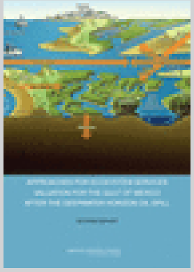

Approaches for Ecosystem Services Valuation for the Gulf of Mexico After the Deepwater Horizon Oil Spill: Interim Report

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APPROACHES FOR ECOSYSTEM SERVICES VALUATION FOR THE GULF OF MEXICO AFTER THE DEEPWATER HORIZON OIL SPILL

INTERIM REPORT

Committee on the Effects of the Deepwater Horizon Mississippi Canyon-252 Oil Spill on Ecosystem Services in the Gulf of Mexico

Ocean Studies Board

Division on Earth and Life Studies

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This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their participation in their review of this report:

Peter Auster (University of Connecticut)
Bruce Bayne (URS Corporation)
Trudy Ann Cameron (University of Oregon)
Dan Doty (Washington State Department of Fish and Wildlife)
Thomas Leschine (University of Washington)
Daniel Magraw (Center for International Environmental Law)
Jacqueline Michel (Reserarch Planning, Inc.)
James Sanchirico (University of California, Davis)

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations nor did they see the final draft of the report before its release. The review of this report was overseen by **Kathleen Segerson**, University of Connecticut, appointed by the Divison on Earth and Life Studies, and **Simon Levin**, Princeton University, appointed by the Report Review Committee, who were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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Appendixes

Summary

On April 20, 2010, the Deepwater Horizon (DWH) platform drilling the Macondo well in Mississippi Canyon Block 252 exploded, killing 11 workers and injuring another 17. The DWH oil spill resulted in nearly 5 million barrels (approximately 200 million gallons) of crude oil spilling into the Gulf of Mexico (GoM). The full impacts of the spill on the GoM and the people who live and work there are unknown but expected to be considerable, and will be expressed over years to decades. In the short term, up to 80,000 square miles of the U.S. Exclusive Economic Zone were closed to fishing, resulting in loss of food, jobs, and recreation.

The DWH oil spill immediately triggered a process under the U.S. Oil Pollution Act of 1990 (OPA) to determine the extent and severity of the "injury" (defined as an observable or measurable adverse change in a natural resource or impairment of a natural resource service) to the public trust, known as the Natural Resource Damage Assessment (NRDA). The assessment, undertaken by the trustees (designated technical experts who act on behalf of the public and who are tasked with assessing the nature and extent of site-related contamination and impacts), requires (1) quantifying the extent of damage; (2) developing, implementing, and monitoring restoration plans; and (3) seeking compensation for the costs of assessment and restoration from those deemed responsible for the injury. The goal of this effort is to "make the environment and the public whole for the injuries to natural resources and services" (NOAA, 1996). The services referred to are the benefits that people receive from the resources.

Historically, damage assessments have measured losses in ecological terms (e.g., number of acres damaged or number of fish killed) and restoration generally follows a methodology of equivalency wherein losses are compensated by the replacement of resources of the same type (e.g., acres of habitat restored or fish stocks replaced). The injuries to the ecosystem and the services it provides are quantified by comparisons to baselines when possible. In some instances, the assessment of injuries has been straightforward because the service products are well characterized in the economic marketplace (e.g., the income loss from the closure of a particular fishery). However, the connections between many service products and ecosystem condition have not been well characterized. In other cases, baseline data may not exist (e.g., hydrocarbon levels in marsh sediments) or baseline ecological data may be available but without an assessment of services (e.g., acreage of wetlands may be known, but not the value to fisheries).

Ecosystem services describe the benefits people receive from a multitude of resources and processes that are provided by ecosystems. They are produced as a consequence of the functioning of the ecosystem—the interactions of plants, animals, and microbes with the environment—and are ubiquitous and immensely valuable to society. They include

- *provisioning services* or the material goods provided by ecosystems (often simplified to food, feed, fuel, and fiber);
- *regulating services* (e.g., climate regulation, flood control, water purification);
- *cultural services* (e.g., recreational, spiritual, aesthetic); and
- *supporting services* (e.g., nutrient cycling, primary production, soil formation).

The magnitude and depth of the DWH event, in concert with the complexity of the GoM ecosystem and the difficulties in establishing baseline values, pose serious challenges to the trustees charged with carrying out the NRDA process, which has historically been applied to shallow-water events of much more limited extent and scale. Recent studies suggest that an “ecosystem services approach” may expand the potential to capture, value, and restore the full breadth of impacts to the ecosystem and the public.

Recognition of the unprecedented nature of the DWH spill and concerns about both short- and long-term impacts on the GoM and its citizens were immediate and international in scope. Among the many concerned with the fate of the GoM and its communities were members of the U.S. Congress, who requested a study by the National Academy of Sciences to assess the impacts of the DWH spill on the natural resources of the Gulf. A committee made up of 16 members representing a broad range of disciplines was formed in January 2011 and met twice in early 2011. To provide advice to the federal agencies during their preparation of the NRDA, the committee was asked to produce an interim report that covers questions 1 through 3 of the Statement of Task (Box S.1). A final report, encompassing the interim report and including questions 4 through 8, will be delivered in the spring of 2013.

BOX S.1 STATEMENT OF TASK

Interim Report questions:

1. What methods are available for identifying and quantifying various ecosystem services? What are the spatial and temporal scales conducive to research, that provide meaningful information for the public and decision makers?
2. What methods and types of information can be used to approximate baselines (but for the spill) for distinguishing effects on ecosystem services specific to the spill?
3. What kinds of valuation methods are appropriate for measuring ecosystem services over time with regard to recovery under the following approaches: natural processes, mitigation, and restoration efforts? What baseline measures are available that would provide benchmarks for recovery and restoration efforts?

Final Report questions:

4. What ecosystem services (provisioning, supporting, regulating, and cultural services) were provided in the Gulf of Mexico Large Marine Ecosystem prior to the oil spill? How do these differ among the subregions of the Gulf of Mexico?
5. In general terms, how did the spill affect each of these services, and what is known about potential long-term impacts given the other stresses, such as coastal wetland loss, on the Gulf ecosystem?
6. How do spill response technologies (e.g., dispersant use, coastal berm construction, absorbent booms, in situ burning) affect ecosystem services, taking into account the relative effectiveness of these techniques in removing or reducing the impacts of spilled oil?
7. In light of the multiple stresses on the Gulf of Mexico ecosystem, what practical approaches can managers take to restore and increase the resiliency of ecosystem services to future events such as the Deepwater Horizon Mississippi Canyon-252 spill? How can the increase in ecosystem resiliency be measured?
8. What long-term research activities and observational systems are needed to understand, monitor, and value trends and variations in ecosystem services and to allow the calculation of indices to compare with benchmark levels as recovery goals for ecosystem services in the Gulf of Mexico?

This report is not intended as a review of the ongoing damage assessment. There is a tremendous amount of important work under way to support the NRDA for the DWH spill; hence a review of this effort would be premature and inappropriate at this time. Instead, the report provides options for expanding the current effort to include the analysis of ecosystem services to help address the unprecedented scale of this spill in U.S. waters and the challenges it presents to those charged with undertaking the damage assessment. The Statement of Task highlights "ecosystem services" as an approach for assessing impact and estimating the value of losses due to injury. Such an approach focuses not only on the restoration of damaged resources (as per NRDA practice) but also on reestablishing the value of those resources to the public. This broader view may be particularly useful in capturing the full spectrum of impacts from this event given the magnitude, duration, depth, and complexity of the DWH spill.

KEY FINDINGS OF INTERIM REPORT

Environmental Context for the Gulf of Mexico

The Gulf of Mexico is remarkably rich and complex and provides a wealth of ecosystem services including tourism worth an estimated $19.7 billion per year, storm surge protection by coastal wetlands, habitat for migrating waterfowl, cycling of nutrients from river discharges, and the unique cultural heritage of coastal communities. In 2008, the GoM accounted for approximately 25 percent of the seafood provided by the contiguous United States. The GoM also provides 29 percent of the oil and 13 percent of the natural gas produced in the United States. The impacts from these societal demands on these critical ecosystem services have often led to the degradation of the health and resilience of the GoM ecosystem.

The unprecedented depth, application of dispersants at the well head, and tremendous volume of oil in the DWH spill complicate the assessment of potential impacts on the deepwater ecosystems of the Gulf, a relatively unstudied realm of abundant marine life including bottom-dwelling fish, deepwater corals, and chemosynthetic communities. To fully quantify the impact of the oil spill thus requires a thorough understanding of the complex interactions and linkages between and among the various components and processes of these ecosystems.

Modification of the GoM ecosystem by a number of human activities makes it more difficult to isolate impacts associated with the DWH spill. In addition to the long-term impacts of the oil and gas industry, there has been a tremendous loss of coastal wetlands, in part due to flood control and navigation projects. Massive "dead zones" of oxygen-depleted water, which may cover thousands of square miles of the Gulf seafloor, form each year as a consequence of plankton blooms stimulated by nutrients from fertilizers used by farmers in the Mississippi watershed.

> **Finding S.1: The Gulf of Mexico comprises a large, complex ecosystem that has been and continues to be subject to both natural and human forces of change. Hence, the baselines against which the impact of the spill can be assessed are both spatially and temporally dynamic.**

Approaches to Assessment and Valuation of Ecosystem Services

The National Oceanic and Atmospheric Administration (NOAA) has developed and used well-recognized and tested methods for assessing injury or impact to natural resources. A simplified summary of these approaches and the data collected to support them is presented in the columns labeled "Damage Assessment Practice" in Table S.1. Under typical practice, losses are generally measured in ecological terms (e.g., number of acres damaged) rather than in terms of losses in the value of ecosystem services. The losses are then used to assess the damages (the debit) to the relevant natural resources. In most cases, those damages (or the debit) translate directly to, or can be scaled to, potential restoration projects that generate "credit" sufficient to offset the debit.

For most NRDA cases, estimating or scaling the restoration requirements generally follows equivalency approaches wherein losses of resources can be compensated with replacements of the same type. Habitat Equivalency Analysis (HEA) measures damages in terms of the number of acres damaged. Resource Equivalency Analysis (REA) focuses mainly on assessing injury to specific organisms rather than on the amount of habitat and is frequently applied in oil spill cases. These equivalency approaches also focus more on the implicit value of the habitat or the organism in an ecological sense rather than the ultimate value of the resource to humans. Restoration thus could be in terms of the acres of habitat that need to be restored, the numbers of wildlife that need to be reintroduced, or other suitable projects allowed under the statute and regulations. Under NRDA, if damages do not translate readily into a particular restoration project, or if restoration projects in proximity to the injury are not readily available, funds may be provided as compensation and applied at a later date when a suitable restoration project is identified. In general, the equivalency approaches (HEA and REA) can be

TABLE S.1 Provision and Valuation for the Services of Hazard Moderation, Food, and Recreation

Damage Assessment Practices			Methodology for the Provision and Valuation of the Ecosystem Services Approach	
Data category	Resource	Typical approach to the assessment	Ecosystem service	Type of data needed for ecological production function
Biological	Wetland	Determine exposure pathways and spatial extent of vegetation oiled; collect and document any dead or oiled wildlife.	Hazard Moderation (reduction in storm surges; see Box 4.1).	A. Plant type (or species), height and density. B. Percentage of area likely to experience acute toxicity and die off. C. Cross-shore and along-shore extent of wetland harmed. D. Estimates of ability of the wetland to reestablish with and without human intervention.
			Food (commercial fisheries).	1. Measures of fishery landings. 2. Measures of fishery stock and recruitment. 3. Estimates of the ability of wetlands to reestablish with and without human intervention.
			Recreation (recreational fisheries).	1. Measures of fishery landings. 2. Measures of fishery stock and recruitment. 3. Estimates of the ability of wetlands to reestablish with and without human intervention.

Ecological production function	Type of data needed for valuation	Valuation method	Type of data needed for valuation of ecosystem service
1. Relationship between plant type, height, density, and areal extent of vegetation and reduction of wave energy and storm surge.	1. Location of structures, infrastructure, agriculture, etc. near the coast. 2. Value of structures, infrastructure.	Avoided cost: calculate the expected damages associated with storm surge. The value of the ecosystem service is equal to the reduction in expected damages.	1. Data on (A), (C), and (D). Data on wetland extent and amount oiled would be collected in a standard NRDA but other data would likely not be. 2. Building the functional relationships to translate from data on plant type, height, density, and extent to likely height of storm surge. This may be done via empirical relationships and/or modeling. 3. Building the functional relationship that translates height of storm surge to expected damage.
1. Relationship between wetland condition and fishery productivity.	1. Market price of commercial fish. 2. Fishing cost per unit effort (capital, labor, fuel).	Market valuation: calculate profit from fishing. Use market price and harvest data to calculate revenue. Use cost data along with revenue calculation to calculate profit.	1. Data on (B) and (C). 2. Building the functional relationship between wetland condition and fishery productivity. This may be done via empirical relationships and/or modeling.
1. Relationship between wetland condition and fishery productivity.	1. Survey information on fishing trips.	Travel cost. Use information on recreation trips, time and resource costs of trips to calculate willingness-to-pay for recreational fishing trips.	1. Data on (2) and (3). 2. Building the functional relationship between wetland condition and fishery productivity. This may be done via empirical relationships and/or modeling. 3. Estimation of value using travel cost (random utility model).

thought of as attempting to make the environment whole in the sense that habitat areas or populations of species have been restored. However, this approach to restoration does not necessarily make the public whole in terms of ecosystem services.

Finding S.2: Habitat and resource equivalency approaches may not capture the whole value provided by large ecosystems such as the Gulf of Mexico because of the complex long-term interactions among ecosystem components.

Of particular concern is the potential for chronic impacts of oil on important natural resources that are not manifested or identified during the injury assessment, nor accounted for in the scaling of the restoration. In this situation, the impacts may not be evident for several years and may require additional human intervention and restoration for mitigation.

Finding S.3: The spatial and temporal scales of the DWH spill and the complexity of the GoM ecosystem make it unlikely that all important long-term impacts can be identified during the initial injury assessment.

There is growing recognition that what is needed for informed management and policy decision making are measures that link human actions to likely changes in ecosystems and that link changes in ecosystems to consequent changes in human well-being. Ecosystem services, the benefits that people receive from ecosystems, provide this link between ecosystem conditions and human well-being. An analysis of how changes in management or in environmental conditions affect the provision of ecosystem services, and the consequent benefits to people, facilitates the comparison of management interventions and changes in environmental conditions and can be used to estimate the impacts of these changes in terms of value to society. Thus an "ecosystem services approach" that focuses not only on the restoration of damaged resources but also on establishing and maintaining the usefulness of those resources to the public may also offer a useful tool for assessing the impact of disasters on the environment.

Finding S.4: Habitat and resource equivalency approaches could be broadened to include an ecosystem services approach by consideration of the extent to which affected areas or resources generate benefits to the public.

It may be possible, however, to include the impact on human benefit in equivalency approaches. For example, the limitation of HEA in the context of making the public or environment whole could be addressed by expanding the definition for one of the more frequently used equivalency metrics—the Service Acre Year (the ecological service provided by one acre of habitat per year where the flow of the service is to another ecological resource)—as the currency by which the value of a habitat is judged.

Finding S.5: A more comprehensive assessment of the overall value of the resources could be obtained by expanding the definition of the Service Acre Year to include services that flow from a habitat or ecological resource to human benefits.

An ecosystem services approach could also help relieve what might be called the NRDA "restoration bottleneck." OPA provides incentives for the NRDA trustees to collect monetary damages from a responsible party to the extent that the trustee can conceive of feasible and productive restoration, rehabilitation, replacement, or acquisition projects. In practice, trustees, the public, and the responsible party often struggle to identify and develop a mutually acceptable project prior to the time of settlement, creating a "bottleneck."

Finding S.6: An ecosystem services approach has the potential to expand the array of possible projects for restoration through alternatives that restore an ecosystem service independently of identification of an equivalent habitat or resource, albeit with the caveat that these projects must in aggregate make the environment and the public whole. Evaluation of the impacts on ecosystem services as part of the damage assessment process would expand the range of mitigation options.

The dynamic nature of ecosystems, composed of interactive complexes of species and their physical environment, challenges any type of assessment process and is even more challenging for a damage assessment of an event with the scope and duration of the DWH spill. Measuring such a change requires estimating the difference in provision and value of ecosystem services after the spill compared to the pre-spill, or baseline, conditions.

Methods to Establish Baselines for Gulf of Mexico Ecosystem Services

An assessment of the impact of an event like the DWH spill requires comparison with conditions in place before the event. In the language of the NRDA process, injuries are quantified by comparing conditions of the injured resource or service to baseline data. The establishment of baseline conditions for a region as vast and complex as the GoM, however, is a daunting task. The physical, chemical, and biological environments of the GoM are not constant. There are natural variations in meteorological and hydrologic conditions that lead to changes in sea surface temperatures, water currents, and flood conditions. These, in turn, lead to changes in chemical and ecological conditions. Assessment in light of these natural processes is further complicated by anthropogenic changes to the environment from construction of levees for storm protection, dredging of waterways for ship passage, construction of permanent infrastructure for oil and gas extraction, and use of fertilizers and pesticides on agricultural fields throughout the associated watersheds. Because ecosystem services in the GoM were already degraded prior to the spill, establishing realistic baselines will be essential in order to distinguish the effects of the oil spill from other prior and concurrent activities.

Our discussion of baselines is focused on representative examples of ecosystem services important to the GoM (Hazard Moderation and Hydrological Balance representing regulating services; Soil and Sediment Balance and Water Quality representing support services; Food; Oil and Gas for provisioning services; and Spiritual, Aesthetic, Historic, Existence, Recreation and Tourism representing cultural services). The discussion highlights examples of key parameters that have been or can be measured to ascertain GoM ecosystem services prior to the DWH oil spill. These examples may be used as a guideline for how to approach the complex problem of determining changes in ecosystem services following the DWH spill. For each service, a brief description of the current state of knowledge is provided, followed by a description of the primary parameters that can be measured and the state-of-the art methods for conducting the measurements. Where possible, references have been provided to databases and publications that may contain relevant information for comparison of ecosystem services before and after the spill. Some of these ecosystem services are understood better than others, as reflected in the variation in the depth of discussion for the different sections that are covered.

An Ecosystem Services Approach to Damage Assessment

The ecosystem services approach requires understanding of three important links:

- Determining the impact of human actions on environmental conditions that affect the structure and function of the ecosystem;

- Establishing how changes in the structure and function of the ecosystem lead to changes in the provision of ecosystem services. This is done through the establishment of ecological production functions—a quantification of the internal processes of the ecosystem; and
- Establishing how changes in the provision of ecosystem services affect human well-being, e.g., how can they be valued?

Impact of Human Actions on the Structure and Function of the Ecosystem

The damage assessment process historically used by NOAA includes widely used and accepted methods for assessing injury or impact to natural resources. The initial steps in assessment of injury involve sampling and analysis of various components of the ecosystem (see columns labeled “Damage Assessment Practice” in Table S.1). Thousands of samples have already been taken and analyses performed, and research and sampling continues through the NRDA process, by academic researchers, the trustees, and by BP and its contractors.

In order to extend the damage assessment practice to include an ecosystem services approach, each ecosystem service would require a specific type of sampling and analysis that complements the existing practice. An example of this extended sampling for coastal protection and fisheries is presented in the columns labeled “Ecosystem Services,” “Type of Data Needed for Ecological Production Function,” and “Ecological Production Function” in Table S.1.

> **Finding S.7: Additional sampling and analyses could facilitate an ecosystem services approach by identifying the impacts on ecosystem function and structure that in turn affect the ecosystem services provided. The collection of these additional data would set the framework for establishing the impact of the spill on ecosystem services.**

Ecological Production Functions

Once the impact on ecosystem function and structure is established, the second step in the ecosystem services approach is the determination of Ecological Production Functions. An Ecological Production Function specifies the output of ecosystem services generated by an ecosystem given its current condition. Changes in ecosystem conditions, either from natural disturbances such as hurricanes, or from human interventions, will in general alter the amount of various services provided.

For some ecosystem services, ecological production functions are fairly well understood and data exist that can be used to quantify the amount of a service provided. For many other ecosystem services, there is either a lack of mechanistic understanding, a lack of data, or both that inhibits accurate quantification of ecosystem services as a function of ecosystem condition.

Moreover, the complexity of marine ecosystems makes it difficult to understand how disturbances to an ecosystem will reverberate through the system and ultimately lead to changes in the provision of ecosystem services. A further complication in predicting the provision of ecosystem services arises from the high level of environmental variability characteristic of many coastal and marine ecosystems.

Models for specific ecosystem services (e.g., food from commercial fisheries) or components of the ecosystem (e.g., wetlands) are more readily available and applied. Examples are given in Table S.1 of the types of additional measurements and analyses that could be made to extend the damage assessment process to incorporate ecological production functions and ecosystem services in particular environments.

A mechanistic understanding of, and model for, the complex linkages and interdependencies of the ecosystem being studied would be of immense value in analyzing ecosystem services. However, a complete ecosystem model is not essential to derive predictive models focused on the provision of specific ecosystem services. Focused models would allow for prediction of the restoration of ecosystem services given the state of the ecosystem (i.e., the ecological production function). In general, establishing models of ecological production functions is perhaps the greatest challenge facing the application of an ecosystem services approach for damage assessment. Utilizing the extensive data that have been collected for the NRDA process and the existing ecosystem models for the GoM presents a unique opportunity for enhancing our understanding of ecological production functions and the provision of ecosystem services in the GoM.

Finding S.8: Measurements and analyses such as illustrated in Table S.1 would allow for the determination of the impact of the DWH spill related to the ecosystem function and structure of coastal wetlands and to quantify the impact on key ecosystem services. Further research is needed to determine what measurements are required to assess other ecosystem services and habitats.

Approaches to Valuing Ecosystem Services

The third component of the ecosystem services approach focuses on establishing the value of ecosystem services—the final step in understanding and quantifying impact. Economics provides a well-developed approach based on the theory of welfare economics to measure values.

To assess the value of changes in ecosystem services from environmental impacts such as an oil spill, economic valuation methods need to be combined with ecological assessments of impacts. Analysis of impacts on the supply of services combined with economic valuation methods can generate estimates of the value of changes in ecosystem services as a result of environmental changes. Three main types of economic valuation methods applied to ecosystem services are as follows:

- **Revealed preference** based on observed economic behavior. These methods include direct market valuation (amount of goods bought and sold and individuals' willingness-to-pay) and non-market approaches using observed behavior like "travel-cost" studies and "hedonic" property pricing methods that use a range of data on property characteristics to predict property price as a function of changes in parameters that can affect property value;
- **Stated preference** based on responses to survey questions, which includes the "contingent valuation method" that surveys people's willingness-to-pay for ecosystem services, "conjoint analysis," and "attribute-based stated choice approach" in which respondents rank alternative scenarios with different environmental attributes; and
- **Cost-based methods,** which look at information about costs rather than trying to estimate benefits. Two commonly used cost-based methods are "avoided damages," which looks at likely damages to be caused with and without environmental protection; and "replacement cost," which estimates the cost of providing the service in an alternate way. Many economists are skeptical about the use of cost-based methods for ecosystem services because they focus on cost rather than benefits, but this approach may be appropriate in certain situations.

Finding S.9: Both market and non-market approaches to valuing ecosystem services have become accepted and established practice over the past two decades since the *Exxon Valdez* oil spill. When appropriately applied, these techniques can generate valid estimates of value for ecosystem services lost due to human-caused and natural events.

Valuation Methods Applied to the Gulf of Mexico

Building on our example of key ecosystem services provided by wetlands (storm protection and fisheries) we now extend our analyses to include methods for valuing ecosystem services (see the columns labeled "Type of Data Needed for Valuation," "Valuation Method," and "Type of Data Needed for Valuation of Ecosystem Service" in Table S.1). Please note, the examples shown in Table S.1 are meant to illustrate how an ecosystem services approach could be incorporated into the existing NRDA process; they are not intended to capture the full complexity of the three component steps involved in the ecosystem services approach or the ongoing NRDA process.

With respect to valuing other ecosystem services, the theoretical foundations and the practical application of both revealed and stated preference approaches are well grounded in a rich literature. Cost-based approaches do not have the same grounding. Nonetheless, an avoided damages cost-based approach may be useful in estimating the value of coastal protection in the GoM. Travel cost approaches are most commonly used for measuring the value of recreational opportunities. Hedonic property price studies could be used to measure changes in values to coastal communities as a result of the DWH oil spill, but their use is limited to capturing only the impacts felt by property owners in coastal communities. Stated preference methods can be used for virtually any ecosystem service, including nutrient regulation, hazard moderation, and erosion control, but careful attention needs to be paid to survey design to get reliable answers to valuation questions. These issues will be examined further in the final report.

> **Finding S.10: Primary research on the values of ecosystem services would provide additional grounding for the DWH damage assessment.**

CONCLUSION

It will take many years to fully understand the long-term effects and impacts of the DWH oil spill, but much effort is being expended to assess the damages caused by the event and to estimate the value of these damages so that appropriate restoration measures can be developed and implemented. Recognizing the complexity of the Gulf of Mexico ecosystem and the magnitude, duration, and depth of the DWH event, the committee concludes that an ecosystem services approach would complement the ongoing approaches to the NRDA process. The ecosystem services approach focuses not only on the restoration of damaged resources but also on establishing and maintaining the usefulness of those resources to the public. Implementation of an ecosystem services approach would require a detailed understanding of the complex linkages among various ecosystem components (ecological production function) in addition to well-established baseline data, both of which are lacking to various degrees in the Gulf of Mexico. Nonetheless, given the vast amount of data currently being collected and research being conducted in the Gulf of Mexico, the committee believes that efforts to apply an ecosystem services approach to the DWH spill would greatly improve understanding of the full suite of impacts and greater options for achieving restoration of the critical services of the Gulf of Mexico ecosystem.

Introduction

> *"Man did not weave the web of life; he is merely a strand in it. Whatever he does to the web, he does to himself."*
>
> —Attributed to "Chief Seattle" (Noah Sealth, 1786-1866)

The public benefits from a wide variety of resources and processes that are provided by natural ecosystems. Collectively, these benefits are known as ecosystem services. Ecosystem services are produced as a byproduct of the functioning of the ecosystem—the interactions of plants, animals, and microbes with the environment. The benefits provided by ecosystem services are ubiquitous and immensely valuable to society. They include

- *Provisioning services* or the material goods provided by ecosystems (often simplified to food, feed, fuel, and fiber);
- *Regulating services* (e.g., climate regulation, flood control, water purification);
- *Cultural services* (e.g., recreational, spiritual, aesthetic); and
- *Supporting services* (e.g., nutrient cycling, primary production, soil formation).

These ecosystem services ultimately underpin the well-being of all people. When events occur that interrupt or interfere with the normal functioning of ecosystems, ecosystem services may be impacted, causing both short- and long-term harm to the ecosystem and those dependent upon it. Understanding and quantifying the nature and level of these impacts is a difficult and complex task, but can be used to establish appropriate procedures for recovery, restoration, management, and, when applicable, for seeking compensation for damages.

The Oil Pollution Act of 1990 creates a formal legal framework for determining when an oil spill results in an "injury" (defined as an observable or measurable adverse change in a natural resource or impairment of a natural resource service) to the "trust" resources or resource services.[1] A

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[1] See http://www.epa.gov/oem/content/lawsregs/opaover.htm.

process known as Natural Resource Damage Assessment (NRDA) is used by "trustees" to determine the extent and severity of that injury. Trustees, who include representatives of the federal government, tribes, and affected state governments, must attempt to (1) quantify the extent of damage; (2) develop, implement, and monitor restoration plans; and (3) seek compensation for the costs of assessment and restoration from those deemed responsible for the injury. The goal of this effort is to "make the environment and the public whole for the injuries to natural resources and services" (NOAA, 1996).

Under common NRDA practice, losses are generally measured in ecological terms (e.g., number of acres damaged or number of fish killed) and restoration generally follows relatively straightforward equivalency approaches (e.g., acres of habitat restored or fish stocks replaced) (described in Chapter 2). The injuries to the ecosystem and the services it provides are quantified by comparing the services to a baseline when possible. When the service is well known (e.g., the income lost from the closure of a particular fishery), the assessment of injuries can be straightforward. However, for other services, their connection to ecosystem condition is less well established because baseline data have not been collected (e.g., hydrocarbon levels in marsh sediments) or baseline ecological data have not been linked to services (e.g., acreage of wetlands but not the value to fisheries).

Additional challenges to assessment arise as the spatial and temporal scale of the injured system, and the complexity of the ecosystem, increase. In these cases it becomes increasingly difficult to understand and account for the full range of ecological impacts and to translate those impacts into reductions of ecosystem services. It also becomes more difficult to determine what the baseline conditions might have been in ecosystems subject to other natural and manmade environmental changes unrelated to a specific event.

