCS Study MMS 95-0023. 338 pp.
www.gomr.mms.gov/PI/PDFImages/ESPIS/3/3323.pdf

Chemo II Second Gulf of Mexico dedicated chemosynthetic community study, primarily above 1,000 meters (3,280 feet) depth

MacDonald, I.R., ed. 2002. *Stability and Change in Gulf of Mexico Chemosynthetic Communities. Volume II: Technical Report*. Prepared by the Geochemical and Environmental Research Group, Texas A&M University. U.S. Department of the Interior, Minerals Management Service, Gulf of Mexico OCS Region, New Orleans. OCS Study MMS 2002-036. 456 pp.
www.gomr.mms.gov/PI/PDFImages/ESPIS/3/3072.pdf

Synthetic mud study

Continental Shelf Associates Inc. 2004. *Final Report: Gulf of Mexico Comprehensive Synthetic Based Muds Monitoring Program Volume 1: Technical*.
www.gomr.mms.gov/PI/PDFImages/ESPIS/2/3049.pdf

Continental Shelf Associates Inc. 2008. *Final Report: Gulf of Mexico Comprehensive Synthetic Based Muds Monitoring Program. Volume I: Technical*.
www.gomr.mms.gov/PI/PDFImages/ESPIS/2/3050.pdf

Continental Shelf Associates, Inc. 2008. *Final Report: Gulf of Mexico Comprehensive Synthetic Based Muds Monitoring Program. Volume II: Technical*.
www.gomr.mms.gov/PI/PDFImages/ESPIS/2/3051.pdf

Lophelia I

CSA International Inc. 2007. *Characterization of Northern Gulf of Mexico Deepwater Hard Bottom Communities with Emphasis on* Lophelia *Coral.* U.S. Department of the Interior, Minerals Management Service, Gulf of Mexico OCS Region, New Orleans. OCS Study MMS 2007-044. 169 pp. + app.
www.gomr.mms.gov/PI/PDFImages/ESPIS/4/4264.pdf

In-depth study of the two most significant *Lophelia* sites

Schroeder, W.W. 2007. *Seafloor Characteristics and Distribution Patterns of* Lophelia pertusa *and Other Sessile Megafauna at Two Upper-Slope Sites in Northeastern Gulf of Mexico.* U.S. Department of the Interior, Minerals Management Service, Gulf of Mexico OCS Region, New Orleans. OCS Study MMS 2007-035. 49 pp.
www.gomr.mms.gov/PI/PDFImages/ESPIS/4/4256.pdf

Companion USGS *Lophelia* study for MMS

Sulak, K.J. *et al.*, eds. 2008. Characterization of Northern Gulf of Mexico Deepwater Hard Bottom Communities with Emphasis on *Lophelia* Coral—*Lophelia* Reef Megafaunal Community Structure, Biotopes, Genetics, Microbial Ecology, and Geology. 2004-2006.
http://fl.biology.usgs.gov/coastaleco/OFR_2008-1148_MMS_2008-015/index.html

Chemo III Interim Report 1 Chemosynthetic communities below 1,000 meters (3,280 feet)

Brooks, J.M., C. Fisher, H. Roberts, B. Bernard, I. McDonald, R. Carney, S. Joye, E. Cordes, G. Wolff, E. Goehring. 2008. *Investigations of Chemosynthetic Communities on the Lower Continental Slope of the Gulf of Mexico: Interim Report 1.* U.S. Department of the Interior, Minerals Management Service, Gulf of Mexico OCS Region, New Orleans. OCS Study MMS 2008-009. 332 pp.
www.gomr.mms.gov/PI/PDFImages/ESPIS/4/4320.pdf

Chemo III Interim Report II Chemosynthetic communities below 1,000 meters (3,280 feet)

Brooks, J.M., C. Fisher, H. Roberts, B. Bernard, I. McDonald, R. Carney, S. Joye, E. Cordes, G. Wolff, E. Goehring. 2009. *Investigations of Chemosynthetic Communities on the Lower Continental Slope of the Gulf of Mexico: Interim Report 2.* U.S. Department of the Interior, Minerals Management Service, Gulf of Mexico OCS Region, New Orleans. OCS Study MMS 2009-046. 360 pp.
www.gomr.mms.gov/PI/PDFImages/ESPIS/4/4877.pdf

NOAA expedition websites

NOAA. "Ocean Expedition." Expedition to the Deep Slope, May 7–June 2, 2006.
http://oceanexplorer.noaa.gov/explorations/06mexico/welcome.html

NOAA. "Ocean Explorer." Expedition to the Deep Slope, June 4–July 6, 2007.
http://oceanexplorer.noaa.gov/explorations/07mexico/welcome.html

Chemo III draft final report complete and in review

DSR II journal now out with 18 papers related to the Chemo III study.

Roberts, H.H. (ed.). 2011. *Gulf of Mexico Cold Seeps. Deep Sea Research Part II: Topical Studies in Oceanography.*
www.sciencedirect.com/science?_ob=PublicationURL&_tockey=%23TOC%236035%232010%23999429978%232642734%23FLA%23&_cdi=6035&_pubType=J&_auth=y&_acct=C000050221&_version=1&_urlVersion=0&_userid=10&md5=f47b5b34742ea0073594e30836c16db4

Major Gulf-wide deepwater benthos study

Rowe, G.T., and M.C. Kennicutt II. 2009. *Northern Gulf of Mexico Continental Slope Habitats and Benthic Ecology Study: Final Report*. U.S. Department of the Interior, Minerals Management. Service, Gulf of Mexico OCS Region, New Orleans. OCS Study MMS 2009-039. 456 pp.
www.gomr.mms.gov/PI/PDFImages/ESPIS/4/4842.pdf

Earlier major Gulf-wide benthic study

Gallaway, B.J., L.R. Martin and R.L. Howard (eds.). *Northern Gulf of Mexico Continental Slope Study Annual Report Year 3 Volume I: Executive Summary.* 1988.
www.gomr.mms.gov/PI/PDFImages/ESPIS/3/3773.pdf

Gallaway, B.J., L.R. Martin and R. L. Howard (eds.). *Northern Gulf of Mexico Continental Slope Study Annual Report Year 3 Volume II: Technical Report.* 1988.
www.gomr.mms.gov/PI/PDFImages/ESPIS/3/3774.pdf

Gallaway, B.J. (ed.). *Northern Gulf of Mexico Continental Slope Study. Final Report. Year 4. Volume I: Executive Summary*. 1988.
www.gomr.mms.gov/PI/PDFImages/ESPIS/3/3695.pdf

Gallaway, B.J. (ed.). 1988. *Northern Gulf of Mexico Continental Slope Study, Final Report: Year 4. Volume II: Synthesis Report*. Final report submitted to the Minerals Management Service, New Orleans. Contract No. 14-12-0001- 30212. OCS Study/MMS 88-0053. 378 pp.
www.gomr.mms.gov/PI/PDFImages/ESPIS/3/3696.pdf

Ongoing *Lophelia* II MMS/NOAA OER study

Profile:

BOEMRE. *Exploration and Research of Northern Gulf of Mexico Deepwater Natural and Artificial Hard Bottom Habitats with Emphasis on Coral Communities: Reefs, Rigs and Wrecks (GM 08-03)*
www.gomr.boemre.gov/homepg/regulate/environ/ongoing_studies/gm/GM-08-03.html

NOAA expedition websites:

NOAA. "Ocean Explorer." Lophelia II 2008: Deepwater Coral Expedition: Reefs, Rigs, and Wrecks. Sept. 20–Oct. 2, 2008.
http://oceanexplorer.noaa.gov/explorations/08lophelia/welcome.html

NOAA. "Ocean Explorer." Lophelia II 2009 *Deepwater Coral Expedition: Reefs, Rigs, and Wrecks* Aug. 19–Sept. 12, 2009.
http://oceanexplorer.noaa.gov/explorations/09lophelia/welcome.html

***Lophelia* II Cruise Reports**

TDI-Brooks International Inc. *Deepwater Program: Exploration and Research of Northern Gulf of Mexico Deepwater Natural and Artificial Hard Bottom Habitats with Emphasis on Coral Communities: Reef, Rigs, and Wrecks "Lophelia II."* Cruise 1 Report. 2008.
www.tdi-bi.com/Lophelia/Data/Loph_Cru1_Rpt-Final.pdf

TDI-Brooks International Inc. *Deepwater Program: Exploration and Research of Northern Gulf of Mexico Deepwater Natural and Artificial Hard Bottom Habitats with Emphasis on Coral Communities: Reef, Rigs, and Wrecks "Lophelia II."* Cruise 2 Report. 2009.
www.tdi-bi.com/Lophelia/Data/Loph_Cru2_Rpt-post.pdf

TDI-Brooks International Inc. *Deepwater Program: Exploration and Research of Northern Gulf of Mexico Deepwater Natural and Artificial Hard Bottom Habitats with Emphasis on Coral Communities: Reef, Rigs, and Wrecks "Lophelia II."* Cruise 3 Report. 2009.
www.tdi-bi.com/Lophelia/Data/RV%20Brown%20LopheliaII%20Cru3%20Report-prt.pdf

This project's baseline data served as a key resource for an NRDA cruise on the R/V Nancy Foster that departed July 16, 2010.

Companion USGS study Lophelia II cruises taking place in similar time frame as above.

Early multidisciplinary Gulf-wide benthic studies

Pequegnat, W. *Ecolgical Aspects of the Upper Continental Slope of the Gulf of Mexico.* Prepared for U.S. Department of the Interior, Bureau of Land Management. 1976.
www.gomr.boemre.gov/PI/PDFImages/ESPIS/4/4105.pdf

Pequegnat, W. *The Ecological Communities of the Continental Slope and Adjacent Regimes of the Northern Gulf of Mexico, Text, Photographic Atlas, and Appendices.* Prepared for U.S. Department of the Interior, Minerals Management Service. 1983.

