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chapter nine

Restoring deepwater coral ecosystems and fisheries after the Deepwater Horizon oil spill

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Contents

Introduction

The Deepwater Horizon oil spill (DWHOS) in 2010 was the largest marine oil spill in U.S. history, unprecedented in its extent and complexity of pollutants and potential impacts. The spill immediately affected deep (>50 m depth) coral ecosystems and, 3 years after the spill, is still threatening both shallow and deep coral communities. Monetary penalties for ecosystem restoration via settlements and litigation may exceed $20 billion and provide unprecedented regional opportunities to support ecosystem-based management (EBM) of Gulf of Mexico ecosystems, including coral ecosystems and associated fisheries. In contrast to ecosystem restoration of coastal habitats and resources, restoration of offshore habitats, where there is often little or no baseline information, is more complex and operationally challenging. This chapter describes the DWHOS restoration science programs and recommends actions they may support to develop EBM for restoring and sustaining deep (>50 m depth) coral ecosystems and fisheries. Recommended restoration actions include support for Gulf of Mexico integrated ecosystem assessment (IEA) to identify coral ecosystem restoration goals, metrics (indicators), and gaps in knowledge; improvement of fisheries-independent survey tools and recreational landings data to inform reef fish stock assessments; support for coral habitat characterization and mapping; support for long-term observing and monitoring; and actions to ensure ecosystem restoration projects and programs engage stakeholders (scientists, decision makers, and citizens) and result in useful outputs.

Oil impacts on coral ecosystems and fisheries

Deep (>50 m depth) coral ecosystems in the Gulf of Mexico consist of hard bottom with beds of soft and hard coral colonies, and bioherms formed by stony corals (Figure 9.1) (Schroeder et al. 2005, Brooke and Schroeder 2007, CSAI 2007). Regional Fishery Management Councils around the United States are imposing conservation measures intended to protect deep coral ecosystems from a variety of stressors including fisheries-related perturbations, climate change, and energy exploration and development activities. In 2010, for example, the South Atlantic Fishery Management Council established five deepwater coral Habitat Areas of Particular Concern (HAPCs) totaling over 627,000 ha (NOAA 2012). Federal regulations in the Gulf of Mexico require oil and gas development activities to avoid potentially biologically sensitive areas, including coral ecosystems (MMS 2009). The Gulf of Mexico Regional Fishery Management Council has designated several shelf-edge banks that support productive coral communities as marine managed areas (Coleman et al. 2004).

The DWHOS at the Macondo well site (Figure 9.1) began on 20 April 2010 after the rig exploded, lasted 87 days, and vented an estimated 4.9 million barrels (±10%) of oil into the deep gulf (FOSC 2011). In addition, the largest amount of dispersant ever used in U.S. waters was applied and included almost 5.3 million liters of Corexit 9527 by air and vessels to the sea surface slick, and over 2.9 million liters of Corexit 9500A at the well head to break up and disperse the oil (FOSC 2011, Kujawinski et al. 2011). During sea surface oil spills, highly water-soluble hydrocarbon components are lost to the atmosphere within hours to days; however, during the DWHOS "…gas and oil experienced a significant residence time in the water column with no opportunity for the release of volatile species to the atmosphere. Hence, water-soluble petroleum compounds dissolved into the water column to a much greater extent than is typically observed for surface spills" (Reddy et al. 2012:20233).

Large parts of the Gulf of Mexico, including both state and federal waters, were closed to fishing during the DWHOS in May–October 2010 (Figure 9.1) (NMFS 2012a). Impacts of