The Gulf of Mexico (GoM), often referred to as the Gulf of Mexico Large Marine Ecosystem (GoM LME), is remarkably rich and complex and provides a wealth of ecosystem services. The Gulf of Mexico provides important regulating, supporting, and cultural services, which include coastal tourism with an estimated worth of $19.7 billion per year (National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling, 2011), storm surge protection by coastal wetlands, habitat for migrating waterfowl, cycling of nutrients from river discharges, and the unique cultural heritage of coastal communities. Provisioning services include food, biochemical and medicinal compounds, clean water, and energy in the form of crude oil and natural gas. In 2008, the GoM commercial fish and shellfish harvest yielded a dockside value of $659 million (1.27 billion pounds; NMFS, 2010). These commercial landings accounted for approximately 25 percent of the seafood provided by the contiguous United States. The GoM also has significant recreational fisheries in which 3.2 million citizens participated in 2008; 92 percent were coastal county residents (NMFS, 2010). Sponges, tunicates, bryozoans, and other invertebrates of offshore hard banks also contribute provisioning ecosystem services such as pharmacological extracts used for treatment of cancer, cardiovascular disease, infections, and inflammation.

The long-term development and maintenance of oil and gas extraction infrastructure has generated a wealth of hydrocarbon resources from the GoM. In 2009, this extensive infrastructure generated offshore production of 29 percent of the total crude oil and 12 percent of the natural gas in the United States[2]; annual oil production in the GoM exceeded 1.6 million barrels of oil per day).[3] However, this industry has also resulted in altered coastal zones and changed physical aspects of the coastline that may affect ecosystem services (Boesch and Rabalais, 1987), constructing numerous structures on the continental shelf and approximately 25,000 miles of active oil and gas pipeline on the GoM seafloor. Other pipeline corridors cross coastal wetlands. Inevitably, minor spills and leaks are associated with large-scale hydrocarbon production and shipping activities, but historically the GoM had been spared from a major industry-related accident.

That historical trend ended on April 20, 2010, when the Deepwater Horizon platform drilling the Macondo well in Mississippi Canyon Block 252 (DWH) exploded, killing 11 oil workers and injuring 17. This event, which resulted in nearly 5 million barrels (>200 million gallons) of crude oil released into the GoM over a period of three months, represents an industrial oil spill of unprecedented magnitude.[4] The depth of the release (~1,500 m) and the potential impact this may have on poorly understood deep-sea ecosystems is also unprecedented. The combination of large commercial (such as menhaden, blue crabs, oysters, and brown, white, and pink shrimp) and recreational fisheries (such as red snapper, sea trout, and red drum), a vibrant tourism industry, and long-established oil production facilities makes the GoM the most economically productive body of water in North America. The spill had an immediate impact on this productivity. In the short term, up to 80,000 square miles of the U.S. Exclusive Economic Zone were closed to fishing, resulting in loss of food, jobs, and recreation. Similarly, coastal tourism, beach-going, boating, and other services were heavily affected. The long-term impacts on these as well as other regulating and supporting

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[2] See http://www.eia.gov/special/gulf_of_mexico/index.cfm.

[3] See http://www.epa.gov/oem/content/lawsregs/opaover.htm.

[4] See http://www.nytimes.com/2010/08/03/us/03flow.html.

services are much more difficult to discern. They may be considerable, and may be expressed over years to decades.

Of particular concern was the introduction of oil and dispersants from the DWH spill at approximately 1,500 m depth directly into a realm of poorly understood but abundant marine life that includes bottom-dwelling fish, deep sea corals, and chemosynthetic microbial communities. As oil and dispersants traveled through the water column, they interacted with microorganisms, zooplankton, pelagic fish, sea turtles, marine mammals, and eventually, as they entered the photic zone, marine plankton, fish and shrimp larvae, and floating eggs in the water column (e.g., bluefin tuna eggs). Some of the mixture made it to the surface onto beaches, and into salt marshes, mangroves, or mudflats; potentially impacting the ecosystems that support important fisheries productivity. Throughout the process, marine and terrestrial birds, reptiles, and other animals may have been exposed to chemically dispersed oil and dispersants (National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling, 2011). To completely understand and quantify the impact of the oil spill thus requires a thorough understanding of the complex interactions and linkages between and among the various components and processes of these ecosystems (Figure I.1).

Complicating an understanding of the impact of the DWH spill is the fact that the GoM is an ecosystem that has been subjected to multiple sources of stress, both natural and manmade, to its ecological services. In addition to the long-term impacts of the oil and gas industry, there has been tremendous loss of coastal wetlands due to multiple interacting natural and human-caused changes in the geology, hydrology, and landscape. Louisiana has lost more than 2,300 square miles of coastal wetlands since initiation of levee-building in 1927 (National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling, 2011) and the dredging of canals for access to oil platforms and navigation. Not only does the flood control system affect wetlands, but it also threatens the very existence of coastal communities that ring the Mississippi Delta. The natural processes of sedimentation and delta construction that have formed and evolved the region's landforms over millennia are no longer in place. Before construction of the Mississippi River basin flood control structures, approximately 400 million metric tons of sediment were delivered annually to the Delta; today it is approximately 145 million metric tons (National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling, 2011). A major component of this loss in sediment load is from the completion of dams and reservoirs on the Missouri River in the 1950s (Blum and Roberts, 2009). Each year nutrients from fertilizers used in Midwestern agriculture are carried down the Mississippi and Atchafalaya

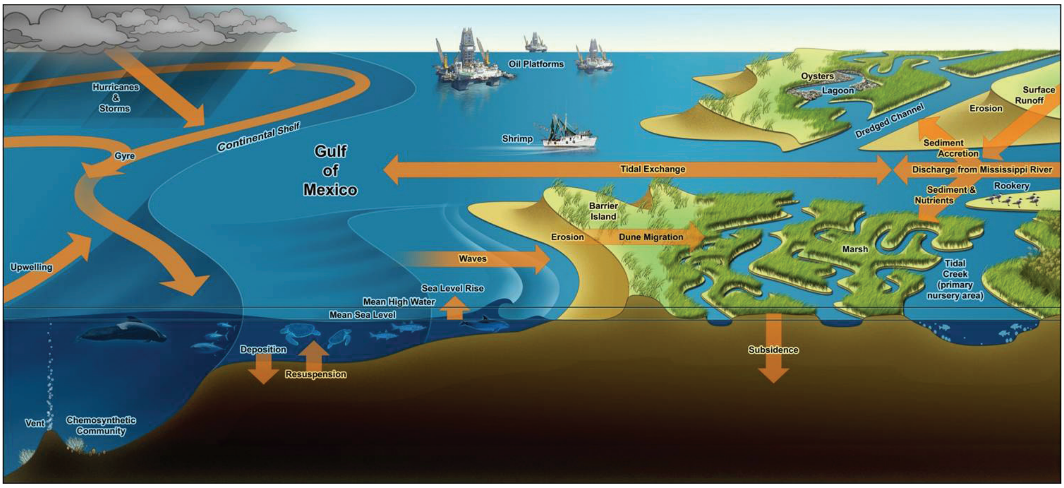

FIGURE I.1 Schematic drawing indicating various components and processes of the GoM ecosystem. A solid understanding of the complex interactions among these components is a key aspect of understanding the impact of the DWH spill on ecosystem services in the GoM. SOURCE: Alan Joyner, Red Twine Art & Design.

rivers, creating plankton blooms in the Gulf that result in the partial (hypoxia) or complete (anoxia) depletion of oxygen, and massive “dead zones” that can cover thousands of square miles of Gulf seafloor. Thus any analysis of the impact of the DWH spill on ecosystem services in the GoM must include consideration that the Gulf has been, and continues to be, affected by non-spill-related phenomena and that the baselines against which the impact of the spill must be judged are both spatially and temporally dynamic.

The magnitude and depth of the DWH event, in concert with the complexity of the GoM LME and the difficulties in establishing baseline values, pose serious challenges to those charged with carrying out the NRDA process, which historically has been applied to shallow-water events of much more limited extent and scale (see Box 2.1 on the North Cape Oil Spill). Indeed the National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling describes the assessment of natural resource damage associated with this particular spill as “the largest and most complex that the government has ever undertaken to assess oil spill impacts” (National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling, 2011).

At the time of writing this interim report, numerous studies focused on trying to understand the impact of the oil spill on the GoM LME are being conducted, including many in support of the NRDA process. Many thousands of samples have been collected and observations made, and studies will continue for some time. Analyses are also under way; some of the results are being published while others are not yet public. It will take many years to fully analyze the data and some impacts may not become apparent until far into the future, if at all. Nonetheless, the government is obligated to conduct a timely NRDA process to address the public's many concerns. An example that highlights the complicated nature of understanding the potential DWH

BOX I.1 DOLPHIN STRANDINGS IN THE GULF OF MEXICO: THE CHALLENGING SEARCH FOR THE CAUSE

From January through April 24, 2011, 192 bottlenose dolphins, *Tursiops truncatus,* stranded along GoM's coast from Florida to the Texas/Louisiana border at quadruple or more the average number recorded in the same period annually from 2002 through 2009. Over a third of them were stillborn and newborn calves. These strandings led to much media attention, public outcry, and the speculation that they were associated with the DWH spill. Strandings in 2010 were also higher than average, peaking in spring and early summer, but with no unusual number of calves.[a] In the midst of that peak came the April 20, 2010, DWH oil spill. On February 28, 2011, the strandings were officially declared an Unusual Mortality Event (NOAA, 2011a), a designation that calls for intensified data and sample collection, and a rigorous, coordinated study into the cause. At the same time, the event was included in the NRDA process, which assesses damages to marine mammals and their habitat attributed to the spill.

A study of this kind begins with the stranding pattern and proceeds to a comprehensive search for clues to mortality. For example, certain offshore forms, like sperm whales, *Physeter macrocephalus,* and pilot whales, *Globicephala* spp., come ashore in the tens to hundreds, at roughly the same time and place, in what are called mass strandings. The underlying cause is thought to be behavioral; once a critical member or number of the school heads to shore, the rest follow (Norris and Dohl, 1980). Bottlenose dolphins, however, do not fall into that category and usually strand alone or as mother-calf pairs. A few come ashore alive and some die on the beach, but most wash up already dead. Finding so many carcasses, as in the present event, suggests that over time, some enduring process or condition at sea is making dolphins sick or killing them.

Knowledge of the animal's life history, its environment, past stranding accounts in the region and elsewhere, and the presence of other suspected conditions help narrow the search from possible to the more probable causes. Might this event be in any way similar to the 1990 episode along the Gulf coast, where impacts is the 2010-2011 stranding of an unusual number of dolphins (many stillborn and newborn calves) along the GoM coast, which spurred a public outcry and immediate association with the DWH event. As detailed in Box I.1 however, many possible causes (natural and manmade) could be linked to the strandings, and only careful study and analysis will determine if the DWH spill was ultimately responsible.

Recognizing the unique aspects of the DWH spill (magnitude, duration, depth, and complexity of the ecosystems involved) and the ramifications of

in the first three months of the year, nearly 300 dead bottlenose dolphins were found on beaches from Florida to Texas? The cause was not established (Kuehl and Haebler, 1995). Could what is happening be the result of poisoning by a natural biotoxin produced by harmful algal blooms, like "red tide" or domoic acid from toxin-producing diatoms and transferred through prey fish? Bottlenose dolphins in Sarasota Bay, Florida, for instance, are commonly exposed to these toxins (Fire et al., 2008) and there is growing evidence that correlates exposure with stranding events along the southeastern and northern Gulf coasts (Flewelling et al., 2005; Fire et al., 2011). Might these strandings be due instead, or in addition to, an infectious disease, such as the ubiquitous morbilliviruses that wreak havoc in dolphins and whales (Duignan et al., 1996)? The stranding pattern supports both possibilities, while not excluding others. Harmful algal blooms can persist for months, as can an infectious disease that spreads from one dolphin to another. The high number of fetuses and young raises pointed questions: does illness cause early termination of pregnancy; are calves more vulnerable; do the mothers die first, leaving them helpless? Could anthropogenic contaminants play a role, such as polychlorinated biphenyls that are known to accumulate in dolphins in the region (Houde et al., 2006) and may reduce their ability to fight disease (Lahvis et al., 1995)? To determine if and how the DWH spill fits into the picture, the study will need to search for measurable differences in those dolphins that stranded before the spill versus after it (Geraci, 1990).

A probe of this depth and scale, on an event of this importance, will yield sufficient information that should shed light on the problem. The challenge, as usual, will be to tease out the cause and account for the roles of other influencing or confounding biological and environmental factors, including the DWH spill.

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[a] See running tally: www.nmfs.noaa.gov/pr/health/mmume/cetacean_gulfofmexico2010.htm.

these on the already complex task of assessing damages through the NRDA process, Congress sought external input on the process from the National Academy of Sciences (NAS). Funding was provided to the National Research Council (the operating arm of the NAS) through the National Oceanic and Atmospheric Administration (NOAA) to study approaches to evaluating the impact of the DWH spill related to the ecosystem services of the GoM. Specifically, the NAS was asked to address the questions listed in Box I.2.

It is important to note that the Statement of Task described above does not include a review of the ongoing damage assessment process. With respect to the DWH spill, such a review would be premature and inappropriate at present. It does, however, recognize (without stating explicitly) the challenges that the DWH spill will place on the ongoing NRDA process and seeks input from the NAS on new approaches that may aid and complement the NRDA process. In particular the Statement of Task focuses on an "ecosystem services" approach (NRC, 2005a) to assessing impact and to estimating the value of losses due to injury. Such an approach focuses not only on the restoration of damaged resources (as per NRDA practice) but also on establishing and maintaining the usefulness of those resources to the public. It is this broader view that may be particularly appropriate to an event of the magnitude, duration, depth, and complexity of the DWH spill.

A committee comprising 16 members (see Appendix A) representing a broad range of relevant disciplines (benthic ecology, biochemistry, biological oceanography, chemistry, ecology, economics, environmental engineering, environmental law, fisheries, geology, geophysics, human dimensions of natural resource management, microbiology, and veterinary medicine) was formed in January 2011 and held its first meeting January 24-25, 2011. To assist the federal agencies in their preparation of the NRDA, the committee was charged with providing an interim report approximately six months following the first meeting that addresses questions 1 through 3 of the Statement of Task. A final report, encompassing the interim report and including questions 4 through 8, is to be delivered after 24 months.

The generic questions 1 through 3 of the Statement of Task that are the focus of this interim report deal with best approaches to the difficult question of estimating the impact on ecosystem services of a human-caused disaster like the DWH spill. They seek to provide guidance on methods for identifying critical ecosystem services, for understanding the relevant spatial and temporal scales that need to be studied, and for establishing the baselines critical in determining the "injuries" caused by the incident. The third question focuses on the specific problem of assigning value to the impacted ecosystem services. These questions are best addressed with reference to

BOX I.2 STATEMENT OF TASK

1. What methods are available for identifying and quantifying various ecosystem services? What are the spatial and temporal scales conducive to research that provide meaningful information for the public and decision makers?
2. What methods and types of information can be used to approximate baselines (but for the spill) for distinguishing effects on ecosystem services specific to the spill?
3. What kinds of valuation methods are appropriate for measuring ecosystem services over time with regard to recovery under the following approaches: natural processes, mitigation, and restoration efforts? What baseline measures are available that would provide benchmarks for recovery and restoration efforts?
4. What ecosystem services (provisioning, supporting, regulating, and cultural services) were provided in the GoM LME prior to the oil spill? How do these differ among the subregions of the GoM?
5. In general terms, how did the spill affect each of these services, and what is known about potential long-term impacts given the other stresses, such as coastal wetland loss, on the Gulf ecosystem?
6. How do spill response technologies (e.g., dispersant use, coastal berm construction, absorbent booms, in situ burning) affect ecosystem services, taking into account the relative effectiveness of these techniques in removing or reducing the impacts of spilled oil?
7. In light of the multiple stresses on the GoM ecosystem, what practical approaches can managers take to restore and increase the resiliency of ecosystem services to future events such as the DWH spill? How can the increase in ecosystem resiliency be measured?
8. What long-term research activities and observational systems are needed to understand, monitor, and value trends and variations in ecosystem services and to allow the calculation of indices to compare with benchmark levels as recovery goals for ecosystem services in the GoM?

ecosystem services provided by the GoM LME and thus we will frame our responses within that context. We also acknowledge that there is a number of human health issues associated with the DWH event, but we will not address them, as they are specifically the subject of an Institute of Medicine (IOM) 2010 letter report: *Research Priorities for Assessing Health Effects from the Gulf of Mexico Oil Spill* (Institute of Medicine, 2010).

The lexicon of natural resource damage assessment uses many words that may seem familiar but have very specific (and sometimes multiple) definitions within the context of the process. Terms that will be used throughout the report are defined below. Chapter 1 outlines the geographic, oceanographic, and ecological context of the GoM LME. Chapter 2 explores the typical practice of damage assessment and introduces the ecosystem services approach to damage assessment. Chapter 3 describes methodologies for establishing baseline information for ecosystem services and, where possible, discusses existing baseline data. Finally, Chapter 4 takes a detailed look at the ecosystem services approach including methods to identify and quantify ecosystem services and, taking this one step further, looks at the most appropriate methodologies for assessing the value of key ecosystem services. Each of these issues, as well as the additional questions presented in the Statement of Task, will be addressed in more detail in the final report.

DEFINITIONS OF TERMS

Ecosystem: A complex, interactive system consisting of all organisms in a particular area, the physical components of the environment within which the organisms interact, physical features including hydrology, temperature, geology, air quality, and others, and the flow and transformation of energy and matter between organisms, and organisms and the environment. Eugene Odum defined an ecosystem as "Any unit that includes all of the organisms (i.e., the 'community') in a given area interacting with the physical environment so that a flow of energy leads to clearly defined trophic structure, biotic diversity, and material cycles (i.e., exchange of materials between living and nonliving parts) within the system" (Odum and Barrett, 2005). Increasingly, it is evident that human beings are a critical component of ecosystems; consideration of ecosystems must include the influence of human social structure on the ecosystem, as well as the influences of the ecosystem on human society.

Large marine ecosystem: In order to define specific large geographic areas for resource management, river basins, estuaries, and coastal shelf areas have been subdivided into "large marine ecosystems" (LMEs). LMEs are defined by unique hydrography, bathymetry, and productivity (Griffis and Kimball, 1996). They may cross international borders, providing unique opportunities and challenges for successful management.

The Gulf of Mexico is recognized as a distinct Large Marine Ecosystem. The GoM LME is one of the most biologically productive in the world. It crosses boundaries between the United States, Cuba, and Mexico and provides an opportunity for transnational management of important natural and cultural resources. Habitats within the GoM LME include coastal wetlands, salt marshes, mangroves, sandy beaches, coastal shelf marine ecosystems, and deep-sea marine ecosystems. Each habitat provides distinct services that need to be accounted for in any valuation of the impacts of the Deepwater Horizon oil spill. The geographic, oceanographic, and ecological contexts of the GoM LME are discussed in Chapter 1.

Ecosystem structure: Ecosystem structure refers to both the (species) composition of the ecosystem (i.e., its various organisms) and the physical and biological organization defining how those parts are organized (NRC, 2005a). The Gulf of Mexico has recently been estimated to contain in excess of 15,000 species exclusive of microbes (Felder and Camp, 2010).

Ecosystem function: A process that takes place in an ecosystem as a result of the interactions of plants, animals, microorganisms, and their environment. Primary production, most notably the generation of plant material, is an example of an ecosystem function (NRC, 2005a). All recognized coastal and oceanic ecosystem functions operate in the Gulf of Mexico.

Ecosystem service: There is a rich and evolving literature on ecosystem services with a variety of definitions (e.g., Westman, 1977; Ehrlich and Mooney, 1983; de Groot, 1987; Barbier, 1994; Costanza et al., 1997; Daily, 1997; Wilson and Carpenter, 1999; de Groot et al., 2002, Millennium Ecosystem Assessment, 2005; NRC, 2005a; EPA, 2009; TEEB, 2009). The common thread through all of these definitions is a relationship between ecosystems and the value humans derive from them. In 2000, the United Nations commissioned the Millennium Ecosystem Assessment (MA) to summarize the current status and future conditions of biodiversity and ecosystems and determine the consequences of ecosystem change for human well-being. The MA defines ecosystem services as "*the benefits provided by ecosystems to humans which contribute to making human life both possible and worth living*." Moreover, the MA defined explicit categories of ecosystem services including provisioning, regulating, cultural, and supporting services. These service categories are now widely accepted. In order to apply the MA definition to the GoM, the definition needs to make explicit the distinction between the different ecosystems present in the GoM LME and the goods and services provided by each.

Value: In this report we use the term value in the way that economists tend to define it. The value of an item is measured by its contribution to human well-being. A measure of the value of a good or service to an individual can be obtained by observing what the individual is willing to give up in exchange for an increase in the good or service. Economists typically attempt to measure benefits in monetary terms by seeing how much an individual would be willing to pay to obtain more of a good or service. Alternatively value can be measured by, what an individual would be willing to accept for less of the good or service. For ecosystem services that are provided to the public at large, the value of a change in the ecosystem service would be found by summing up the estimated values across all individuals affected by a change in the provision of the service. This aggregated value would then represent an overall societal value that occurs because of a *change* in the ecosystem.

Economists have several methods that may be used to determine the value of particular ecosystem services. These methods are generally divided into market valuation methods that are based on market prices, and non-market values in which proxies for prices are developed either from observed behavior (revealed preference methods) or from responses to survey questions (stated preference methods). Some ecosystem services contribute to marketed commodities (e.g., commercial fisheries) but most ecosystem services do not. It tends to be more difficult to place an economic value on a service where there is no actively traded good or service in a market. Though even among non-marketed ecosystem services there is a range of difficulty, with those that affect recreation being more amenable to valuation than the existence value of a species or spiritual or aesthetic values. This committee has been tasked with describing the strengths and weaknesses of various valuation methods rather than placing a specific monetary value or some other quantitative estimate of value on the impact of the DWH spill on ecosystem services. Approaches to valuation of ecosystem services will be discussed in Chapter 4.

Baseline: The condition of the natural resources and services that would have existed had the incident not occurred.[5] Within the context of the DWH spill and a system like the GoM that has numerous factors impacting ecosystem health, the concept is to establish conditions "but for the spill." Approaches for establishing baselines for various ecosystem services and baseline data sources (if available) for the GoM LME will be presented in

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[5] See http://www.dem.ri.gov/topics/erp/app2_3.pdf.

Chapter 3.

Resilience: Narrowly defined, resilience is the ability of an ecosystem to recover following a perturbation. As described in the NRC report *Increasing Capacity for Stewardship of Oceans and Coasts* (2008b), "Resilience thinking is one new approach to addressing the decline in the capacity of communities, ecosystems, and landscapes to provide essential services. The intent is to recognize the complexity and variability of ecosystems, including the human component, and to build nature-human systems that can adapt to incorporate new knowledge or adjust to changing conditions."

1

Physiographic, Oceanographic, and Ecological Context of the Gulf of Mexico

Unique aspects of the Gulf of Mexico (GoM), its abundant hydrocarbon resources and the exceptional habitat and ecosystems at risk, cannot be understood without an initial consideration of the processes responsible for creation and maintenance of the basin and its ecosystems. Thus, we begin our report with an overview of the geographic, oceanographic, and ecological setting of the GoM. It is only within this context that we can properly identify appropriate approaches for delineating, quantifying, and valuing the impact of the Deepwater Horizon Mississippi Canyon-252 (DWH) oil spill on ecosystem services and hope to understand the complex and dynamically changing baselines associated with the GoM. We also recognize that the term "baseline" has a specific meaning in the context of the Natural Resource Damage Assessment program (see Definitions in Introduction) and will endeavor to incorporate that into our analysis and discussion.

GEOLOGIC AND PHYSIOGRAPHIC SETTING

The modern GoM originated approximately 200 million years ago (mya) with rifting of the supercontinent of Pangaea. As this rifting continued, the continental crust thinned and eventually shallow basins were flooded with sea water through a connection to the Pacific Ocean. During this time (approximately 180-200 mya) thick deposits of salt and other evaporates accumulated in the shallow basin (Salvador, 1991). Today this salt plays a key role in creating an environment that is conducive to the accumulation and production of hydrocarbons. As rifting continued, the basin deepened, the Yucatan Peninsula rotated from Florida (Pindell and Kennan, 2009), Atlantic waters entered, and salt deposition stopped. The overall process resulted in a shelf-rimmed basin approximately 3,500 m deep with steep carbonate banks at the eastern (West Florida Escarpment) and southern (Campeche Escarpment) margins (Figure 1.1).

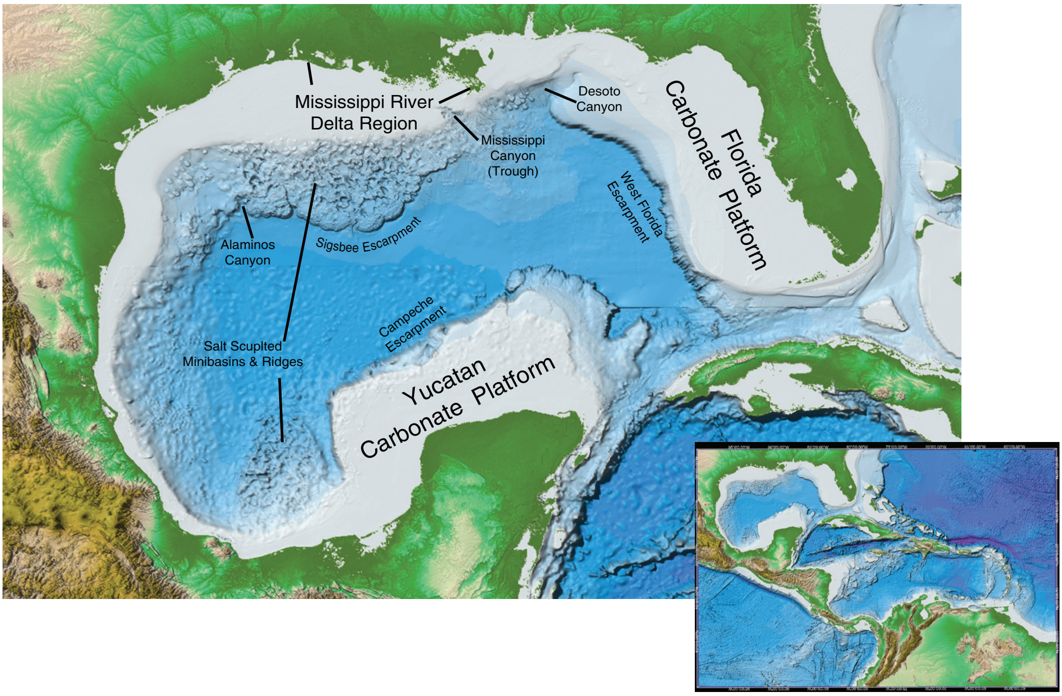

FIGURE 1.1 ETOPO1 Global Relief Model of the Gulf of Mexico Large Marine Ecosystem with inset of the Gulf-Caribbean complex (based on data from Amante and Eakins, 2009).
SOURCE: Based on data from Amante, C. and B. W. Eakins, ETOPO1 1 Arc-Minute Global Relief Model: Procedures, Data Sources and Analysis. NOAA Technical Memorandum NESDIS NGDC-24, 19 pp, March 2009. Image constructed using Fledermaus visualization software (http://www.ivs3d.com/products/fledermaus/).

Since the time of this rifting and deepening of the basin (about 180 mya), the GoM has continuously received large amounts of sediment from the surrounding continents with by far the greatest input coming from the central portion of the North American continent. The modern Mississippi and Atchafalaya rivers, with their extensive deltas and a deep-sea fan, are the most recent manifestations of this sedimentation. The organic debris, particulates, and dissolved nutrients introduced into the Gulf by these rivers ensured high primary productivity, high carbon-content sediments, and abundant hydrocarbon resource rocks. The subsidence of the basin along with the massive sediment loads provided by river input created the appropriate burial conditions (pressure and heat) to form oil and gas from these source rocks. Movement of the deeply buried salt created traps and paths for the oil and gas as well as a unique morphology of basins and domes in some areas of the slope (Figure 1.1). The GoM was, through its geologic past, an ideal environment for the generation and accumulation of recoverable hydrocarbon resources.

The entire continental margin in the northern GoM continues to be shaped by high sediment loads and the movement of salt within the strata of the margin. The salt tectonics (movement) generates hydrocarbon migration paths from source to reservoir. The Macondo well targeted hydrocarbons trapped in Miocene (~12 mya) sand strata that are bounded by several salt dome features. Frequently, the migration paths lead to the sediment surface (Roberts and Carney, 1997) resulting in the creation of cold seep communities dependent on chemically extreme conditions. Seepage from these conduits results in the natural injection of gas, liquid hydrocarbons, and brines into the deep water of the Gulf.

In addition to the impact of salt migration, typical margin-forming processes like sea-level change, erosion, and currents have also shaped the margin and impacted the creation of submarine canyons. The result is a series of seafloor ridges, minibasins, canyons, and escarpments (Jackson et al., 2010) (Figure 1.1). As topographically complex as the Gulf margin is, however, the largest portion of this system is blanketed with sediments built up from terrestrial runoff and from the remains of pelagic organisms forming a vast soft-bottom habitat.