MMS/USGS mesophotic coral studies

Continental Shelf Associates Inc. and Texas A&M University, Geochemical and Environmental Research Group. 2001. *Mississippi/Alabama Pinnacle Trend Ecosystem Monitoring, Final Synthesis Report.* U.S. Department of the Interior, Geological Survey, Biological Resources Division, USGS BSR 2001-0007 and Minerals Management Service, Gulf of Mexico Regions, New Orleans, OCS Study MMS 2001-080. 415 pp + apps.
www.gomr.mms.gov/PI/PDFImages/ESPIS/3/3136.pdf

Continental Shelf Associates Inc. and Texas A&M University, Geochemical and Environmental Research Group. 1999. *Northeastern Gulf of Mexico Coastal and Marine Ecosystem Program: Ecosystem Monitoring, Mississippi/Alabama Shelf; Third Annual Interim Report.* U.S. Department of the Interior, U.S. Geological Survey, Biological Resources Division, USGS/BRD/CR-1999-0005 and Minerals Management Service, Gulf of Mexico OCS Region, New Orleans, OCS Study MMS 99-0055. 211 pp.
www.gomr.mms.gov/PI/PDFImages/ESPIS/3/3210.pdf

Continental Shelf Associates Inc. 1992. *Mississippi-Alabama Shelf Pinnacle Trend Habitat Mapping Study.* OCS Study/MMS 92-0026. U.S. Department of the Interior, Minerals Management Service, Gulf of Mexico OCS Regional Office, New Orleans. 75 pp. + app.
www.gomr.mms.gov/PI/PDFImages/ESPIS/3/3629.pdf

Brooks, J.M., and C.P. Giammona (eds.). *Mississippi-Alabama Marine Ecosystem Study Annual Report, Year 2. Volume 1*: Technical Narrative. 1990. OCS Study/MMS-89-0095. U.S. Department of Interior, Minerals Management Service, Gulf of Mexico OCS Regional Office, New Orleans. Contract No. 14-12-0001-30346. 348 pp.
www.gomr.mms.gov/PI/PDFImages/ESPIS/3/3670.pdf

Brooks, J.M., C.P. Giammona and R.M. Darnell (eds.). *Mississippi/Alabama Marine Ecosystem Study. Annual Report Year 1, Volume I : Technical Narrative*. 1989. OCS Study/MMS-88-0071. U.S. Department of Interior, Minerals Management Service, Gulf of Mexico OCS Regional Office, New Orleans. Contract No. 14-12-0001-30346. 258 pp.
www.gomr.mms.gov/PI/PDFImages/ESPIS/3/3703.pdf

Significant study related to impacts from drilling in water depths of about 1,000 meters (3,280 feet)

Continental Shelf Associates Inc. *Effects of Oil and Gas Exploration and Development at Selected Continental Slope Sites in the Gulf of Mexico. Volume II: Technical Report*.
www.gomr.boemre.gov/PI/PDFImages/ESPIS/3/3875.pdf

Fact Sheet

Restoration principles

1. Restoration should be conducted within a context of understanding the historical baseline conditions and functioning of the pristine coastal ecosystem before human intervention, even though reestablishing the pristine state is not a realistic restoration goal.
2. Restoration actions to maintain and create resiliency should be based on an understanding of how past and ongoing stressors have compromised resilience to future perturbations.
3. Addressing impacts of the DWH oil release should be integrated into a holistic understanding of how all stressors may potentially combine to destabilize the ecosystem by passing through a critical threshold and into an undesirable state of the system.
4. Restoration should be holistic, not piecemeal, and should be durable and sustainable under the conditions of dynamic change expected in the Gulf for a century and longer. Traditional tests of restoration appropriateness of "in-place" and "in-kind" are likely to fail the criteria for sustainability under a changing climate, rising sea level and more intensely stormy regime unless resilience to such environmental changes is successfully built into restoration actions.
5. The preparation of this report is motivated by the unique opportunity emerging from the DWH oil spill to carry out meaningful, effective and durable restoration of Gulf ecosystems, addressing not only impacts of oil but also long-standing degradation in a coordinated program.
6. The rationale for assembling this group of scientists was based upon breadth of expertise, experience with ecosystem dynamics and past restoration efforts, and benefits of melding local Gulf knowledge with broader national experience.
7. Release of the report is scheduled to precede restoration decisions made by the various organizations charged with different aspects of Gulf ecosystem restoration.

Characteristics of the Deepwater Horizon oil and gas release

1. The Deepwater Horizon (DWH) oil well blowout led to the largest oil spill in U.S. waters, releasing 4.9 million barrels of oil.
2. Unlike previous spills in shallow water, the DWH blowout occurred in deep waters (1,500 meters), where turbulent discharge of hot, pressurized oil and gas entrained cold seawater, producing a variety of dispersed phases that included small oil droplets, gas bubbles, oil-gas emulsions and gas hydrates.
3. Much of that oil and essentially all of the gaseous hydrocarbons were retained at substantial depths below the sea surface, where methane and other hydrocarbon gases stimulated the production of heterotrophic microbes in intrusion layers 800 to 1,200 m deep.
4. The agglomeration of oil particles, inorganic sediments and marine snow, mediated by adhesive bacterial exudates, triggered downward oil transport and some deposition onto the seafloor.
5. About half of the oil reached the surface but it weathered substantially during ascent to form orange-brown rivulets and became less cohesive than expected for a surface release of crude oil.
6. After weeks of transport in oceanic eddies, during which oil affected floating *Sargassum* habitat, its associated biota, and other animals using the sea surface, some of the weathered oil grounded on and damaged marsh, beach, sea grass, and oyster reef habitats across five Gulf of Mexico states.
7. Among several aggressive responses to the spill was application of 1.8 million gallons of chemical dispersants, not only dropped upon the sea surface but also injected into the plume at the wellhead.
8. The occurrence of a deep-water spill of this magnitude and with these characteristics was unprecedented.

Ecosystem and natural resource impacts of the oil and gas release

1. Oil on the sea surface fouled, injured and killed many seabirds, especially gulls, terns, northern gannets, brown pelicans and black skimmers, as well as sea turtles and bottlenose dolphins.
2. Dispersed oil throughout the water column put at risk early life stages of many commercially valuable marine animals, such as bluefin tuna, blue crabs, penaeid shrimps and many fish.
3. Delivery of ecosystem services from oiled shoreline habitats was suppressed, with variable durations of injury probably dependent on the degree to which oil became buried in anoxic conditions.

4. Coastal bird and wildlife oiling and losses occurred in shoreline habitats, affecting ground- and low-nesting birds, rails and other marsh birds, waders, shorebirds and scavengers.

5. Concern over food contamination led to closure of commercial and recreational fisheries for shrimps, oyster, blue crabs, reef fish and other finfish, resulting in higher abundances of many species throughout the 2010 summer and confounding our ability to separate direct toxic effects from indirect effects of reduced fishing.

6. Collateral damage associated with many response actions included the effects of dispersant toxicity, habitat damage from berm construction, loss of invertebrate prey from beach disturbance, physical damage to marsh edges by breakaway booms, mortality of surface organisms during oil burning and oil skimming, and destruction of oyster reefs caused by river diversions.

7. The long persistence of oil in *Sargassum* habitat harmed the associated sea turtles, juvenile bluefin tuna, wahoo, cobia and other higher trophic-level species through acute and chronic exposures.

8. Benthic invertebrates of the deep sea such as iconic corals, sponges and echinoderms on hard bottoms and infaunal invertebrates in soft-sediment habitats were damaged by apparent oil deposition within an undetermined distance from the wellhead.

9. Pelagic organisms were exposed to the highly dispersed oil droplets as well as dispersant to an unprecedented degree, harming particle feeders such as salps near the surface and analogous animals in the deep sea via chemical toxicity and the physical fouling of feeding and respiratory organs.

10. Ecosystem consequences of exposures to toxicants at the base of the pelagic food chains and the massive organic carbon subsidy to the shallow and deep ocean remain uncertain, requiring new advances in oil spill oceanography to assess. The indirect impacts are likely to play out over longer time frames.

Gulf ecosystem stressors

1. The increased frequency of intense hurricanes arising from global change exposes the Gulf Coast to greater risks of catastrophic flooding, shoreline erosion and associated geomorphic changes such as land loss in vulnerable areas and reductions in elevation of coastal barriers.

2. Subsidence, sea level rise and marsh channelization from historical petroleum-industry activities led to losses in coastal habitats, coastal barrier protections and ecosystem services.

3. Excessive nutrient (largely nitrogen) loading from agriculture and other anthropogenic sources extending into the Mississippi River watershed and airshed and along the Gulf Coast has caused eutrophication of estuaries and the continental shelf and resulted in a massive hypoxic area the size of Massachusetts where commercially viable populations of shrimp and fish are absent.

4. The exploitation of apex predators such as sharks and bluefin tuna have propelled the ecosystem toward the functional extinction of this trophic level in the Gulf, removing a potentially regulating process that inhibits unnatural trophic cascades, stabilizes community composition and sustains the abundances of other fished species.

5. Disturbance from bottom trawling and dredging has preferentially removed habitat-providing, epibiotic benthic invertebrates from the shelf seafloor and now repeatedly resets the succession of soft-sediment benthic communities to early successional stages populated by opportunistic species.

6. Enhanced concentrations of carbon dioxide in the atmosphere from fossil fuel combustion are increasing the acidification of coastal ocean waters. This global acidification signal is being amplified, especially in bottom waters, as a consequence of eutrophication.

7. Development of low-lying lands and coastal barriers has degraded and destroyed shoreline habitats and led to engineering of structural responses and dredge-and-fill projects to protect housing and infrastructure at risk, but such responses interfere with natural rollover and transgression of barrier islands and resilience of natural shoreline habitats.

8. Sea level rise puts major Gulf cities such as New Orleans and Houston at risk of flooding and, in combination with hurricanes, makes the long-term human occupation of the Mississippi Delta and coastal barrier shorelines of all Gulf states problematic if not unsustainable. This set of conditions poses extreme socioeconomic challenges: How can resilience of human communities, local culture and ecosystems be sustained or created when maintaining coastal residency increasingly risks property and life, yet retreating inland by entire communities challenges the fabric and glue of social cohesion and place-based history?

Proposed restoration actions

THEME 1
Assess and repair damage from the DWH and other stresses

1. Restore shoreline habitats directly and indirectly damaged by the oil release.
2. Investigate effects of oil on deep-sea ecosystems and test capacity of restoration for ecosystem services.
3. Determine effects of the DWH oil spill on *Sargassum* and restore it as a habitat for associated fish and wildlife.
4. Modify farming practices in the Mississippi basin to reduce nutrient loading.
5. Reduce fish and wildlife casualties resulting from water debris.
6. Restore water flows, water quality, riparian habitats and ecosystem services of smaller rivers.

THEME 2
Protect existing habitats and populations

7. Preserve functionally valuable habitat for fish and wildlife sanctuaries to enhance injured species recovery.
8. Implement and augment existing recovery plan actions for species injured by the DWH oil spill.
9. Maintain and enforce existing legislative protections for habitat, fish and wildlife to promote public health and ecosystem services.
10. Create networks of protected habitats to enhance fish stocks and valuable species.

THEME 3
Integrate sustainable human use with ecological processes

11. Engage Gulf Coast communities to adapt to increasing coastal inundation while sustaining nurture of fish and wildlife.
12. Manage Gulf fisheries sustainably by recognizing ecosystem processes.
13. Assess damage from shrimp trawling and potential fishery benefits of no-trawling protections.
14. Endow Gulf capacity building in social-environmental monitoring and problem solving.
15. Communicate within Gulf communities to inspire informed environmental decisions.

Endnotes

Note from p. 19

1. The Santa Barbara blowout released 100,000 barrels of crude oil, a small fraction of the 4.9 million barrels released during the 85 days of gushing oil at the Macondo site, yet the 1969 incident also fouled and killed many seabirds and coated beaches and rocky shores.

Notes from p. 69

2. The Florida Panhandle is a 320-kilometer stretch between Alabama and Apalachicola that is characterized by barrier island buffers.

3. The Florida Big Bend is a 320-kilometer stretch between Apalachee Bay and Anclote Key characterized by the absence of barrier island buffers.

Able, K. W., D. M. Nemerson, P. R. Light, and R. O. Bush. 2002. Initial response of fishes to marsh restoration at a former salt hay farm bordering Delaware Bay. Pages 749-773 *in* M. P. Weinstein and D. A. Kreeger, editors. Concepts and Controversies in Tidal Marsh Ecology. Kluwer Academic Publishers, Dordrecht.

Allen, E. B., W. W. Covington, and D. A. Falk. 1997. Developing the conceptual basis for restoration ecology. Restoration Ecology 5:275-276.