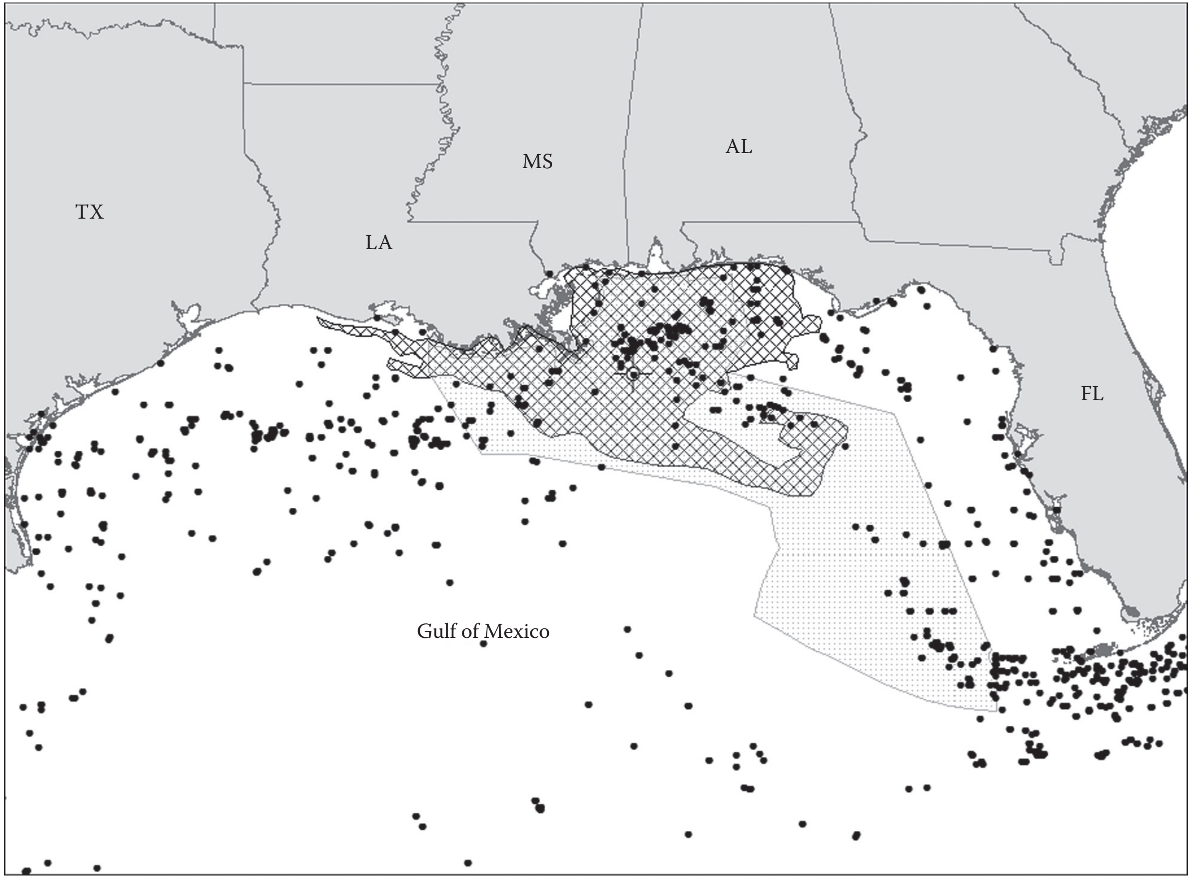

Figure 9.1 DWHOS spill extent (cross-hatched polygon; from NOAA Subsurface Monitoring Unit. 2013. BP Deepwater Horizon Oil Spill Cumulative NESDIS SAR Composite. Layer created by NESDIS Satellite Analysis Branch, 9/28/11 using ESRI ArcGIS 9.3. Available from: http://gomex.erma.noaa.gov/.), fishery closure (stippled polygon; from NMFS (National Marine Fisheries Service). 2011. ERMA Deepwater Gulf Response: Cumulative Emergency Fishery Closure. Layer created by SERO GIS Coordinator, April 2011, using ESRI ArcGIS 9.3. Available from: http://gomex.erma.noaa.gov/.), and known locations of habitat-forming soft and hard coral ecosystems at >50 m depth. (From Etnoyer, PJ. 2009. NOAA Gulf of Mexico Digital Atlas: Gulf of Mexico Deep Sea Coral Database. Layer created by P. Etnoyer, August 2009, using ESRI ArcGIS 9.3. Available from: http://gulfatlas.noaa.gov.)

the DWHOS on the recreational and commercial industries of Louisiana alone may have cost \$285–\$428 million in lost revenue by 2013, resulting in the loss of 2700–4000 jobs, and lost employee earnings of \$68–\$103 million (IEM 2010). While the Gulf Coast Claims Facility has paid out over \$700 million to the gulfwide fishing industry, the long-term consequences of the oil spill on the fishing industry have yet to be assessed (NMFS 2012a). Notwithstanding the direct damages and impacts of the spill, gulf fisheries, wildlife, and associated habitats have been under stress for decades from environmental degradation (EPA 2011), overfishing and gear impacts (NMFS 2012b), invasive species (Schofield 2010), and climate change (Osgood 2008).

Oil spills have lethal and sublethal impacts on coral ecosystems. Many factors complicate assessment of DWHOS damage to Gulf of Mexico coral ecosystems, for example, the nature of the spill (e.g., size, location, composition, and timing), differences in resilience (ecosystem, species, organismal), acute versus chronic impacts, and synergistic disturbances (NOAA 2001, Oil Spill Commission 2011). In areas with natural hydrocarbon seepage like the northern gulf shelf and slope (MacDonald et al. 1995), corals may also adapt to background levels of oil and gas exposure (Al-Dahash and Mahmoud 2012). *Lophelia pertusa* bioherms and communities co-occur with cold seep communities in the northern gulf, although they settle and grow best in areas of inactive seepage on authigenic carbonate substrate, fed by pelagic versus seep-generated production (Becker et al. 2009). Oil pollution, including chemically enhanced fractions (e.g., with dispersants), may inhibit coral growth, reduce productivity, cause tissue loss, increase coral larvae mortality, reduce larval fitness, and impede larval settlement in preferred habitats (Loya and Rinkevich 1980, NOAA 2001, Yender et al. 2010, Goodbody-Gringley et al. 2013). Few studies, however, have considered lethal and sublethal effects on deep coral ecosystems below 50 m depth. Gass and Roberts (2006) reported that deepwater oil and gas activities may cause *L. pertusa* mortality and highlighted the lack of basic biological information for this species and associated communities.

Although post-DWHOS surveys did not detect DWHOS pollutants on shallow hermatypic coral reefs off Texas or Florida (Oil Spill Commission 2011, Goodbody-Gringley 2013), the areal extent of the spill covered shelf-edge and slope coral ecosystems from Florida to Louisiana (Figure 9.1) (Paul et al. 2013). White et al. (2012) provided evidence of impacts on a deep sea coral ecosystem 11 km from the DWHOS well site, including dead and dying corals and endemic invertebrates (brittle stars). Goodbody-Gringley et al. (2013) showed increased mortality and reduced settlement success of scleractinian coral larvae in the presence of specific components of the DWHOS spill (Louisiana sweet crude and dispersant).

In addition to coral protected areas in the Florida Keys, shallow (<50 m depth) and deeper mesophotic (50–150 m) coral reefs and beds across the Gulf of Mexico are designated as essential fish habitat for managed reef fisheries (GMFMC 2010) and HAPCs with constraints on fishing activities (NOAA 2013). Gulf regional fishery management plans cover 142 coral taxa and 31 reef-associated fish species including many demersal species of grouper, snapper, and shrimp, and pelagic species such as amberjack and tuna (GMFMC 2012). Loss of coral habitat (live cover and rugosity) in the Caribbean region is linked to declines in reef fisheries (Bellwood et al. 2004, Hoegh-Guldberg et al. 2007). Deep coral ecosystems in the northern gulf do not yet experience intense fishing pressure or related protections, although some endemic species such as red and golden crabs, royal red shrimp, and barrelfish have fisheries in other regions (Brooke and Schroeder 2007).