DELTA ENVIRONMENTS AND NEARSHORE HABITATS

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

Sediment deposition and accumulation are essential for maintaining the delta, offsetting natural subsidence, and preventing drowning of wetlands. Over tens of thousands of years, the flow of sediment-laden freshwater created a series of delta lobes that prograded (moved seaward), subsided, and switched across the northern Gulf coastal landscape, establishing a deltaic plain that eventually formed the current Mississippi River delta about 1,000 years ago (Penland et al., 1988). Alongshore flow of water and sandy sediments formed ridges and cheniers (historic barrier ridges) at different locations as sea level changed, which, in turn, provided forested canopy areas. As the delta formation prograded, barrier island arcs formed. Over time the barrier islands fragmented into smaller islands with coastal lagoons. Smaller rivers created smaller deltas or drowned river basins that became bays and estuaries. Multiple habitats were shaped over geologic time, which continue to experience natural evolution modified by human activities and the persistent need for sediment input to counteract increasing sea level rise.

Wetlands across the coast were historically sustained by substantial input of river sediments. Over two centuries, the transformation to a primarily agricultural landscape, with water systems engineered for drainage of agricultural lands, navigation, and flood control, has altered the river basin landscape, changed flow regimes, and reduced the suspended sediment load. These changes have lessened the ability of the watershed to buffer the effect of excess nutrients and other pollutants and have contributed to the loss of landforms in the watershed and at the coast (Boesch et al., 1994; Turner and Rabalais, 2003). Watershed manipulations along with natural deltaic processes and intense human development of the coastal zone have resulted in the loss of over 5,000 km^2 of wetlands since the 1930s (updated from Barras, 2006).

Meade (1995) estimated that the sediment load of the Mississippi River since the beginning of the twentieth century is roughly half of its contribution in the early 1700s. During the twentieth century, the hydrology of the Mississippi River system was greatly altered by locks, dams, reservoirs, earthwork levees, channel straightening, and spillways for purposes of flood protection, navigation, and water supply. The largest decrease in suspended sediments occurred after 1950, when the natural sources of sediments in the drainage basin were cut off from the Mississippi River mainstem by the construction of large reservoirs on the Missouri and Arkansas rivers (Meade and Parker, 1985; NRC, 2008a; Blum and Roberts, 2009). For the period 1975-2006, the mean suspended load for the combined Mississippi and Atchafalaya rivers was 205 mt y^{-1} (Blum and Roberts, 2009), less than the time-average rates for sediment storage that were necessary to construct the current delta plain. Thus the modern delta plain is limited in sediment supply and will undergo substantial drowning by 2100 because sea level is now rising at least three times faster than during delta-plain construction (Blum and Roberts, 2009). This change in sedimentation rates is just one part of the dynamic baseline for the GoM that must be considered when assessing impacts on ecosystem services in this region.

METEOROLOGIC AND OCEANOGRAPHIC SETTING

Meteorology

Wind plays an important role in shaping the physical environment of the GoM. Yet, there is a surprising lack of literature providing an overview of the region's meteorology. One of the better analyses comes from Mueller and Willis (1983), who examined a 30-year record from New Orleans and characterized the weather into eight types, further categorized by three indices:

1. Continental Index (CI) characterized by northerly winds and dry cooler air.
2. Tropical Index (TI) characterized by southerly warm and moist winds.
3. Storminess Index (SI) characterized by strong winds driven by extratropical storms in the winter and tropical storms in the summer.

From October to January, the CI occurs approximately 60 percent of the time, and then drops steadily to a minimum in July. Conversely the TI peaks near 90 percent from June to August but is much less pronounced during October to February, when it reaches a minimum near 20 percent. The SI peaks at about 50 percent during the months of December to February when extratropical or "winter" storms pass on approximately a biweekly basis; from April through October, the SI is approximately 25 percent. In addition to the larger scale processes identified above, land-sea breezes generated by cooler land temperatures at night are prominent in some parts of the Gulf, especially coastal Texas (Yocke et al., 2000). They tend to be weakest off Louisiana, probably due to the predominance of swamps and a poorly defined coastline. Spatially, the land-sea breezes extend at most about 50 km offshore.

A considerable number of meteorological measurements (wind velocity, pressure, temperature, and humidity) are available from land-based coastal sites as well as offshore buoys. The primary sources of data are archived at the National Data Buoy Center (NDBC) although a substantial number of measurements are collected by buoys operated by the Texas General Land Office.[1] Yocke et al. (2000) provide a summary of NDBC and coastal measurements in the northeastern Gulf from 1996 to 1997. Figure 1.2 illustrates wind roses for NDBC 42001 located roughly in the center of the Gulf at 26°N, 89.7°W. Plots near the northern coast look qualitatively similar. Since

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[1] See http://tabs-os.gerg.tamu.edu/tglo/.

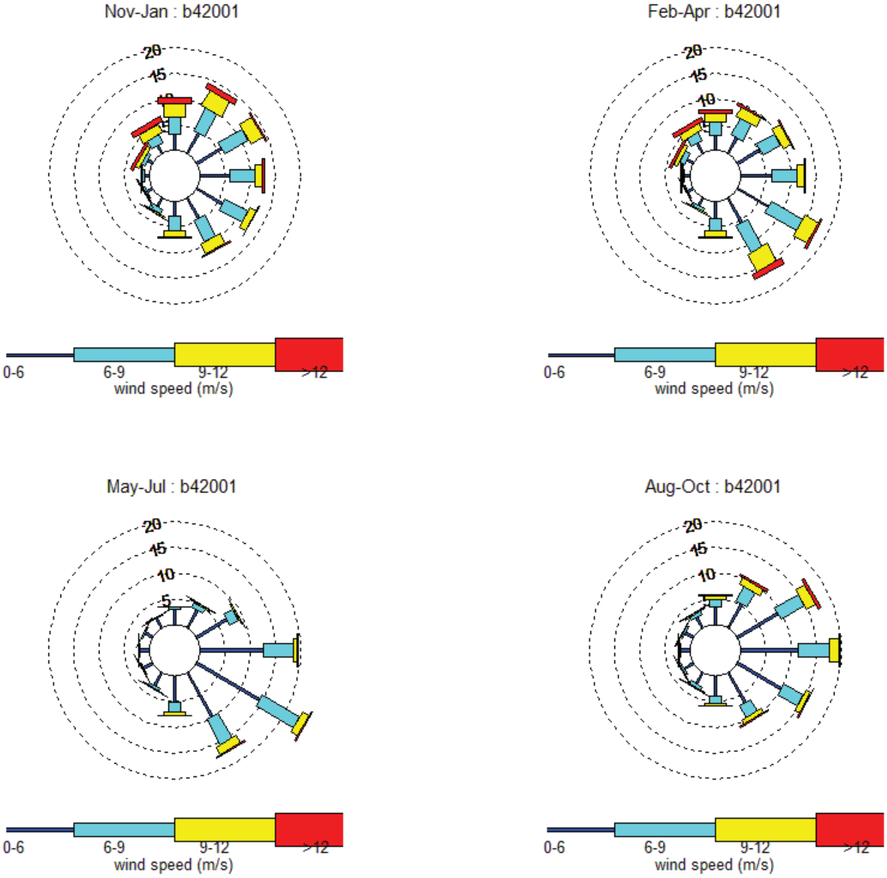

FIGURE 1.2 Seasonal wind roses for NDBC Buoy 42001 located roughly in the center of the Gulf. The dotted circles indicate the percent time of occurrence while the colors indicate the speed bin.
SOURCE: Image created by committee using data from NOAA's National Data Buoy Center, station 42001 (http://www.ndbc.noaa.gov/station_page.php?station=42001).

the Gulf tends to be relatively warm and humid, it is a primary source of moisture for rain over approximately half of the continental United States (Vachon et al., 2010).

Physical Oceanography

The GoM is the largest and northernmost series of basins forming the Gulf-Caribbean complex (see Figure 1.1). Semi-isolated on the western periphery of the Atlantic, the pelagic components of the complex are very closely linked to the larger ocean by the intensified western boundary current of the North Atlantic gyre. Surface waters of this current flow through the shallow gaps between Caribbean islands and enter the Gulf through the Yucatan Strait, exiting through the Florida Strait. Deep flow is less well understood within the two deep channels connecting the Caribbean to the Atlantic. The multiple types of ocean currents in the Gulf have been analyzed and summarized in the literature, including a Gulf-wide summary by Wiseman and Sturges (1999); a thorough analysis and synthesis of historical data in deepwater by Nowlin et al. (2000); and a more recent anthology of papers on Gulf circulation, most focused on deepwater, by Sturgis and Lugo-Fernandez (2005), with one paper in the anthology specifically summarizing the state of knowledge (Schmitz et al., 2005).

Deepwater Circulation

In the east-central Gulf, ocean currents in the upper 1,000 m of the water column are often dominated by the Loop Current, a warm ocean current that eventually joins the Gulf Stream (Figure 1.3). The northward extent of the Loop varies by 400 km over the span of roughly a year, at times extending north to the outer shelf of Louisiana, Mississippi, Alabama, and the Florida Panhandle. During this northward extension, the Loop "pinches" west of Key West and forms an eddy (henceforth referred to as an "LCE," Loop Current Eddy) of 150-400 km in diameter. Eventually the LCE migrates to the west at about 2-5 km d^{-1}. After a journey of several months it collides with the western Gulf shelf where it slowly decays over the course of a year. Horizontally, the currents in an LCE vary nearly linearly from a peak of 1-2 m s^{-1} at the outer edge to near zero at the center. Below 75 m depth, the currents decay exponentially and are minimal by 1,000 m (Cooper et al., 1990).

The Loop Current and LCE serve as important transport mechanisms in the Gulf, bringing in approximately 28×10^6 m^3 s^{-1} of relatively warm, salty Caribbean waters. While attached to the Florida Current, most of this water exits a week or so later through the Florida Strait, after the Loop has entrained some indigenous Gulf water and diffused some of its own salty warm water into the Gulf. The more significant transport occurs when an LCE separates and later unravels in the western Gulf. Both mechanisms work to transport pollutants and shelf waters, including freshwater runoff with its constituents (sediment, nutrients, pollutants, and organic carbon) from the major Gulf rivers.

In addition to the LCEs, the Gulf is teeming with mesoscale eddies

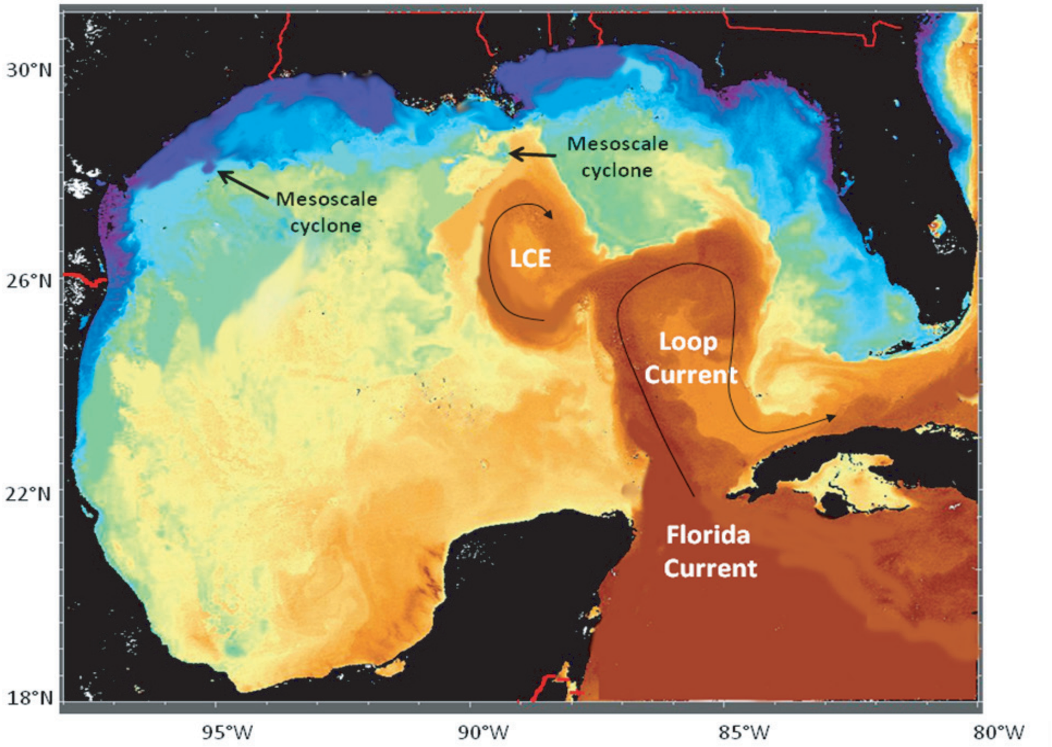

FIGURE 1.3 Infrared satellite image showing major surface currents in the Gulf (LCE = Loop Current Eddy). Red colors indicate warm water while blue colors indicate cold water.
SOURCE: Copyright © 2011 The Johns Hopkins University Applied Physics Laboratory. All Rights Reserved.

(cyclones) on the order of 30 km in diameter with peak speeds of 50 cm s^{-1} (Schmitz et al., 2005; Figure 1.3). Some are generated by the strong shear found along the periphery of the Loop Current and LCE but others form along additional fronts, as demonstrated by the eddy separating colder and fresher shelf and slope waters (Figure 1.3). As with the LCEs, mesoscale eddies have the potential to transport freshwater constituents over distances, although the amount of transport is limited by the smaller size (30 km) and shorter life spans (on the order of one week). Both LCEs and mesoscale eddies are important means of transporting water between the shelf and the deeper Gulf (Schmitz et al., 2005).

Another persistent and energetic deepwater current in the Gulf can be traced to planetary waves, also known as Rossby Waves, which were first documented by Hamilton (1990). These ubiquitous waves have periods on the order of 14 days and propagate across the deepwater Gulf generating currents on the order of 15 cm s^{-1} through much of the water column. Within a few kilometers of the Sigsbee Escarpment (Figure 1.1), the sharp topography can trap and substantially intensify these planetary waves, generating currents on the order of 100 cm s^{-1} near the bottom in 2,000 m of water (Dukhovskoy et al., 2009). Because these waves have long wavelengths, on the order of 100 km, they are also capable of transporting pollutants or other materials some distance over a one-to-two-week period. The oscillatory nature of waves, however, might also cause pollutants to be returned when the current reverses direction. This phenomenon was thought to be the mechanism of transport for the large deepwater plume of oil from the Macondo wellhead (Camilli et al., 2010).

Currents driven by astronomical tides in the deepwater Gulf are weak in amplitude with small spatial changes in phase (Reid and Whitaker, 1981). Typical currents in deepwater are less than 2 cm s^{-1}. Mean wind-driven currents in the deepwater Gulf are not readily discernible although a number of authors conjecture the existence of weak anticyclonic gyres in the western and central Gulf that could be partially driven by large-scale winds (see Schmitz et al., 2005). Despite the weak mean winds, the Gulf is subjected to strong storm winds. During hurricanes, currents on the order of 2 m s^{-1} can be generated over the mixed layer for a few hours. These storms can also generate inertial currents with periods of approximately 24 hours and oscillations of 50 cm s^{-1} that reach deep into the water column and persist for several days after storm passage (Brooks, 1983). The storm-driven response during winter storms is much weaker than during hurricanes, reflecting the weaker winds and the deeper mixed layer typical of fall-winter months. Because the currents are primarily oscillatory, inertial currents cannot transport pollutants more than a few tens of kilometers.

There have been few published investigations of the deeper layers of the Gulf with the major exception of DeHaan and Sturges (2005) and Weatherly et al. (2005); the currents they discuss are only a few cm s^{-1} in strength.

Shelf Circulation

Circulation on the shelf is closely tied to the local topography reflecting the importance of friction in the current dynamics. In general, tidal currents are on the order of 5 cm s^{-1}. Regardless of the location, winds are a factor especially during tropical cyclones or winter storms. The transfer of wind energy through the water column is dramatically affected by stratification induced by solar heating and the substantial freshwater discharge from the major rivers in the Gulf. When this stratification is strongest, near-bottom currents become uncorrelated with the local winds, although if the winds change rapidly some wind energy penetrates downward via inertial oscillations (Wiseman et al., 2004).

Other significant types of currents vary according to the region as follows:

- The west Florida shelf is discussed in some detail by Weisberg et al. (2005). Wind forcing is dominant over most of the shelf with upwelling in the winter and downwelling in the summer. The Loop Current sets up a large-scale sea-level gradient along the shelf that models suggest can generate substantial southerly currents.
- On the Mississippi-Alabama shelf, the discharge from the Mobile-Tombigbee, Pascagoula, Pearl, and Mississippi rivers are an important influence on near-surface stratification, which in turn affects the transfer of wind through the water column. A mean cyclonic surface circulation has been suggested by Dinnel (1988), although there is no evidence of this circulation in the more recent analysis of DiMarco et al. (2005). On the outer shelf, major intrusions of the Loop Current and LCE occur every few years and can persist for one to two months causing large exchanges between the shelf and slope as summarized by Schmitz et al. (2005).
- On the Louisiana-Texas shelf, the Mississippi and Atchafalaya rivers play a large role in modifying the vertical stratification, which in turn affects the transfer of wind through the water column. The general circulation pattern is a large but weak (on the order of 5 cm s^{-1} on average) cyclonic cell, though its direction can be reversed during mid-summer in the presence of stronger westerly winds (Cochrane and Kelly, 1986). Upwelling favorable conditions can occur with winds from the north in the summer (Wisemann et al., 2004).

Estuarine Circulation

Numerous estuaries break up the coastline along the northern Gulf. An extensive system of bayous surrounds the Mississippi and Atchafalaya rivers. Currents in these areas are dominated by river discharges and wind. Direct transfer of wind momentum to the lower water column is often constrained by freshwater stratification but, given the close proximity of land, the wind can also set up larger scale pressure gradients that effectively drive flow beneath the mixed layer.

ECOLOGICAL SETTING

Habitat Characterization

Within the context of ecosystem services, habitat provides one description of ecosystem structure. Stated simply, habitat is the place where an organism or a recurrent suite of organisms lives. Given that biotic content is the primary criteria for recognition of habitats, the geospatial task of mapping habitats should be based on the single criterion of a comprehensive biotic inventory, at least conceptually. Unfortunately, such highly detailed surveys are seldom feasible over management-relevant spatial scales and time constraints. Habitat mapping, therefore, proceeds with the use of alternative criteria. Among the numerous alternatives in use, one requires narrowing actual biotic surveys to a few indicator species (e.g., mangrove habitat, fish habitat, brown pelican habitat, red snapper habitat, cold coral habitat, etc.). Habitats can also be delineated on the basis of abiotic factors known to have a strong correlation with a particular suite of species (e.g., low salinity habitat, subtidal habitat, deepwater habitat, etc.). In an attempt to include many types of information in habitat classifications various metrics have been proposed; Diaz et al. (2004) identified 64 separate metrics that have been used or proposed. With such a multitude of criteria, it is easy to understand that Franschetti et al. (2008) found 1,121 European marine habitats, but was able to reduce them to a list of only 94.

Among the marine habitats, coastal ones are the best characterized and delineated. The importance of emergent vegetation, where present, as a structuring component of habitat has led to a long-standing tradition of classification based on plant cover. The strong correlation between plant community and abiotic factors such as inundation, salinity, and substrate allow non-biotic mapping of habitats that are largely consistent with biotic criteria. Beyond the beach and progressing into deeper water, characterizing habitats becomes increasingly tentative. Data for strictly biotic criteria are increasingly hard to gather, and the use of a few "indicator species" probably has minimal ecological relevance. Advancement in acoustic seafloor mapping has resulted in considerable interest in habitat classification using remote and rapid surveys of bathymetric and seafloor characteristics (Kenny et al., 2003; Todd and Greene, 2008). The unfortunate limitation of these approaches lies in the difficulty of determining if a substantial correlation with seafloor biology exists (Diaz et al., 2004; Stevens and Connolly, 2004). The approach may be best applied to bathymetric relief seafloors. It may be far less useful when applied to the far more common mud bottoms like those across much of the GoM (Zajac, 2008).

Even though the continental shelf and slope of the GoM are probably the most extensively surveyed part of the U.S. Exclusive Economic Zone (EEZ), due in large part to the energy industry's interest in gas and oil extraction from these areas, little use has been made of these largely proprietary data to classify habitats. Two notable exceptions of available bathymetric survey data were used to identify topographic highs and possible hard bottom on the shelf and slope. These were surveys of the Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE, formerly Minerals Management Service) for fluid and gas expulsion (Chem III, Roberts et al., 2008) and deepwater *Lophelia* spp. corals (Lophelia II, project under way). The data produced from these industry-related surveys are online.[2] The identified geologic features in both shallow and deep waters provide habitat for protected corals and seep communities. Actual confirmation of the habitat type is based upon direct faunal sampling and imaging of the biota.

In summary, marine habitats are almost never identified and mapped on the basis of a single main criterion. Multiple criteria are applied, producing numerous and often overlapping classifications. While potentially confusing, the reality of nature is that no single factor or even suite of factors consistently controls the biota living across the many gradients encountered in the ocean. One thing is most certain, the more a seemingly homogeneous habitat is studied, the more complex it is shown to be.

Inshore Habitats of the GOM

Inshore habitats of the northern GoM range from uplands through intertidal areas and wetlands to open bodies of water in bays and lagoons sheltered from the open Gulf by barrier island formations or emptied through tidal passes and open connections with Gulf waters. At the interface of upland and open water are numerous types of wetlands that receive periodic or tidally influenced submersion of soils and plants. Classes of wetlands that occur within the GoM are estuarine emergent (e.g., tidal marshes), estuarine shrub-scrub (e.g., mangroves), freshwater emergent (e.g., freshwater marsh or floatant), and freshwater shrub-scrub and forested (e.g., cypress swamps) (Cowardin et al., 1979).

Typical tidal marshes along the northern rim are *Spartina patens* and *Spartina alterniflora* marshes; the former are found in upland, brackish conditions less frequently submerged, and the latter form expansive landscapes

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[2] See http://www.boemre.gov/offshore/mapping/SeismicWaterBottomAnomalies.htm.

in frequently flooded saline waters. Black needlerush, *Juncus romerianus,* grows on elevated mud deposits and is usually flooded only during high tide. Sawgrass, *Cladium jamaicense*, occupies an intermediate marsh zone, preferring lower salinities and more flooding than other marsh species, a good indication of regular freshwater flow. Marshes are interspersed with elevations, hammocks, or cheniers that support coastal forests.

Mangroves (*Avicennia germinans)* dominate coastal wetlands in tropical and subtropical latitudes and occur primarily in Texas and Florida, but also in Louisiana, Mississippi, and Alabama depending on temperature regimes. Mangroves are sensitive to cold temperatures and tend to be smaller in the northern part of their range. Severe freezes that typically occur in 10-year cycles kill back mangroves, which can take 5-10 years to reestablish. In the meantime, the mangroves are replaced by smooth cordgrass (*Spartina alterniflora*) until the mangroves recover. Along the most northern coasts of the GoM, *Spartina alterniflora* marshes compete with mangroves for domination of the saltier parts of the system.

The marsh is dotted with treed islands of coastal forest, commonly called hammocks. These hammocks have little tolerance for salt and grow only where the elevation is high enough to prevent flooding during high tides. The most common tree species on a coastal hammock are sabal palm (*Sabal palmetto*), red cedar (*Juniperus silicicola*), pine (*Pinus elliottii*), and live oak (*Quercus virginiana*).

Mud or sand tidal flats form above the mean high water, just beyond the reach of the highest tides in the high marsh. Only occasional storm-driven high tides flood the tidal flats. Salts accumulate because there is not enough flushing to wash them away and only the most salt-tolerant plants such as pickleweed and glassworts grow in a tidal flat.

Open water areas of the northern GoM are usually in the form of lagoons and bays. The formation of different habitats depends on substrate type (mud to sand) and depth. Open bay and estuarine waters are soft-bottom habitats that usually lack visible vegetation. In shallower intertidal muddy areas, oyster reefs develop along tidal creeks and open water where the tidal setting is low-energy with adequate but not excessive freshwater flow from surface runoff or river input. Oyster reefs are bioherms; they form a biologically based substrate for use by other organisms. In sandier protected bay and lagoon settings, submerged seagrass meadows are common where water clarity is suitable for their growth. Common sea grasses in the northern Gulf are turtle grass (*Thalassia testidinum*), shoal grass (*Halodule wrightii*), manatee grass (*Syringodium filiforme*), widgeon grass (*Ruppia maritima*), and star grass (*Halophila engelmannii*).

Coastal habitats provide a wide range of ecosystem services, including support for fishery production, water quality improvement, nutrient cycling, wildlife habitat provision, recreational opportunities, storm surge protection, carbon sequestration, and social support of coastal-based economies, such as oyster harvesting, tourism (specifically ecotourism), resource extraction, and water-borne transportation. These coastal habitats provide shelter and food resources for fishes, crustaceans, and shellfish.

Wetlands are widely recognized for their capacity to remove nutrients and pollutants from overlying waters, in effect improving water quality, recycling reactive nitrogen to N_2 gas and reducing the potential for eutrophication, defined as the increase in the rate of primary production and accumulation of resulting organic carbon in an aquatic system (modified Rabalais, 2004 and Nixon, 1995). Eutrophication is manifested as turbid waters, growth of filamentous algae on seagrass blades, noxious and harmful algal blooms, and oxygen depletion (as microbes decompose the accumulating carbon). The removal of nitrogen depends on the type of wetland, the concentration of nitrogen entering the wetland, the water residence time, and the acreage available for the denitrification process.

Offshore Habitats

Offshore habitats of the northern GoM start at the low-tide level on coastal shores and extend to the Sigsbee abyssal plain with a maximum depth > 3,800 m. About 40 percent of the area is covered by vertically mixed shelf water that is influenced by freshwater inflows of the 20 large river systems draining into the coast. The break between continental shelf and slope varies around the circumference of the Gulf. In general it begins between 100 and 150 m giving the shelf a width ranging from 90 km off southern Texas to 220 km off Florida. Unusually narrow 12 km and 32 km shelves are encountered off the mouth of the Mississippi River and at the head of Desoto Canyon. The substrate is predominantly near-shore sands grading seaward to silt and mud. There is a related transition in the species composition of bottom fauna. Shelf populations of the shrimp *Litopenaeus setiferus* and *Farfantepenaeus aztecus* support a major commercial fishery. Fish such as red snapper (*Lutjanus campechanus*) support both commercial and recreational fisheries. The shelf contains essential habitat for estuarine-dependent species with life histories that include an estuary-to-ocean migration.

The periphery of the Gulf of Mexico is characterized by a remarkable diversity of hard-bottom features rising from the seafloor and forming a series of elevated bathymetric features. Some of these features are ancient shorelines, others former seabeds thrust up by salt movement. Still others originate from ancient coral reef growth. These hard banks support diverse communities of tropical and subtropical plants, invertebrates, and fishes and are considered to be sensitive habitats. The structures that rise a few meters above the surrounding seafloor, such as a series of shoals off the Atchafalaya River delta, provide refugia from seasonal bottom-water hypoxia on the northern Gulf of Mexico. Middle and outer shelf hard-bottom structures are mostly drowned reefs, or are associated with salt domes and outcrops of limestone, sandstone, claystone, and siltstone with a variety of soft coral, sponge, and macroalgae. These banks are considered to be critical spawning habitat for many commercially important species of groupers and snappers. Banks reaching to the euphotic zone and supporting coral reefs are few in the northernmost Gulf (East and West Flower Garden Banks) but become increasingly abundant on the central and southern Florida coast (Pulley Ridge and Tortugas Bank). The coral framework is dominated by *Montastrea annulari, Montastrea cavernosa, Diploria strigosa,* and *Porites astreoides*. Like coral reefs everywhere, the Gulf reefs are biodiversity hotspots with strong aesthetic appeal that support fisheries, biological prospecting, and recreational uses. Some of these high-diversity habitats can be found within one of the designated areas of the National Marine Sanctuary Program, or are listed as a Habitat of Particular Concern by BOEMRE for restricted activities.

Offshore from the edge of the shelf, two oceanographic features previously described impact the habitats of the deep basin: the Loop Current that brings Caribbean waters into the Gulf from its southwestern boundary of the Yucatan Strait and the anticyclonic cell circulation along the western side. These two features are distinct because of seasonal differences in the depth of their thermoclines (Cochrane, 1972) that create conditions for different marine community composition. In the northern GoM, the continental slope is atypically diverse due to the unusual combination of geological processes described earlier. The complex geomorphologies of the sediment slope and its basins and ridges have diverse fauna with typical depth-related declines in biomass and species, replacement deposits, and an overall maximum species richness that occurs at mid-slope depths. Fishes and crabs decrease in diversity with depth, while echinoderms and sediment-dwelling worms increase. The biological communities of the vast mud bottoms are the last consumers of organic carbon before the residual carbon becomes buried. Fisheries exploitation of deepwater is minimal, but specialized trawl fisheries exist for royal red shrimp (*Hymenoenaeus robustus*), rock shrimp (*Sicyonia brevirostris*), and calico scallop (*Agropecten gibbus*).

Surface-water habitats such as Sargassum mats (Wells and Rooker, 2004) and water column communities are influenced by a number of important oceanographic variables, including

1. dissolved oxygen levels (Prince and Goodyear, 2006),
2. the location of the thermocline (Bigelow and Maunder, 2007),
3. light levels (Dewar et al., 2011), and
4. the presence of oceanic fronts in the edges of the Loop Current and ocean eddies (Kleisner et al., 2007).