Alexander, R.B., R.A. Smith, G.E. Schwarz, E.W. Boyer, J.V. Nolan and J.W. Brakebill. 2008. Differences in phosphorus and nitrogen delivery to the Gulf of Mexico from the Mississippi River Basin. Environmental Science and Technology 42: 822-830.

Anthony, K. R. N., J. A. Maynard, G. Diaz-Pulido, P. J. Mumby, P. A. Marshall, L. Cao, and O. Hoegh-Guldberg. 2011. Ocean acidification and warming will lower coral reef resilience. Global Change Biology 17:1798-1808.

Aronson, J., J. N. Blignaut, S. J. Milton, D. Le Maitre, K. J. Esler, A. Limouzin, C. Fontaine, M. P. de Wit, W. Mugido, P. Prinsloo, L. van der Elst, and N. Lederer. 2010. Are socioeconomic benefits of restoration adequately quantified? A meta-analysis of recent papers (2000-2008) in Restoration Ecology and 12 other scientific journals. Restoration Ecology 18:143-154.

Baguley, J., P. Montagna, W. Lee, L. Hyde, and G. Rowe. 2006. Spatial and bathymetric trends in Harpacticoida (Copepoda) community structure in the northern Gulf of Mexico deep-sea. Journal of Experimental Marine Biology and Ecology 330:327-341.

Ballantine, W. J. 1995. Networks of “no-take” marine reserves are practical and necessary. Pages 13-20 *in* N. L. Shackell and J. H. M. Willison, editors. Marine protected Areas and Sustainable Fisheries. Science and Management of Protected Areas Association, Nova Scotia, Canada.

Ballantine, W. J. 1997. Design principles for systems of “no-take” marine reserves. Fisheries Center, University of British Columbia, Vancouver.

Baron, J. S., N. L. Poff, P. L. Angermeier, C. N. Dahm, P. H. Gleick, N. G. Hairston, R. B. Jackson, C. A. Johnston, B. D. Richter, and A. D. Steinman. 2002. Meeting ecological and societal needs for freshwater. Ecological Applications 12:1247-1260.

Barras, J., S. Beville, D. Britsch, S. Hartley, S. Hawes, J. Johnston, P. Kemp, Q. Kinler, A. Martucci, J. Porthouse, D. Reed, K. Roy, S. Sapkota, and J. Suhayda. 2003. Historical and projected coastal Louisiana land changes: 1978-2050: USGS open file report 03-334. 39 pages. USGS.

Batie, S. S. 2009. Green payments and the US Farm Bill: information and policy challenges. Frontiers in Ecology and the Environment 7:380-388.

Baum, J. K., and R. A. Myers. 2004. Shifting baselines and the decline of pelagic sharks in the Gulf of Mexico. Ecology Letters 7:135-145.

Baumann, R. H., and R. E. Turner. 1990. Direct impacts of outer continental shelf activities on wetland loss in the central Gulf of Mexico. Environmental Geology and Water Sciences 15:189-198.

Beck, M. W., R. D. Brumbaugh, L. Airoldi, A. Carranza, L. D. Coen, C. Crawford, O. Defeo, G. J. Edgar, B. Hancock, M. C. Kay, H. S. Lenihan, M. W. Luckenbach, C. L. Toropova, G. Zhang, and X. Guo. 2011. Oyster reefs at risk and recommendations for conservation, restoration, and management. BioScience 61:107-116.

Beman, J. M., C. E. Chow, A. L. King, Y. Feng, J. A. Fuhrman, A. Andersson, N. R. Bates, B. N. Popp, and D. A. Hutchins. 2011. Global declines in oceanic nitrification rates as a consequence of ocean acidification. Proceedings of the National Academy of Sciences 108:208-213.

Bernhardt, E. S., M. A. Palmer, J. D. Allan, G. Alexander, K. Barnas, S. Brooks, J. Carr, S. Clayton, C. Dahm, J. Follstad-Shah, D. Galat, S. Gloss, P. Goodwin, D. Hart, B. Hassett, R. Jenkinson, S. Katz, G. M. Kondolf, P. S. Lake, R. Lave, J. L. Meyer, T. K. O’Donnell, B. Pagano, B. Powell, and E. Sudduth. 2005. Synthesizing U.S. river restoration efforts. Science 308:636-637.

Biggs, D., C. Hu, and F. Mullerkarger. 2008. Remotely sensed sea-surface chlorophyll and POC flux at Deep Gulf of Mexico Benthos sampling stations. Deep Sea Research Part II: Topical Studies in Oceanography 55:2555-2562.

Bjorndal, K. A., B. W. Bowen, M. Chaloupka, L. B. Crowder, S. S. Heppell, C. M. Jones, M. E. Lutcavage, D. Policansky, A. R. Solow, and B. E. Witherington. 2011. Better science needed for restoration in the Gulf of Mexico. Science 331:537-538.

Boesch, D. F. 2002. Challenges and opportunities for science in reducing nutrient over-enrichment of coastal ecosystems. Estuaries 25:886-900.

Boody, G., B. Vondracek, D. A. Andow, M. Krinke, J. Westra, J. Zimmerman, and P. Welle. 2005. Multifunctional agriculture in the United States. BioScience 55:27-38.

Botsford, L. W., J. C. Castilla, and C. H. Peterson. 1997. The management of fisheries and marine ecosystems.

Boufadel, M. C., Y. Sharifi, B. Van Aken, B. A. Wrenn, and K. Lee. 2010. Nutrient and oxygen concentrations within the sediments of an Alaskan beach polluted with the Exxon Valdez oil spill. Environmental Science & Technology 44:7418-7424.

Breitburg, D. L., J. K. Craig, R. S. Fulford, K. A. Rose, W. R. Boynton, D. C. Brady, B. J. Ciotti, R. J. Diaz, K. D. Friedland, J. D. Hagy, D. R. Hart, A. H. Hines, E. D. Houde, S. E. Kolesar, S. W. Nixon, J. A. Rice, D. H. Secor, and T. E. Targett. 2009. Nutrient enrichment and fisheries exploitation: interactive effects on estuarine living resources and their management. Hydrobiologia 629:31-47.

Brewer, G. D., and P. C. Stern (Eds.). 2005. Decision Making for the Environment: Social and Behavioral Science Research Priorities. The National Academies Press, Washington, D.C. 296 pages.

Britsch, L. D., and J. B. Dunbar. 1993. Land loss rates: Louisiana coastal plain. Journal of Coastal Research 9:324-338.

Brooks, J. M., M. C. Kennicutt II, C. R. Fisher, S. A. Macko, K. Cole, J. J. Childress, R. R. Bidigare, and R. D. Vetter. 1987. Deep-sea hydrocarbon seep communities: evidence for energy and nutritional carbon sources. Science 238: 1138-1142.

Broome, S. W., E. D. Seneca, and W. W. Woodhouse. 1986. Long-term growth and development of transplants of the salt-marsh grass Spartina alterniflora. Estuaries 9:63-74.

Broussard, W., R. E. Turner, and J. Westra. Submitted. Federal farm policies and agricultural landscapes influence surface water quality.

Burkholder, J., D. Tomasko, and B. Touchette. 2007. Seagrasses and eutrophication. Journal of Experimental Marine Biology and Ecology 350:46-72.

Caddy, J. F. 1993. Toward a comparative evaluation of human impacts on fishery ecosystems of enclosed and semi-enclosed seas. Reviews in Fisheries Science 1:57-95.

Caddy, J. F. 2000. Marine catchment basin effects versus impacts of fisheries on semi-enclosed seas. ICES Journal of Marine Science 57:628-640.

Cai, W. J., W. J. Huang, M. C. Murrell, J. C. Lehrter, S. E. Lohrenz, Y. Wang, X. Guo, P. Zhao, K. Gundersen, and J. T. Hollibaugh. in review. Eutrophication-driven hypoxia and increasing atmospheric pCO_2 enhance ocean acidification and denitrification. Nature Geoscience.

Camilli, R., C. M. Reddy, D. R. Yoerger, B. A. S. Van Mooy, M. V. Jakuba, J. C. Kinsey, C. P. McIntyre, S. P. Sylva, and J. V. Maloney. 2010. Tracking hydrocarbon plume transport and biodegradation at Deepwater Horizon. Science 330:201-204.

Carnegie, R. B. 2009. Diseases of concern in molluscan aquaculture. Southern Regional Aquatic Center Publication No. 4704.

Carney, R. S. 2010. Stable isotope trophic patterns in echinoderm megafauna in close proximity to and remote from Gulf of Mexico lower slope hydrocarbon seeps. Deep-Sea Research II 57:1965-1971.

Carr, M. H., J. E. Neigel, J. A. Estes, S. Andelman, R. R. Warner, and J. L. Largier. 2003. Comparing marine and terrestrial ecosystems: implications for the design of coastal marine reserves. Ecological Applications 13:S90-S107.

Chambers, R. 2009. Introduction to: participatory learning and Action 60: community-based adaptation to climate change. International Institute for Environment and Development, London.

Chapoton, R. B. 1970. History and status of the Gulf of Mexico's menhaden purse seine fishery. Journal of the Elisha Mitchell Scientific Society 86:183-184.

Chapoton, R. B. 1971. The future of the gulf menhaden, the United State's largest fishery. Proceedings of the Gulf and Caribbean Fisheries Institute 24:134-143.

Claassen, R., V. E. Breneman, S. Bucholtz, A. Cattaneo, R. C. Johansson, and M. J. Morehart. 2004. Environmental compliance in U.S. agricultural policy: past performance and future potential. United States Department of Agriculture, Economic Research Service, Washington, D.C.

Claassen, R., M. Aillery, and C. Nickerson. 2007. Integrating commodity and conservation programs: design options and outcomes. U.S. Department of Agriculture-Economic Research Report, Washington, D.C.

Coats, R. N., P. B. Williams, C. K. Cuffy, J. B. Zedler, and D. Reed. 1995. Design guidelines for tidal channels in coastal wetlands. U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS.

Coleman, F. C., C. C. Koenig, and L. A. Collins. 1996. Reproductive styles of shallow-water groupers (Pisces: Serranidae) in the eastern Gulf of Mexico and the consequences of fishing spawning aggregations. Environmental Biology of Fishes 47:129-141.

Coleman, F. C., C. C. Koenig, G. R. Huntsman, J. A. Musick, A. M. Eklund, J. C. McGovern, R. W. Chapman, G. R. Sedberry, and C. B. Grimes. 2000. Long-lived reef fishes: the grouper-snapper complex. Fisheries 25:14-20.

Coleman, F. C., W. F. Figueira, and J. S. Ueland. 2004a. The impact of United States recreational fisheries on marine fish populations. Science 305:1958-1960.

Coleman, F. C., P. Baker, and C. C. Koenig. 2004b. A review of Gulf of Mexico Marine Protected Areas: successes, failures, and lessons learned. Fisheries 29:10-21.

Coleman, F. C., and L. E. Petes. 2010. Life history trade-offs in marine organisms: consequences of climate change. *in* W. H. Rodgers, Jr., J. Barcelos, A. Moritz, and M. Robinson-Dorn, editors. Climate Change: A Reader. Carolina Academic Press, Durham, NC.

Coleman, F. C., K. C. Scanlon, and C. C. Koenig. In press. Groupers on the edge: shelf-edge spawning habitat in and around marine reserves on the northeastern Gulf of Mexico. The Professional Geographer.