Oil pollutants may also have direct impacts on fish species associated with coral ecosystems. Peterson et al. (2003) noted that long-term exposure of fish embryos to weathered oil (three- to five-ringed polycyclic aromatic hydrocarbons [PAHs]) at ppb concentrations has population consequences through indirect effects on growth, deformities, and behavior, with long-term consequences on mortality and reproduction. Murawski et al. (in press) correlated proximity to the DWHOS well site with increased PAHs in livers and lesions on various species of reef fish.

Ecosystem restoration after Deepwater Horizon oil spill (DWHOS)

The purpose of the Oil Pollution Act of 1990 enacted after the *Exxon Valdez* oil spill is "…to make the environment and public whole for injury to or loss of natural resources and services as a result of a discharge or substantial threat of a discharge of oil (referred to as an 'incident')" (NOAA 1996:1). This objective is achieved through restoration, rehabilitation, replacement, or acquisition of equivalent natural resources or services that were injured or lost as a result of the spill. The size and complexity of the DWHOS coupled with the lack of baseline data on marine resources in the Gulf of Mexico is complicating efforts to assess injuries and seek compensation from responsible parties. This complexity is also reflected in the variety of claims, settlements, and litigation that may result in penalties potentially distributed to hundreds of programs and thousands of projects supporting gulf ecosystem and economic recovery. Penalties for both civil and criminal charges have been levied against a variety of responsible parties to assist this recovery, with much more pending future litigations or settlements (Figure 9.2). The funded programs are all tasked with supporting ecosystem restoration to some degree (Table 9.1).

Still pending as of September 2013, Clean Water Act (CWA) civil penalties may be the largest source of funding for ecosystem restoration. The act makes it unlawful to discharge oil into navigable waters or along shorelines. Fines range from $1100 to $4300 per barrel discharged

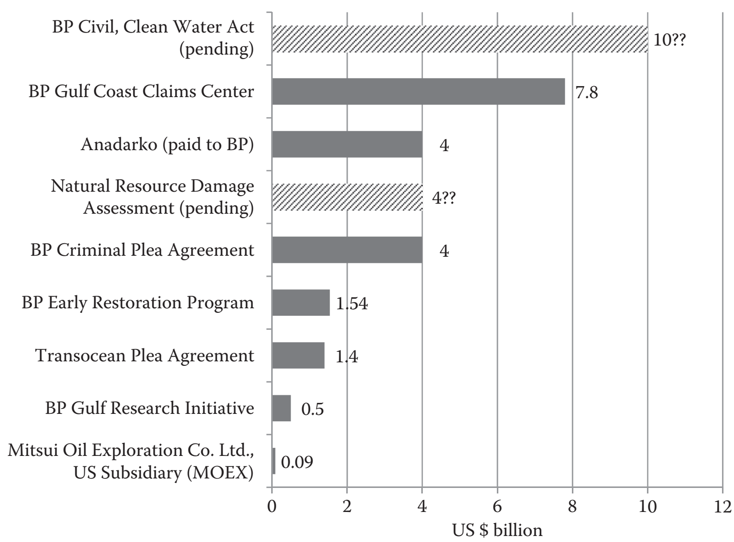

Figure 9.2 Breakdown of existing and pending ecosystem restoration funding from DWHOS civil and criminal penalties. Cross-hatched penalties are pending trials and amounts are unknown, conservative estimates as of March 2014.

Table 9.1 Ecosystem Restoration Programs Funded by DWHOS Penalties as of March 2014

Program	Ecosystem objectives	Funding (9/1/13)	Source
Gulf of Mexico Research Initiative (GOMRI)	Oil spill impacts research may support restoration applications	$500 million	BP
National Academy of Science (NAS)	Strategies and technologies for monitoring and protecting human and environmental health (gulf or other areas); oil/gas exploration safety	$500 million	BP and Transocean criminal settlements
North American Wetlands Conservation Fund (NAWCF)	Wetlands restoration and conservation projects located in gulf states or otherwise designed to benefit migratory bird species and other wildlife and habitat affected by oil spill	$100 million	BP settlement
National Fish and Wildlife Foundation (NFWF)	Natural resource restoration in AL, FL, MS, and TX; resilient coastal ecosystems and barrier island restoration/creation in LA, according to the LA Coastal Master Plan	$2.6 billion	BP and Transocean criminal settlements
Natural Resources Damage Assessment (NRDA), Early Restoration	Restoration activities aimed at returning natural resources or services to prespill baseline condition and compensating for interim losses, according to NRDA findings	$1.54 billion	BP
RESTORE Act, Section 1603, direct component	35% of $800 million from Transocean settlement; primarily for economic recovery; objectives include restoration and protection of the natural resources, ecosystems, fisheries, marine and wildlife habitats, beaches, and coastal wetlands of the Gulf Coast region; mitigation of damage to fish, wildlife, and natural resources; and implementation of a federally approved marine, coastal, or comprehensive conservation management plan, including fisheries monitoring (Department of the Treasury 2013)	$280 million	Transocean criminal settlement
RESTORE Act. Section 1603, comprehensive plan component	30% of $800 million from Transocean settlement; for projects and programs, using the best available science, that would restore and protect the natural resources, ecosystems, fisheries, marine and wildlife habitats, beaches, coastal wetlands, and economy of the Gulf Coast region (Department of the Treasury 2013)	$240 million	Transocean criminal settlement