The thermocline can be a boundary for many epipelagic (upper water) organisms. Mesopelagic organisms occupy the waters below this boundary, while photosynthetic organisms are absent in the bathypelagic zone which is almost completely absent of light. Most organisms remain within their respective zones, but some migrate between the epipelagic and mesopelagic in search of prey, for example swordfish (*Xiphias gladius*) (Dewar et al., 2011) and blue marlin (*Makaira nigicans*) (Kraus and Rooker, 2007). Other organisms such as zooplankton and sperm whales (*Physeter macrocephalus*) may migrate over the full depth of the water column. The vertical zones extend over smaller or larger horizontal scales for epipelagic and mesopelagic fish (Kleisner et al., 2010). While the deep seafloor has traditionally been considered an ecological sink receiving food from shallower water but contributing little in the upward direction, this view is changing (Tenore et al., 2006). Many deep-sea animals produce eggs and larvae that develop among surface water food webs and participate in shallow water food webs. Zooplankton serve as conveyors of carbon from the surface to greater depths. Sperm whales forage at great depths (Amano and Yoshioka, 2003), but must return to the surface to breath. Throughout the water column and deep seafloor, microbes are contributing to the larger marine ecosystem by returning nutrients through their metabolic functions.

The deep slope contains special habitats associated with the geochemistry of upward migrating salt, seeping hydrocarbons, and the precipitation of calcium carbonate (Roberts and Carney, 1997). Active sites are associated with chemosynthetic communities dominated by bathymodiolid mussels and vestimentiferan tubeworms; species composition changes with depth in a manner similar to mud-bottom species. Carbonate features with minimal to no seepage support a diverse fauna of sessile and rock boring fauna. Unique chemosynthetic and deep coral communities, such as *Lophelia pertussa*, are biodiversity "hotspots" that receive regulatory protection from offshore drilling. They are widely appreciated as natural systems and iconic species of the deepwater GoM ecosystems.

Food Webs and Trophic Interactions

While the GoM's physical habitats provide ecosystem boundaries, their components link through complex trophic interactions. A food web is formed by linkages between multiple organisms in a complex feeding hierarchy that changes in time and in response to external factors (Pimm et al., 1991). The number of links in the food chain that one organism is removed from another describes the organism's trophic level. There are rarely more than four or five levels (primary producers, herbivores, omnivores, and carnivores) in a food web, because only a fraction (10-20 percent) of the energy at each level can be incorporated by the next level up. However, the organization within each level and interactions among the levels may be more complex than previously thought (Allen and Fulton, 2010; Montagnes et al., 2010). Each species in an ecosystem is affected by other organisms, interactions between trophic levels, and the environment. There are few single prey-single predator relationships, such that if one species is removed from an ecosystem, several other species will be affected. Multi-level trophic interactions may be more reflective of changes in trophic structure and potential ecosystem services than the presence, absence, or relative abundance of a species. Changes in trophic levels of global and regional catches are considered by the Food and Agriculture Organization (2002) as a better reflection of trends in fisheries than the proportion of fish stocks that are reported as depleted, overexploited, fully exploited, and moderately exploited (Food and Agriculture Organization, 2002). On the other hand, trophic level metrics, such as mean trophic level, were not found to be useful indicators of marine biodiversity and ecosystem status, particularly fisheries status, because the metrics are influenced by changes in economics, management, fishing technology, and targeting patterns (Branch et al., 2010).

Biodiversity

Biodiversity is the degree of variation of life forms within an ecosystem or biome. It is often a good measure of the health of an ecosystem. Biodiversity contributes to the stability of ecosystems, due to the diversity of functional responses of community members to perturbation. From the point of view of an individual organism, the ability to recover from a disturbance can vary with different life history characteristics. For example, when an organism can exploit a wide range of resources (as a generalist), a decrease in biodiversity is often less likely to impact that organism. However, an organism that can exploit only a limited range of resources (a specialist) is more likely to be affected by a decrease in biodiversity. Biodiversity in the

GoM, as elsewhere, is threatened by a number of factors including overexploitation of living resources, reduced water quality, coastal development, shipping, invasive species, factors associated with global climate change, the expansion of hypoxic and anoxic zones, and increases in harmful algal blooms (Fautin et al., 2010). Trophic structure and the complex dynamics of trophic level interactions affect the rate at which a population will recover from a negative impact.

Felder and Camp (2009) conducted the most recent, comprehensive biodiversity survey of the Gulf. The high diversity of marine life that exists in the Gulf makes it one of the most biodiverse oceanic water bodies on the planet (Fautin et al., 2010). Unfortunately, detailed studies of biodiversity in the GoM have been limited to a few well-studied regions including the northwestern Gulf oil and gas region, the Florida Keys, and areas of known high biodiversity like oyster reefs and seagrass beds. The effects of preserving diversity can be broadly beneficial to a wide spectrum of important ecosystem services, including fisheries, water quality, recreation, and shoreline protection. Conserving diversity increases the likelihood that ecosystems can adapt and recover following disturbances from natural or anthropogenic causes (Palumbi et al., 2009). Plant and animal species of interest—including keystone (organisms that play an influential role in maintaining ecosystem structure), indicator (species that indicate the presence of certain environmental conditions), commercially important, and endangered species of the GoM—are highlighted in Table 1.1.

Microbial Diversity

Biodiversity takes on a different meaning when applied to the two microbial domains of life, the Bacteria and the Archaea (single-celled organisms that lack a nucleus). Microbes dominate the global ocean, both in terms of numerical abundance (averaging 10^6 per milliliter of seawater for an estimated total of 10^{30} in the global water column) and of biomass, up to 90 percent of the total (Fuhrman et al., 1989; Whitman et al., 1998). Microbial biodiversity exceeds all plants and animals combined. Using state-of-the-art, high-throughput DNA sequencing during the recently completed Census of Marine Life, researchers discovered that the ocean contains, at a minimum, many millions of species of Bacteria and Archaea (20,000 in a single liter; Amaral-Zettler et al., 2010). Although the Census of Marine Life was an extensive global endeavor, only a single location in the GoM (Mississippi Canyon 118 on the Louisiana continental slope at 900 m depth) was surveyed for microbes and results are not yet published. In general, the

TABLE 1.1 Species of Interest in the GoM Large Marine Ecosystem

Name	Species	Significance
Kemp's Ridley sea turtle	*Lepidochelys kempii*	most endangered marine turtle in the world; keystone species
Whooping crane	*Grus americana*	endangered
West Indian manatee	*Trichechus manatus* ssp. *latirostris*	endangered; keystone species
Menhaden	*Brevoortia patronus*	largest commercial fishery by weight
Penaeid shrimp	*Litopenaeus setiferus* (white), *Farfantepenaeus duorarum* (pink), *Farfantepenaeus aztecus* (brown)	highest monetary value commercial fishery
Grouper and snapper	various	offshore commercially and recreationally important
Atlantic croaker	*Micropogonias undulatus*	indicator species
American oyster	*Crassostrea virginica*	commercial coastal fishery; indicator species
Blue crab	*Callinectes sapidus*	commercial coastal fishery
Spiny lobster	*Panulirus argus*	southern Gulf commercial fishery
Pink conch	*Eustrombus gigas*	regulated recreational fishery
Spotted sea trout	*Cynoscion nebulosus*	northern Gulf recreational fishery
Red drum	*Sciaenops ocellatus*	northern Gulf recreational fishery
Red snapper	*Lutjanus campecheanus*	northwestern Gulf recreational fishery
Bottlenose dolphin	*Tursiops truncatus*	well known by public; keystone species
American alligator	*Alligator mississippiensis*	keystone species
American crocodile	*Crocodylus acutus*	keystone species
Smooth cordgrass	*Spartina alterniflora*	keystone species
Saltmeadow cordgrass	*Spartina patens*	keystone species
Common reed	*Phragmites australis*	indicator species
Maidencane	*Panicum hemitomon*	indicator species

SOURCE: Derived from Fautin et al., 2010.

widespread occurrence of marine microbes, their ability to reproduce rapidly when conditions allow, and the functional redundancy built into their communities mean that environmental changes and anthropogenic impacts do not imperil the existence of specific groups, such as those that recycle nutrients, degrade hydrocarbons, or provide chemosynthetically derived food for higher organisms at hydrocarbon seeps. Instead, altered environmental conditions favor the reproduction and actions of those microbes best suited to prevailing conditions. A case in point is the DWH plume that stimulated the growth of deep-sea indigenous γ-proteobacteria that are closely related to known petroleum degraders (Hazen et al., 2010).

Human Interactions and Coastal Communities

There is a wide range of human communities affected by and interacting with various components of the GoM ecosystem, depending on what assumptions are made regarding boundaries and scope of interaction. For example, consumers worldwide who eat seafood harvested from the GoM are ultimately affected by the availability and quality of commercial fish and shellfish stocks in the Gulf. Groups outside the region, however, often have alternatives for purchasing fish from other U.S. regions and internationally. Obtaining seafood from other sources threatens businesses around the Gulf region. People living in or near the GoM system may rely on specific Gulf resources which cannot be easily substituted.

Coastal U.S. counties in the GoM include 142 jurisdictions, as defined by the Strategic Environmental Assessments Division of the National Oceanic and Atmospheric Administration (NOAA). Wilson and Fischetti (2010) suggest an environmentally based approach for classifying coastal counties to understand the interplay between human activities and water and habitat quality along the coast, and include a greater area than simply the group of counties that physically border the water. To be considered a coastal county in the NOAA system, a county must meet at least one of the following criteria: "1) at least 15 percent of a county's total land area is located within the Nation's coastal watershed; or 2) a portion of or an entire county accounts for at least 15 percent of a coastal cataloguing unit."[3]

U.S. GoM coastal counties comprise 115,000 square miles of land area (Bureau of the Census Statistical Abstract[4]), with 20.4 million residents, reflecting 7 percent of the overall U.S. population as of July 1, 2009. Residents in these counties occupied 9,144,000 housing units; and in 2008, 463,000 non-farm business establishments employed 7,028,000 non-farm employees. Employment in coastal counties comprises about 18 percent of all employment in the Gulf Coast states, although the proportion ranges as high as 34 percent in Louisiana and 31 percent in Florida (Adams et al., 2004).

Major occupations in the northern Gulf of Mexico region as reported in 2010 include oil and gas drilling, water transportation-related industries, and leisure and hospitality, the latter particularly related to gaming and ca-

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[3] See http://www.census.gov/geo/landview/lv6help/coastal_cty.pdf.

[4] See http://www.census.gov/compendia/statab/2011/tables/11s0026.pdf.

sinos but also including other types of recreation (Bureau of Labor Statistics, U.S. Department of Labor[5]). Tourism continues to be a key driver of coastal economic and property development (Yoskowitz, 2009).

Commercial fishing is prominent in the Gulf economy, with commercial fisheries landings accounting for about 25 percent of all U.S. seafood landings and about 21 percent of the total U.S. dockside fisheries value (Adams et al., 2004). The Gulf fishery is characterized by a diverse fleet of vessels harvesting from open water to near shore, including nearly 25,000 commercial fishing craft representing close to one-third of the entire U.S. commercial fishing fleet (Adams et al., 2004). In 2008, 165 processing plants and 229 wholesale plants employed nearly 10,000 workers that supported the commercial fishery.[6] In addition, the recreational fishing industry supports employment in coastal counties (Adams et al., 2004).

GoM Fisheries

The diversity of fishery species in the GoM is listed in the fishery management plans of the GoM Fishery Management Council (GoM FMC, 2010). The species list includes 3 mackerels, 14 snappers, 15 groupers, 5 tilefish, 4 jacks, 2 sand perches, 1 gray triggerfish, 1 hogfish, 4 shrimp, 2 lobsters, and 2 stone crabs. There are other important species that occur in the GoM that are managed under the highly migratory species fishery management plan (NOAA, 2004). These include 8 species of tuna, 6 billfish, and 72 species of sharks. This accounting does not include all harvested species because many of lesser economic importance are not listed individually in the plans, for example, dolphinfish, a species recognized to be part of the coastal migratory pelagic fishery but not part of the managed units. There are also important fishery species exclusively managed by coastal states, including some commercially important estuarine species (e.g., sea trout and mullet) and those reserved for recreational use, such as snook, tarpon, and bonefish.

Aquaculture

The GoM FMC manages offshore aquaculture operations in federal waters of the Gulf. Although at present there are few aquaculture operations in federal waters the potential use area is large and ranges throughout the Gulf (Figure 1.4; GoM FMC, 2009).

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[5] See http://www.bls.gov/oes/highlight_gulf.htm.

[6] See http://www.st.nmfs.noaa.gov/st1/fus/fus09/10_industrial2009.pdf.

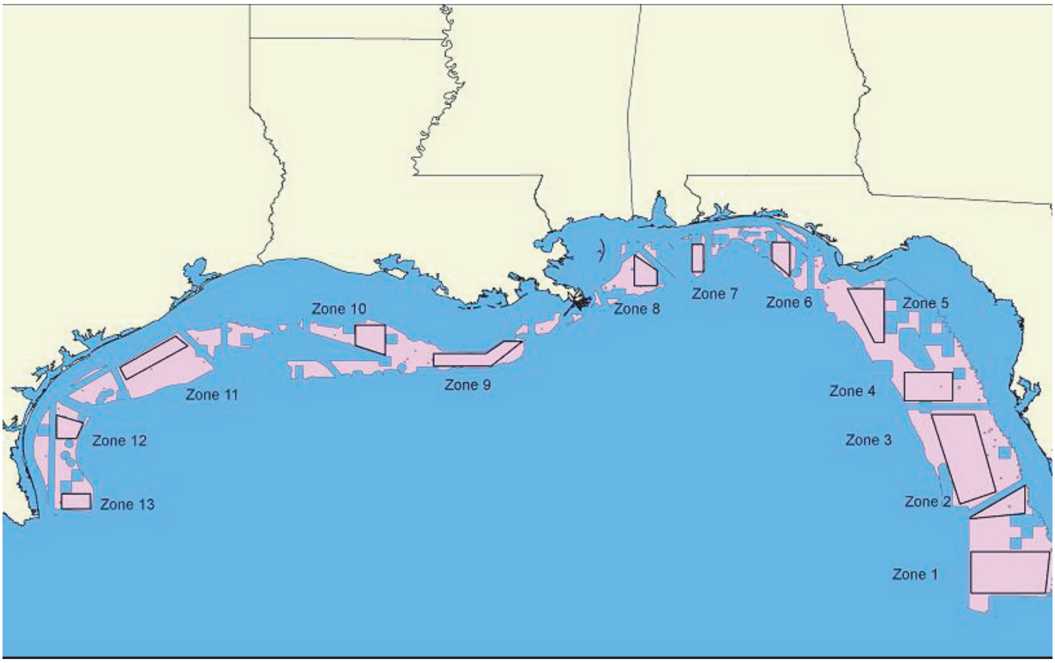

FIGURE 1.4 Potential for offshore aquaculture in the GoM. Pink represents all areas considered suitable for aquaculture in the Gulf EEZ (28,719 nm^2). Zones 1–13 (10,392 nm^2) are preferred zones under the GoM FMC aquaculture plan.
SOURCE: GoM FMC, 2009.

SUMMARY

This chapter presents an overview of the remarkably complex geological, meteorological, oceanographic, and biological processes, a variety of habitats, and complex ecological and human interactions at work in the Gulf.

Geological processes working over millennia set the stage in the GoM, creating a region of high productivity and accumulation of abundant hydrocarbon resources. In the northern GoM, the Mississippi River shaped, and continues to shape, the coastal areas with sediment-rich waters continuously reforming the landscape into the Mississippi and Atchafalaya river deltas. The Gulf's oceanic environment is largely determined by wind and currents, which respectively establish the regional weather patterns and serve as an important transit system for pollutants and runoff throughout Gulf waters. The region is also characterized by diverse ecological habitats, ranging from highly productive, vegetated intertidal zones and wetlands along the shore to less productive benthic and pelagic habitats of the open waters. These habitats provide the setting for the Gulf's prolific biodiversity—plants, animals, and microorganisms—whose maintenance is essential to healthy and stable ecosystems.

The GoM is a rich environment with abundant natural resources, diverse habitats, and biodiversity. Many human communities live in the region and rely on the various ecosystem services for their economic livelihood. In addition to the estimated 20.4 million residents, the Gulf of Mexico is home to oil and gas production, commercial fisheries, transportation, and recreational industries. The GoM is highly productive in both renewable and non-renewable resources. Fisheries and tourism have long co-existed with the petrochemical industry along much of the Gulf of Mexico shoreline, with the exception of Florida.

Renewable and living resources and the food webs and habitats that support them were exposed to varying levels of toxicity and exposure to oil and natural gas from the Macondo well. The effects of the oiling are currently being assessed in many habitats, across complex food webs, with regard to short- and long-term impacts, as altered biogeochemical cycling, and in relationship to ecosystem functioning. Some GoM ecosystems and processes are well known, but knowledge in many cases may be sparse. This uneven understanding of the ecosystem and processes is not uncommon but creates uncertainty that has to be acknowledged as data and findings are synthesized. The ability to detect impacts of the oil spill by way of the health of organisms or the level of ecosystem functioning will require adequate data and multiple lines of evidence of altered ecosystem processes. Failure to recognize essential factors or processes within (and between) ecosystems of the Gulf region may result in improper characterization or in misrepresentation of the full range of ecosystem functions that support ecosystem services.

> **Finding 1.1: The Gulf of Mexico comprises a large, complex ecosystem that has been and continues to be subject to both natural and human forces of change. Hence, the baselines against which the impact of the spill can be assessed are both spatially and temporally dynamic.**

2

Approaches to Damage Assessment and Valuation of Ecosystem Services

Humans modify ecosystems in both intentional and unintentional ways, and impacts at the ecosystem scale, in turn, have both direct and indirect effects on human well-being. There is growing recognition that what is needed for informed environmental management and policy are measures that (a) link human actions to likely changes in ecosystems and (b) link changes in ecosystems to consequent changes in human well-being (Millennium Ecosystem Assessment, 2005; NRC, 2005a; TEEB, 2010). An analysis of environmental impacts can provide the link between human actions and environmental conditions. An analysis of ecosystem services—the benefits that people receive from ecosystems—can provide the link between ecosystem conditions and human well-being.

We begin this chapter with a brief outline of the important components of an ecosystem services approach, as well as issues related to assessing impacts and quantifying ecosystem services. A more detailed description of the ecosystem services approach and methods for valuation is presented in Chapter 4. Chapter 2 will review the Natural Resource Damage Assessment (NRDA) process in the context of the Deepwater Horizon (DWH) spill. We discuss the NRDA process so that we can build upon it and offer suggestions for how it could incorporate an ecosystem services approach, which we believe to be a useful complement to the existing NRDA process.

AN APPROACH TO EVALUATING IMPACTS ON THE VALUE OF ECOSYSTEM SERVICES

Measuring the impact of the DWH oil spill on the value of ecosystem services requires assessing how the accident led to change in ecosystems, and how these changes led to changes in the provision and value of ecosystem services. Measuring such changes requires estimating the difference in the provision and value of ecosystem services with, versus without, the oil spill. Much of the data for establishing baseline conditions—the status of the ecosystem had the spill not occurred—need to be collected as soon as possible after the start of the spill and before the effects are manifested. Without this effort, most regions would have insufficient observations to document the conditions of habitats and species at the time of the spill; an important consideration given that ecosystems are not static and change in response to other human activities. Often the closest that one can come to evaluating conditions *post facto* is to assemble evidence on conditions prior to the spill, or "baseline conditions." Chapter 3 discusses baseline conditions in the Gulf of Mexico (GoM). As outlined in Chapter 1, an issue with using baseline conditions to assess what the present situation would be without the oil spill is that there are numerous other dynamic processes besides the oil spill that affect ecosystems and the services they provide, complicating the task of isolating the impact of the oil spill.

To measure the impact of human actions, either intentional actions brought about by a policy or management change, or unintentional actions, like an oil spill, requires understanding three important links (Figure 2.1). First, what are the impacts of human actions on environmental conditions that affect the structure or function of ecosystems? Ecosystem functions describe the internal processes of the ecosystem (e.g., energy fluxes, nutrient recycling, food-web interactions) while structure refers to the organization of the biophysical components that determine ecosystem functioning. Much of the current scientific work in the Gulf is an attempt to assess the chemical, physical, and biological impacts of the oil spill—an important first step in discerning the impact on ecosystem structure and function. Natural disturbances, such as a hurricane or changes in precipitation that affect discharge from the Mississippi River, also have impacts that lead to changes in environmental conditions. Again, as discussed in Chapter 1, natural variation can make it difficult to disentangle impacts of the oil spill from other factors influencing environmental conditions. This reality will be a fundamental challenge in all work related to the GoM oil spill.

Second, how do changes in the structure and function of ecosystems lead to changes in the provision of ecosystem services? "Ecological production functions" are used to describe the provision of ecosystem services as determined by the structure and function of ecosystems. They can be thought of as a "transfer function" or model that quantitatively describes the inter-relations of the ecosystem in such a way that changes in ecosystem condition (e.g., loss of habitat) translate to impact on ecosystem services (e.g., shrimp fishery yields). Ecological production functions can be used to predict how the provision of various ecosystem services changes with

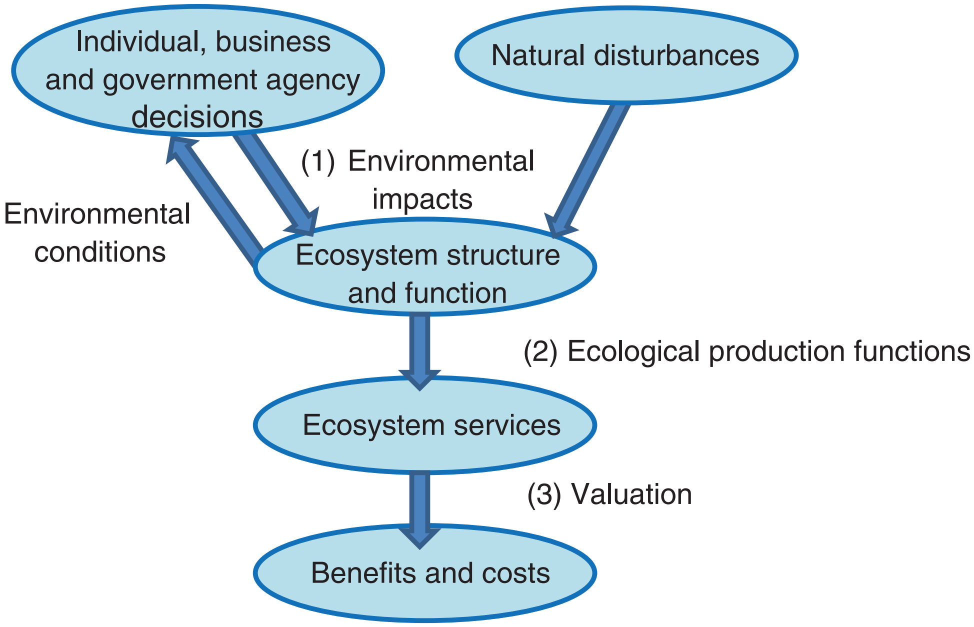

FIGURE 2.1 The three important links from human actions to human well-being: environmental impacts, ecological production functions and valuation.
Adapted from NRC, 2005a.

changes in ecosystem structure and function. But, ecosystem function and structure and ecosystem services are not synonymous. Granek et al. (2009) give the following example to illustrate the difference between ecosystem structure and function and ecosystem service. "Mangroves, seagrass beds, and coastal marshes provide habitat for juvenile fishes (ecosystem function), which ultimately may contribute to commercial and recreational fish landings (ecosystem service), and wave attenuation (ecosystem function), which may provide protection (ecosystem service) for coastal property from storm surge. Alerting decision makers that habitat has been lost without connecting that loss to the decline of valuable fish harvests or coastal protection does not effectively communicate the importance or severity of that loss relative to the suite of issues managers are asked to address." In the Granek et al. (2009) example, an ecological production function can be used to relate nursery habitat (structure/function) to a change in fishery productivity (service) or change in vegetation with wave attenuation (structure/function) to a change in coastal protection (service).

Third, how do changes in the provision of ecosystem services affect human well-being, and how can the value of the changes in services in terms of human well-being be quantified? An increase in the flow of ecosystem services generates benefits to people. A measure of the value of the benefit of ecosystem services to an individual can be obtained by observing what the individual is willing to give up in exchange for an increase in the flow of ecosystem services. Economists typically attempt to measure benefits in monetary terms by seeing how much an individual would be willing to pay to obtain more of an ecosystem service or, alternatively, what an individual would be willing to accept for a decline in an ecosystem service. Both market and non-market valuation methods can be used to estimate willingness to pay or willingness to accept. More detailed discussions of valuation applied to ecosystem services are presented in Chapter 4. Summing up the estimated values across all individuals affected by a change in services can generate an overall societal value that occurs because of the *change* in the ecosystem.

Much of the early work that attempted to quantify and value ecosystem services focused on estimates of the total value of ecosystem services rather than the policy-relevant (or in our case DWH-relevant) question of the *change* in value of services with change in management or environmental conditions. Costanza et al. (1997) used estimates of the value of ecosystem services by major ecosystem types to get an estimate of the value per hectare, which was then multiplied by the amount of area to get a total value of services by ecosystem type. Aggregating across these ecosystem types then generated an estimate of the annual value of the Earth's ecosystem services of $33 trillion (with a standard error of plus or minus $18 trillion). This high-profile study was criticized by economists for misusing the results of studies of small-scale local changes in the context of large-scale changes (see, for example, Bockstael et al., 2000). Such exercises as in the Costanza et al. (1997) study may be potentially useful for highlighting the overall importance of ecosystem services but are not directly relevant to situations like the DWH oil spill. What is needed to evaluate an event like the DWH spill is to ask how the quantity or value of the ecosystem services in the GoM would differ with, versus without, the oil spill, i.e., what is the *change* in the value of services with the spill. The total value of ecosystem services is not relevant in this situation.

Given this brief introduction to the ecosystem services approach for assessing the impact of an event like the DWH on the ecosystems of the GoM, we now briefly review the NRDA process—the approach being used to evaluate damages associated with the DWH spill. In Chapter 4 we expand on our discussion of the ecosystem services approach and offer suggestions for how it could complement the NRDA process.

NATURAL RESOURCE DAMAGE ASSESSMENT

There are two overarching federal statutes that established the NRDA process: the Comprehensive Environmental Response and Compensation Liability Act of 1980 (CERCLA) and the Oil Pollution Act of 1990 (OPA). Both of these statutes specify that the Executive Branch, through the President, has the responsibility for protecting and, where necessary, restoring the natural resources of the United States. The President is given the authority to delegate this responsibility and has done so through several federal departments. Those departments, in coordination with their state and tribal counterparts, are collectively termed as the natural resource trustees (33 U.S.C. Sec. 2607(b)(2); 33 U.S.C. Sec. 2607(b)(3), (4)). Trustees are responsible for acting on behalf of the President and the public to undertake NRDA and seek proper compensation and restoration for damages to natural resources.

The *Exxon Valdez* spill in Prince William Sound, Alaska, in 1989 led to the passage of the OPA in 1990 and to subsequent provisions for undertaking NRDA for oil spills. The Department of Commerce, through the National Oceanic and Atmospheric Administration (NOAA), is responsible for the NRDA process in response to oil spills in marine ecosystems. The OPA defines natural resources as land, fish, wildlife, biota, air, water, ground water, drinking water supplies, and other such resources belonging to, managed by, held in trust by, appertaining to, or otherwise controlled by the United States (including the resources of the exclusive economic zone), any state or local government or Indian tribe, or any foreign government (33 U.S.C. Sec. 2701(20) (see case study Box 2.1). Given that the committee is focused on the DWH spill, the discussion that follows will deal specifically with NRDA under OPA as implemented by NOAA.[1]

NOAA has a three-phase approach to NRDA:

1. preassessment,
2. restoration planning, and
3. restoration implementation.

The phases and methods are generally described in the applicable regulations (15 C.F.R. Sec. 990) and in NOAA's Damage Assessment, Restoration, and Remediation Program guidance documents (Huguenin et al., 1996; Reinharz and Michel, 1996) (Figure 2.2).

During the preassessment phase, trustees seek to determine if there has

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[1] See http://www.darrp.noaa.gov/about/laws.html#OilPollution.

BOX 2.1 *NORTH CAPE* OIL SPILL AND OPA: HIGHLIGHTING THE DAMAGE ASSESSMENT AND RESTORATION EFFORTS FOR IMPACTED LOBSTERS AND LOONS

The 1996 *North Cape* spill was the first opportunity for the U.S. government to apply the recently developed NRDA protocols under the Oil Pollution Act of 1990 (OPA). The spill occurred during a severe winter storm in January 1996, when the barge *North Cape* released 828,000 gallons of home heating and diesel fuel in the Block Island Sound of Rhode Island causing the closure of a 650 km^2 area of the Sound. The high winds (upward of 100 $km\ h^{-1}$) and rough seas (5-7 m) mixed the oil throughout the water column and surf zone within 24 hours, exposing shellfish, lobsters, birds, and other organisms to oil.

Among the affected species, lobsters (*Homarus americanus*) were one of the most impacted, due in large part to the fact that a majority of the exposed individuals were vulnerable juveniles. The following exemplifies some of the efforts taken by the trustees—designated technical experts who act on behalf of the public and who are tasked with assessing the nature and extent of site-related contamination and impacts. These trustees are also tasked with deciding on the appropriate levels of restoration. In this example, the focus was on the commercially important lobster population.