Collie, J., G. Escanero, and P. Valentine. 1997. Effects of bottom fishing on the benthic megafauna of Georges Bank. Marine Ecology Progress Series 155:159-172.

Congressional Budget Office (CBO). 2010. Public spending on transportation and water infrastructure.

Conner, C., A. Conway, B. Benedict, and B. Christensen. 1982. Modeling the Apalachicola system: a hydrodynamic graphic and water quality model with a hydrodynamic and water quality atlas of Apalachicola Bay. 89 pages. Gainesville, FL.

Conner, W.H. and J.R. Toliver. 1990. Long-term trends in the bald-cyrpess (*Taxodium distichum*) resource in Louisiana (U.S.A.). Forest Ecology and Management 33/34: 543-557.

Cordes, E., S. Carney, S. Hourdez, R. Carney, J. Brooks, and C. Fisher. 2007. Cold seeps of the deep Gulf of Mexico: community structure and biogeographic comparisons to Atlantic equatorial belt seep communities. Deep Sea Research Part I 54:637-653.

Costanza, R., B. Fisher, K. Mulder, S. Liu, and T. Christopher. 2007. Biodiversity and ecosystem services: a multi-scale empirical study of the relationship between species richness and net primary production. Ecological Economics 61: 478-491.

Cox, T. S., J. D. Glover, D. L. Van Tassel, C. M. Cox, and L. R. DeHaan. 2006. Prospects for developing perennial grain crops. BioScience 56:649-659.

Craig, R. K. 2000. Local or national- the increasing federalization of nonpoint source pollution regulation. Journal of Environmental Law and Litigation 15:179-233.

Craig, R. K. 2002. Sustaining the unknown seas: changes in U.S. ocean policy and regulation since Rio '92. Environmental Law Reporter 32:10190-10218.

Crossett, K. M., T. J. Culliton, P. C. Wiley, and T. R. Goodspeed. 2004. Population trends along the coastal United States:1980-2008. National Oceanic and Atmospheric Administration, Silver Spring, MD.

Crowder, L. B., S. J. Lyman, W. F. Figueira, and J. Priddy. 2000. Source-sink population dynamics and the problem of siting marine reserves. Bulletin of Marine Science 66:799-820.

Crowder, L. B., E. L. Hazen, N. Avissar, R. Bjorkland, C. Latanich, and M. B. Ogburn. 2008. The impacts of fisheries on marine ecosystems and the transition to ecosystem-based management. Annual Review of Ecology, Evolution, and Systematics 39:259-278.

Crumpton, W.G., G.A. Stenback, B.A. Miller, and M.J. Helmers. 2006. Potential Benefits of Wetland Filters for Tile Drainage Systems: Impact on Nitrate Loads to Mississippi River Subbasins. Final project report to U.S. Department of Agriculture Project number: IOW06682.

Culbertson, J., I. Valiela, E. Peacock, C. Reddy, A. Carter, and R. Vanderkruik. 2007. Long-term biological effects of petroleum residues on fiddler crabs in salt marshes. Marine Pollution Bulletin 54:955-962.

Dame, R. F., R. G. Zingmark, and E. Haskin. 1984. Oyster reefs as processors of estuarine materials. Journal of Experimental Marine Biology and Ecology 83:239-247.

Darst, M. R., and H. M. Light. 2008. Drier forest composition associated with hydrologic change in the Apalachicola River Floodplain, Florida. 81 pages. Scientific Investigations Report, U.S. Geological Survey, Reston, VA.

Davis, D. W. 1973. Louisiana canals and their influence on wetland development. Ph.D. Dissertation, Louisiana State University, Baton Rouge, LA.

Day Jr., J. W., D. Pont, P. F. Hensel, and C. Ibañez. 1995. Impacts of sea-level rise on deltas in the Gulf of Mexico and the Mediterranean: the importance of pulsing events to sustainability. Estuaries 18:636-647.

Day Jr., J., J. Barras, E. Clairain, J. Johnston, D. Justic, G. Kemp, J. Ko, R. Lane, W. Mitsch, and G. Steyer. 2005. Implications of global climatic change and energy cost and availability for the restoration of the Mississippi delta. Ecological Engineering 24:253-265.

Dayton, P. K., S. F. Thrush, M. T. Agardy, and R. J. Hofman. 1995. Environmental effects of marine fishing. Aquatic Conservation: Marine and Freshwater Ecosystems 5:205-232.

Dayton, P. K. 1998. Reversal of the burden of proof in fisheries management. Science 279:821 -822.

Department of Energy (DOE). 2011. Strategic Petroleum Reserve. fossil.energy.gov/programs/reserves/spr/

Diaz, R. J. 2001. Overview of hypoxia around the world. Journal of Environmental Quality 30:275-281.

Diaz, R. J., and R. Rosenberg. 2008. Spreading dead zones and consequences for marine ecosystems. Science 321: 926 -929.

Dierks, A. R., R. C. Highsmith, V. L. Asper, D. Joung, Z. Zhou, L. Guo, A. M. Shiller, S. B. Joye, A. P. Teske, N. Guinasso, T. L. Wade, and S. E. Lohrenz. 2010. Characterization of subsurface polycyclic aromatic hydrocarbons at the Deepwater Horizon site. Geophysical Research Letters 37:1-6.

Dimitri, C., A. Effland, and N. Conklin. 2005. The 20th Century transformation of U.S. agriculture and farm policy; Economic Research Service Economic Information Bulletin Number 3. U.S. Department of Agriculture, Washington, D.C.

Donlan, M., M. Sperduto, and C. Herbert. 2003. Compensatory mitigation for injury to a threatened or endangered species: scaling piping plover restoration. Marine Ecology Progress Series 264:213-219.

Doughty, R.W. 1984. Sea turtles in Texas: a forgotten commerce. The Southwestern Historical Quarterly 88: 43-70.

Duarte, C. M., D. J. Conley, J. Carstensen, and M. Sánchez-Camacho. 2009. Return to Neverland: shifting baselines affect eutrophication restoration targets. Estuaries and Coasts 32:29-36.

Ducklow, H. W., D. A. Purdie, P. J. L. Williams, and J. M. Davies. 1986. Bacterioplankton: a sink for carbon in a coastal marine plankton community. Science 232:865-867.

Duke, T., and W. L. Kruczynski. 1992. Status and trends of emergent and submerged vegetated habitats, Gulf of Mexico, U.S.A. 161 pages. U.S. Environmental Protection Agency.

English, E. P., C. H. Peterson, and C. M. Voss. 2009. Ecology and economics of restoration scaling. 193 pages. Coastal Response Research Center, University of New Hampshire, Durham, NH.

Entergy Corporation. 2010. Building a resilient energy Gulf Coast: executive report. 11 pages.

Estes, J. A., and D. O. Duggins. 1995. Sea otters and kelp forests in Alaska: generality and variation in a community ecological paradigm. Ecological Monographs 65:75-100.

Exxon Valdez Oil Spill Trustee Council (EVOSTC). 1994. Exxon Valdez oil spill restoration plan. 98 pages. Exxon Valdes Oil Spill Trustee Council, Anchorage, AK.

Farley, B. 2005. Fishing Yesterday's Gulf Coast. Texas A&M University Press, College Station, TX.

Farrow, S. 1996. Marine protected areas: emerging economics. Marine Policy 20:439-446.

Fayanju, S. 2010, September 17. Roads, railways, runways...and restoration: the case for a swamp stimulus. Environmental Defense Fund. Retrieved from http://blogs.edf.org/restorationandresilience/.

Fischhoff, B. 2007. Nonpersuasive communication about matters of greatest urgency: climate change. Environmental Science & Technology 41:7204-7208.

Fisher, C. 2010, November 3. The Final Dive. November 3 Log. NOAA. Retrieved from http://oceanexplorer.noaa.gov/explorations/10lophelia/logs/nov3/nov3.html.

Fitzhugh, T. W., and B. D. Richter. 2004. Quenching urban thirst: growing cities and their impacts on freshwater ecosystems. BioScience 54:741-754.

Fodrie, F. J., and K. L. Heck. 2011. Response of coastal fishes to the Gulf of Mexico oil disaster. PLoS ONE.

Fonseca, M. S., W. J. Kenworthy, and G. W. Thayer. 1998. Guildlines for the conservation and restoration of seagrasses in the United States and adjacent waters. 222 pages. NOAA Coastal Ocean Office, Silver Spring, MD.

Fonseca, M., B. E. Julius, and W. J. Kenworthy. 2000. Integrating biology and economics in seagrass restoration: how much is enough and why? Ecological Engineering 15:227-237.

Fourqurean, J. W., and M. B. Robblee. 1999. Florida Bay: a history of recent ecological changes. Estuaries 22:345-357.

Francis, R. C., M. A. Hixon, M. E. Clarke, S. A. Murawski, and S. Ralston. 2007. Ten commandments for ecosystem-based fisheries scientists. Fisheries 32:217-233.

Frazier, D. E. 1967. Recent deltaic deposits of the Mississippi River, their development and chronology. Transactions of the Gulf Coast Association of Geological Societies 17:287-315.

Fulton, E., A. Smith, and A. Punt. 2005. Which ecological indicators can robustly detect effects of fishing? ICES Journal of Marine Science 62:540-551.

Gabryscrh, K., and L. S. Coplin. 1990. Land Surface Subsidence resulting from groundwater withdrawals in the Houston-Galveston Region, Texas, through 1987. 53 pages. U.S. Geological Survey, Washington, D. C.

Gaines, S.D., C. White , M.H. Carr, and S.R. Palumbi. 2010. Designing marine reserve networks for both conservation and fisheries management. Proceedings of the U.S. National Academy of Sciences. Doi:10.1073/pnas.0906473107.

Gardner, J., P. Dartnell, L. Mayer, J. Hughesclarke, B. Calder, and G. Duffy. 2005. Shelf-edge deltas and drowned barrier-island complexes on the northwest Florida outer continental shelf. Geomorphology 64:133-166.

Gerrodette, T., P. K. Dayton, S. Macinko, and M. J. Fogarty. 2002. Precautionary management of marine fisheries: moving beyond burden of proof. Bulletin of Marine Science 70:657-668.

Gilbes, F., C. Tomas, J. J. Walsh, and F. E. Müller-Karger. 1996. An episodic chlorophyll plume on the West Florida Shelf. Continental Shelf Research 16:1201-1224.

Gilbes, F., F. E. Müller-Karger, and C. E. Del Castillo. 2002. New evidence for the West Florida Shelf plume. Continental Shelf Research 22:2479-2496.

Glover, J. P., C. M. Cox, and J. P. Reaganold. 2007. Future farming: a return to roots? Scientific American 297:81-89.

Goeden, G. B. 1982. Intensive fishing and a "keystone" predator species: ingredients for community instability. Biological Conservation 22:273-281.

Grabowski, J. H., and C. H. Peterson. 2007. Restoring oyster reefs to recover ecosystem services. Pages 281-298 Ecosystem Engineers - Plants to Protists. Academic Press.

Graham, B., W. R. Reilly, F. Beinecke, D. F. Boesch, T. D. Garcia, C. A. Murray, and F. Ulmer. 2011a. Deep water: the Gulf oil disaster and the future of offshore drilling: report to the president. 398 pages. National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling, Washington, D.C.