Table 9.1 (Continued) Ecosystem Restoration Programs Funded by DWHOS Penalties as of March 2014

Program	Ecosystem objectives	Funding (9/1/13)	Source
RESTORE Act, Section 1603, spill impact component	30% of $800 million from Transocean settlement; projects, programs, and activities included in state expenditure plans must contribute to the overall economic and ecological recovery of the Gulf Coast, address the objectives in the Comprehensive Plan, and be preapproved by council (Department of the Treasury 2013)	$240 million	Transocean criminal settlement
RESTORE Act, Section 1604, NOAA ecosystem restoration science program	2.5% of $800 million from Transocean settlement for: marine and estuarine research, monitoring and ocean observing; data collection and stock assessments; pilot programs for fishery independent data and reduction of exploitation of spawning aggregations (Department of the Treasury 2013)	$20 million	Transocean criminal settlement
RESTORE Act, Section 1605, centers of excellence	2.5% of $800 million from Transocean settlement; for science and technology development in support of ecosystem restoration	$20 million	Transocean criminal settlement

(CWA 2002). The civil case against BP and other responsible parties began in February 2013 and may not end until 2015. Total penalties may reach $20 billion if the responsible parties are deemed criminally negligent and the amount of oil spilled during the 87-day event is estimated to be 4.9 million barrels (FOSC 2011). CWA penalties for oil discharge are normally deposited into the Oil Spill Liability Trust Fund and used to pay for oil pollution removal costs and natural resource damage assessments, among other activities. In the case of the DWHOS, however, the Resources and Ecosystems Sustainability, Tourist Opportunities, and Revived Economies of the Gulf Coast States Act (RESTORE Act) directs that 80% of CWA penalties are put into a Gulf Coast Restoration Trust Fund (Trust Fund) (Public Law 112-141 2012) and are divided among five "components" (Table 9.1) (Department of the Treasury 2013).

The Gulf Coast Ecosystem Restoration Council, established in Section 1603 of the RESTORE Act, released its initial comprehensive restoration plan in 2013 (GCERC 2013a) including Appendix A, a draft list of the types of projects that may be supported by the council, as obtained from council members (GCERC 2013b); <2% (i.e., eight) of 585 projects in Appendix A relate to restoring and sustaining offshore ocean habitats and resources. A single project addresses shallow coral reefs off Florida. When combined with early restoration program projects approved as of May 2013 by the NRDA Trustees (Deepwater Horizon Natural Resource Trustees 2012a,b, 2013), the types of projects proposed to date disproportionately deal with coastal restoration or lost human use and not the restoration of ocean ecosystems, despite the fact that the blowout occurred in 1200 m of water, 68 km from land, and the majority of unrecovered oil ended up in shelf and slope waters and sediments (FOSC 2011, Reddy et al. 2012).

Restoration options for shallow coral reefs resemble those for other coastal ecosystems in that direct interventions (e.g., transplants, removal of derelict fishing gear, debris cleanup) can be employed. For impacted corals in 1000–1500 m of water southwest of the DWHOS well site (White et al. 2012), direct interventions may not be practical. For deep coral ecosystems, where conventional restoration options falter, restoration may entail measures to monitor long-term recovery, protect and sustain ecosystem goods and services, and rebuild ecosystem resilience.

The natural resources damage assessment process primarily bases its restoration targets on equivalency analysis wherein the damaged habitat or resource is made whole by returning it to baseline conditions or by protecting an equivalent amount of like habitat or resource in another location (NOAA 1996). The lack of data and information from remote offshore habitats and resources may result in both inadequate assessment of damages and a lack of baseline information required for traditional restoration approaches. As indicated by the National Research Council (NRC 2012), these approaches severely limit restoration options and do "not make the public whole," as measured by the value of all the ecosystem services that flow from the affected areas. The NRC (2013) recommends an ecosystem services approach to assessment and restoration that aims to restore all the services provided by the impacted habitats and resources. For deep coral ecosystems, this vital information on their ecologic and economic importance is unknown and must be assessed both for restoration and the sustainability of related ecosystem goods and services.

Recommended deep coral ecosystem restoration actions

Recommended actions are organized into three groups of objectives intended to promote EBM for deep (>50 m depth) coral ecosystems and associated living resources, as well as other gulf ocean ecosystem goods and services (Table 9.2, Figure 9.3). Objective

Table 9.2 Recommended Objectives and Tasks to Support EBM Funded by Gulf Restoration Programs

Objectives	Actions
A: Identify priority needs and gaps in knowledge for comanagement of gulf deep coral ecosystems	1. Review EBM successes and lessons learned from other ecosystems. 2. Engage stakeholders in developing EBM operational frameworks for coral ecosystem goods and services that identify science goals, gaps in science information, management priorities, and desired outcomes.
B: Conduct research, monitoring, and technology developments required to fill gaps	1. Expand surveys and research needed, as determined by gap analyses, to support management of activities that affect coral ecosystems. 2. Develop and fund an expanded (applications, time and space scales) gulfwide observing and monitoring program. 3. Develop and apply ecosystem models to support decision makers. 4. Support and incentivize new technologies to improve fisheries efficiency and reduce the negative impacts of fishing activities on coral ecosystems. 5. Determine socioeconomic value of coral ecosystem services.
C: Support information management and synthesis	1. Integrate data, derivative products, and research results to support EBM for coral ecosystems. 2. Support synthesis of useful products for managers and communication to all stakeholders.