Using diver surveys of lobster abundance (Cobb et al., 1999), the trustees estimated from sampling data that nearly 3 million lobsters killed by the spill washed up on the beach (Gibson et al., 1997). Three sampling stations were used and classified according to their proximity to the site of the spill: impact (nearest the site of the spill), control (clearly unaffected by oil), and transitional (between control and impact areas) based on reported records of beach strandings of lobsters and results of model simulations of the trajectory of the oil in the sediments. Because it was very unlikely that all lobsters killed by the spill washed up ashore, abundances were interpolated from both historical and sampled data and it was estimated that approximately 9 million lobsters were killed by the spill, of which 82 percent were juvenile (Gibson et al., 1997). Recovery time was anticipated to be four to five years for the lobster population to return to baseline levels which corresponds with the number of years it takes a juvenile lobster to reach legal harvest size.

Under OPA, the law required that impacted populations be restored to pre-spill levels. The final determination, using lobster mortality rates and other life history statistics, estimated that the 9 million lobsters lost could be replaced from approximately 18 billion eggs, which in turn would be the output of approximately 1 million adult female lobsters. The restoration efforts then led to a series of introductions of lobsters purchased by both the responsible parties and by the trustees. The lobsters were purchased from regional sources and marked with "V-notches" (clipping a notch out of the tails) to identify them as restocked lobsters that were to be released by the lobstermen if harvested in local traps. Included in the restoration efforts were education programs for the lobstermen and seafood distributors, calculations of estimated non-compliance and the subsequent adjustments to the numbers of restocked lobsters, as well as monitoring and enforcement programs.

The goal of the program was to replace the lobsters that were killed in the *North Cape* spill. By protecting the restocked lobsters until the v-notches disappeared through successive molts, the delays in their harvest helped ensure that egg production led to increased numbers of juvenile and adult lobster populations. This restoration effort was part of a larger effort to "make the environment and public whole for the injuries to natural resources and services losses resulting from the spill."[a]

Also impacted by the spill were loons (*Gavia immer*). For the loon population, the trustees used the observed mortality (67) to estimate a total mortality by employing a multiplier to account for dead loons not found. This approach led to the calculation of a total mortality of 402, indicating that five unobserved dead loons were counted for each observed mortality. As with the lobsters, recovery times (12 percent per year) were estimated using the life history, population information, and survival rates of the loons. The trustees also used a maximum life span of 24 years. Using these factors, it was concluded that with the death of 402 loons there was a loss of 3,641 loon-years.

As per the OPA, it was necessary to restore the loons that perished from the *North Cape* oil spill. But in this case, it was determined that restoring the summer breeding populations was best achieved via the protection of nearly 1.5 million acres of Maine forests and lakes that provide nesting habitat for at least 125 loon pairs[b] that were expected to overwinter in Rhode Island. The trustees along with local, state, and federal agencies, as well as non-governmental organizations and conservation groups, provided the funds to secure these lands.

This example of restoration as per OPA underscores the efforts taken to restore loons that were killed in the state of Rhode Island through the protection and subsequent breeding of loons in the state of Maine. While this potentially restored the loon population, the question remains whether the people of Rhode Island felt they were made whole. It also raises questions of compensation as a function of time.

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[a] See http://globalrestorationnetwork.org/database/case-study/?id=283.

[b] See http://www.fws.gov/contaminants/restorationplans/NorthCape/NorthCapeFactSheetGeneral.pdf.

been a release of hazardous substances or oil, and the source. Once those are known, the second phase of restoration planning involves a number of sub-phases. In the case of the DWH, during the preassessment phase the source of the discharge of oil was clearly evident, and the trustees quickly recognized the potential for exposure of important natural resources to the oil soon after the incident began. Thus the preassessment phase soon evolved into the restoration planning phase. Ultimately the goal of restoration planning is to identify and quantify any injuries (impacts) to natural resources, and to estimate the amount of natural resources that have been lost. Trustees are given wide latitude in their use of assessment procedures (15 C.F.R. 990.27), including procedures to estimate natural resource losses

FIGURE 2.2 Overview of the Natural Resource Damage Assessment (NRDA) process under the Oil Pollution Act (OPA) of 1990 (Huguenin et al., 1996).

and how to value those losses (15 C.F.R. 990.53). However, the regulations must be followed in order to obtain a rebuttable presumption (an assumption of fact accepted by the courts until disproved) if the process or results of the NRDA are challenged legally. Over the past 10-15 years, the practice of NRDA by NOAA and co-trustees for oil spills has evolved; the experience gained has been useful in improving the overall process (Barnthouse and Stahl, 2002; U.S. Department of Interior, 2007; Zafonte and Hampton, 2007). Even with the diversity of practical experience gained over the years, and with a fairly wide variety of historical events to draw upon, few if any of these historical events compare with the spatial and temporal scale of the DWH spill. As a consequence, the DWH spill presents a challenge for the ongoing NRDA efforts.

Injury Assessment

Under the OPA regulations, injury is defined as an observable or measurable adverse change in a natural resource or impairment of an ecosystem service. For example, oil from DWH that coats wetland plants or sea birds provides a small, yet highly visible example of injury to natural resources. As noted above, NOAA has developed and used well-recognized approaches for assessing injury or impact to natural resources, and many of these methods have been and continue to be employed for the DWH spill. In general, when assessing injuries (see 15 C.F.R. 990.27), trustees determine whether there is:

- an exposure pathway between the source and a natural resource,
- an adverse change in that natural resource as a result of exposure to the discharge, or
- an injury to a natural resource or impairment of a natural resource service as a result of response actions or a substantial threat of a discharge.

A simplified summary of approaches and the types of data collected under the NOAA guidelines (Huguenin et al., 1996) are shown in Table 2.1. As we note later in Chapter 4, numerous Technical Working Groups, composed of representatives from the natural resource trustees and others, are identifying data needs and designing and implementing studies to collect those data. These groups have been very active since the spill was first discovered, and some will continue their work and data collection for some time to come.

TABLE 2.1 Simplified Example of Commonly Collected Data for Injury and Impact Assessment That Would Be Relevant to the DWH Spill

Data Category	Basis	Approach
Chemical	Trustees need to establish source of the oil, nature and extent of spill, potential migration pathways of the oil, and potential exposure of key receptors (surface water, sediments, biota, and habitats).	Sample and analyze media such as (1) surface water, (2) sediment, and (3) biota (wetland vegetation, marine mammals, reptiles, fish, etc.) in the vicinity of the spill and proximal to it where oil may be expected to migrate.
Biological	Trustees need to establish what biological resources have been exposed to the oil, and whether or not they have been harmed.	1. Sample wetland vegetation to determine extent of oiling, 2. collect and document any oiled waterfowl and seabirds, 3. collect and document any oiled marine mammals, reptiles, etc. in open ocean areas and near shore where appropriate.

This example focuses primarily on an estuarine wetland since these habitats tend to have good supporting physical, chemical, and biological data and are habitats well known to NRDA practitioners and non-practitioners. Less emphasis is placed on the open ocean even though it may be the largest area (receptor) exposed to the oil. Some organisms of specific interest to the trustees and the public (marine mammals for example) are included.
Modified from Huguenin et al. (1996).

We provide Table 2.1 to indicate how an ecosystem services approach could be incorporated into the NRDA process for the DWH spill. Table 2.1 is not representative of the full complexity of studies being undertaken for the DWH by the trustees, BP, and associated contractors. Rather, it is a simplified illustration of the kinds of data typically collected for NRDA and their basis in the regulations.

As we discuss later in the report (Chapter 4), there is a potential to reframe existing data or include additional types of data in Table 2.1 that would augment those data sets typically developed for NRDA purposes by NOAA, and in doing so, support an ecosystem services approach.

Restoration Selection

During the restoration planning phase, trustees have additional responsibilities once the injuries have been identified and quantified. Trustees estimate the natural resource losses based on the extent of the injuries. Under NRDA practice, losses are generally measured in ecological terms (e.g., number of acres damaged, number of sea birds oiled or found dead) rather than in terms of losses in the value of ecosystem services (Dunford et al., 2004; Zafonte and Hampton, 2007). The losses determined by the NRDA process can then be used to assess the damages (the "debit") to the relevant natural resources. In most cases, those damages (or the debit) translate directly (or can be scaled) into potential restoration projects that generate "credit" sufficient to offset the "debit." For most NRDA cases, estimating or scaling the amount of restoration required generally follows equivalency approaches that are described in more detail later in this section. Restoration objectives can be the acres of habitat that need to be restored, the numbers of wildlife (birds for example) that need to be replaced, or other suitable projects allowed under the statute and regulations. These equivalency approaches also take into account the extent to which these habitats and resources would have recovered in the absence of human actions. Where damages do not translate easily into a particular restoration project, or where restoration projects in proximity to the injury are not readily feasible, funds may be provided as compensation and applied at a later date when a suitable restoration project is identified.

Current equivalency approaches may not necessarily capture the whole value provided by complex and/or long-term interactions within ecosystems. One scenario where problems may arise is in the case of chronic impacts of oil on an important natural resource that are not manifested or identified during the injury assessment, nor accounted for in the scaling of the restoration. In this situation the impacts may not be realized for several years and require additional human intervention and restoration to mitigate them (see also Coglianese, 2010). Given the spatial and temporal scales of the DWH spill, this issue will require additional attention during the development of restoration and monitoring plans, and exemplifies where the incorporation of ecosystem services analysis potentially will be of benefit. For example, the current assessment of injuries and service loss may lead to restoration in the near term. The assessment may also focus on restoration projects identified at that point in time. However, there may be future injuries and service losses identified through monitoring, and in that case suitable restoration projects may be more limited in number or type, in which case having an ecosystem services approach may again prove beneficial.

We also considered that in the current situation, and in reference to ecosystem services, that some potential impacts from the spill may not be known for some time, particularly where those impacts are detected far afield of the spill. Our focus has been on potential impacts within the GoM and adjoining states, and less on those that might be found in the future in the Caribbean or along the East Coast of the United States. In the event that impacts are detected in the future in the Caribbean or along the East Coast, having a wider suite of potential restoration projects to draw upon will be of benefit.

> **Finding 2.1: The spatial and temporal scales of the DWH spill and the complexity of the GoM ecosystem make it unlikely that all important long-term impacts can be identified during the initial injury assessment.**

After the injuries have been documented and quantified, the trustees, must "develop and implement a plan for the restoration, rehabilitation, replacement, or acquisition of the equivalent, of the natural resources under their trusteeship" (33 U.S.C. Sec. 2706(c)), using the relevant information developed for the case. To proceed with restoration planning, trustees also quantify the degree and spatial and temporal extent of injuries. Injuries are quantified by comparing the condition of the injured natural resources or services to baseline data, as necessary (Injury Assessment: Guidance Document for Natural Resource Damage Assessment Under the Oil Pollution Act of 1990, the Damage Assessment and Restoration Program, NOAA, August 1996, at p. 1-4, sec. 1.4.2.1). The restoration plan typically is prepared at the end of the assessment process and is subject to public review and comment. These steps, injury assessment and restoration planning, are central to the goal of the OPA, 33 U.S.C. 2701 et seq., *"to make the environment and public whole for injuries to natural resources and services resulting from an incident involving a discharge or substantial threat of a discharge of oil* (incident). This goal is achieved through the return of the injured natural resources and services to baseline and compensation for interim losses of such natural resources and services from the date of the incident until recovery. The purpose of this part is to promote expeditious and cost-effective restoration of natural resources and services injured as a result of an incident. To fulfill this purpose, this part provides a natural resource damage assessment process for developing a plan for restoration of the injured natural resources and services and pursuing implementation or funding of the plan by responsible parties. This part also provides an administrative process for involving interested parties in the assessment, a range of assessment procedures for identifying and evaluating injuries to natural resources and services, and a means for selecting restoration actions from a reasonable range of alternatives" (*emphasis supplied*).

There are two key points to emphasize with the NRDA process, particularly regarding the use of equivalency approaches and restoration planning. First, pursuant to the OPA and implementing regulations, assessment and restoration responsibilities are inseparable but tend to be managed in two distinct steps. Under the OPA, the measure of natural resource damages is the cost of restoring, rehabilitating, replacing, or acquiring the equivalent of the damaged natural resources; the diminution in value of those natural resources pending restoration; plus the reasonable cost of assessing those damages (33 U.S.C. Sec. 2706(d)(1)). Moreover, "*Sums recovered under this Act* by a Federal, State, Indian, or foreign trustee for natural resource damages under section 2702(b)(2)(A) of this title *shall be retained by the trustee* in a revolving trust account, without further appropriation, *for use only to reimburse or pay costs incurred by the trustee under subsection (c) of this section with respect to the damaged natural resources*. Any amounts in excess of those required for these reimbursements and costs shall be deposited in the Fund" (33 U.S.C. 2706(f)) (*emphasis supplied*). In other words, these funds are only to be used for restoring, rehabilitating, replacing, or acquiring the equivalent of the damaged resources.

We will refer to these actions collectively as "restoration options." Thus, the trustee must assess damages from the responsible party or parties while attempting to keep in mind the potential feasible restoration options. Put differently, because restoration options represent the currency in which the responsible party or parties must pay for damages, the trustee should have a comprehensive understanding of the menu of restoration options throughout the damage assessment process. In the case where an oil spill results in injury to resources or services for which restoration options have not previously been developed, it is incumbent upon the trustees to explore and develop new suitable options. In addition, the trustees need to have a reasonable working knowledge of restoration projects that may be of interest to non-governmental organizations and the public, because they will have input to the final selection process. Further, the interests of the public will vary with the locale, habitats involved, and socio-economic settings of the area.

The separation of damage assessment from analysis of restoration options has been a challenge for NRDA practitioners for many years (Stahl et al., 2008). Despite using the term "restoration planning" to describe the second phase of the three-phase process, NOAA and other trustees tend to conduct the injury identification and quantification first. This is understandable as often the demands on the staff can be significant during the response period and data collection efforts. Sometimes it results in restoration option development being left for a later time. However, damage assessment is dependent upon restoration options. This reality has led to the development of a relatively new concept called "restoration up front (RUF)" (Stahl et al., 2008). The RUF concept was developed jointly among NRDA practitioners in the public and private sectors, and evolved from collective experiences of those working both on CERLCA and OPA-type cases. The collective experience was that while time is spent responding to a spill, then assessing and quantifying the injuries, high-value restoration opportunities in the area of injury can be time-sensitive and thus "lost" if they are not addressed quickly. Since the RUF concept was developed, NOAA has developed policies that provide their NRDA practitioners with guidance on managing restoration opportunities early in the restoration planning process (NOAA, 2007b). One year after the spill, BP and the trustees reached an early restoration agreement in which BP agreed to provide up to $1 billion to allow early implementation of time-sensitive restoration projects, much the same as was described under the RUF concept. And, as noted earlier, public input to the selection process will be a key element in helping to decide which projects are funded and which ones are not.

The second key point, specifically related to ecosystem services, is that NOAA's regulations require it to make "the environment and the public whole for injuries to natural resources and services" (15 C.F.R. 990.10). NOAA has historically relied on ecological-based equivalency approaches for assessing damages rather than approaches that restore the value of ecosystem services. These two approaches are as follows:

- Habitat Equivalency Analysis (HEA) measures damages in terms of the number of acres damaged. HEA fails to explicitly account for the fact that the value of a particular ecosystem service is dependent on the connection between that service and the public's ability to use or to benefit from that service (Roach and Wade, 2006; Dunford et al., 2004); and
- Resource Equivalency Analysis (REA) focuses mainly on assessing injury to specific organisms rather than on the amount of habitat and is frequently applied to oil spills (Zafonte and Hampton, 2007). REA has some of the same drawbacks as noted for HEA, and is illustrated in the North Cape spill example (Box 2.1).

These approaches were designed to provide a tool that would allow both the responsible party and the natural resource trustees to estimate potential injury and scale restoration needs (Dunford et al., 2004). Each approach allows for inputs stemming from direct measurements in the field and laboratory, or through inputs derived from the published literature. Dunford et al. (2004) and Zafonte and Hampton (2007) detail a number of the strengths and weaknesses of these methods, including issues related to spatial and temporal coverage and time factors (or service discounting). These methods have a rich history of use in cases over the years and are likely to be used in the DWH case. Thus in evaluating the potential for an ecosystem services approach to damage assessment, we seek methods that may complement and expand on HEA and REA.

In general, there is a tension between equivalency approaches such as HEA and REA, which are based on equivalency of habitat or organisms, and the ecosystem services approach based on equivalency of value of services. The committee plans to return to this issue in the final report. Further, this discussion should not be construed as an endorsement by the committee for a particular kind, size, or location of a restoration project, but as an illustration of difficulties involved with valuing specific restoration efforts in an ecosystem services context versus a resource equivalency context.

The challenge of equivalency or restoring the value of ecosystem services raises an additional issue of the distribution of benefits and costs across members of the public, i.e., restoration of value for whom? When an ecosystem is damaged near community A but restoration occurs near community B, the public in general might be made whole in the sense that the total value of ecosystem services is equivalent with restoration as before damage occurred, but community A remains worse off with the damage while community B is better off with the restoration. There will inevitably be some dislocation of benefits across time and space in any NRDA process. Dislocation of benefits across time raises issues of discounting. Discounting is the standard technique in economics for comparing future costs and benefits with present costs and benefits and is also used in NRDA (NOAA, 1999). The choice of a discount rate can reflect a value judgment about the "useful" life of an asset from which there will flow a stream of benefits. Choosing an appropriate discount rate for long-lived natural assets, such as those in the GoM ecosystems, can be challenging and will ultimately involve societal preferences at some level. Distributional questions, across both time and space, represent an important dimension that requires special attention, and will no doubt involve considerable discourse among the state and federal agencies and those affected communities. The North Cape spill (Box 2.1) provides a good example of the REA approach applied in this case to loss of lobsters and loons. The trustees were faced with restoring specific (or individual) resources and used REA rather than HEA. REA is more appropriate in those instances where individual or specific resources are harmed and restoration scaling for those specific resources is required. In other instances, particularly where a specific habitat (for example, wetland) has been injured, HEA may be more appropriate.

Finding 2.2: Although the equivalency approaches (HEA and REA) attempt to make the environment whole in the sense that habitats or populations of species are restored, this type of restoration does not necessarily make the public whole, as measured by the value of ecosystem services.

In Chapter 4 we discuss further the potential application of these equivalency approaches to the DWH restoration planning process, and some of the strengths and weaknesses associated with them. Here we provide a simple example to illustrate how attempts to value ecosystem services can address the shortcomings of equivalence approaches. Consider two acres of ecologically identical and equally impacted estuarine wetlands, Whiteacre and Blackacre. Whiteacre is located 100 miles further from a human population center than Blackacre. Assume under HEA the injury to Blackacre and Whiteacre are identical; however, the loss in value of ecosystem service could be substantially different. If Blackacre provides cheaper and easier public access for hunting and fishing, then oil-related impacts to Blackacre would result in a greater reduction in the value of ecosystem services than identical oil-related impacts to Whiteacre. The reason is that the ecosystem services approach takes into account the value of the resource to humans, whereas HEA and REA tend to place less (or no) emphasis on this aspect and focus more on the value of the habitat or the organism in an ecological sense. However, the calculus for accounting for ecosystem services at each site may differ, owing to the complexity in assessing those services for human benefit. The committee recognizes that NRDA typically emphasizes restoring resources near where they were damaged to reduce the difference in value caused by differences in location. Further, some NRDA practitioners emphasize the importance of restoration of ecological *and* human values (Knetsch, 2007; Abson and Mette, 2010).

To date, however, the majority of NRDAs do not appear to have utilized an ecosystem services approach, based on informal surveys of government and private sector practitioners conducted for the U.S. Department of the Interior (2007). The lack of application of ecosystem service valuation to NRDA does not appear to be due to a restricting provision in the statutes or in the regulations (see 15 C.F.R. 990.27; Gouguet et al., 2009; Munns et al., 2009). Recently, there appears to be more interest by federal agencies in using an ecosystem services approach in their decision processes (Slack, 2010; Compton, 2011).

Finding 2.3: Applied equivalency approaches focus more on the implicit value of the habitat or the organism in an ecological sense rather than the ultimate value of the resource to humans.

Finding 2.4: Habitat and resource equivalency approaches could be broadened to include an ecosystem services approach by consideration of the extent to which affected areas or resources generate benefits to the public.

One way in which this gap could be closed is through an expansion of the concept of the Service Acre Year (or SAY) that has been used in HEA. A SAY is the ecological service provided by one acre of habitat per year, where the flow of that service is to another ecological resource rather than to humans (Dunford et al., 2004; Stahl et al., 2008). The expansion of the definition of the SAY to include the value of services that flow from that habitat or ecological resource in terms of human benefits would readily incorporate ecosystem services into the ongoing NRDA process. In the example considered above, Blackacre would have higher SAY values per acre than Whiteacre to capture the fact that Blackacre provides greater public access and therefore generates greater value of ecosystem services. We caution that this hypothetical example does not include issues such as the public's value for that wetland not related to access, the ability of wetlands to recover without human intervention, and other factors that could influence the comparison of the two wetlands. Nevertheless, expanding the concept of SAY to include the value of ecosystem services would allow practitioners to evaluate more fully the potential injury or impact to the GoM from the DWH spill, and provide a wider spectrum of restoration options than might result through the current approach. In addition, where it is difficult to restore resource values directly, thinking clearly about what public values have been damaged could help direct restoration efforts that make the public whole.

Finding 2.5: A more comprehensive assessment of the overall value of the resources could be obtained by expanding the definition of the Service Acre Year to include services that flow from a habitat or ecological resource to human benefits.

While the example of expanding the SAY is one potential avenue that trustees might pursue to incorporate an ecosystem services approach into the current NRDA process, we recognize it is not a panacea. For example, incorporating an ecosystem services approach within the HEA method may be possible in the case of an injured habitat such as estuarine wetland but is likely to prove more challenging where the REA method is used to estimate loss and scale restoration for a specific organism. The majority of the area injured by the DWH spill is the open ocean, and the HEA approach may not be appropriate in this situation compared to REA. We provide more discussion on this point in Chapter 4.

Despite the challenges noted thus far, the valuation of ecosystem services could be included as a more central component of the NRDA process by interpreting 'that which makes the public whole' as the provision of ecosystem services of equivalent value. Consider, for example, the case of wetlands that we discussed in Table 2.1. These habitats are relatively well known and tend to have substantive supportive information whether physical, chemical, or biological in nature. These supportive data will be useful in the conduct of an ecosystem services analysis, a point we have touched on already and which we focus on again in Chapter 4.

If the public resources in question are viewed as only containing ecosystem functions provided by the wetlands, then the restoration, rehabilitation, replacement, or acquisition projects will focus on restoring ecosystem functions by improving or protecting wetlands. If, on the other hand, the public resources are construed as containing the ecosystem services provided by the wetlands (e.g., flood prevention, water filtration, and recreational opportunities), then the trustee could undertake a wide range of projects in an effort to make the public whole. From an ecosystem services perspective, restoring the categories of services noted above could be undertaken through a wide variety of projects that may diverge from a strictly ecologically based effort, such as physically replacing or restoring the injured wetland. Hypothetically, these could include such actions as constructing seawalls and storm-water treatment systems or enhancing or subsidizing hunting or fishing opportunities. In a strict ecosystem services evaluation, these projects could replace the services lost. However, this example is provided for illustrative purposes only, and the actual evaluation and selection of projects would be subject to discussion and review among the federal and state trustees, the public, and other interested stakeholders. In the latter context, preference is likely to be given to in-kind, in-place projects that provide services that reflect both ecological and human-based values. Making the public whole by restoring the value of ecosystem services versus making the environment whole by restoring equivalent habitat (HEA) or organisms (REA) could result in different restoration activities being undertaken. When possible, restoring damaged resources to their original condition will satisfy both making the environment and the public whole. Of course, even when restoring damaged resources to their original condition is possible, trustees must face questions of how to account for damages from interim loss of resources between the time of injury and time of full restoration. For both interim lost resources due to damages and for cases where it is not possible to fully restore damaged resources, the equivalency question is unavoidable: trustees must answer the question of what restoration activities will provide a set of equivalent resources that make the environment and the public whole. As discussed above, simple application of HEA and REA that focuses on number of acres or numbers of organisms will not necessarily make the public whole because the value of ecosystem services might not be fully restored. On the other hand, restoring the value of ecosystem services might not necessarily result in making the environment whole. An ecosystem services approach that restores the value of ecosystem services via human-engineered substitutes (e.g., building a flood wall or a water filtration plant) may not result in making the environment whole. Restoration of services via human-engineered substitutes would probably not satisfy the requirement of making the environment whole even if the value of ecosystem services is restored. We return to the discussion of equivalency in Chapter 4.

Consideration of the value of ecosystem services rather than equivalency of habitat or population could help relieve what might be called the NRDA "restoration bottleneck." While NRDA requires the trustees to assess and recover monetary damages from responsible parties, it also encourages the trustees to fully spend those funds on restoring, rehabilitating, replacing, or acquiring the equivalent of the damaged natural resources (33 U.S.C. 2706(f)). "Restoration bottleneck" refers to the fact that a NRDA trustee can collect money damages from a responsible party only to the extent that the trustee can conceive of feasible, productive restoration, rehabilitation, replacement, or acquisition projects. In practice, trustees, the public, and the responsible party often struggle to identify and develop a mutually acceptable project prior to the time of settlement, creating a "bottleneck."

Finding 2.6: An ecosystem services approach has the potential to expand the array of possible projects for restoration through alternatives that restore an ecosystem service independently of identification of an equivalent habitat or resource, albeit with the caveat that these projects must in aggregate make the environment and the public whole. Evaluation of the impacts on ecosystem services as part of the damage assessment process would expand the range of mitigation options.

Under the OPA, the federal government is required to seek reparation for damages to natural resources due to oil spills. The NRDA process is the primary tool by which the government assesses the damage to natural resources, and within that process, has been the application of equivalency methods, HEA and REA. Unfortunately, this process relies on an assessment that does not necessarily address the reality that an ecosystem is a dynamic and interactive complex of species and their physical environment (Kornfield, 2011). Furthermore, the existing NRDA process may not adequately integrate the additional complexity of space and time into the assessment, which is a particular challenge when assessing the impacts of an event with the scope and duration of the DWH spill. The underlying question that the NRDA practitioners would like to address is "how did the quantity and value of ecosystem services change due to the DWH oil spill?" The ecosystem services approach can be useful in answering this question. An ecosystem services approach may provide a useful addition to the ongoing NRDA process as it avoids the "restoration bottleneck" by expanding the array of projects suitable for funding. This approach brings the "value" into human benefits rather than solely addressing habitat for habitat's sake.

> **Finding 2.7: Habitat and resource equivalency approaches may not capture the whole value provided by large ecosystems such as the Gulf of Mexico because of the complex long-term interactions among ecosystem components.**

A more detailed discussion of this approach and specific recommendations for its implementation with respect to a few key ecosystem services are found in Chapter 4.

3

Methods to Establish Baselines for Gulf of Mexico Ecosystem Services

An assessment of the impact of an event like the Deepwater Horizon Mississippi Canyon-252 (DWH) spill must be viewed with respect to the conditions in place before the event (discussed in Chapter 2). In the language of the Natural Resource Damage Assessment process, injuries are quantified by comparison of the conditions of the injured resource or service to baseline data. The establishment of baseline conditions for a region as vast and complex as the Gulf of Mexico (GoM), however, is a daunting task. The physical, chemical, and biological environments of the GoM are not constant (outlined in Chapter 1). There are natural variations in meteorological and hydrologic conditions that lead to changes in sea surface temperatures, water currents, and flood conditions. These, in turn, lead to changes in chemical and ecological conditions. Assessment in light of these natural processes is further complicated by anthropogenic changes to the environment as humans build levees for storm protection, dredge waterways for ship passage, construct permanent infrastructure for oil and gas extraction, and fertilize agricultural fields throughout the watershed. The GoM Large Marine Ecosystem was degraded prior to the spill, so establishing dynamic baselines for each of the important ecosystem services is vital before the effects of the oil spill can be established.

While the charges to the committee with respect to baselines (questions 2 and 3 in the Statement of Task) are generic in nature, we believe the discussion of baseline data is better served within the context of specific, GoM-relevant ecosystem services. As the concept of ecosystem services has evolved, numerous authors and studies have identified a wide range of ecosystem services. The specific categories of these services (i.e., are they provisioning, regulating, supporting, or cultural) are often the subject of debate; however, there is little question that these services ultimately provide benefit to humans. In June 2010, a panel of experts from the Gulf region was convened in Bay St. Louis, Mississippi, to consider the ecosystem services that were most relevant to the GoM. Representatives from academic institutions, non-governmental organizations, private enterprise, and state and federal governments contributed to the discussion and identified 19 ecosystem services contributed by the GoM (listed in Table 3.1). The committee used the output of the Bay St. Louis Ecosystem Services Workshop as a starting place for its discussion of what services were relevant for the Gulf and then went through its own deliberations in order to refine the list. A complete discussion of the baseline data for each of these ecosystem services is far beyond the scope of this interim report. We will thus focus our discussion of baselines on representative examples of ecosystem services important in the GoM. This discussion is not comprehensive, but rather highlights examples of key parameters that have been or can be measured to ascertain GoM ecosystem services prior to the DWH oil spill. These examples may also be used as a guideline for how to approach the complex problem of determining changes in ecosystem services following the DWH oil spill. For each service, a brief description of the current state of knowledge is provided, followed by a description of the primary parameters that can be measured and the state-of-the-art methods for conducting the measurements. Where possible, references have been provided to databases and publications that may contain relevant information for comparison of ecosystem services before and after the spill. Some of these ecosystem services are understood better than others, as is apparent in the variation in the depth of coverage for the different sections that follow.