Graham, N. A. J., P. Chabanet, R. D. Evans, S. Jennings, Y. Letourneur, A. M. MacNeil, T. R. McClanahan, M. C. Öhman, N. V. C. Polunin, and S. K. Wilson. 2011b. Extinction vulnerability of coral reef fishes. Ecology Letters 14:341-348.

Graham, W. M., R. H. Condon, R. H. Carmichael, I. D'Ambra, H. K. Patterson, L. J. Linn, and F. J. Hernandez Jr. 2010.
Oil carbon entered the coastal planktonic food web during the Deepwater Horizon oil spill. Environmental Research Letters 5:1-18.

Grimes, C. B. 2001. Fishery production and the Mississippi River discharge. Fisheries 26:17-26.

Gulf States Marine Fisheries Commission (GSMFC). 2008. Southeast Area Monitoring and Assessment Program (SEAMAP). www.gsmfc.org/default.php?p=sm_ov.htm.

Handley, L., D. Altsman, and R. DeMay (eds.). 2007. Seagrass status and trends in the northern Gulf of Mexico: 1940-2002. 267 pages. U.S. Geological Survey Scientific Investigations Report, U.S. Geological Survey, Reston VA.

Hazen, T. C., E. A. Dubinsky, T. Z. DeSantis, G. L. Andersen, Y. M. Piceno, N. Singh, J. K. Jansson, A. Probst, S. E. Borglin, J. L. Fortney, W. T. Stringfellow, M. Bill, M. E. Conrad, L. M. Tom, K. L. Chavarria, T. R. Alusi, R. Lamendella, D. C. Joyner, C. Spier, J. Baelum, M. Auer, M. L. Zemla, R. Chakraborty, E. L. Sonnenthal, P. D'haeseleer, H.-Y. N. Holman, S. Osman, Z. Lu, J. D. Van Nostrand, Y. Deng, J. Zhou, and O. U. Mason. 2010. Deep-sea oil plume enriches indigenous oil-degrading bacteria. Science 330:204 -208.

He, R., and R. H. Weisberg. 2003. A loop current intrusion case study on the west Florida shelf. Journal of Physical Oceanography 33:465-477.

Heck, K. L., T. J. B. Carruthers, C. M. Duarte, A. R. Hughes, G. Kendrick, R. J. Orth, and S. W. Williams. 2008. Trophic transfers from seagrass meadows subsidize diverse marine and terrestrial consumers. Ecosystems 11:1198-1210.

HéGaret, H., G. H. Wikfors, and S. E. Shumway. 2007. Diverse feeding responses of five species of bivalve mollusc when exposed to three species of harmful algae. Journal of Shellfish Research 26:549-559.

Houck, O. 2006. Can we save New Orleans? Tulane Environmental Law Journal 19: 68 pages.

Howes, N. C., D. M. FitzGerald, Z. J. Hughes, I. Y. Georgiou, M. A. Kulp, M. D. Miner, J. M. Smith, and J. A. Barras. 2010. Hurricane-induced failure of low salinity wetlands. Proceedings of the National Academy of Sciences 107: 14014-14019.

Huang, W., and M. Spaulding. 2002. Modelling residence-time response to freshwater input in Apalachicola Bay, Florida, USA. Hydrological Processes 16:3051-3064.

Hughes, A. R., K. J. Bando, L. F. Rodriguez, and S. L. Williams. 2004. Relative effects of grazers and nutrients on seagrasses: a meta-analysis approach. Marine Ecology Progress Series 282:87-99.

Intergovernmental Panel on Climate Change (IPCC). 2007. Climate Change 2007: Synthesis Report. Contribution of working groups I, II, and III to the fourth assessment report of the Intergovernmental Panel on Climate Change. 104 pages. Intergovernmental Panel on Climate Change, Geneva, CH.

Jackson, J. B. C. 1997. Reefs since Columbus. Coral Reefs 16:S23-S32.

Jackson, J. B. C., M. X. Kirby, W. H. Berger, K. A. Bjorndal, L. W. Botsford, B. J. Bourque, R. H. Bradbury, R. Cooke, J. Erlandson, J. A. Estes, T. P. Hughes, S. Kidwell, C. B. Lange, H. S. Lenihan, J. M. Pandolfi, C. H. Peterson, R. S. Steneck, M. J. Tegner, and R. R. Warner. 2001. Historical overfishing and the recent collapse of coastal ecosystems. Science 293:629-638.

Jackson, J. B. C. 2010. The future of the oceans past. Philosophical Transactions of the Royal Society: Biological Sciences 365:3765-3778.

Jackson, J. B. C., K. Alexander, and E. Sala (Eds.). 2011. Shifting Baselines: The Past and the Future of Ocean Fisheries. Island Press, Washington, D.C. 284 pages.

Johansson, J. O. R., and R. R. Lewis, III. 1992. Recent improvements of water quality and biological indicators in Hillsborough Bay, a highly impacted subdivision of Tampa Bay, Florida, USA. Pages 1199-1215 *in* R. A. Vollenweider, R. Marchetti, and R. Viviani, editors. Science of the Total Environment. Elsevier, New York.

Jones, J. B. 1992. Environmental impact of trawling on the seabed: a review. New Zealand Journal of Marine and Freshwater Research 26:59-67.

Jordan, N., G. Boody, W. Broussard, J. D. Glover, D. Keeney, B. H. McCown, G. McIsaac, M. Muller, H. Murray, J. Neal, C. Pansing, R. E. Turner, K. Warner, and D. Wyse. 2007. Sustainable development of the agricultural bio-economy. Science 316:1570-1571.

Joye, S. B., I. R. MacDonald, I. Leifer, and V. Asper. 2011. Magnitude and oxidation potential of hydrocarbon gases released from the BP oil well blowout. Nature Geoscience 4:160-164.

Kearney, M., C.A. Riter, and R. E. Turner. 2011. Freshwater diversions for marsh restoration in Louisiana: Twenty-six years of changing vegetative cover and marsh area. Geophysical Research Letters 38, L16405, doi:10.1029/2011GL047847.

Kennish, M. J. 2002. Environmental threats and environmental future of estuaries. Environmental Conservation 29:78-107.

Kesel, R. H. 1988. The decline in the suspended load of the lower Mississippi River and its influence on adjacent wetlands. Environmental Geology and Water Sciences 11:271-281.

Kessler, J. D., D. L. Valentine, M. C. Redmond, M. Du, E. W. Chan, S. D. Mendes, E. W. Quiroz, C. J. Villanueva, S. S. Shusta, L. M. Werra, S. A. Yvon-Lewis, and T. C. Weber. 2011. A persistent oxygen anomaly reveals the fate of spilled methane in the deep Gulf of Mexico. Science 331:312-315.

Key, N., and M. J. Roberts. 2006. Government payments and farm business survival. American Journal of Agricultural Economics 88:382-392.

Key, N., and M. J. Roberts. 2007. Cropland concentrating faster where payments are higher. Amber waves 5:30-35.

Kideys, A. E. 2002. Fall and rise of the Black Sea ecosystem. Science 297:1482-1484.

Kimbrough, K. L., W. E. Johnson, G. G. Lauenstein, J. D. Christensen and D. A. Apeti. 2008. An Assessment of Two Decades of Contaminant Monitoring in the Nation's Coastal Zone. Silver Spring, MD. NOAA Technical Memorandum NOS NCCOS 74. 105 pp.

Knowlton, N., and J. B. C. Jackson. 2008. Shifting baselines, local impacts, and global change on coral reefs. PLoS Biology 6:0215-0220.

Koenig, C. C., and F. C. Coleman. 1998. Absolute abundance and survival of juvenile gags in sea grass beds of the Northeastern Gulf of Mexico. Transactions of the American Fisheries Society 127:44-55.

Koenig, C. C., F. C. Coleman, C. B. Grimes, G. R. Fitzhugh, K. M. Scanlon, C. T. Gledhill, and M. Grace. 2000. Protection of fish spawning habitat for the conservation of warm-temperate reef-fish fisheries of shelf-edge reefs of Florida. Bulletin of Marine Science 66:593-616.

Koenig, C. C., A. N. Shepard, J. K. Reed, F. C. Coleman, S. D. Brooke, J. Brusher, and K. M. Scanlon. 2005. Habitat and fish populations in the deep-sea Oculina coral ecosystem of the Western Atlantic. Pages 795-805 *in* P. W. Barnes and J. P. Thomas, editors. Benthic Habitats and the Effects of Fishing. American Fisheries Society, Bethesda, MD.

Koenig, C. C., and F. C. Coleman. In prep. Protection of grouper and red snapper spawning in marine reserves: demographics, movements, survival and spillover effects in the eastern Gulf of Mexico.

Kujawinski, E. B., M. C. Kido Soule, D. L. Valentine, A. K. Boysen, K. Longnecker, and M. C. Redmond. 2011. Fate of dispersants associated with the Deepwater Horizon oil spill. Environmental Science & Technology 45:1298-1306.

Kuletz, K. J., D. K. Marks, N. L. Naslund, N. G. Goodson, and M. B. Cody. 1994. Information needs for habitat protection: marbled murrelet habitat identification. Restoration project 93051b. Exxon Valdez oil spill restoration project final report. 70 pages. Technical Report, Fish and Wildlife Service, Anchorage, AK.

Kurlansky, M. 2002. Salt: A World History. Walker Publishing Company, Inc., New York, New York. 498 pages.

Landsberg, J. 2002. The effects of harmful algal blooms on aquatic organisms. Reviews in Fisheries Science 10:113-390.

Laska, S., K. Peterson, M. E. Alcina, J. West, A. Volion, B. Tranchina, and R. Krajeski. 2010. Enhancing Gulf of Mexico coastal communities through participatory community engagement. NOAA Coastal Services Center, Charleston, SC.

Lee, D., S. Penland, D. Lavoie, L. Martinez. 2006. Barrier Island Comprehensive Monitoring Program (BICM) shoreline change analysis of coastal Louisiana: 1855-2005. www.ladigitalcoast.uno.edu/maps.html.

Lenihan, H. S., and C. H. Peterson. 1998. How habitat degradation through fishery disturbance enhances impacts of hypoxia on oyster reefs. Ecological Applications 8:128-140.

Lenihan, H. S. 1999. Physical-biological coupling on oyster reefs: how habitat structure influences individual performance. Ecological Monographs 69:251-275.

Lenihan, H. S., C. H. Peterson, J. E. Byers, J. H. Grabowski, G. W. Thayer, and D. R. Colby. 2001. Cascading of habitat degradation: oyster reefs invaded by refugee fishes escaping stress. Ecological Applications 11:764-782.

Lenihan, H. S., C. H. Peterson, S. L. Kim, K. E. Conlan, R. Fairey, C. McDonald, J. H. Grabowski, and J. S. Oliver. 2003. Variation in marine benthic community composition allows discrimination of multiple stressors. Marine Ecology Progress Series 261:63-73.

Leonard L., T. Clayton, and O. Pilkey. 1990. An analysis of replenished beach design parameters on U.S. east coast barrier islands. Journal of Coastal Research 6:15-36.

Leslie, H. M., and A. P. Kinzig. 2009. Resilience science. Pages 55-73 *in* K. McLeod and H. Leslie, editors. Ecosystem-based Management for the Oceans. Island Press, Washington DC.

Levin, P. S., M. J. Fogarty, S. A. Murawski, and D. Fluharty. 2009. Integrated ecosystem assessments: developing the scientific basis for ecosystem-based management of the ocean. PLoS Biology 7:23-28.