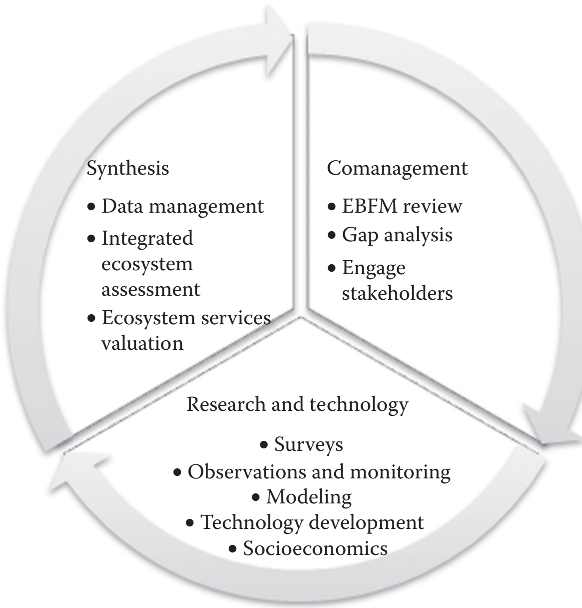

Figure 9.3 Recommended actions to enable EBM for gulf deep coral ecosystem goods and services represent a continuum including comanagement (Objective A), research and technology (Objective B), and synthesis (Objective C).

A actions provide the planning frameworks and foundational gap analyses required to prioritize Objective B actions, including data collection, research, and technology development. Objective C utilizes the resulting data and information to support analyses, syntheses, and products required by decision makers to assess risks and uncertainty, evaluate the success of a gulf regional recovery, and adapt management options and work plans (Garcia and Cochrane 2005, Granek et al. 2010). As envisaged, the gulf restoration programs will collaboratively sponsor relevant outputs for a gulfwide restoration plan (Table 9.3). Identification of restoration program sponsors is not meant to imply they will support these tasks alone, but must coordinate with and build on existing program and agency capabilities.

Objective A: Identify priority needs and gaps in knowledge for comanagement of Gulf of Mexico coral ecosystems

Action A1: Review ecosystem-based management (EBM) successes and lessons learned from other ecosystems

EBM may fail for many reasons including insufficient funding, political stalemates, lack of effective governance, and inadequate science (Granek et al. 2010). These challenges vary across the spectrum of management tools used to implement EBM (Garcia and Cochrane 2005, Curtin and Prellezo 2010). Murawski (2007) documented experiences of efforts to accomplish multistakeholder decision making to effect ecosystem objectives at regional scales, and recommended that an initial step towards EBM should be a systematic assessment ways managers communicated with and adapted to stakeholder concerns, and other collaborative methods to enhance communications and leveraging

Table 9.3 Outputs and Sponsors for Recommended Tasks

Objectives	Task	Suggested outputs	Proposed sponsor
A: Comanagement	1. Review EBM from other ecosystems	Review report of EBM successes and lessons learned to inform gulf regional coral ecosystem effort	RA1604 competitive contract/ grant
	2. Engage stakeholders to identify gaps/ priorities	EBM implementation plan for coral ecosystems developed through comanagement at appropriate temporal/spatial scales	RA1604 fund working group led by GMFMC and GSMFC to develop EBM implementation plan for corals; workshops to develop plans should be cofunded by NAS, NFWF, and RA1603
B: Data and technology	1. Expand surveys/ research	Increased fisheries-independent and -dependent sampling and survey efforts to address gaps and needs identified by Action A2 frameworks	RA1603 council and states allocations support for permanent fund to increase and stabilize support for fisheries-independent monitoring and NOAA Marine Recreational Information Program; RA1604 and NFWF programs focus on research and technologies to improve sampling, landings data, assess fishing pressure, and understand fisheries ecology
		Coral habitat maps for the entire gulf exclusive economic zone (EEZ) supported through collaboration of existing data and information management partners in the gulf	RA1603 council and state funding to expand seafloor habitat mapping coverage of gulf EEZ–survey time and information management services; any related project funded by restoration programs should contribute mapping data/metadata for archival and public access
		New research discoveries applied to EBM science needs identified in Action A2	Joint RA1604 and 1605 competitive program

Table 9.3 (Continued) Outputs and Sponsors for Recommended Tasks

Objectives	Task	Suggested outputs	Proposed sponsor
	2. Develop observing and monitoring program	Promote and fund development of GCOOS (2011) build-out plan elements that support EBM data and information needs; new technologies to enhance gulf observing system	RA1603 council and state funding to support initial investment for backbone infrastructure, determined after implementation plan is finalized, and endowment or permanent fund ($1 billion minimum) for annual operating costs; RA1604, RA1605, NAS, and NFWF utilize program data for research and develop and utilize new technologies (e.g., platforms, sensors) that enhance applications
	3. Ecosystem models	Gulfwide conceptual models; coral ecosystem models for ecological forecasting; regional ecosystem modeling working group	RA1604 for support of current NOAA efforts and proposed outputs; NFWF for development of new products and applications via open competition
	4. Support technology developments	New technologies applied in support of EBM, resulting in reduced bycatch, and less destructive, more efficient fishing gear	Joint RA1604 and 1605 competitive program
	5. Socio economic values	Improved online public databases for all ecosystem values related to coral ecosystem services	NAS fund grants including deep coral ecosystem valuation studies via competition with RFP building on NRC (2012, 2013); NAS fund contracts to support existing efforts (e.g., Gecoserv 2013, NOEP 2012)
C: Synthesis	1. Integrate data, products, and results	Gulfwide restoration information system including data archives and policies; applications of new information technology tools for facilitating access to data and data derivative products to support EBM decision makers	RA1603 council establish information management (IM) policies, requirements, and best practices for all restoration funded programs; RA1604 support competitive grants/contracts and internal support for continued improvement and use of existing IM programs; RA1604 sponsor grants/contracts for new products; all restoration projects contribute related data to the proposed system-of-systems