TABLE 3.1 List of Ecosystem Services[a] Identified at the "GoM Ecosystem Services Workshop"

Nutrient Balance (Supporting)
Hydrological Balance (Supporting)
Climate Balance (Regulating)
Pollutant Attenuation (Regulating)
Gas Balance (Supporting)
Water Quality (Regulating)
Water Quantity (Supporting)
Air Supply (Regulating)
Food (Provisioning)
Raw Materials (Provisioning)
Medicinal Resources (Provisioning)
Ornamental Resources (Provisioning)
Science and Education (Cultural)
Biological Interactions (Supporting)
Soil and Sediment Balance (Supporting)
Spiritual and Historic (Cultural)
Aesthetics and Existence (Cultural)
Recreational Opportunities (Cultural)
Hazard Moderation (Regulating)

[a] The committee acknowledges that the use of the term "balance" for some ecosystem services identified in Table 3.1 is a simplification of the ecological processes and functions and may not capture all of the complex interactions that take place within and between various ecosystems.
SOURCE: Yoskowitz et al., 2010.

REGULATING SERVICES

Hazard Moderation

Changing Distributions of Salt Marshes and Mangroves

The value of ecosystem services that accrue from the intertidal wetlands of the Mississippi River delta and adjacent Gulf Coast are directly related to the total area of wetland and plant community composition. Current literature suggests that ecosystem services like wave attenuation by intertidal wetlands are non-linearly related to area with diminishing returns to scale (Barbier et al., 2008), while others suggest a nearly linear relationship (Costanza et al., 2008). Regardless, change in total wetland area is still the most direct and practical measurement of change in ecosystem services in Gulf Coast wetlands.

The wetlands in the Gulf Coast region are changing on several time scales. There is a long-term loss of wetlands due to subsidence, sea-level rise, and a variety of other issues (Boesch et al., 1994; Morton et al., 2002; Bernier et al., 2006). There are also episodic changes due to storms (Turner et al., 2007; Steyer et al., 2010) and now possibly those associated with the DWH oil spill. Distinguishing the background trends and variability associated with storms, droughts, and other factors from oil-spill-related effects will be challenging. The effort will require sampling large areas with sufficient temporal frequency and spatial detail to resolve episodic changes using a combination of ground surveys and remote sensing. Fortunately, the tools exist and the groundwork is in place for detecting changes in GoM coastal wetlands.

Advances in technology and decreasing cost are making remote sensing (RS) and geographic information systems the tools of choice for classifying and quantifying coastal landscapes. RS, or the capture and analysis of spectral information from a remote target, is a highly effective method for analyzing estuarine and coastal landscapes (Phinn et al., 2000; Klemas, 2001; Kelly and Tuxen, 2009) used to efficiently map, monitor, and detect change in wetlands (Zhang et al., 1997). Satellites carrying sensors with spatial resolutions of 1-5 m and spectral resolutions of 200 nm are being launched to more accurately detect these changes (Klemas, 2001). The classification of wetland area and plant communities is also improving as data from satellites are combined with those collected from fixed-wing aircraft. LIDAR (Light Detection and Ranging), an optical system that can measure the distance to a target and other properties using pulses from a laser, is one of the sensors now commonly included on fixed-wing aircraft. This tool is used to construct digital elevation models and to develop digital profiles of plant canopies. Classification schemes based on combinations of these data sources can delineate wetland plant communities with a high degree (76-97 percent) of accuracy (Gilmore et al., 2008), and temporal changes can be resolved with repeated measurements.

In 1990, the U.S. Congress enacted the Coastal Wetlands Planning, Protection and Restoration Act (CWPPRA) in response to ongoing wetland loss along Louisiana's coast. CWPPRA authorized funding in 2003 for the Louisiana Office of Coastal Protection and Restoration (OCPR) and the U.S. Geological Survey (USGS) to implement a Coastwide Reference Monitoring System (CRMS) as a mechanism to monitor and evaluate the effectiveness of CWPPRA projects across the region (Steyer et al., 2003). A consequence of this monitoring program was the selection, approval, and securing of 390 reference sites with a fixed annual sampling design that have been used to establish the status and trends of existing wetlands. These 390 CRMS sites are located within nine coastal basins covering the Louisiana coast. Sample collection from the ground began in 2005 and will be an important complement to remote sensing techniques for establishing baseline data for wetlands.

Hydrologic Balance

Adequate flow of water in the hydrologic cycle from ocean to land to rivers to the sea is modulated by ecosystems and human activities that are intertwined with this cycle. Potential interruption of hydrologic balance and impacts may have resulted from two aspects of the DWH oil spill: (1) interruption of evapotranspiration of water from the sea surface by oil slicks and plumes and (2) the human management of the freshwater discharge of the Mississippi River to prevent the inflow of oil into coastal areas. The first aspect is important because most of the moisture available to the center of the lower 48 states, an area from eastern Ohio through eastern Alabama to the area from western Wisconsin through western Texas, is derived from the GoM (Vachon et al., 2010). Fifty percent of the moisture from Minnesota to Montana south through New Mexico derives from the GoM. Any significant interruption of the GoM hydrologic cycle through temperature shifts or lack of evapotranspiration would disrupt the flow of moisture inland, weather patterns, and climate. While this ecosystem service is significant, it is unlikely that the presence of oil in the open waters of the GoM over 10,000 km^2, at maximal extent, would have affected the hydrologic cycle.

On the other hand, the decision of the State of Louisiana to divert Mississippi River water through the Davis Pond Diversion and the Canaervon

Diversion was responsible for a sharp lowering of salinities in receiving waters along with excess loads of nitrogen and phosphorus. The freshwater input was coincident with the deaths of oysters and the nutrients with the formation of large algal blooms, including some harmful species, and hypoxia to the east of the Mississippi River delta. This change in hydrologic balance could be considered an indirect effect of the DWH oil spill. Basin-wide shifts in water storage and discharge are quite variable as a result of climate and local meteorology. A change in seasonal or annual discharge resulting from changes in evapotranspiration in the Gulf of Mexico where the oil plume covered surface waters is difficult to determine or was not determined; furthermore, any shift in water content would be difficult to discern within the variability of the background data. Water discharge data are available from the USGS, the Louisiana Department of Natural Resources (LDNR), the U.S. Army Corps of Engineers (USACE), and individual states. Data for the diversions of water at the time of the oil spill are with the USGS, USACE, and the LDNR, OCPR, and stored in the USGS database. For example, as of May 10, 2010, there were seven diversions and siphons and one navigation lock opened to move water out of the Mississippi River and into coastal wetlands. Four diversions or siphons and a lock are located in Plaquemines Parish while three are in St. Bernard and one in St. Charles. The total measurable flow from these diversions is 29,550 cubic feet per second consisting of the following in cubic feet per second (CFS):

- Bayou Lamoque Diversion: Plaquemines Parish. 7,500 CFS (capacity 12,000)
- Davis Pond Diversion: St. Charles Parish. 10,650 CFS (capacity 10,650)[1]
- Violet Siphon: St. Bernard Parish. 200 CFS (capacity 200)
- Caernarvon Diversion: St. Bernard Parish. 8,000 CFS (capacity 8,800)[2]
- Whites Ditch Siphon: Plaquemines Parish. 200 CFS (capacity 200)
- Naomi Siphon: Plaquemines Parish. 1,500 CFS (capacity 1,500)
- West Pointe a la Hache Siphon: Plaquemines Parish. 1,500 CFS (capacity 1,500)[3]

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[1] See http://waterdata.usgs.gov/la/nwis/uv?dd_cd=17&format=gif&period=7&site_no=295501090190400.

[2] See http://waterdata.usgs.gov/la/nwis/uv/?site_no=295124089542100&PARAmeter_cd=00065,72020,63160,00060.

[3] See http://emergency.louisiana.gov/Releases/05122010-Lamoque.html.

SUPPORTING SERVICES

Soil and Sediment Balance

One of the key benefits of salt marsh and mangrove ecosystems is their propensity to maintain the relative elevation of their habitat in equilibrium with mean sea level (Redfield and Rubin, 1962; McKee and Faulkner, 2000; Morris et al., 2002). Salt marshes and mangroves compensate for rising sea level, within limits, by trapping sediment, increasing root biomass and accumulating soil organic matter. In so doing they maintain a buffer between human infrastructure and the sea, minimizing the impacts of wave energy (e.g., Vosse, 2008). Feedback from several environmental inputs such as flood duration, plant growth, and sedimentation rate help characterize how marshes have responded to sea level. For marshes situated high in the intertidal zone, a rise in sea level stimulates growth and biomass density. With greater plant density, sedimentation increases and contributes to the relative elevation of the marsh surface (Morris et al., 2002). Marsh vegetation grows in a well-defined vertical range within the intertidal zone, and its growth is maximized at a particular elevation. Provided the marsh elevation is optimal for growth, the marsh can survive. However, there is a limiting rate of local sea-level rise (including subsidence), a threshold above which the marsh cannot trap sediment and accrete organic matter rapidly enough to keep pace (Morris et al., 2002). Moreover, this limit is sensitive to variables such as exposure to toxic hydrocarbons and dispersants that affect growth (Lin and Mendelssohn, 2004) irrespective of relative elevation.

The mechanics of the process of sedimentation in marshes is well known. There is a low turbulence zone near the mud surface of a salt marsh where the rate of particle settling is increased. For emergent *Spartina* canopies the maximal velocity gradient is shifted upward compared to a standard boundary layer over bare sediment and the turbulence is attenuated near the bed, which enhances sediment deposition and protects the bed against subsequent erosion (Neumeier and Amos, 2006).

Measurements of sediment accretion and relative surface elevation are currently being taken at CRMS sites (Figure 3.1) throughout the coast (Steyer et al., 1995). A few of these sites were impacted by oil (personal communication, Brady Couvillion, U.S. Geological Survey; personal observation by committee, 2011). Nevertheless, the distribution of CRMS sites provides important information about the status and trends of existing wetlands.

At CRMS sites repeated measurements of relative marsh elevation are made using the Surface-Elevation Table (SET) technique (Cahoon et al., 2000). A SET is a portable, mechanical leveling device designed to attach to

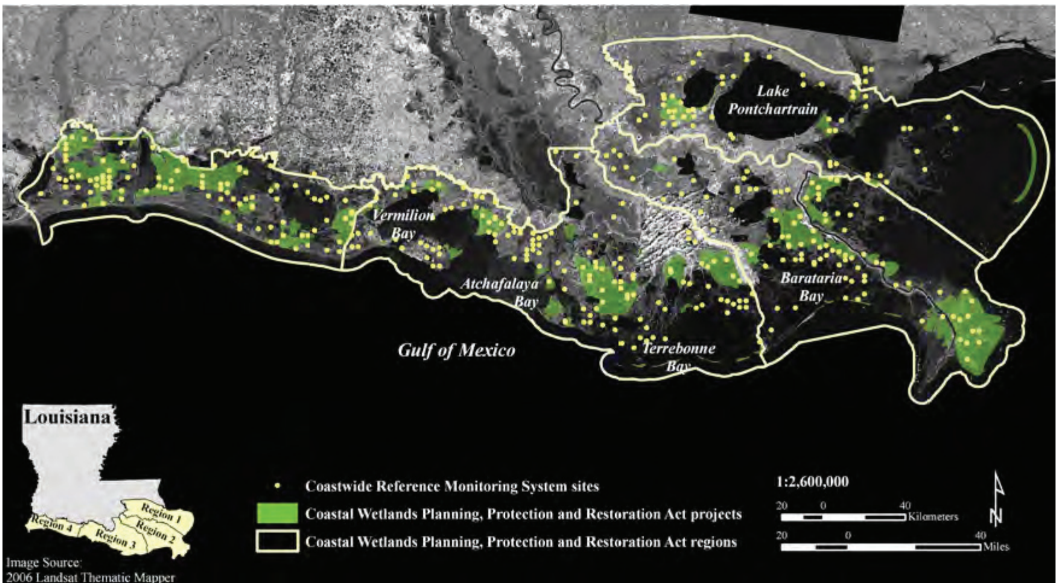

FIGURE 3.1 Map of CRMS sites throughout coastal Louisiana in relation to four regions defined by the Coastal Wetlands Planning, Protection and Restoration Act (CWPPRA) and CWPPRA projects coastwide.
SOURCE: Steyer et al., 2003; the National Library of Medicine.

a benchmark pipe driven into the ground to the point of refusal (Boumans and Day, 1993; Cahoon et al., 2000). Change in elevation is determined by comparing repeated measures of monthly samples relative to the means of the first measurements.

Water Quality—Nutrient Regulation[4]

Ecosystems receive nutrient inputs and process nutrients through nutrient uptake, regeneration, and transformation. Nutrient processing includes the natural functions of nutrient cycling in wetlands, submerged vegetation, and subsurface sediments along the gradient of tidally influenced ecosystems to across the continental shelf soft-bottom habitats and into similar ecosystems of the deep GoM. The nutrients most often considered are nitrogen and phosphorus because an excess of these nutrients can enhance

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[4] As water quality in the GoM coastal waters is significantly influenced by nutrient regulation, discussion of these two ecosystem services has been combined in this section.

primary production and lead to eutrophication and negative impacts such as reduced water clarity, noxious and harmful algal blooms, and oxygen depletion. In addition, silica is important because it is required by diatoms, the dominant primary producers at the base of aquatic food webs. Decreases in silica loads or an imbalance of the ratio of either nitrogen or phosphorus to silica can cause the phytoplankton community to shift composition to non-diatom phytoplankton including toxic dinoflagellates or cyanobacteria. The ecosystem service provided by nutrient cycling is the maintenance of major nutrients within acceptable concentrations, so that negative impacts, such as eutrophication and altered trophic structure, are minimized.

Much of the variation in water quality in the GoM coastal waters is driven by inputs from the Mississippi River, delivering 80 percent of the freshwater inflow, 91 percent of the annual nitrogen load, and 88 percent of the phosphorus load to the northern part of the Gulf (Turner et al., 2007). Measurement of nutrient concentrations is important since it yields valuable information regarding primary production in the region (Lohrenz et al., 1997). The measurement of nutrient concentrations is also valuable in terms of oil spills, since nutrients play an important role in the microbial biodegradation of hydrocarbons (Leahy and Colwell, 1990) and also in terms of organic loading from surface phytoplankton production. Both degradation processes lower the saturation of dissolved oxygen (DO), creating oxygen anomalies in deep waters where hydrocarbons are present (Kessler et al., 2011) or leading to large and perennial "dead zones" (areas of oxygen depletion on the Louisiana continental shelf) (Rabalais et al., 2002, 2007b).

According to Farber et al. (2006) the service of nutrient processing is somewhat amenable to economic valuation, which can be measured by its impact on water quality through avoided treatment costs. Wetlands are widely recognized for their capacity to remove nutrients from overlying waters, in effect improving water quality (Engle, 2011). The ability of wetlands and soft-bottom sediments to cycle nutrients could potentially be disrupted by the presence of hydrocarbons layering the sediments or potentially damaging the health and vitality of wetlands and is thus a major consideration in assessing ecosystem services as part of a damage assessment.

Increases in nutrient loads, primarily nitrogen and phosphorus, often lead to eutrophication, the increase in carbon production through photosynthesis and accumulation of that carbon in the aquatic system (Rabalais, 2004; modified from Nixon, 1995). Negative impacts of eutrophication are oxygen deficiency (hypoxia) and harmful algal blooms. When DO concentrations fall below a certain level to create a low oxygen condition known as hypoxia, and this condition persists, the biodiversity and availability of suitable habitat for most sea life is compromised. Certain mobile species will migrate away from the affected area, but sessile or burrowing species may die (Engle et al., 1997; Rabalais and Turner, 2001). When a density barrier (pycnocline) due to salinity or temperature differences, or both, is present in the water column, diffusion of oxygen from surface waters is inhibited across this barrier so that consumption of oxygen by aerobic bacteria depletes the oxygen in the water below the barrier at a much greater rate than it can be supplied. The resultant hypoxia can become so severe that the behavior, physiology, and capacity of organisms to survive are threatened. The northern Gulf of Mexico has two areas of lower oxygen: (1) a 300- to 800-m-thick layer of natural low oxygen in water depths of 1,000 m or deeper in the open Gulf of Mexico (Conseil Permanent International pour l'Exploration de la Mer, 1936) and (2) the human-caused low oxygen area on the Louisiana continental shelf resulting from increasing and excess nutrient loads (Rabalais et al., 2002) (see Box 3.1).

Water quality data including nutrients are available at the USGS[5] for major rivers. Individual states also maintain water quality data in support of U.S. Environmental Protection Agency (EPA) requirements of the Clean Water Act for drinking water and for determination of impaired uses. The availability of nutrient data for specific areas potentially affected by the oil spill is limited. Also, the data for uptake and regeneration of multiple forms of nutrients, nitrogen, and phosphorus within wetlands are sparse and data within oiled wetlands are essentially non-existent.

In terms of baseline DO data for the GoM, a nationwide review of DO conditions in estuaries was undertaken by the Ocean Assessments Division of NOAA to collate historical data from individual estuaries in the GoM and report on the status of Gulf-wide DO conditions (Rabalais et al., 1985; Windsor, 1985). These reports combined data from numerous programs to identify sites with definite DO problems or with marginal or deteriorating water quality. The most recent compilation of estuarine condition, including DO, in GoM estuaries and some offshore waters is in Bricker et al. (2007). Offshore and open Gulf of Mexico water quality data including nutrients are mostly stored at the NOAA National Oceanographic Data Center.[6]

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[5] See http://toxics.usgs.gov/hypoxia/mississippi/.

[6] See http://www.nodc.noaa.gov/.

BOX 3.1 HYPOXIA IN THE GoM

For almost 30 years, scientists have been monitoring DO concentrations in the bottom waters of the northern GoM to better understand the distribution and dynamics of hypoxia in the region (Rabalais et al., 2007b). Large areas of the GoM are seasonally hypoxic, reaching 22,000 km^2, the size of the state of Maryland.[a] Hypoxia results from the stimulation of algal and bacterial production due to excess nitrogen and phosphorus delivered by the Mississippi-Atchafalaya River Basin (Turner et al., 2007; Greene et al., 2009) and is maintained by the seasonal stratification of Gulf waters (Rabalais et al., 2007a). The general consensus is that hypoxia in the northern GoM has worsened over the past century as nutrient loads increased (Rabalais et al., 2007b; EPA, 2009). The number and duration of hypoxic and severely hypoxic events vary from year to year according to nutrient loading, freshwater discharge, and weather patterns (Turner et al., 2006; Greene et al., 2009). The most important factors in determining the hypoxic potential of estuaries are the tendency for stratification, the rate of flushing, and the extent of organic loading.

The loss of ecosystem services in the form of fish kills, benthic defaunation, decreased diversity of fish and benthic invertebrates, and disruption of nutrient cycling are attributed to hypoxia or anoxia (absence of DO) (Rabalais and Turner, 2001). Large-scale economic consequences include reduced production of commercially and recreationally valuable fish and shellfish (Diaz and Rosenberg, 1995; Breitburg, 2002), changes in the relative importance of various trophic pathways within food webs (Caddy, 1993; Turner et al., 1998; Breitburg et al., 2009), and a reduction in the economic value of some fisheries (Lipton and Hicks, 2003; Mistiaen et al., 2003).

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[a] See http://www.gulfhypoxia.net.

PROVISIONING SERVICES

Food

Indirect and direct food provisioning are recognized ecosystem services. For example, consider a deep-shelf hard-bottom ecosystem within the GoM. The ecosystem's ability to produce organisms that are consumed by humans (food) is dependent on a relatively stable ocean environment, and a complex food web that contains a large number of organisms not directly consumed by humans (the indirect provisioning component). In addition, this system, like most marine systems, may depend on the productivity of neighboring ecosystems, such as nutrient inputs from shallower waters, because ocean basins have strong ecological connectivity. Any change to a part of this system may directly or indirectly change food provisioning. Harvest of food species may reduce their population to levels that make it less productive. Similarly, the harvest of food species may alter the balance in the food chain, changing the ability of the ecosystem to support food production.

Because food provisioning includes artisanal fishing but is mostly captured through commercial fisheries, and because state and federal governments regularly model and collect data on commercial fisheries, baseline data on the kinds and amount of direct food provisioning are available. The primary database for U.S. commercial fisheries is maintained by the National Marine Fisheries Service (NMFS).[7] Details regarding regional landings data can also be gleaned from databases maintained by NMFS' Southeast Fisheries Science Center.[8]

Important commercial species in the Gulf region include oysters, shrimp, menhaden, red snapper, tunas, groupers, crawfish, mullets, blue crab, and stone crab; from 2000 to 2009 these species or species groups represented an average of 96 percent of total landings. In 2009, finfish and shellfish landings in the GoM totaled 1.4 billion pounds and earned $629 million in revenues (NOAA, 2010a). Historical data on landings provide a way to estimate the historic economic value of commercial fisheries at the dock. Commercial fisheries data are expected to include both indirect and direct food provisioning values. Commonly used multipliers can provide estimates of the economic benefits generated by seafood products as they move through processing, wholesale, transport, and retail phases. The economic value of seafood to consumers, or consumer surplus, is more difficult to measure.

Understanding ecosystem dynamics that regulate food production, however, is much more challenging. Government agencies emphasize collection of data on the removal of managed species, including those that are a source of food, recreation, or that have a special conservation value (marine mammals, sea turtles, corals). The same agencies put much less effort into collection of data on species that may be affected by fishing but do not have a commercial value (by-catch). The result of such monitoring represents an uneven coverage of the different components of the ecosystem that may be supporting food production. Returning to the example of the hard bottom, generally there will be detailed information on the major species of harvested fish, but much less data on all other species, some of which may be supporting the harvested species.

In addition to data on landings, pre-spill stock assessment processes

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[7] See http://www.st.nmfs.noaa.gov/st1/commercial/index.html.

[8] See http://www.sefsc.noaa.gov/data/landings.htm.

can supply information on projected post-spill landings. In the case of a rebuilding fishery, data on historic landings, projected over the recovery period, would underestimate the loss of "but-for-the-spill" potential landings. At the same time, those parties representing the public's interests in a damage assessment case (i.e., trustees) should also consider the extent to which the spill might increase future landings by necessitating temporary fishery closures that might accelerate rebuilding of overfished stocks. Although stock assessment processes do commonly make predictions on future yield it is less common to have predictions on the economic value of "but-for-the-spill" yields. The reason is that predictions of seafood demand and prices are often a function of global markets and not exclusively of regional production.

Nineteen percent of the U.S. fish catch over the period from 2003-2008 was not destined for direct human consumption but rather for other products such as fish meal and fish oil (NOAA, 2010b). The Gulf menhaden fishery, which primarily operates in Louisiana, is the second largest U.S. fishery by weight, producing approximately 500,000 tons a year of landed catch (Vaughan et al., 2007). This fishery produces 60 percent of the total U.S. catch not destined for human consumption (NOAA, 2010a,b). In addition to fish meal and fish oil, a significant portion of menhaden catch is used as bait in other fisheries such as those for crustaceans and various finfish (VanderKooy and Smith, 2002). Fish oil is mainly used in products for human consumption but a small portion is used for livestock and aquaculture feeds (VanderKooy and Smith, 2002).

Assessment of this stock is based on fishery-independent data on juvenile abundance, fishery-dependent data on adult abundance, landing statistics and life history parameters. A catch-at-age model applied to these data by Vaughan et al. (2007) obtained relatively precise estimates indicating that as of 2004 the stock and fishery were operating sustainably within the limits set by managers. This estimation of stock status allows the NMFS to release annual forecasts of catch for the GoM menhaden fishery that have historically been accurate within 14 percent (NOAA, 2011b).

VanderKooy and Smith (2002) cite oil spills and petroleum extraction as potentially having negative effects on fish survival and recruitment of Gulf menhaden. Other factors, related to the interactions of natural events and human activity (hurricanes, climate cycles, pollution, coastal development, wetland degradation wetland loss, river runoff, algal blooms, hypoxic zones), can also affect fishery operations and the abundance and survival of Gulf menhaden (VanderKooy and Smith, 2002; Vaughan et al., 2007) or other species (Chesney and Baltz, 2001).

Raw Material Services from Oil and Gas

The Gulf of Mexico is a major source of oil and gas as a provisioning ecosystem service. According to the Bureau of Ocean Energy, Management, Regulation and Enforcement (BOEMRE), the GoM Outer Continental Shelf produced 510 million barrels of oil and 2.8 trillion cubic feet of gas in 2009, which amounts to about 29 percent of all the oil produced in the United States and 13 percent of gas. The history of oil production from the Gulf from 1970 to 2008 indicates that while production in shallow water has been rapidly declining, production in deep water has risen dramatically and accounted for 76 percent of offshore production in the Gulf by 2008 (Figure 3.2).[9]

This oil and gas production provides valuable resources as essential raw ingredients for fuels, lubricants, plastics, medicines, fertilizers, etc. The 4,000 active and inactive production rigs also provide a substrate as artificial reefs upon which organisms settle and create diverse marine communities to which fish are attracted, but note that these rigs can also have negative environmental impacts. This example of the rigs generating both positive and negative environmental effects highlights a societal tension between ecosystem services and the benefits that they provide in the GoM and elsewhere. Improvements to one service may actually come at the expense of another. For example, enhancing the regulating services such as hazard moderation (by protecting intact wetlands and mangroves that provide storm surge protection) may come at the expense of other services such as provisioning services provided by the raw materials such as gas and oil.

Calculating a baseline of raw material resources provided by oil and gas would require quantifying each of these items. Estimating some of them is fairly straightforward using existing databases, e.g., using known prices and production volumes from the BOEMRE database as cited above. Other items, such as provisioning of hard substrates for diverse biological communities, are more difficult to quantify.

Loss of oil and gas resources as a result of the DWH spill are ultimately attributable to delays in bringing on new production through drilling moratoria and longer permitting times. Deepwater drilling activity since the DWH spill dropped by about 65 percent; in shallow water the drop has been less severe but is still 35 percent as of March 2011 (Figure 3.3).

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[9] See http://www.boemre.gov/stats/-OCSproduction.htm.

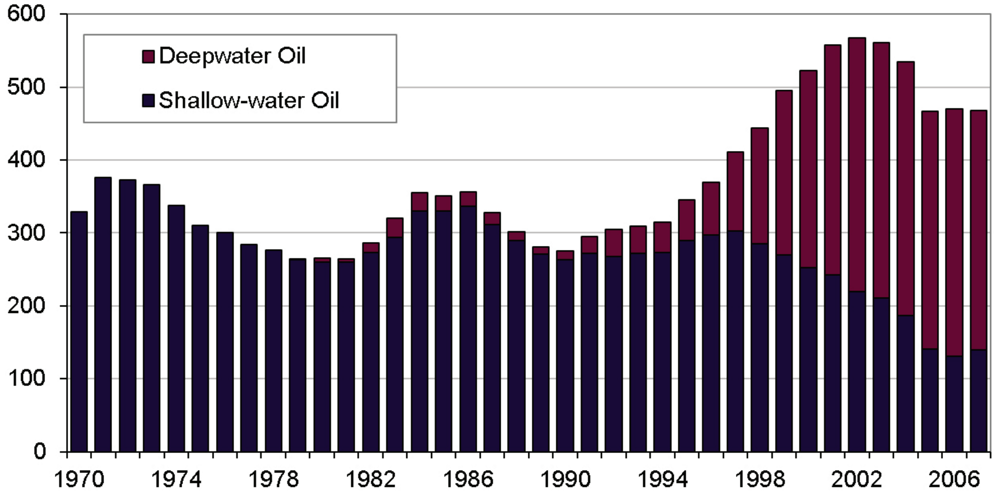

FIGURE 3.2 History of annual oil production in the GoM (from BOEMRE).
SOURCES: U.S. Department of the Interior, 2011; RigData, 2009; with permission from David E. Dismukes, Louisiana State University, Center for Energy Studies.

CULTURAL SERVICES

Spiritual and Historic

Spiritual and historic connections to land and water are what define many communities and people around the world, and this is true for the Gulf coast. From the Biloxi-Chitimacha, Houma, and Atakapa-Ishak tribes, to the Cajun (French Acadians), and to the Hmong and Vietnamese fishing communities, to name just a few, there is an important attachment to the land and water. Through generations, indigenous peoples have grown to depend on their environment for essential resources, and therefore have a stake in restoring, maintaining, and enhancing its biological diversity (Gadgil et al., 1993). The very nature of this ecosystem service makes it difficult to measure its importance in any form, much less monetary value. Yet, spiritual and historic connections are passions of individuals and communities that motivate them to action.