Livingston, R. J., R. L. Iverson, R. H. Estabrook, V. E. Keys, and J. Taylor, Jr. 1974. Major features of the Apalachicola Bay system: physiography, biota, and resource management. Florida Scientist 37:245-271.

Livingston, R. J. 1997. Trophic response of estuarine fishes to long-term changes of river runoff. Bulletin of Marine Science 60:984-1004.

Livingston, R. J., X. Niu, F. G. Lewis, and G. C. Woodsum. 1997. Freshwater input to a Gulf estuary: long-term control of trophic organization. Ecological Applications 7:277-299.

Livingston, R. J. 2000. Eutrophication Processes in Coastal Systems: Origin and Succession of Plankton Blooms and Effects on Secondary Production, 1st edition. CRC Press, Boca Raton, FL. 327 pages.

Livingston, R. J. 2001. Bloom successions in coastal systems. Honolulu, HI.

Livingston, R. J. 2007. Phytoplankton bloom effects on a gulf estuary: water quality changes and biological response. Ecological Applications 17:S110-S128.

Lotze, H. K., H. S. Lenihan, B. J. Bourque, R. H. Bradbury, R. G. Cooke, M. C. Kay, S. M. Kidwell, M. X. Kirby, C. H. Peterson, and J. B. C. Jackson. 2006. Depletion, degradation, and recovery potential of estuaries and coastal seas. Science 312:1806-1809.

Mabus, R. 2010. America's Gulf coast: a long term recovery plan after the Deepwater Horizon oil spill. 130 pages.

MacKenzie, C.L. Jr. 1996. History of oystering in the United States and Canada, featuring the eight greatest oyster estuaries. Marine Fisheries Review 58: 1-78.

McClanahan, T. R., N. A. Muthiga, A. T. Kamukuru, H. Machano, and R. W. Kiambo. 1999. The effects of marine parks and fishing on coral reefs of northern Tanzania. Biological Conservation 89:161-182.

Mississippi Comprehensive Wildlife Management Plan (MCWMP). 2007. Mississippi Comprehensive Wildlife Management Plan: Chapter 4. Habitat type. Section 14. Estuary and Mississippi Sound (inside or associated with barrier islands). 22 pages.

Millennium Ecosystem Assessment (MEA). 2005. Ecosystems and Human Well-Being: Wetlands and Water. World Resources Institute, Washington, D.C.

Miller, J. E., and E. R. Jones. 2003. A study of shoreline trash: 1989-1998 Padre Island National Seashore. National Park Service, U.S. Department of the Interior.

Milly, P. C. D., J. Betancourt, M. Falkenmark, R. M. Hirsch, Z. W. Kundzewicz, D. P. Lettenmaier, and R. J. Stouffer. 2008. Climate change: stationarity is dead: whither water management? Science 319:573-574.

Minello, T. J., and L. P. Rozas. 2002. Nekton in Gulf coast wetlands: fine-scale distributions, landscape patterns, and restoration implications. Ecological Applications 12:441-455.

Mississippi River/Gulf of Mexico Watershed Nutrient Task Force. 2001. Action plan for reducing, mitigating, and controlling hypoxia in the northern Gulf of Mexico. 36 pages. U.S. Environmental Protection Agency, Office of Wetlands, Oceans and Watersheds, Washington, D.C.

Moore, J. E., B. P. Wallace, R. L. Lewison, R. Žydelis, T. M. Cox, and L. B. Crowder. 2009. A review of marine mammal, sea turtle and seabird bycatch in USA fisheries and the role of policy in shaping management. Marine Policy 33:435-451.

Morey, S. L., P. J. Martin, J. J. O'Brien, A. A. Wallcraft, and J. Zavala-Hidalgo. 2003a. Export pathways for river discharged fresh water in the northern Gulf of Mexico. Journal of Geophysical Research 108:Article 3303.

Morey, S. L., W. W. Schroeder, J. J. O'Brien, and J. Zavala-Hidalgo. 2003b. The annual cycle of riverine influence in the eastern Gulf of Mexico basin. Geophysical Research Letters 30:Article 1867.

Morey, S. L., D. S. Dukhovskoy, and M. A. Bourassa. 2009. Connectivity between variability of the Apalachicola River flow and the biophysical oceanic properties of the northern West Florida Shelf. Continental Shelf Research 29:1264-1275.

Morris, J. T. 1991. Effects of nitrogen loading on wetland ecosystems with particular reference to atmospheric deposition. Annual Review of Ecology and Systematics 22:257-279.

Mortazavi, B., R. L. Iverson, W. M. Landing, and W. Huang. 2000a. Phosphorus budget of Apalachicola Bay: a river-dominated estuary in the northeastern Gulf of Mexico. Marine Ecology Progress Series 198:33-42.

Mortazavi, B., R. L. Iverson, W. M. Landing, F. G. Lewis, and W. Huang. 2000b. Control of phytoplankton production and biomass in a river-dominated estuary: Apalachicola Bay, Florida, USA. Marine Ecology Progress Series 198:19-31.

Mortazavi, B., R. L. Iverson, and W. Huang. 2001. Dissolved organic nitrogen and nitrate in Apalachicola Bay, Florida: spatial distributions and monthly budgets. Marine Ecology Progress Series 214:79-91.

Morton, R. A. 2008. Historical changes in the Mississippi-Alabama barrier-island chain and the roles of extreme storms, sea level, and human activities. Journal of Coastal Research 246:1587-1600.

Moshiri, G. A., N. G. Aumen, and W. G. Crumpton. 1981. Reversal of the eutrophication process: a case study. Pages 373-390 *in* B. J. Neilson and L. E. Cronin, editors. Estuaries and Nutrients. Humana Press, Clifton NJ.

Murawski, S. 2007. Ten myths concerning ecosystem approaches to marine resource management. Marine Policy 31:681-690.

Myers, R. A., J. K. Baum, T. D. Shepherd, S. P. Powers, and C. H. Peterson. 2007. Cascading effects of the loss of apex predatory sharks from a coastal ocean. Science 315:1846-1850.

Nassauer, J. I., M. V. Santelmann, and D. Scavia. 2007. From the Corn Belt to the Gulf: Societal and Environmental Implications of Alternative Agricultural Futures. Resources for the Future, Washington. 237 pages.

National Marine Fisheries Service (NMFS). 2010. Fisheries Economics of the United States, 2009. U.S. Dept. Commerce, NOAA Tech. Memo. NMFS-F/SPO-118.

National Oceanic and Atmospheric Administration (NOAA). 1995. Habitat equivalency analysis: an overview. Damage Assessment and Restoration Program, National Oceanographic and Atmospheric Administration, Silver Spring, MD.

National Oceanic and Atmospheric Administration (NOAA). 2009. NOAA National Sea Grant College Program: strategic plan 2009-2013. 28 pages.

National Research Council (NRC). 1995. Clean Ships, Clean Ports, Clean Oceans: Controlling Garbage and Plastic Wastes at Sea. The National Academies Press, Washington, D.C. 384 pages.

National Research Council (NRC). 2001a. Compensating For Wetland Losses Under the Clean Water Act. National Academies Press, Washington, D.C. 421 pages.

National Research Council (NRC). 2001b. Marine protected areas: tools for sustaining ocean ecosystems. National Academies Press, Washington, DC.

National Research Council (NRC). 2002. Effects of Trawling and Dredging on Seafloor Habitat. National Academies Press, Washington, D.C. 227 pages.

National Research Council (NRC). 2003. Oil in the Sea III: Inputs, Fates, and Effects. National Academies Press, Washington, D.C. 280 pages.

National Research Council (NRC). 2004. Improving the Use of the "Best Scientific Information Available" Standard in Fisheries Management. National Academies Press, Washington, D.C. 118 pages.

National Research Council (NRC). 2008. Tackling Marine Debris in the 21st Century. The National Academies Press, Washington, D.C. 218 pages.

Neal, J. T. 1997. Mine-induced sinkholes over the US strategic petroleum reserve (SPR) storage facility at Weeks Island, Louisiana: Geologic mitigation and environmental monitoring. 5 pages.

Neal, J. T., S. J. Bauer, and B. L. Ehgartner. 1998. Mine-induced sinkholes over the US Strategic Petroleum Reserve (SPR) storage facility at Weeks Island, Louisiana: geological causes and effects. 15 pages.

Nelson, J. R., R. Wilson, F. C. Coleman, and C. C. Koenig. In press. Flux by fin: fish mediated carbon and nutrient flux in the northeast Gulf of Mexico. Ecological Applications.

Nicholson, W. R. 1978. Movements and population structure of Atlantic menhaden indicated by tag returns. Estuaries 1:141-150.

Nixon, S. W., and B. A. Buckley. 2002. "A strikingly rich zone"—nutrient enrichment and secondary production in coastal marine ecosystems. Estuaries 25:782-796.

Norse, E. A., and J. Amos. 2010. Impacts, perception, and policy implications of the Deepwater Horizon oil and gas disaster. Environmental Law Reporter 40:11058-11073.

O'Connell, M. T., T. D. Shepherd, A. M. U. O'Connell, and R. A. Myers. 2007. Long-term declines in two apex predators, bull sharks (Carcharhinus leucas) and alligator gar (Atractosteus spatula), in Lake Pontchartrain, an oilgohaline estuary in southeastern Louisiana. Estuaries and Coasts 30:567-574.

Ocean Conservancy. 2010. Trash travels: from our hands to the sea, around the globe, and through time. Ocean Conservancy, Washington, DC. 60 pages.

Okey, T., G. A. Vargo, S. Mackinson, M. Vasconcellos, B. Mahmoudi, and C. A. Meyer. 2004. Simulating community effects of sea floor shading by plankton blooms over the West Florida Shelf. Ecological Modelling 172:339-359.

Orth, R. J., and J. van Montfrans. 1990. Utilization of marsh and seagrass habitats by early stages of Callinectes sapidus: a latitudinal perspective. Bulletin of Marine Science 46:126-144.

Paerl, H. W., J. L. Pinckney, J. M. Fear, and B. L. Peierls. 1998. Ecosystem responses to internal and watershed organic matter loading: consequences for hypoxia in the eutrophying Neuse River Estuary, North Carolina, USA. Marine Ecology Progress Series 166:17-25.

Paerl, H. W., L. M. Valdes, B. L. Peierls, J. E. Adolf, and L. W. Harding. 2006. Anthropogenic and climatic influences on the eutrophication of large estuarine ecosystems. Limnology and Oceanography 51:448-462. Palmer, M. A., R. F. Ambrose, and N. L. Poff. 1997. Ecological theory and community restoration ecology. Restoration Ecology 5: 291-300.

Palmer, M.A., R.F. Ambrose, and N.L. Poff. 1997. Ecological theory and community restoration ecology. Restoration Ecology 5:291-300.

Pandolfi, J. M., J. B. C. Jackson, N. Baron, R. H. Bradbury, H. M. Guzman, T. P. Huges, C. V. Kappel, F. Micheli, J. C. Ogden, H. P. Possingham, and E. Sala. 2005. Are U.S. coral reefs on the slippery slope to slime? Science 307: 1725-1726.

Parmesan, C., and G. Yohe. 2003. A globally coherent fingerprint of climate change impacts across natural systems. Nature 421:37-42.

Pauly, D., V. Christensen, J. Dalsgaard, R. Froese, and F. Torres Jr. 1998. Fishing down marine food webs. Science 279:860-863.