(*continued*)

Table 9.3 (Continued) Outputs and Sponsors for Recommended Tasks

Objectives	Task	Suggested outputs	Proposed sponsor
	2. Support synthesis outputs	Gulfwide integrated ecosystem assessment (IEA) including coral ecosystem indicators, as paper and electronic (Web-based, interactive) report; coral ecosystem chapter of Gulf Report Card report, also developed as interactive Web-based products accessible on various platforms (e.g., mobile phones)	Joint RA1603 and NAS contract for up to 10 years; RA1604 mixed (internal and external) funding model support for NOAA IEA team efforts

Note: See Table 9.1 for sponsor program names and objectives.

of capabilities and resources. Regional examples of efforts to implement EBM for coral ecosystems include management plans for the Florida Keys and Flower Garden Banks National Marine Sanctuaries, both of which cover shallow and deep coral ecosystems (FKNMS 2007, FGBNMS 2012), and the South Atlantic Fishery Management Council's comprehensive ecosystem amendment related to designated coral HAPCs (SAFMC 2009). This review should be carried out prior to implementation of restoration projects for coral ecosystems.

Action A2: Engage stakeholders in developing EBM operational frameworks for coral ecosystem goods and services that identify science goals, gaps in science information, management priorities, and desired outcomes

The Food and Agriculture Organization of the United Nations (FAO) defined a process for operational implementation of regional EBM for ocean resources, which includes setting high-level policy goals and operational objectives; developing indicators, reference points, and decision rules for the application of measures; and monitoring and evaluating performance (FAO 2005). The Gulf Coast Ecosystem Restoration Council's initial comprehensive restoration plan (GCERC 2013a) includes strategic objectives but little detail on how it will solicit, select, and integrate sponsored projects. Prior to implementing regional restoration, the council and related state plan leadership should make use of established guidance to develop operational frameworks for prioritized ecosystem services, including coral habitat and associated fisheries (e.g., FAO 2005). Federal and state agencies should establish and coordinate a comanaged entity responsible for engaging coral ecosystem stakeholders (scientists, managers, public users) in the tasks of developing, integrating, and sustaining restoration plans at the appropriate temporal and spatial scales to support adaptive management (Wilson 2006, Ostrom 2009, Gutierrez et al. 2011).

Objective B: Conduct research, monitoring, modeling, and technology developments required to fill gaps and support adaptive management

Action B1: Expand surveys and research needed, as determined by gap analyses, to support management of activities that affect coral ecosystems

Stock assessments require data and information on both fish populations and fisheries. In 2002, the National Marine Fisheries Service and regional management councils in the gulf, Caribbean, and U.S. South Atlantic established the Southeast Data Assessment and Review (SEDAR) process to improve the rigor and transparency of stock assessments. "Benchmark assessments" entail a full suite of data, models, and related peer review and may take over a year to complete. In addition to benchmark assessments, more frequent updates may be done once an assessment is approved through SEDAR, requiring new input data and few, if any, model configuration improvements (SEDAR 2012). These assessments and related ecosystem models require inputs from historic and current data sources for gulf commercial and recreational fisheries, with continuous, long-term time series being particularly valuable for detecting population changes over time. Both fishery-dependent and fishery-independent data need to be enhanced in quality, time, and space. This is particularly true and challenging for deep reef (>300 m) fisheries, which cannot be sampled using traditional trawl surveys, most acoustic technologies, or scuba divers (e.g., Foster et al. 2013, McIntyre et al. 2013, Price et al. 2013).

Efforts to enhance and supplement fisheries and ecosystem data collection should build on and improve existing data collection programs, for example, the Southeast Area Monitoring and Assessment Program (SEAMAP) in the South Atlantic, Caribbean, and Gulf of Mexico regions, which received an inadequate total (all three regions) of $5 million in FY2012 for fisheries-independent data collection. SEAMAP annual reports (e.g., SEAMAP 2012) summarize the traditional activities employed, including surveys, data management and synthesis, and planning and reporting. For coral ecosystems, these must be supplemented with new nondestructive, innovative assessment approaches (see Action B4 later in this chapter). Priority activities should be guided by the planning activities recommended in Actions A1 and A2.

A related critical need is to enhance and improve recreational fisheries-dependent data collections (NRC 2006) including increase Access Point Angler Intercept Surveys (APAIS) in the National Oceanic and Atmospheric Administration's (NOAA) Marine Recreational Information Program; standardize sampling protocol and estimators for state and federal programs; and require charter boat, head boat, and other for-hire recreational fishing operations to maintain electronic logbooks of fish landed and kept, as well as fish caught and released.

Deep coral ecosystems in the Gulf of Mexico are, in general, poorly mapped. Seafloor habitat mapping information is required to support both the sustainability of exploited populations and the maintenance of biological diversity. Maps required should depict cumulative area impacted by all human activities (e.g., oil and gas development, fishing effort by gear types); distribution of habitats and diversity of key taxa (e.g., structure forming and bed corals); and linkages between habitat and the dynamics of exploited populations (Auster 2001). Although the gulf seafloor may be extensively mapped in support of oil and gas exploration-related activities, these data were not collected for the purpose of mapping habitats and associated biotic communities, and are not easily accessible. Resulting map products supported by restoration program efforts need to be quality controlled and easily accessible for all constituents. Priority targets need to include ultra-deep oil and gas lease blocks in pending lease sales, and known and predicted (based on habitat suitability models, e.g., Guinotte and Davies 2012, Kinlan et al. 2014) deep coral ecosystems in the gulf.