As an example of the spiritual and historic importance of our natural environment, the Millennium Ecosystem Assessment addressed the function of forests: "Forests play important cultural, spiritual, and recreational roles in many societies. For many indigenous and otherwise traditional societies,

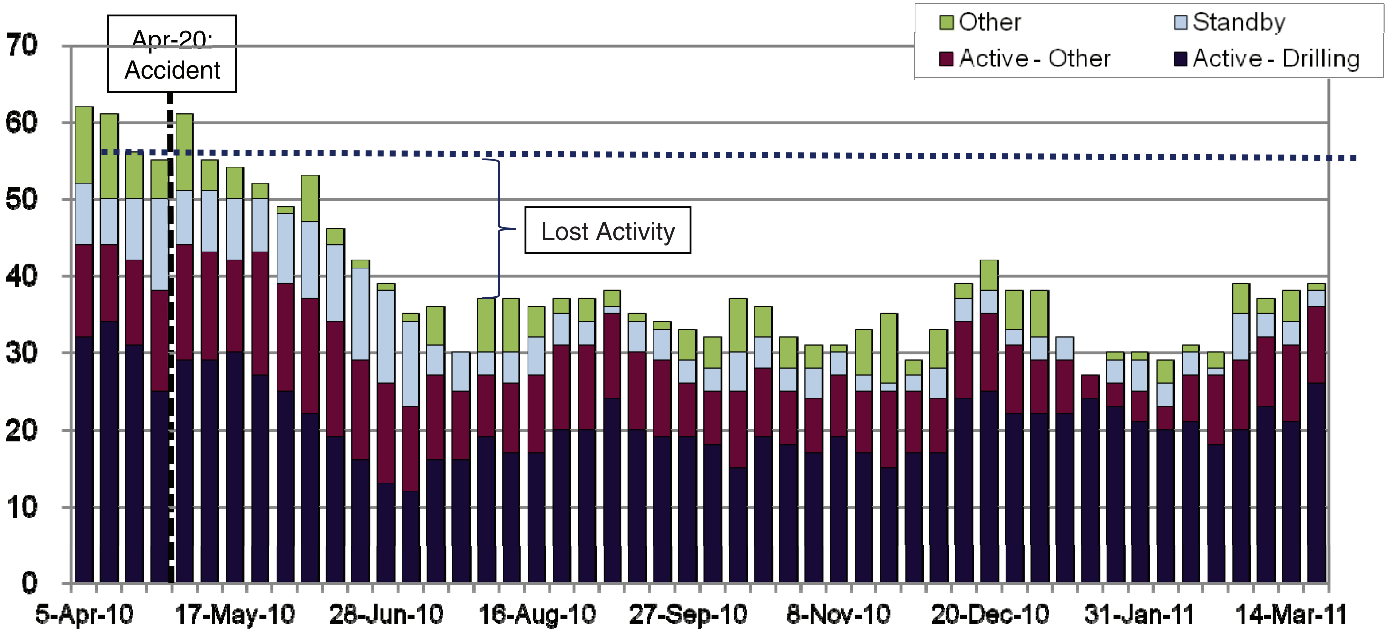

FIGURE 3.3 Time history of the number of drill rigs operating in the Gulf from April 2010 to March 2011.
SOURCES: U.S. Department of the Interior, 2011; Rig Data, 2009; with permission from David E. Dismukes, Louisiana State University, Center for Energy Studies.

forests play an important role in cultural and spiritual traditions and, in some cases, are integral to the very definition and survival of distinct cultures and peoples. Forests also continue to play an important role in providing recreation and spiritual solace in more modernized, secular societies, and forests and trees are symbolically and spiritually important in most of the world's major religious traditions" (Millennium Ecosystem Assessment, 2005). This same statement is appropriate for the bayous, bottomland hardwoods, salt and freshwater wetlands, and barrier islands of the Gulf.

It is difficult to quantify the value of the spiritual and historic attachment to land and water. Catastrophic events, whether acute (oil spills or hurricanes) or gradual (decrease in sediment load or sea-level rise), impact both communities and individuals. As a result of the *Exxon Valdez* oil spill, the community culture, which was characterized by a fishing lifestyle and connections to the natural environment before the spill, then shifted to a community that was involved only in cleanup operations. The spill also disrupted the traditional practice of sharing and exchanging subsistence harvests, an important identity of Alaskan indigenous people (Picou et al., 2009). Community beliefs are that when sacred sites are destroyed alternatives do not exist, and totem species that become impaired or extinct cannot be replaced (Cooper, 2009). Communities along the Gulf coast and especially the Mississippi River delta region have been dealing with adversity for decades mainly due to habitat loss and multiple hurricanes. Early evidence suggests that many of the issues associated with the *Exxon Valdez* oil spill are occurring with the DWH oil spill (Ritchie et al., 2011). An important part of the Cajun and Native American identity is commercial fishing and the link to coastal waters. The threat to livelihoods is also a threat to their identity of self-reliance and independence (Guarino, 2010). Similar threats to the livelihoods of immigrant cultures (from Filipino fishers with shrimp drying platforms and Croatian oystermen in the 1800s to more recent Vietnamese and Hmong shrimp trawlers) are equally important.

Endemic and translocated cultures are facing challenges associated with changing environmental conditions and social pressures. The important traditional subsistence hunting and fishing that is part of their everyday lives is being recognized formally by the Gulf Coast Claims Facility. As one individual put it, the subsistence claims are "a claim that my lifestyle has been adversely impacted by my inability to any longer live off the resources that I hunt or catch . . . what I could go hunt or fish I now have to go buy" (Budreau, 2011). These sorts of impacts on spiritual or cultural values also raise concerns related to environmental justice.[10]

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[10] See http://ssrn.com/abstract=1949421.

Perhaps the most important contribution of trying to evaluate spiritual ecosystem services might be that it acts as a reminder that there are values that cannot be reduced to figures (Cooper, 2009).

Aesthetics and Existence

Gulf ecosystems provide value to people in the form of aesthetic experiences and existence amenities. Aesthetic experiences are provided to the general public insofar as they visit beaches, watch wildlife, and enjoy navigating through inland and offshore areas. Existence amenities include knowledge or awareness about specific components of the GoM system, such as knowing that migrating birds use habitats in the northern Gulf of Mexico, as well as more abstract ideas such as feeling a sense of inspiration from or harmony with nature as represented by the GoM, or associating the GoM with a strong emotional attachment. While these amenities range from fairly concrete to substantively more abstract, they are nevertheless real in economic terms. It is well documented that people value knowing that oceans and wetlands are healthy (Baird, 1995; Turner et al., 2000), that fish and wildlife populations exist, and that systems and their component parts will be available for their children and grandchildren to enjoy.

Data on aesthetic values can be directly obtained from reports on tourism spending and the relative value of coastal property and, indirectly, from economic studies using methods such as travel cost and the hedonic valuation of real property. Because there is no market capturing existence values, estimates can only be obtained through indirect methods such as surveys of willingness-to-pay or willingness-to-accept and other forms of contingent valuation (see Chapter 4).

Recreational Opportunities and Tourism

Recreation and tourism are one of the most direct aesthetic links that people have with the environment and these services can generate large benefits, especially in the context of coastal and marine ecosystems. Tourism, as it is often defined, involves travel of at least a given distance (e.g., 50 miles or more) to engage in recreation. We use the term recreational services to cover both recreation and tourism. Recreational services along the Gulf coast include fishing, hunting, bird watching, camping, hiking, beach going, boating, diving, snorkeling, and swimming. The economic impact of recreational services can be significant. In 2008, the coastal congressional districts of the Gulf States experienced a level of travel spending of

TABLE 3.2 GoM Saltwater Anglers and Days, 2006 (population 16 years and older; number in thousands).

State Where Fishing Took Place	Anglers					
	Total Anglers, Residents and Nonresidents		State Residents		Nonresidents	
	Number	Percent	Number	Percent	Number	Percent
Alabama	153	100	89	59	63[a]	41[a]
Florida	2,002	100	1,286	64	716	36
Louisiana	289	100	248	86	42[a]	14[a]
Mississippi	66[a]	100[a]	57[a]	87[a]	. . .	. . .
Texas	1,147	100	1,070	93	77	7

[a] Estimates based on a sample size of 10-29 thousand.
SOURCE: *National Survey of Fishing, Hunting, and Wildlife-Associated Recreation.*

$53 billion and travel employment of 605,000 (U.S. Travel Association, 2009).

An important source of wildlife-based recreation statistics is the *National Survey of Fishing, Hunting, and Wildlife-Associated Recreation* that is conducted every five years by the U.S. Fish and Wildlife Service, in association with the Census Bureau. The most recent of these surveys, conducted in 2006 (U.S. Department of Interior, 2007), reports statistics on the number of participants, days participated, trips taken, species targeted, expenditures, and demographic characteristics of participants. Survey questions and methodology were similar to surveys conducted in 2001, 1996, and 1991 so that estimates across surveys are comparable, allowing trends to be calculated. Separate statistics are collected for freshwater versus saltwater fishing; no distinction is made between coastal and inland hunting and wildlife watching. Table 3.2 presents data from the report for GoM states. Florida and Texas dominate the number of recreational anglers and angler days in the Gulf and for the country as well.

An important source of saltwater recreational fishing data is the NOAA Fisheries Marine Recreational Information Program (formerly the Marine Recreational Fisheries Statistics Survey).[11] The purpose of this program is to gather information on participation, fishing effort, catch, and socio-economic characteristics of the participants. Data can be retrieved using a number of filters including dates, waves (two month time periods), geographical area that includes states or regions, the type of fishing (shore, charter, party boat,

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[11] See http://www.st.nmfs.noaa.gov/st1/recreational/index.html.

Days of Fishing					
Total Days, Residents and Nonresidents		Days by State Residents		Days by Nonresidents	
Number	Percent	Number	Percent	Number	Percent
758	100	530	70	229[a]	30[a]
23,077	100	19,553	85	3,524	15
2,975	100	2,541	85	433[a]	15[a]
590[a]	100[a]	573[a]	*97[a]	. . .	. . .
15,143	100	14,380	95	762	5

etc.), fishing area (state waters, federal waters, inshore, etc.), type of catch (caught and released, used for bait, kept), and by weight or numbers. The statistics do not include any data from Texas, because they have elected not to participate.

Systematic data are generally not available for other forms of outdoor recreation not covered by the *National Survey of Fishing, Hunting, and Wildlife-Associated Recreation* and the Marine Recreational Information Program. There are, however, some other studies that are conducted for specified regions and/or activities (see Fesenmaier et al., 1989; Gillig et al., 2000, Scott and Associates, 2004; NOEP, 2006).

A recent report prepared for the Louisiana Office of Tourism attempts to quantify the impact of the oil spill on tourism in that state (Tourism Economics, 2010). They report that visits to state parks were down 5 percent in the second quarter of 2010 versus the second quarter of 2009. Second, and more telling of the impact of the spill, is that fishing license revenue was down by 45 percent versus the same period the year before. Much of this downturn can be correlated to fishing closures that were instituted as a result of the oil spill.

SUMMARY

This chapter provides a preliminary discussion for identifying and describing the appropriate methods and types of information available to approximate baselines, and for distinguishing effects on ecosystem services specific to the spill. As a starting point, the committee utilized a list of ecosystem services in the GoM that were identified by regional experts (Yoskowitz et al., 2010). Here we presented some of those ecosystem services with reasonable and calculable values and supporting databases.

This chapter is not intended to be comprehensive, but rather to highlight key parameters and provide guidance for determining changes in various ecosystem services. In approaching this task, three fundamental questions were addressed for each service specified: (1) describe the current state of knowledge, (2) identify the important measurable parameters, and (3) identify the best methods available to conduct those measurements. As reflected in this chapter, research and data for some services are much more readily available than others. Additionally, we must acknowledge there are many aspects of Gulf ecosystems that are dynamically changing from both natural and human-caused processes. This reality will make identifying appropriate baseline information a particular challenge.

4

An Ecosystem Services Approach to Damage Assessment

The ecosystem services approach focuses not only on the restoration of damaged resources but also on establishing and maintaining the value of benefits derived from ecosystems to the public. This broader view may be of value for understanding an event of the magnitude, duration, and complexity of the Deepwater Horizon (DWH) spill and may offer more options for approaches to restoration. Final decisions on restoration projects will, of course, be an open process that includes stakeholders from local communities as well as the state and federal natural resources trustees. The incorporation of an ecosystem services approach to the damage assessment process should be beneficial in identifying a larger suite of restoration alternatives that can then be offered as options to the wider group of stakeholders.

In the Statement of Task (see Box S.1) the question "What are the available methods for identifying and quantifying the ecosystem services in the Gulf of Mexico (GoM)?" is posed. The committee deconstructed that question into the following: "What are the approaches to assessing the impacts of the DWH oil spill that affect the structure or function of the GoM ecosystem and how can these be translated into changes in quantity and value of ecosystem services?" In light of ongoing assessment efforts, it is important to ensure that evaluations of the impacts of human actions on the GoM are conducted in a systematic and uniform manner so that the results could be applicable to the ecosystem services analysis as well as to the damage assessment process. It is likely that some of the wealth of data collected for the ongoing damage assessment will be readily applicable to the ecosystem services analysis. A unique opportunity exists to benefit from the application of new approaches to both available data sets and emerging results from ongoing and future research to understand the impacts of the DWH oil spill and large-scale oil spills in general.

Chapter 2 provides a detailed characterization of the approach to evaluating impacts on the value of ecosystem services, including the questions that need to be addressed in order to adequately characterize those impacts (see Figure 2.1). These questions—What are the impacts of human actions on environmental conditions that affect the structure or function of ecosystems? How do changes in the structure and function of ecosystems lead to changes in the provision of ecosystem services? How do changes in the provision of ecosystem services affect human well-being, and how can the value of the changes in services in terms of human well-being be quantified?—and the logic behind them set the stage for what is likely to have been done early in the Natural Resource Damage Assessment (NRDA) process, whether for the DWH spill or other incidents. Extending this process to consider how these impacts affect the provision of ecosystem services and ultimately how this leads to changes in human well-being is discussed in the following sections of this chapter.

ECOLOGICAL PRODUCTION FUNCTIONS: FROM ECOSYSTEM STRUCTURE AND FUNCTION TO ECOSYSTEM SERVICES

Production functions are a standard tool used by economists to describe how inputs can be transformed into outputs. A production function gives the feasible output of goods and services that can be produced from a given set of inputs. For example, what is the maximum amount of steel (output) that can be produced from a given amount of iron ore, energy, machinery, and labor (inputs)? The notion of production functions applied to ecological systems has a long history in agricultural economics (e.g., crop yield functions) and resource economics (e.g., bioeconomic modeling of fisheries and forestry). Production functions have also been applied recently to the provision of ecosystem services (e.g., NRC, 2005a; Barbier, 2007; Daily et al., 2009; Tallis and Polasky, 2009). An ecological production function specifies the output of ecosystem services generated by an ecosystem given its current condition. Changes in ecosystem conditions, either from natural disturbances such as hurricanes, or from human disturbances such as an oil spill, will in general alter the amount of various ecosystem services provided. For example, degradation of coastal marshes may reduce protection from storm surges and reduce nursery habitat for fish, among other services.

For some ecosystem services, ecological production functions are fairly well understood and data exist that can be used to quantify the amount of a service provided. A good example of a fairly well understood and well studied ecosystem service is carbon sequestration in above-ground biomass for terrestrial ecosystems, particularly for forests. The U.S. Forest Service collects data on biomass in forests by stand age and tree species for different areas of the country (Smith and Smith, 2006). These data, along with knowledge of the carbon ratio in biomass, can be used to calculate carbon sequestered in forests. In marine systems, production function approaches have been used to study the productivity of fisheries as a function of ecosystem conditions (Lynne et al., 1981; Kahn and Kemp, 1985; Ellis and Fisher, 1987; McConnell and Strand, 1989; Swallow, 1994; Parks and Bonifaz, 1997; Barbier and Strand, 1998; Barbier, 2000, 2003; Sathirathai and Barbier, 2001; Barbier et al., 2002) although there is far greater uncertainty in the functional relationship between habitat conditions and fishery productivity.

Table 4.1 expands the basic damage assessment approach presented in Table 2.1 to include data collection and analyses necessary to establish ecological production functions for two key ecosystem services in the Gulf of Mexico, hazard moderation (in the form of storm protection) and food (in the form of nursery habitat for fisheries). While in general a greater amount of vegetation or animal material (e.g., mangroves and oyster beds) will lead to greater dissipation of wave energy and provide more protection from coastal storms, the degree of protection will depend upon the timing of storms relative to the tide, height of the storm surge, the direction of the wind, speed of passage, and other factors. For many marine species, survival of larvae will depend upon water column conditions and currents at the time of spawning and quality and quantity of nursery habitat leading to highly variable recruitment from year to year.

Finding 4.1: Additional sampling and analyses could facilitate an ecosystem services approach by identifying the impacts on ecosystem function and structure that in turn affect the ecosystem services provided. The collection of these additional data would set the framework for establishing the impact of the spill on ecosystem services.

An example of an ecological production function for a key ecosystem service provided by coastal wetlands—hazard moderation (via storm surge protection)—is provided below (Box 4.1). This example outlines the challenges faced by those seeking to capture the full suite of ecosystem services in a complex environment, as well as the potential benefits of this broader view in assessing the impact of damages to the environment.

For many other ecosystem services, there is either a lack of mechanistic understanding, a lack of data, or both that prevents accurate quantification of ecosystem services as a function of ecosystem condition. Marine ecosystems are complex with many interacting processes and complex food-web dynamics. Such complexity makes it difficult to understand how disturbances

TABLE 4.1 An Expansion of Table 2.1 to Illustrate the Data and Methods Needed for an Ecological Production Function Approach for the Ecosystem Services of Hazard Moderation and Food from Coastal Wetlands.

			Assessment Process for Ecosystem Services Approach			
Data Category	Resource	Typical Approach to the Assessment	Ecosystem Service	Type of Data Needed	Ecological Production Function	Type of Data Needed for Ecosystem Service
Biological	Wetland	Determine spatial extent of vegetation oiled; collect and document any dead or oiled wildlife.	Hazard Moderation (reduction in storm surges; see Box 4.1).	1. Plant type (or species), height and density. 2. Percentage of area likely to experience acute toxicity and die off. 3. Cross-shore and along-shore extent of wetland harmed. 4. Estimates of ability of the wetland to reestablish with and without human intervention.	1. Relationship between plant type, height, density, and areal extent of vegetation and reduction of wave energy. 2. Relationship of reduction in wave energy to likely reduction in storm surge.	1. Collecting data on (1), (3), and (4). Data on wetland extent and amount oiled would be collected in a standard NRDA but other data would likely not be. 2. Building the functional relationships to translate from data on plant height, density and extent to likely height of storm surge. This may be done via empirical relationships and/or modeling.
			Food (production from commercial and recreational fisheries; see Box 4.2)	1. Measures of fishery landings. 2. Measures of fishery stock and recruitment. 3. Estimates of the ability of wetlands to re-establish with and without human intervention.	1. Relationship between wetland condition and fishery productivity	1. Collecting data on (2) and (3). 2. Building the functional relationship between wetland condition and fishery productivity. This may be done via empirical relationships and/or modeling.

BOX 4.1 HAZARD MODERATION (STORM SURGE PROTECTION): REGULATING SERVICE

Coastal wetlands include salt marshes and mangroves and can reduce the damaging effects of hurricanes on coastal communities (Badola and Husain, 2005; Danielsen et al., 2005; Das and Vincent, 2009).

Our knowledge of fluid dynamics and of the physical processes that govern the behavior of waves has advanced to the point where we can explain why wetlands reduce wave energy and protect coastal infrastructure (Massel et al., 1999; Narayan and Singh, 2006; Quartel et al., 2007; Vosse, 2008; Krauss et al., 2009). Reduction of wave energy depends on the structure of the plant canopy, its height and density, and the cross-shore and along-shore extent of the wetland (Narayan and Singh, 2006; Koch et al., 2009; Massel et al., 1999). The velocity of water traveling within a plant canopy is relatively lower than flow velocities above the canopy. Canopy height in relation to water depth is relevant because flow through the vegetation encounters a different level of friction than the water above the vegetation. Therefore, the total friction in the water column will be different as a function of depth for vegetated and non-vegetated areas. Because a mangrove canopy is taller and exerts more drag than a salt marsh community, mangroves are more effective at reducing wave energy than salt marshes. Quartel et al. (2007) suggested that the drag force exerted by a mangrove forest is a function of the projected cross-sectional area of the submerged canopy (denoted as A in the equation $C_D = 0.6e^{0.15A}$). For the same muddy surface without mangroves the drag is a constant 0.6. Mazda et al. (1997) observed that 100 m^2 of mangrove forest was capable of reducing wave energy by 20 percent. Reduction in water levels across a mangrove area in Florida was 9.4 cm km^{-1} (Krauss et al., 2009). The dissipation of wave energy is also affected by topography. In a modeling study of sea-level rise and storm surge across the Louisiana coast, Vosse (2008) found that when the relative land elevation was decreased by 20 cm, wave heights increased 5-10 cm across the model domain, and when relative land elevation decreased 50 cm, wave heights increased 10-20 cm. The conclusion is that friction by the plant canopy dissipates energy and reduces wave heights, but the effect of the wetland surface depends on water depth. In the future, the effect of wetland surge dissipation will depend on the survival of the wetlands, because wetland survival will have a great effect on the height of the storm surge relative to mean sea level.

to an ecosystem will reverberate through the system and ultimately lead to changes in the provision of ecosystem services. A further complication in predicting the provision of ecosystem services arises from variability in environmental conditions that are characteristic of many coastal and marine ecosystems (Koch et al., 2009).

Ideally, a thorough ecosystem services analysis would be based on a mechanistic understanding of, and model for, the complex linkages and interdependencies of the ecosystem being studied. Such a model would allow for predicting the provision of ecosystem services given the state of the ecosystem (i.e., the ecological production function). Establishing such an ecosystem model is perhaps the greatest challenge facing the application of an ecosystem services approach for damage assessment. One complicating aspect is that the damage assessment process does not lend itself to collecting data that would better inform our basic understanding of variability in biological processes across the GoM. Because of this and other factors, a complete ecosystem model for the Gulf of Mexico has yet to be developed. However, several marine ecosystem models have been developed that could be useful for analysis of ecosystem services in the Gulf of Mexico such as Atlantis (Fulton et al., 2011), Ecopath with Ecosim,[1] and Marine InVEST (Guerry et al., 2011[2]). These models, and others, span a range of data requirements and modeling sophistication. Application of these models to a system as complex as the Gulf of Mexico in order to analyze the impact of an event of the magnitude of the DWH oil spill would require extensive data collection, model testing, and verification. Given the magnitude of the impacts and the importance of many GoM ecosystem services, however, such efforts may be justified. Models for specific ecosystem services (e.g., fisheries) or components of the ecosystem (e.g., wetlands) are more readily available and more easily applied and do not necessarily require extensive ecosystem modeling efforts in order to be successful. There may also be cases where the lack of scientific understanding, paucity of data, or the degree of environmental variability may be simply too great at this time to afford much confidence in predicting the quantity or value of ecosystem services generated. That said, utilizing the extensive data that have been collected for the damage assessment process in the GoM and the existing ecosystem models for the GoM presents a unique opportunity for enhancing our understanding of ecological production functions and the provision of ecosystem services in the GoM.

> **Finding 4.2: An ecosystem services approach to damage assessment and valuation offers great promise but accurate estimates may be limited to cases in which there is a mechanistic understanding of the service's production function and environmental conditions are not highly variable. In other cases, however, the lack of scientific understanding, paucity of data, or great environmental variability may preclude quantification of ecosystem services with reasonable confidence.**

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[1] See http://www.ecopath.org/.

[2] See http://www.naturalcapitalproject.org/InVEST.html.

APPROACHES TO VALUING ECOSYSTEM SERVICES

In Chapter 2 we addressed the question "what are the impacts of human actions on environmental conditions that affect the structure or function of ecosystems?" In the section above we discussed ecological production functions and their role in addressing "how do changes in the structure and function of ecosystems lead to changes in the provision of ecosystem services?" The next component of the ecosystem services approach focuses on establishing the value of ecosystem services. The value of an ecosystem service is the contribution of the service to human well-being. Ideally, valuation methods can provide a quantitative measure in a common metric to facilitate comparisons across services that indicates how much the availability of the service contributes to the improvement in human well-being. For example, how much money would people be willing to give up in exchange for restoring a coastal ecosystem? Answering this question involves identifying what ecosystem services might be affected by the restoration and by how much. For example, restoration might lead to improved fishing, improvement in water quality, and greater storm protection. Economic methods can then be applied to assess how valuable these changes in services are. Improved fishing may be quite valuable for commercial fishermen and avid recreational fishermen (and possibly for those who eat a lot of fish), but may be relatively unimportant for those who do not fish or consume seafood. Alternatively, in the case of damage to the environment that reduces services, valuation methods can be applied to assess how much value has been lost.

Economics provides well-developed methods grounded in established economic theory to measure values (see Freeman, 2003 for a thorough discussion of economic approaches to valuation and Chapter 4 in NRC, 2005a for a discussion of economic valuation techniques applied to ecosystem services). Economic analysis of ecosystem services can generate estimates of the value of services in terms of a common (monetary) metric. The economic approach to valuation begins with individuals and the tradeoffs they are willing to make. Economists assume that individuals have well-defined and stable preferences. Given preferences, the value of an ecosystem service can be measured in terms of what the individual would be willing to give up to get more of the ecosystem service. By measuring what an individual is willing to give up in terms of a common monetary metric, the economic approach to valuation generates measures of the relative value of goods and services.

Valuing multiple ecosystem services at one time with one survey is not commonly undertaken primarily to avoid survey respondent fatigue. The more questions and text, and the greater complexity of the valuation scenario due to multiple services, the less reliable the answers will be for a given survey. Given the spatial extent of the DWH spill and the varied habitats impacted, there are numerous ecosystem services that could potentially be affected. The scope of the ecosystem services valuation exercises for a spill of this size could be challenging for the current practice of stated preference methods. Many ecosystem services are public goods. In economic terms, public goods are "non-rival" in consumption (one person's use of a public good does not diminish the use of another) and "non-excludable" (once it is supplied it is freely available to everyone). For example, the light from a lighthouse is a public good. The light provides navigation services to all ships that pass within sight of it. Similarly, coastal ecosystem restoration may provide public goods of storm protection services and water purification services, which are then freely available to all nearby residents.

To assess the value of a public good requires adding up the value to all beneficiaries of the public good. Assessing the value of public goods is complicated by the fact that there is often no direct signal of value for many of the beneficiaries. For example, how can a public agency assess the value of the navigation service provided by the lighthouse or storm protection and water purification services provided by a coastal ecosystem? Closely related to the concept of public goods is the concept of common property resources. Common property resources, like oyster beds or fisheries, are resources subject to use by multiple parties. Because each user does not typically take into account the negative effect of their use on others, common property resources often suffer from over-use. In the extreme, when there are no limits on who can exploit the resource ("open access"), severe over-harvesting can occur, a result known as the "tragedy of the commons." Below we describe some methods economists use to estimate the value of ecosystem services focusing on tools for "non-market" valuation that are particularly relevant to ecosystem services.

The economic approach to valuation of ecosystem services has its critics (e.g., McCauley, 2006; Norton and Noonan, 2007). Some environmental philosophers argue that nature has intrinsic value, i.e., value in and of itself, regardless of whether or not nature contributes to human well-being through the provision of ecosystem services (e.g., Norton, 1986; Rolston, 1988), and that humans have inherent obligations to protect and conserve nature. These duties cannot be avoided merely because some individual or group would benefit by doing so. Other critics of economic approaches to valuation question the accuracy of standard assumptions in economic models. Psychologists question the assumption that people have well-defined, stable and consistent preferences that they bring to decision making. A body of work in both psychology and behavioral economics has documented systematic departures from classic assumptions of rational behavior (e.g., Kahneman and Tversky, 1979; Ariely, 2009). A body of experimental evidence suggests that people often construct their preferences when called upon to make decisions and are therefore sensitive to the context and framing of decisions (e.g., Lichtenstein and Slovic, 2006). Sociologists question the central focus on individuals and individual decisions, which they feel does not give proper consideration to how values are shaped by larger groups, norms, and culture. Despite these criticisms, virtually all valuation of ecosystem services to date has used the economic approach to quantify values. Other approaches to valuation of ecosystem services exist and these are briefly discussed later in this chapter in the section "Other Methods" (and see also EPA SAB, 2009 for a review of both economic and non-economic approaches).

ECONOMIC VALUATION METHODS

Economists have developed a variety of methods to quantify values of environmental and natural resources. Although some natural resources are traded in markets where prices can be used to value these resources, most elements of environmental quality are not traded in markets and have no direct measure of value. Economists have developed methods of non-market valuation over the last several decades that can be applied to value environmental quality and resources not traded in markets (Freeman, 2003). These methods were developed long before ecosystem services were part of the vernacular of how one describes the relationship between the environment and humans.

To assess the value of changes in ecosystem services from environmental impacts such as an oil spill, economic valuation methods need to be combined with ecological assessments of impacts. For example, changes in marsh, seagrass, oyster reefs, mangroves, and other habitats impacted by the oil spill could have a direct impact on ecosystem services supplied by these systems. Analysis of impacts on the supply of services combined with economic valuation methods can generate estimates of the value of changes in ecosystem services as a result of environmental changes. For example, Bell (1997) linked recreational catch to fishing effort and the contribution of wetlands to fishing productivity to estimate the value of wetlands in supporting recreational fishing. Lynne et al. (1981) related blue crab productivity and value to salt marsh along Florida's Gulf Coast and found that the marginal value productivity of marsh varies with marsh area and fishing effort.