Pequegnat, W. E., B. J. Gallaway, and L. H. Pequegnat. 1990. Aspects of the ecology of the deep-water fauna of the Gulf of Mexico. American Zoologist 30:45-64.

Peterson, C. H., and R. N. Lipcius. 2003. Conceptual progress towards predicting quantitative ecosystem benefits of ecological restorations. Marine Ecology Progress Series 264:297-307.

Peterson, C. H., J. H. Grabowski, and S. P. Powers. 2003a. Estimated enhancement of fish production resulting from restoring oyster reef habitat: quantitative valuation. Marine Ecology Progress Series 264:249-264.

Peterson, C. H., S. D. Rice, J. W. Short, D. Esler, J. L. Bodkin, B. E. Ballachey, and D. B. Irons. 2003b. Long-term ecosystem response to the Exxon Valdez oil spill. Science 302:2082-2086.

Peterson, C. H., and M. J. Bishop. 2005. Assessing the environmental impacts of beach nourishment. BioScience 55:887-896.

Peterson, C. H., M. J. Bishop, G. A. Johnson, L. M. D'anna, and L. M. Manning. 2006. Exploiting beach filling as an unaffordable experiment: benthic intertidal impacts propagating upwards to shorebirds. Journal of Experimental Marine Biology and Ecology 338:205-221.

Peterson, C. H., R. T. Barber, H. K. Cottingham, H. K. Lotze, C. A. Simenstad, R. R. Christian, M. F. Piehler, and J. Wilson. 2008. In preliminary review of adaptation options for climate-sensitive ecosystems and resources. Pages 7-1--7-108 *in* S. H. Julius and J. M. West, editors. National Estuaries. Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research, U.S. Environmental Protection Agency, Washington, D.C.

Peterson, C. H., S. S. Anderson, G. N. Cherr, R. F. Ambrose, S. Anghera, S. Bay, M. Blum, R. Condon, T. A. Dean, M. Graham, M. Guzy, S. E. Hampton, S. Joye, J. Lambrinos, B. Mate, D. Meffert, S. P. Powers, P. Somasundaran, R. B. Spies, C. M. Taylor, R. Tjeerdema, and E. E. Adams. In press. A tale of two spills: novel science and policy implications of an emerging new oil spill paradigm. BioScience.

Peterson, G. W., and R. E. Turner. 1994. The value of salt marsh edge vs interior as a habitat for fish and decapod crustaceans in a Louisiana tidal marsh. Estuaries 17:235-262.

Peterson, G., C. R. Allen, and C. S. Holling. 1998. Ecological resilience, biodiversity, and scale. Ecosystems 1:6-18.

Pikitch, E. K., C. Santora, E. A. Babcock, A. Bakun, R. Bonfil, D. O. Conover, P. Dayton, P. Doukakis, D. Fluharty, B. Heneman, E. D. Houde, J. Link, P. A. Livingston, M. Mangel, M. K. McAllister, J. Pope, and K. J. Sainsbury. 2004. Ecosystem-based fishery management. Science 305:346-347.

Pomeroy, L. R. 1974. The ocean's food web, a changing paradigm. BioScience 24:499-504.

Pomeroy, L. R. 1979. Secondary production mechanisms of continental shelf communities. Pages 163-186 *in* R. J. Livingston, editor. Ecological Processes in Coastal and Marine Systems. Plenum Publishing Corporation, New York.

Powell, S. M., R. L. Haedrich, and J. D. McEachran. 2003. The deep-sea demersal fish fauna of the northern Gulf of Mexico. Journal of Northwest Atlantic Fishery Science 31:19-33.

Pringle, C. M. 2001. Hydrologic connectivity and the management of biological reserves: a global perspective. Ecological Applications 11:981-998.

Pritchard, E. S. (Ed.). 2005. Fisheries of the United States 2004. NOAA's National Marine Fisheries Service, Office of Science and Technology, Fisheries Statistics Division, Silver Spring, MD. 109 pages.

Prouty, N., E. Roark, N. Buster, and S. Ross. 2011. Growth rate and age distribution of deep-sea black corals in the Gulf of Mexico. Marine Ecology Progress Series 423:101-115.

Putland, J. N., and R. L. Iverson. 2007a. Ecology of Acartia tonsa in Apalachicola Bay, Florida, and implications of river water diversion. Marine Ecology Progress Series 340:173-187.

Putland, J. N., and R. L. Iverson. 2007b. Microzooplankton: major herbivores in an estuarine planktonic food web. Marine Ecology Progress Series 345:63-73.

Rabalais, N. N. 2002. Nitrogen in aquatic ecosystems. AMBIO 31:102-112.

Rabalais, N. N., R. E. Turner, and D. Scavia. 2002. Beyond science into policy: Gulf of Mexico hypoxia and the Mississippi River. BioScience 52:129-142.

Rabalais, N. N., R. E. Turner, B. K. Sen Gupta, D. F. Boesch, P. Chapman, and M. C. Murrell. 2007. Hypoxia in the northern Gulf of Mexico: does the science support the plan to reduce, mitigate, and control hypoxia? Estuaries and Coasts 30:753-772.

Rabalais N.N., R.E. Turner, Louisiana Universities Marine Consortium, and Louisiana State University. 2010. Area of Mid-Summer Bottom Water Hypoxia. www.gulfhypoxia.net/research/Shelfwide%20Cruises/.

Rahmstorf, S., A. Cazenave, J. A. Church, J. E. Hansen, R. F. Keeling, D. E. Parker, and R. C. J. Somerville. 2007. Recent climate observations compared to projections. Science 316:709.

Rakocinski, C.F., Heard, R.W., LeCroy, S.E., McLelleand, J.A., and Simons, T. 1996. Responses by macrobenthic assemblages to extensive beach restoration at Perdido Key, Florida, USA. Journal of Coastal Research 16:368-378.

Reed, D. J. 2000. Coastal biogeomorphology: an integrated approach to understanding the evolution, morphology, and sustainability of temperate coastal marshes. Pages 347-361 *in* J. E. Hobbie, editor. Estuarine science: A Synthetic Approach to Research and Practice. Island Press, Washington, D.C.

Reed, D. J. 2002. Sea-level rise and coastal marsh sustainability: geological and ecological factors in the Mississippi delta plain. Geomorphology 48:233-243.

Rex, M., and R. Etter. 2010. Deep-sea biodiversity: pattern and scale. Harvard University Press, Cambridge, MA. 354 pages.

Rice, J., and M. Rochet. 2005. A framework for selecting a suite of indicators for fisheries management. ICES Journal of Marine Science 62:516-527.

Rice, S. D., R. B. Spies, D. A. Wolfe, and B. A. Wright. 1996. Proceedings of the "Exxon Valdez" oil spill symposium, American Fisheries Society symposium 18. Bethesda, MD.

Richter, B. D., R. Mathews, D. L. Harrison, and R. Wigington. 2003. Ecologically sustainable water management: managing river flows for ecological integrity. Ecological Applications 13:206-224.

Roberts, H. H. 2010. Gulf of Mexico cold seeps. Deep Sea Research Part II 57:1835-2060.

Roberts, M. J., and N. Key. 2008. Agricultural payments and land concentration: a semiparametric spatial regression analysis. American Journal of Agricultural Economics 90:627-643.

Rosa, E. A., and L. Clark. In press. A collective hunch? Risk as the real and the elusive. Journal of Environmental Studies and Sciences.

Rosenau, J. C., G. L. Faulkner, C. W. J. Hendry, and R. W. Hull. 1977. Springs of Florida. Florida Bureau of Geology Bulletin 31:438-453.

Rosenberg, A. A., and P. A. Sandifer. 2009. What do managers need? Pages 13-30 *in* K. McLeod and H. Leslie, editors. Ecosystem-based Management for the Oceans. Island Press, Washington DC.

Roux, D. J., P. J. Ashton, J. L. Nel, and H. M. MacKay. 2008. Improving cross-sector policy integration and cooperation in support of freshwater conservation. Conservation Biology 22:1382-1387.

Rowe, G. T. 1971. Benthic biomass and surface productivity. Pages 441-454 *in* J. Costlow, editor. Fertility of the Sea. Gordon and Breach, New York.

Rowe, G. T. 1983. Biomass and production of the deep-sea benthos. Pages 97-121 *in* G. Rowe, editor. The Sea, Vol. 8, Deep-Sea Biology. Wiley-Interscience, New York.

Rowe, G. T., and M. C. Kennicutt. 2008. Introduction to the Deep Gulf of Mexico Benthos Program. Deep Sea Research Part II: Topical Studies in Oceanography 55:2536-2540.

Ruhl, H. A., and K. L. Smith Jr. 2004. Shifts in deep-sea community structure linked to climate and food supply. Science 305:513-515.

Scavia, D., J. C. Field, D. F. Boesch, R. W. Buddemeier, V. Burkett, D. R. Cayan, M. Fogarty, M. A. Harwell, R. W. Howarth, C. Mason, D. J. Reed, T. C. Royer, A. H. Sallenger, and J. G. Titus. 2002. Climate change impacts on U. S. coastal and marine ecosystems. Estuaries 25:149-164.

Scheffer, M., S. Carpenter, J. A. Foley, C. Folke, and B. Walker. 2001. Catastrophic shifts in ecosystems. Nature 413:591-596.

Schulte, D. M., R. P. Burke, and R. N. Lipcius. 2009. Unprecedented restoration of a native oyster metapopulation. Science 325:1124-1128.

Scott, T. M., G. H. Means, R. P. Meegan, R. C. Means, S. B. Upchurch, R. E. Copeland, J. Jones, T. Roberts, and A. Willet. 2004. Springs of Florida. Florida Geological Survey, Tallahassee, FL. 5 pages.

Sklar, F. H., and J. A. Browder. 1998. Coastal environmental impacts brought about by alterations to freshwater flow in the Gulf of Mexico. Environmental Management 22:547-562.

Smith, J. W. 1991. The Atlantic and Gulf menhaden fisheries: origins, harvesting technologies, biostatistical monitoring, recent trends in fisheries statistics, and forecasting. Marine Fisheries Review 53:28-39.

Soliman, Y., and G. Rowe. 2008. Secondary production of Ampelisca mississippiana Soliman and Wicksten 2007 (Amphipoda, Crustacea) in the head of the Mississippi Canyon, northern Gulf of Mexico. Deep Sea Research Part II: Topical Studies in Oceanography 55:2692-2698.

Soltwedel, T., E. Bauerfeind, M. Bergmann, N. Budaeva, E. Hoste, N. Jaeckisch, K. Von Juterzenka, J. Matthiessen, V. Mokievsky, E. Nothig, N. Queric, B. Sablotny, E. Sauter, I. Schewe, B. Urban-Malinga, J. Wegner, M. Wlodarska-Kowalczuk, and M. Klages. 2005. Hausgarten: multidisciplinary investigations at a deep-sea, long-term observatory in the Arctic Ocean. Oceanography 18:46-61.

Sommer, T., C. Armor, R. Baxter, R. Breuer, L. Brown, M. Chotkowski, S. Culberson, F. Feyrer, M. Gingras, B. Herbold, W. Kimmerer, A. Mueller-Solger, M. Nobriga, and K. Souza. 2007. The collapse of pelagic fishes in the upper San Francisco Estuary. Fisheries 32:270-277.