Exploration in the context of the gulf most often refers to oil and gas prospecting. The Gulf of Mexico Ecosystem Restoration Task Force (GCERTF 2011:50), however, called for "… investing in research and basic exploration to understand the ecosystems in the gulf and how they can be resilient to impacts from episodic events, such as hurricanes or oil spills, and long-term changes such as climate impacts." The GCERC comprehensive restoration plan (GCERC 2013b) list of proposed projects must include exploratory research projects that address gaps identified in the development of EBM operational frameworks (Action A2), utilize mapping products to target and explore new gulf frontiers, and invest in developing advanced technologies (i.e., Class I research ship for the gulf, and undersea technologies such as robotic and human-occupied vehicles). Exploration is expensive and should be coordinated and leveraged with programs that now support frontier science such as the Bureau of Ocean Energy Management (BOEM), the National Science Foundation (NSF), NOAA's cooperative institutes in the gulf region, and NOAA's Ocean Exploration Program.

Action B2: Develop and fund an expanded (applications, time and space scales) gulfwide observing and monitoring program

The Gulf Coast Ecosystem Restoration Council's comprehensive restoration plan calls for both project-level and regional ecosystem monitoring to support science-based decision making (GCERC 2013a). Monitoring requires integration of input from observations and research (Busch and Trexler 2003). As Weisberg (2011:38) observed, "fisheries science cannot advance by just studying fish. Instead, the entire context in which fish make their living must be understood." Several plans now exist for regional ocean observing systems and required priority observations, for example, the Gulf of Mexico Coastal Ocean Observing System (GCOOS) draft "build out" plan (GCOOS 2011). Development of a gulfwide observing and monitoring program in support of gulf restoration and EBM should include the following critical elements related to coral ecosystems:

1. Interdisciplinary approaches to collecting data and conducting research on all key ecosystem components—physical, chemical, and biological. An acoustic (passive and active) network, similar to Canada's Acoustic Ocean Tracking Network (OTN) (Block et al. 2012, Welch et al. 2012) should be deployed at deep gulf stations. Observations from ships, buoys, moorings, remote sensing, and gliders are required to support high-resolution habitat maps, resource surveys (fisheries-dependent and -independent), and water quality monitoring.
2. A permanent endowment that provides on-going support from interest versus principal is recommended to sustain required observing network operations. Data collection must be sustained at operational levels for the long term. Cowan et al. (2012:506) observed that EBM may be hindered by the ability and willingness of society "…to understand and tolerate the tradeoffs needed to forego short-term economic benefits, and to abandon open-access utilization of natural resources, in favor of protecting or restoring ecosystem goods and service over much longer time periods." Most ocean ecosystem observation efforts in the gulf have been sustained by short-term grants and contracts and terminated at the end of the award period.
3. Data collection must be sustained at appropriate temporal and spatial scales. Appropriate scales in an EBM context for coral ecosystems vary from large-scale (decades in time, hectares in distance) oceanographic and climatic processes (e.g., North Atlantic Oscillation, Pacific Decadal Oscillation, location and paths of

boundary currents, upwelling zones) to intermediate and local-scale features in time and space (e.g., bathymetry, substrate types, localized upwelling, jets, and riverine plumes). Operational frameworks developed in Action A2 will help define the required density of observations.

4. Technology innovations to improve the pace, scope, and efficiency of observing and monitoring efforts. Annual operating costs must include funding for capitalization that maintains and repairs existing assets, and integrates new technologies into the gulfwide observing and monitoring network, resulting in improvements in the efficiency, effectiveness, and relevance of observations and resulting science.

Action B3: Develop and apply ecosystem models to support decision makers

Cowan et al. (2012) argued for a holistic ecosystem modeling approach to support EBM, while acknowledging the empirical challenge of ecosystem-scale applications, and deficiencies in providing an actual basis for tactical decision making in any particular fishery. Murawski (2007) suggested both conceptual and mathematical modeling efforts are warranted. Conceptual models of coral ecosystem functions (including basic food webs, keystone species and fisheries, and factors that impact on productivity and sustainability) are needed to help guide "…the establishment of plausible subsets of potential outcomes, particularly in an adaptive management scenario, where provisional management policies are considered 'experiments' for the purposes of gathering additional information" (Murawski 2007:686). These conceptual models should be associated with operational frameworks developed in Action A2.

Plagányi (2007) reviewed the strengths and limitations of multispecies and ecosystem models, and noted that their forecasting skill is constrained by limitations in fundamental knowledge of ecosystem dynamics and structure. Ecological forecasting is central to EBM, allowing managers to assess diverse policy options prior to implementation (Kaplan et al. 2012). More sophisticated mathematical modeling of ecosystem interactions and the bioeconomic impacts of stressors and policy choices are used to predict change and identify feasible subsets of management options. These are particularly needed for coral ecosystems that are sensitive to a range of stressors in time and space. Given the range and scope of possible modeling solutions, and their importance to effective EBM, the Gulf Ecosystem Restoration Council should convene a standing (sustained) working group for ecosystem modeling to develop an action plan as part of the comprehensive restoration plan (GCERC 2013a).

Action B4: Support and incentivize new technologies to improve fisheries efficiency and reduce the negative impacts of fishing activities on coral ecosystems

Research priority 4 of the National Ocean Policy Plan (SOST 2013) calls for both applied research and technological development to support marine natural resources. In addition to exploration, research and mapping technologies addressed in Action B1, and observing and monitoring technologies in Action B2, innovative technologies are needed to reduce bycatch, overfishing, and habitat degradation. Nondestructive fishing and assessment technologies are particularly needed for coral habitats that can be destroyed in a day and take decades or more to recover (Reed et al. 2007). Additionally, these technologies may offer less expensive, faster, and safer approaches for fish stock and habitat assessment (Foster et al. 2013). Priorities should again emerge from gap analyses in Action A2. Research and development programs sponsored by RESTORE Act Section 1604 and 1605 programs should have a cooperative element, whereby stakeholders (e.g., the fishing and diving communities) participate in the planning and implementation of projects by providing ships, gear, or expertise and by helping to ensure innovations achieved to support EBM science are also applied to improve fishing operations.

Action B5: Determine socioeconomic value of coral ecosystem services

The Gulf Task Force called for expanding ecosystem services and benefit analysis tools and capabilities to determine the socioeconomic benefits that ecosystems provide throughout the gulf region (GCERTF 2011). Several studies highlight the benefits and need to improve the assessment and valuation of ecosystem services, including both market and nonmarket values (e.g., Granek et al. 2010, Barbier et al. 2011). The National Ocean Economics Program (NOEP 2012) adequately estimates the market values of ocean and coastal services, although these are at least a year out of date, and the database does not include nonmarket values. Available inventories for gulf nonmarket valuation studies by ecosystem service and habitat type (Gecoserv 2013, NOEP 2013) do not currently include any studies for deep coral ecosystems in the gulf. Funding should be provided to facilitate and expand the delivery of NOEP data and derivatives, including the development of nonmarket values for major estuarine, coastal, and oceanic ecosystems that can be applied across the gulf landscape and seascape.

Objective C: Support information management and synthesis

Action C1: Integrate data, derivative products, and research results to support EBM for coral ecosystems

The Gulf Coast Ecosystem Restoration Task Force initiated by executive order right after the DWHOS in 2010 was charged with creating a comprehensive gulf restoration strategy (GCERTF 2011). This plan prioritized the development of decision-making visualization aids that were overlaid on the myriad uses of the gulf which can potentially interact with energy and mineral development. Actions recommended by Garcia and Cochrane (2005) to support EBM include the need to develop and build on existing information platforms to integrate information and data on indicators for different fisheries and ecosystems, and to create and distribute large-scale, multicriteria descriptions of ecosystems (functions, structure, and services) using accessible information technologies such as global information systems (GIS) and Web-based databases. Several gulf-based regional partners have advanced data and information management using open architecture software, cloud services, public repositories, and innovative visualization tools. These should be reviewed and scaled up for gulf-wide application. The challenge will be to integrate interoperable, quality-controlled, and accessible (with metadata records) ecological data sets into these archives, usually designed to hold geospatial data and metadata records. Programs such as NOAA's Deep Sea Coral Program is making strides in working with scientists in the grant stages to develop data management agreements that recognize intellectual property rights and promote the sharing and integration of ecological information into national databases. All restoration programs should strive to provide access via this system-of-systems through standardization of data collection protocols and policies that require sharing by funded projects.

Action C2: Support synthesis of useful products for managers and communication to all stakeholders

The Gulf Task Force strategy recommendations also mentioned the need to develop integrated decision-support tools and systems, including expansion and enhancement of predictive, simulation, and risk assessment models and ecological forecasting capabilities, and to establish indicators of success and monitoring assessments to evaluate how well program elements meet their stated goals (GCERTF 2011). These are priority objectives in IEAs, as defined by Levin et al. (2009). A gulf interagency IEA has been underway since 2010, intended to provide a framework for organizing and synthesizing science to inform multiscale, multisector EBM (Schirripa et al. 2012). This interagency effort should continue and expand to include new partners from science, management, and industry, and a joint education campaign should be launched that explains the assessment process to students, professionals, and the public.

The task force recommended development of a gulfwide progress report to provide "summary status information on ecosystem endpoints and communicate progress of management in improving ecosystem functions and services" (GCERTF 2011). This objective should be addressed in collaboration with the gulf IEA, which includes identification and tracking of ecosystem indicators. As McKinney et al. (2011) envisaged for their Report Card project, the goal is to develop a graphical representation of the environmental condition of the gulf that will be science based, widely accessible, and readily understandable by policy makers, stakeholders, scientists, and, most importantly, the American public. They use a drivers-pressures-stressors-state-impacts-response (DPSSIR) conceptual framework to guide and focus scientific research on identifying and addressing the most important risks to priority ecosystem services, including "a broad diversity of ecosystem types, from deepwater bottom communities, pelagic habitats, coral reefs, sea grass communities, salt and freshwater marshes, and riverine systems to barrier islands, coastal forests, and the larger watershed." A coral ecosystems chapter should be developed in collaboration with the gulf IEA project (Schirripa et al. 2012).

Conclusion

The recommended action plan will build the capacity required to develop an EBM approach for gulf deep (>50 m depth) coral ecosystems. Science programs required to support EBM have been grossly underfunded in comparison to programs seeking to address the economic impact of the DWHOS on the gulf's ecosystems, from estuaries to the deep sea (Shepard et al. in press). Coral ecosystems are among the most vulnerable and least understood ecosystems potentially affected by the DWHOS. Civil and criminal penalties for ecosystem restoration are an unprecedented opportunity to adequately support the science and EBM actions required to sustain gulf ecosystem goods and services for many generations. These funds are being distributed to a variety of state and federal programs with, in many cases, overlapping objectives and nonoverlapping management structures. The recommended EBM approach will help focus and coordinate these programs, address both primary (direct) and compensatory damages required to restore coral ecosystems, and mitigate regional ecosystem degradation that has been happening over decades due to a mix of stressors. Proposed sponsors and outputs provide a framework for performance evaluation. Success will not just compensate for damages by restoring the system to prespill conditions, a benchmark for natural resource damage assessment restoration (NOAA 1996), but may reverse decades of environmental degradation and sustain gulf coral ecosystem goods and services for generations.

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