St. Mary, C. M., C. W. Osenberg, T. K. Frazer, and W. J. Lindberg. 2000. Stage structure, density dependence and the efficacy of marine reserves. Bulletin of Marine Science 66:675-690.

Stedman, S., and T. E. Dahl. 2008. Status and trends of wetlands in the coastal watersheds of the Eastern United States 1998-2004. National Oceanic and Atmospheric Administration, National Marine Fisheries Service and U.S. Department of the Interior, Fish and Wildlife Service.

Sullivan, P., D. Hellerstein, L. Hansen, R. Johansson, S. Koenig, R. Lubowski, W. McBride, D. McGranahan, M. Roberts, S. Vogel, and S. Bucholtz. 2004. The conservation reserve program: economic implications for rural America. Pages 1-112. U.S. Department of Agriculture-Econominc Research Service.

Swenson, E. M., and R. E. Turner. 1987. Spoil banks: effects on a coastal marsh water-level regime. Estuarine, Coastal and Shelf Science 24:599-609.

Taniguchi, M., W. C. Burnett, J. E. Cable, and J. V. Turner. 2002. Investigation of submarine groundwater discharge. Hydrological Processes 16:2115-2129.

Teal, J. M., and R. W. Howarth. 1984. Oil spill studies: a review of ecological effects. Environmental Management 8:27-43.

Teal, J. M., and L. Weishar. 2005. Ecological engineering, adaptive management, and restoration management in Delaware Bay salt marsh restoration. Ecological Engineering 25:304-314.

Teal, J. M., and S. B. Peterson. 2009. The use of science in the restoration of northeastern U.S. salt marshes. Pages 267-283 *in* B. R. Siliman, E. D. Grosholz, and M. D. Bertness, editors. Human Impacts on Salt Marshes. University of California Press.

Thomsen, M., and K. Mcglathery. 2006. Effects of accumulations of sediments and drift algae on recruitment of sessile organisms associated with oyster reefs. Journal of Experimental Marine Biology and Ecology 328:22-34.

Titus, J. G., and C. Richman. 2001. Maps of lands vulnerable to sea level rise: modeled elevations along the US Atlantic and Gulf coasts. Climate Research 18:205-228.

Toner, M. 2003. Chlorophyll dispersal by eddy-eddy interactions in the Gulf of Mexico. Journal of Geophysical Research 108:1-12.

Tribbia, J., and S. C. Moser. 2008. More than information: what coastal managers need to plan for climate change. Environmental Science & Policy 11:315-328.

Turner, R. E. 1997. Wetland loss in the northern Gulf of Mexico: multiple working hypotheses. Estuaries 20:1-13.

Turner, R. E. 2001. Of manatees, mangroves, and the Mississippi River: is there an estuarine signature for the Gulf of Mexico? Estuaries 24:139-150.

Turner, R. E., and N. N. Rabalais. 2003. Linking landscape and water quality in the Mississippi River basin for 200 years. BioScience 53:563-572.

Turner, R. E. 2004. Coastal wetland subsidence arising from local hydrologic manipulations. Estuaries 27:265-272.

Turner, R. E., N. N. Rabalais, R. B. Alexan, G. McIsaac, and R. W. Howarth. 2007a. Characterization of nutrient , organic carbon, and sediment loads and concentrations from the Mississippi River into the Northern Gulf of Mexico. Estuaries and Coasts 30:773-790.

Turner, R.E., E.M. Swenson, C.S. Milan and J.M. Lee. 2007b. Hurricane signals in salt marsh sediments: inorganic sources and soil volume. Limnology and Oceanography 52: 1231-1238.

Turner, R. E., N. N. Rabalais, and D. Justic. 2008. Gulf of Mexico hypoxia: alternate states and a legacy. Environmental Science & Technology 42:2323-2327.

Turner, R. E. 2009. Doubt and the values of an ignorance-based world view for restoration: coastal Louisiana wetlands. Estuaries and Coasts 32:1054-1068.

Turner, R. E., B. L. Howes, J. M. Teal, C. S. Milan, E. M. Swenson, and D. D. Goehringer-Toner. 2009. Salt marshes and eutrophication: an unsustainable outcome. Limnology and Oceanography 54:1634-1642.

Turner, R. E. 2010. Beneath the salt marsh canopy: loss of soil strength with increasing nutrient loads. Estuaries and Coasts 33:1-10.

Ueland, J. S. 2005. Ecological modeling and human dimensions of mangrove change in Florida. Dissertation, Florida State University, Tallahassee, Fl.

United Nations Environment Programme (UNEP). 2009. Marine litter: a global challenge. 232 pages. United Nations Environment Programme, Nairobi.

United Nations Food and Agricultural Organization (UN FAO). 2005. Country profile: United States of America.

U.S. Department of Interior (USDOI) and U.S. Geological Survey (USGS). 2008. Nutrient contributions to the Gulf, by state. National Water-Quality Assessment Program. water.usgs.gov/nawqa/sparrow/gulf_findings/by_state.html.

U. S. Environmental Protection Agency (USEPA). 2006. Wadeable streams assessment: a collaborative survey of the nation's streams. U.S. Environmental Protection Agency, Office of Water and Office of Research and Development, Washington, D.C. 113 pages.

U.S. Environmental Protection Agency (USEPA). 2008. National Coastal Condition Report III, chapter 5 part 3: Gulf Coast coastal condition. Pages 144-162. U.S. Environmental Protection Agency, Washington, D.C.

U.S. Environmental Protection Agency (USEPA). 2010. National lakes assessment: a collaborative survey of the nation's lakes. U.S. Environmental Protection Agency, Office of Water and Office of Research and Development, Washington, D.C. 118 pages.

U.S. Environmental Protection Agency Science Advisory Board (USEPA Science Advisory Board). 2007. Hypoxia in the northern Gulf of Mexico: an update. 34 pages. United States Environmental Protection Agency, Washington, D.C.

Valiela, I., and M. L. Cole. 2002. Comparative evidence that salt marshes and mangroves may protect seagrass meadows from land-derived nitrogen loads. Ecosystems 5:92-102.

Vardaro, M., K. L. Smith Jr., G. Rowe, I. Priede, P. Bagley, B. Bett, H. Ruhl, D. Bailey, B. Bazika, Sangolay, A. Walls, and J. Clarke. In press. Deep-ocean environmental long-term observatory system at bathyal depths in the southeast Atlantic off the coast of Angola: preliminary studies.

Vazquez, F. G., V. K. Sharma, and L. Perez-Cruz. 2002. Concentrations of elements and metals in sediments of the southeastern Gulf of Mexico. Environmental Geology 42:41-46.

Vedlitz, A., L. T. Alston, S. B. Laska, R. B. Gramling, M. A. Harwell, and H. D. Worthen. 2007. Project final report: use of science in Gulf of Mexico decision making involving climate change. Project funded by the U.S. Environmental Protection Agency under cooperative agreement No. R-83023601-0. 276 pages.

Vermeer, M., and S. Rahmstorf. 2009. Global sea level linked to global temperature. Proceedings of the National Academy of Sciences 106:21527-21532.

Vetter, E. W., and P. K. Dayton. 1998. Macrofaunal communities within and adjacent to a detritus-rich submarine canyon system. Deep Sea Research Part II: Topical Studies in Oceanography 45:25-54.

Walker, R. T., W. D. Solecki, and C. Harwell. 1997. Land use dynamics and ecological transition: the case of south Florida. Urban Ecosystems 1:37-47.

Walsh, J. J., R. H. Weisberg, J. M. Lenes, F. R. Chen, D. A. Dieterle, L. Zheng, K. L. Carder, G. A. Vargo, J. A. Havens, and E. Peebles. 2009. Isotopic evidence for dead fish maintenance of Florida red tides, with implications for coastal fisheries over both source regions of the west Florida shelf and within downstream waters of the south Atlantic bight. Progress In Oceanography 80:51-73.

Wang, P., T. M. Beck, and T. M. Roberts. 2011. Modeling regional-scale sediment transport and medium-term morphology change at a dual-inlet system examined with the Coastal Modeling System (CMS): a case study at Johns Pass and Blind Pass, west-central Florida. Journal of Coastal Research 59:49-60.

Ward, T. J., D. Heinemann, and N. Evans. 2001. The role of marine reserves as fisheries management tools: a review of concepts, evidence and international experience. 192 pages. Bureau of Rural Sciences, Canberra, Australia.

Watling, L., and E. A. Norse. 1998. Disturbance of the seabed by mobile fishing gear: a comparison to forest clearcutting. Conservation Biology 12:1180-1197.

Waycott, M., C. M. Duarte, T. J. B. Carruthers, R. J. Orth, W. C. Dennison, S. Olyarnik, A. Calladine, J. W. Fourqurean, K. L. Heck, A. R. Hughes, G. A. Kendrick, W. J. Kenworthy, F. T. Short, and S. L. Williams. 2009. Accelerating loss of seagrasses across the globe threatens coastal ecosystems. Proceedings of the National Academy of Sciences 106: 12377-12381.

Wei, C.-L., G. T. Rowe, G. F. Hubbard, A. H. Scheltema, G. D. F. Wilson, I. Petrescu, J. Foster, M. K. Wicksten, M. Chen, R. Davenport, Y. Soliman, and Y. Wang. 2010. Bethymetric zonation for deep-sea macrofauna in relation to export of surface phytoplankton production. Marine Ecology Progress Series 399:1-14.

Wei, C.-L., G. T. Rowe, R. L. Haedrich, and G. S. Boland. In prep. a. Long-term observations of epibenthic fish zonation in the deep northern Gulf of Mexico.

Wei, C.-L., G. T. Rowe, E. E. Briones, C. Nunnally, and Y. Soliman. In prep. b. Standing stocks and body size of deep-sea macrofauna: what is the baseline prior to the 2010 BP oil spill in the Northern Gulf of Mexico?

Weishar, L., J. Teal, and R. Hinkle. 2005. Designing large-scale wetland restoration for Delaware Bay. Ecological Engineering 25:231-239.

Wells, R. J. D., J. H. Cowan, and W. F. Patterson. 2008. Habitat use and the effect of shrimp trawling on fish and invertebrate communities over the northern Gulf of Mexico continental shelf. International Council for the Exploration of the Sea Journal of Marine Science 65:1610-1619.

White, W. A., and T. A. Tremblay. 1995. Submergence of wetlands as a result of human-induced subsidence and faulting along the upper Texas Gulf Coast. Journal of Coastal Research 11:788-807.

Wiener, J. G., and M. B. Sandheinrich. 2010. Contaminants in the upper Mississippi River: historic trends, responses to regulatory controls, and emerging concerns. Hydrobiologia 640:49-70.

Zavala-Hidalgo, J., A. Gallegos-García, B. Martínez-López, S. L. Morey, and J. J. O'Brien. 2006. Seasonal upwelling on the western and southern shelves of the Gulf of Mexico. Ocean Dynamics 56:333-338.

Zedler, J. B. 2004. Compensating for wetland losses in the United States. Ibis 146:92-100.

Design by Imaginary Office www.imaginaryoffice.com

A barrier island in Louisiana's Barataria Bay is surrounded by boom after the April 2010 Deepwater Horizon oil spill. Photo: Tyrone Turner/ National Geographic Stock

THE PEW ENVIRONMENT GROUP

Philadelphia, PA 19103
215-575-9050
Washington, DC 20004
202-552-2000

www.PewEnvironment.org