There are three main types of valuation methods applied to ecosystem services:

- revealed preference based on observed economic behavior,
- stated preference based on responses to survey questions, and
- cost-based methods such as avoided damages and replacement cost.

Revealed preference and stated preference methods generate estimates of benefits consistent with economic notions of what individuals would be willing to give up in terms of other goods or services to get more of an ecosystem service. Avoided damage, though labeled as a cost-based method, can also be thought of as measuring benefits. Damages are a cost while avoided damages are a benefit. For example, typically the marginal benefit of pollution abatement is viewed as equivalent to the marginal damages from pollution, i.e., the benefit of not polluting is not incurring the associated damages. Replacement cost, however, is a measure of costs rather than benefits. Because replacement costs measures costs not benefits, some economists do not include these approaches as a valid way to measure the value of ecosystem services. However, many economists view replacement costs as a valid approach to measuring what is lost when ecosystem services are lost or diminished as long as certain restrictive conditions, discussed below, are met.

Revealed Preference Methods

Under the broad heading of revealed preference methods, which infer economic values based on observed behavior, are various methods of both market and non-market valuation. For goods and services traded in markets, data on the amount bought and sold at various prices can be used to establish estimates of demand (willingness-to-pay) functions that measure the value of the goods and services to consumers. The value of a good or service can be measured by what an individual would be willing to pay to get more of the good or service. Market prices are what an individual actually has to pay to get more of the good or service. The gap between the individual's willingness to pay and what they have to pay (price) is called consumer surplus and represents a monetary value of the gain in welfare to the individual from purchasing the good or service. An estimate of the willingness-to-pay can be derived from market data by noting that people should be willing to purchase the good up to the point at which willingness-to-pay is equal to price. By observing how much of each good or service is purchased at different prices one can recover an estimate of the willingness-to-pay for different amounts of the good or service (see Freeman, 2003 for a more complete discussion). Some marine ecosystem services produce marketed goods for which market prices can be used for purposes of valuation. Commercial fisheries are a prime example. The most difficult part of measuring the impact of the DWH oil spill on commercial fisheries is not the valuation component to understand willingness-to-pay, but rather, measuring the impact of the spill on fishery productivity. Getting an estimate on the impact of the spill on fishery productivity requires estimating the change in productivity through time and not just the initial impact. That said, there remain challenges to valuation even with observable market prices. When consumers are uninformed about actual environmental conditions their choices may not accurately reflect their preferences (this issue is a concern for all valuation methods). Other issues related specifically to the commercial fishing example include uncertainty over how much and how long fears of contamination will depress demand for fish from the GoM and the difficulty of getting accurate cost data with which to estimate economic rents.

For most ecosystem services, however, markets do not exist, making estimation of values from ecosystem services more difficult. Without market prices other non-market methods must be used as proxies for prices. In some cases, the value of these non-marketed ecosystem services can be estimated using data on observed behavior of how much of a service is utilized and the cost to the individual of utilizing the service (e.g., travel cost methods), or by using data on related goods and services such as housing values (e.g., hedonic property price methods).

Travel cost studies (see example in Box 4.2) use information on trips that individuals make to recreational sites and the expenditures of time and money involved in making the trip (Freeman, 2003). Travel cost studies typically use “random utility models” in which the value (utility) of a visit to a given recreational site is a function of distance from sites, site access fees, observable site characteristics (environmental quality, site facilities, etc.), observable characteristics of individuals (income, education, etc.), as well as unobservable characteristics of the individual (idiosyncratic preferences). Travel cost methods allow an analyst to trace out a demand function for site visits by varying the implicit price of a visit (travel cost plus access fees) faced by individuals and observing the number of trips taken. Further, by looking at sites of varying environmental quality, the value of improved environmental quality can be estimated.

A number of studies have used travel cost methods in the Gulf region

BOX 4.2 RECREATIONAL CHARTER FISHING CASE STUDY

Saltwater fishing, using personal equipment or guides in the inshore areas and charter boats for offshore, is an important part of the identity of the Gulf Coast. Whole communities identify with this lifestyle and it is an important economic engine, for example Port Aransas, Texas; Venice, Louisiana; Biloxi/Gulfport, Mississippi; Orange Beach, Alabama; and Destin, Florida. One estimate puts the economic output of recreational saltwater fishing in the Gulf in 2006 at $8.1 billion dollars, which is about one-quarter of the total for the United States and it also accounted for 82,741 jobs (Southwick Associates, 2007). In that same year approximately 3.6 million anglers spent 424 million angler days saltwater fishing in Gulf waters (U.S. Department of the Interior, 2007). While not the predominant type of fishing in the Gulf, charter boats are still an important component of the recreational effort and help determine how many individuals access offshore waters.

A dramatic shift in recreational fishing took place as a result of the oil spill, based on data from the Marine Recreational Information Program (MRIP) of the National Marine Fisheries Service for charter boat trips during May-August each year. From 2000 to 2009 the average number of charter boat trips per year in the Gulf (excluding Texas) was 226,192 and the west coast of Florida typically accounted for 75 percent of this business. In 2010 the number of trips dropped to 163,081 and even more illuminating of the impact of the oil spill was that Florida now accounted for 95 percent of that business (see figure).[a] In July and August of 2010 almost all of the activity took place in Florida with only 1,607 trips occurring in the remaining states. This is not surprising given that fishery closures during these months included over 30 percent of the federal waters of the GoM and virtually all marine waters up to over 100 miles offshore of the coasts of eastern Louisiana (east of Morgan City), Alabama, Mississippi, and 30 miles of the western panhandle of Florida.[b]

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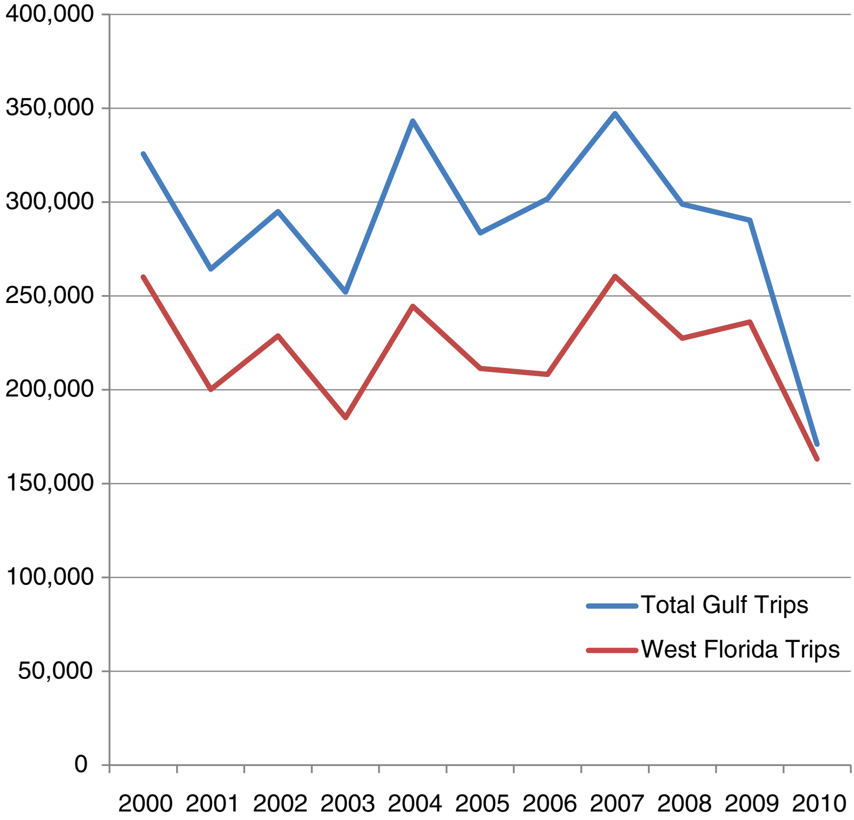
[a] The data fields selected in the Marine Recreational Information Program under Angler Effort are Waves = 3 & 4, Geographical Area = GOM, Type of Fishing = Charter Boats, Fishing Area = All Ocean Combined.
[b] See http://sero.nmfs.noaa.gov/ClosureSizeandPercentCoverage.htm.

to assess the recreational value attributed to wetlands (Farber and Costanza, 1987; Costanza et al., 1989), beaches (Bell and Leeworthy, 1990; Freeman, 1995), and coral reefs (Bhat, 2003). Bhat (2003) interviewed 200 people in the Florida Keys and gathered information on the number of times they had visited the Keys, how far they traveled, how long it took them, their mode of transport, as well as demographic characteristics. Bhat (2003) found the use value per person per trip of the coral reefs in the Keys was $463 (1996 dollars) in its current state. When the quality of the coral was hypothetically improved by 100 percent, the use value increased to $783, demonstrating the monetary value of an improved environmental quality.

"Hedonic" property pricing methods use data on property values, char-

GOM Charter Boat Trips, 2000-2010.



acteristics of the property (lot size, structure square footage, age of structure, etc.), neighborhood characteristics, and environmental characteristics to estimate a multiple regression equation that predicts property price as a function of a change in a characteristic that affects property value. The results of the analysis can be used to assess how property values will likely change if environmental quality is changed, holding other characteristics that affect property value fixed. For example, how would two houses that are identical in lot size, square footage, number of bedrooms, age, etc., differ in value when one is located near a nice beach and the other located near a polluted beach? The hedonic property price method has been used widely to value such things as wetlands (Thibodeau and Ostro, 1981; Doss and Taff, 1996;

Mahan et al., 2000), parks and open space (Crompton, 2001; Lutzenhiser and Netusil, 2001), and views (Bourassa et al., 2004; Sander and Polasky, 2010). Hedonic property price analysis could be used to assess whether the DWH oil spill has had a negative impact on the value of coastal properties, but otherwise this method may be of limited utility in the case of the DWH spill.

A third revealed preference non-market valuation method is based on expenditures made by individuals or households to avoid health or environmental risks and is called averting behavior. Averting behavior methods are typically employed to measure the value that individual(s) place on avoiding undesirable health impacts such as the amount that households pay for water filtration or bottled water to avoid drinking perceived contaminated water (Dickie, 2003). For example, how much expense is incurred to buy filters or bottled water (Harrington et al., 1989; Abdalla et al., 1992)? Expenditures to avoid damages might not always be a good estimate of the willingness-to-pay (Courant and Porter, 1981). This method is likely to have limited applicability in the case of the DWH oil spill.

Stated-Preference Methods

Stated-preference methods use surveys where respondents are asked a series of questions in order to gain information about their values and preferences (Mitchell and Carson, 1989; Freeman, 2003). One of the stated preference methods is the contingent valuation method (CVM), which is used to elicit values that people place on an ecosystem service where implicit or explicit market price information does not exist (NRC, 2005a). Survey questions may directly elicit information about willingness to pay for an increase in an ecosystem service or willingness to accept a reduction in an ecosystem service. Alternatively, respondents may be asked whether they are willing to pay a specified value for a certain amount of an ecosystem service. A willingness-to-pay function can be derived varying the values and observing the proportion of respondents answering that they would be willing to pay that amount. CVM was used to value natural resource damage in the *Exxon Valdez* oil spill. The widely divergent estimates of CVM held by experts hired by Exxon and by the trustees in the case led NOAA to form a blue-ribbon panel to discuss the merits of CVM. The panel concluded that CVM was a valid non-market valuation method and could be used in NRDA cases and provided guidance on best practices (Arrow et al., 1993). However, the use of CVM to estimate environmental values remains controversial (see, for example, Hausman, 1993; Diamond and Hausman, 1994; Hanemann, 1994; Carson et al., 2001) and it has not been used extensively in NRDA cases since the *Exxon Valdez*. On the other hand, there have been numerous CVM studies published over the past two decades. CVM studies applied in the Gulf coast include analysis of the value of habitat (Shivlani et al., 2003), recreational opportunities (Bergstrom et al., 1990; Barbier et al., 1997; Henderson and O'Neil, 2003; Murley et al., 2003; Johns et al., 2004), and water supply, regulation, and nutrient cycling for freshwater wetlands (Shrestha and Alavalapati, 2004).

Another use of CVM to quantify economic value of ecosystem services is conjoint analysis. This technique grew out of the marketing literature (Green and Srinivasan, 1978, 1990) where it was utilized to estimate prices for products given different product attributes. In environmental applications, respondents are asked to rank the alternative scenarios, each of which may have several attributes that change between the alternatives. By examining the trade-offs among the attributes, marginal willingness-to-pay for the attribute can be calculated when one of those attributes is price (Freeman, 2003). Similar to the conjoint method is the attribute-based stated-choice approach. Adamowicz et al. (1998) argue that stated-choice methods are more appropriate for assessing the impact on ecosystem services. The goal is to put the decision-maker in a realistic setting so they can compare alternatives that are described in terms of attributes. For example, Milon and Scrogin (2006) used the stated-choice method to assess the value of potential restoration plans for the Florida Everglades. Their results showed that individuals would be willing to pay more for structural restoration (e.g., increasing the number of wetland, dryland, and estuarine dependent species) than functional restoration (e.g., changing water flows that impact habitats).

The use of stated-preference methods remains controversial in NRDA cases, whether it is CVM, conjoint analysis, or other variants. Proponents claim that these methods can generate reliable estimates of environmental value provided that best practices are followed; furthermore, for non-use values such as existence values, stated preference are the only available methods. On the other hand, critics claim that such methods are unreliable and point to cases in which different framing of questions has generated widely divergent estimates of value. The committee was not asked to evaluate the merits of using stated-preference methods in NRDA and does not take a position on its use.

Cost-Based Methods

Some estimates of the value of ecosystem services have been generated by looking at costs incurred when the ecosystem services are lost or degraded. There are two sorts of cost-based methods that are commonly used in valuing ecosystem services—avoided damages and replacement costs. An avoided damaged approach estimates how damages would increase if the ecosystem service were diminished or absent. Replacement costs estimates the cost of providing the service via some alternative means. The method of avoided damages to value an ecosystem services uses estimates of likely damages that would be incurred with and without the ecosystem service. Avoided damages from maintaining an ecosystem that provides protection against storms, floods or other natural disasters are a measure of benefits provided by the ecosystem. This method is probably the most common method used to value coastal protection (Badola and Husain, 2005; Danielsen et al., 2005; Costanza, 2008; Das and Vincent, 2009). The value of coastal protection afforded by coastal wetlands is estimated by finding the difference in likely damages to coastal communities from a hurricane or other storm event in the case with intact coastal marshes versus degraded or no coastal marshes to absorb wave energy and reduce storm surge. For example, Costanza et al. (2008) used a regression model to analyze the damages from 34 major U.S. hurricanes since 1980. While wind speed was an important variable in estimating damage, they also found that wetlands helped to reduce damages. The estimated yearly marginal value of wetlands in the Gulf region in their analysis ranged from a low of \$126 $ha^{-1}yr^{-1}$ in Louisiana to a high of \$14,155 $ha^{-1}yr^{-1}$ in Alabama.

Another commonly used cost-based method to generate a value for ecosystem services is replacement cost, which is the cost of providing the service an alternative way such as replacing the service provided by ecosystems with a human-engineered approach. For example, clean drinking water can be provided by natural processes in intact watersheds or provided through a water filtration system. The most commonly cited example for the value of ecosystem services is the Catskills watershed providing clean drinking water for New York City. Replacing the clean water provided by the watersheds with a water filtration plan was estimated to cost \$6 to \$8 billion (Chichilnisky and Heal, 1998).

Many economists are skeptical of the use of replacement cost as a method of valuation, even though it is often used in valuing ecosystem services. The main reason for skepticism is that replacement cost is about cost rather than directly a measure of benefits. However, replacement cost can address the value of ecosystem provision of a service in certain instances (NRC, 2005a; EPA, 2009). To be a valid measure of the value of what an ecosystem provides, three conditions must be met (Shabman and Batie, 1978):

- there is a human-engineered solution that provides equivalent quality/quantity of the service provided by the ecosystem,
- the human-engineered solution is the least cost alternative of providing the service, and
- individuals in aggregate would be willing to incur the cost if the ecosystem service were not available.

If these conditions are satisfied, then the cost of replacement represents a lower bound of the value of what is lost when the ecosystem service is diminished or lost.

Benefit Transfer

Undertaking revealed, preference or stated, preference studies often involves expenditure of considerable time and resources. In cases where the time frame of analysis is short and the questions at stake are small in magnitude it may not be worthwhile undertaking original research to estimate environmental benefits. In such cases, benefit transfer can be used and in fact has been widely applied (EPA, 2009). Benefit transfer uses existing estimates of value from primary studies conducted in one location and applies them to a different location. In this sense, benefit transfer is not a valuation method in the same vein as those discussed above because it merely offers guidance on existing estimates that might be used in a new setting. There are two benefits transfer approaches commonly used: single point or average transfer, and function transfer. The single point or average transfer takes estimates from existing studies and applies those values to the new policy site. A function transfer can customize a value for the policy site using an estimated equation derived from the statistical relationship between the willingness-to-pay of individuals and their socio-economic characteristics (Freeman, 2003; NRC, 2005a). The function transfer is likely to be superior unless the application site is highly similar to the site where the original study was undertaken in all observable dimensions. In the case of the DWH spill and the impacted areas of the Gulf, it is unlikely that there are study sites of the appropriate scale and complexity that would be appropriate for comparison and transfer. Benefit transfer has a number of limitations and is not a good substitute for conducting primary research at the policy site of interest. For the Gulf of Mexico an additional major limitation of using benefit transfer is the lack of primary studies applicable to the habitats and ecosystem services for the region.[3] A special issue of *Ecological Economics* (Wilson and Hoehn, 2006) outlines the challenges of applying benefit transfer. Some benefit transfer studies have been conducted in the Gulf region focusing on the services provided by saltwater and freshwater wetlands, such as recreation, waste regulation, and gas regulation (Kazmierczak, 2001; Jenkins et al., 2010).

Finding 4.3: Primary research on the values of ecosystem services would provide additional grounding for the DWH damage assessment.

Valuation Studies of Previous Oil Spills

Valuation studies of previous oil spills provide a foundation from which to discuss valuation methodologies for ecosystem services potentially impacted by the DWH spill. The *Exxon Valdez* spill was the starting point for the application and evaluation of non-market valuation techniques for natural resource damage impacts. The national study conducted after the *Exxon Valdez* oil spill (Carson et al., 1997, 2003) to assess the damage to passive use values focused a debate on the appropriateness of CVMs to estimate damages. As a result NOAA formed its "blue ribbon panel" to assess the use of the CVM for passive use values and concluded that "useful information" conveyed for damage assessment (Arrow et al., 1993). Similar studies followed the 2002 *Prestige* oil spill in Europe. Loureiro et al. (2009) conducted a contingent valuation study, the first in Europe after a large oil spill, and found that the environmental and passive use losses for Spanish society was around 574 million euros. Other research was conducted on "what-if" scenarios, taking advantage of the notoriety of the *Prestige* spill. Van Biervliet et al. (2005, 2006) conducted an economic assessment of the loss of non-use values resulting from oil spill scenarios along the Belgian coast. Estimation results suggest that welfare losses might range from 120 million euros to 606 million euros and a program targeted at the prevention of oil spills could easily be defended as long as costs are no higher than 120 million euros.

Because oil spills may affect the livelihoods of those directly tied to the coast and sea, a number of studies have looked at these impacts, specifically. Hausman et al. (1995) modeled recreational demand behavior in Alaska to estimate welfare losses suffered by recreational users as a result of the *Exxon Valdez* oil spill. They found the loss to be less than $5 million. The social costs from a diminished commercial fishery in south-central Alaska, an important economic engine, was determined using a market model with an

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[3] See www.GecoServ.org for a gap analysis of valuation studies.

upper bound of the first-year social costs of $108 million and second-year effects as high as $47 million (Cohen, 1995). Garza-Gil et al. (2006) estimate the short-term economic damages from the *Prestige* oil spill in the Galician fishing and tourist activities could have reached five times more than the applicable limit of compensations. Utilizing landings in a purely market approach, Negro et al. (2009) show that some species landings increased after the spill while others decreased, relative to landings before the spill. They note the limitations of this approach in linking changes on landings to the *Prestige* oil spill and conclude that landings are sensitive to fishing effort, predator-prey interaction, and species sensitivity to oil.

Finding 4.4: Both market and non-market approaches to valuing ecosystem services have become accepted and established practice over the past two decades since the *Exxon Valdez* oil spill. When appropriately applied, these techniques can generate valid estimates of value for ecosystem services lost due to human-caused and natural events.

Other Methods

There are a number of additional methods that are outside the traditional environmental and natural resource economics toolkit. Many of these other methods are reviewed in a recent study published by the U.S. EPA's Science Advisory Board (EPA, 2009). These methods include social-psychological approaches that measure attitudes, preferences, and intentions; methods that involve individual narratives or focus groups; and behavioral observation methods. Additionally, civic valuation measures values when people consider their role as "citizen," while referenda and initiatives provide information on how members of the voting public value action involving the environment, and citizen valuation juries measure stated values. Studies of voting on referenda and citizen valuation juries can provide information useful in estimating values (e.g., Vossler et al., 2003) but other methods are further afield and are not necessarily consistent with the economic approach to valuation. Several methods mentioned in the U.S. EPA Science Advisory Board study (EPA, 2009) focus more on the ecological function of habitats rather than on economic valuation of ecosystem services and so are more similar to HEA and REA. These methods include ecosystem benefit indicators, conservation valuation, energy analysis, and ecological footprint analysis. These latter approaches are generally not consistent with an economic valuation approach and would need additional justification before being adopted.

TABLE 4.2 Examples of GoM Ecosystem Services Values

Habitat	Service	Adjusted Values (2008)	Units	Method	Author
Beach	Recreation	$144	per visit	Travel cost	Freeman (1995)
Beach	Recreation	$70	per person/ per day	Travel cost	Bell & Leeworthy (1990)
Coral Reefs	Recreation	$635	per person/ per day	Travel cost	Bhat (2003)
Saltwater Wetland	Recreation	$30	per hectare/ per year	Travel cost	Farber & Costanza (1987)
Saltwater Wetland	Food	$3	per hectare	Market prices	Lynne et al. (1981)
Saltwater Wetland	Recreation	$19,300	per hectare/ per year	Contigent valuation	Bell (1997)
Saltwater Wetland	Recreation	$216	per hectare/ per year	Contigent valuation	Bergstrom et al. (1990)
Saltwater Wetland	Waste Regulation	$681	per hectare/ per year	Benefit transfer	Kazmierczak (2001)

Valuation Methods Applied to the Gulf of Mexico

Table 4.2 summarizes some of the studies mentioned above and provides a limited number of examples and results of where monetary valuation techniques have been used in the GoM region. These examples are by no means a complete list of studies conducted in the Gulf or an endorsement of these particular findings but are reported for illustrative purposes. It should be noted that the values generated from these studies are dependent on place and situation and thus are driven in a large part by the socio-economic characteristics of the respondents. However, these studies provide an important foundation from which additional Gulf-specific studies can be built.

Many services, especially those of a provisional or cultural nature, can have a monetary impact well beyond their immediate environs. These "economic impacts" from the oil spill can disrupt whole industries as is illustrated by the discussion on charter fishing in Box 4.2. Here the monetary impact is felt not only by the charter boat operators but also the supplier of fuel, lodging, food services, tackle, and equipment and by the employees of these establishments whose paychecks might be reduced. The same sort of impacts could be felt in any of the industries that were disrupted by the spill including commercial fishing, tourism, and oil and gas exploration and production as well as for industries that rely on products from the GoM yet are based outside the GoM region.

The theoretical foundations and the practical application of both revealed and stated preference approaches are well grounded in a rich literature. Cost-based approaches do not have the same grounding. Nonetheless, an avoided damages approach may be useful in estimating the value of coastal protection. Replacement cost might also be used but only if certain conditions described above are satisfied. The appropriate valuation methods to employ are dependent upon what ecosystem services are being measured, which is equivalent to saying it is important to have the right equipment for the sport in which you are participating. Travel cost approaches are most commonly used for measuring the value of recreational opportunities. Hedonic property price studies could be used to measure changes in values to coastal communities as a result of the DWH oil spill, but their use is limited to capturing only the impacts felt by property owners in coastal communities. Stated-preference methods can be used for virtually any ecosystem service, including nutrient regulation, storm protection, and erosion control, but careful attention needs to be paid to survey design to get reliable answers to valuation questions. Given the scope and scale of impact, the NRDA process would require rigorously derived values of ecosystem services impacted by the oil spill which would necessitate original valuation studies rather than relying on benefits transfer. However, values from previous work can be an important check on the validity of values estimated in oil spill-specific studies.

All of the economic valuation methods identified above can be effective in measuring value when applied appropriately and employing “best practices.” The NOAA Blue Ribbon panel (Arrow et al., 1993), for example, discusses at length a “best-practices” approach when utilizing a contingent valuation in order to generate useful information for damage assessment.

Examples for the Extension of an Ecosystem Services Approach to Include Valuation

Having discussed both the data and methods for assessing impact and quantifying the provision of ecosystem services for the case of wetlands and the ecosystem services of coastal protection and fisheries in the Gulf of Mexico (Table 4.1), we now extend these examples to include the valuation of ecosystem services (Table 4.3). To reiterate, the examples shown in Table 4.3 are meant to illustrate how an ecosystem services approach could be incorporated into the existing NRDA process; they are not intended to capture the full complexity of the three component steps involved in the ecosystem services approach or the ongoing NRDA process.

TABLE 4.3 Provision and Valuation for Coastal Wetlands for the Services of Hazard Moderation, Food, and Recreation

Damage Assessment Practices			Methodology for the Provision and Valuation of the Ecosystem Services Approach	
Data category	Resource	Typical approach to the assessment	Ecosystem Service	Type of data needed for ecological production function
Biological	Wetland	Determine exposure pathway and spatial extent of vegetation oiled; collect and document any dead or oiled wildlife.	Hazard Moderation (reduction in storm surges; see Box 4.1)	1. Plant type, (or species), height and density. 2. Percentage of area likely to experience acute toxicity and die off. 3. Cross-shore and along-shore extent of wetland harmed. 4. Estimates of ability of the wetland to reestablish with and without human intervention.
			Food (commercial fisheries)	1. Measures of fishery landings. 2. Measures of fishery stock and recruitment. 3. Estimates of the ability of wetlands to reestablish with and without human intervention.
			Recreation (Recreational fisheries)	1. Measures of fishery landings. 2. Measures of fishery stock and recruitment. 3. Estimates of the ability of wetlands to reestablish with and without human intervention.

Ecological production function	Type of data needed for valuation	Valuation method	Type of data needed for valuation of ecosystem service
1. Relationship between plant type, height, density, and areal extent of vegetation and reduction of wave energy. 2. Relationship of reduction in wave energy to likely reduction in storm surge.	1. Location of structures, infrastructure, agriculture, etc. near the coast. 2. Value of structures, infrastructure.	Avoided cost: calculate the expected damages associated with storm surge. The value of the ecosystem service is equal to the reduction in expected damages.	1. Collecting data on (1), (3), and (4). Data on wetland extent and amount oiled would be collected in a standard NRDA but other data would likely not be. 2. Building the functional relationships to translate from data on plant height, density and extent to likely height of storm surge. This may be done via empirical relationships and/or modeling. 3. Building the functional relationship that translates height of storm surge to expected damage.
1. Relationship between wetland condition and fishery productivity.	1. Market price of commercial fish. 2. Fishing cost per unit effort (capital, labor, fuel).	Market valuation: calculate profit from fishing. Use market price and harvest data to calculate revenue. Use cost data along with revenue calculation to calculate profit.	1. Collecting data on (2) and (3). 2. Building the functional relationship between wetland condition and fishery productivity. This may be done via empirical relationships and/or modeling.
1. Relationship between wetland condition and fishery productivity.	1. Survey information on fishing trips.	Travel cost. Use information on recreation trips, time and resource costs of trips to calculate willingness-to-pay for recreational fishing trips.	1. Collecting data on (2) and (3). 2. Building the functional relationship between wetland condition and fishery productivity. This may be done via empirical relationships and/or modeling. 3. Estimation of value using travel cost (random utility model).

Finding 4.5: Measurements and analysis such as illustrated in Table 4.3 would allow for the determination of the impact of the DWH spill related to the ecosystem function and structure of coastal wetlands and to quantify the impact on key ecosystem services. Further research is needed to determine the required measurements for the assessment of other ecosystem services and habitats.

SUMMARY

While the committee strongly believes that an ecosystem services approach has great potential, we also understand that it would be often difficult to implement due to limited understanding and limited data. The linkages between human actions, ecosystem structure and function, and the provision of ecosystem services are complex owing to system dynamics in which there is seldom a single impact and the fact that the occurrence of multiple impacts often results in non-linear changes. There are large gaps in current understanding of ecosystems and their provision of services, and often a paucity of data to quantify these services (Chee, 2004). There may also be unidentified links and feedbacks in ecosystems (Walker et al., 2009). In the context of the DWH spill, complex and interconnected system dynamics can make it difficult to isolate the impact of a single decision or action on overall system behavior. In addition, because of complex interconnections in systems, the impact of an action or decision at a particular place at a particular time can have impacts over large spatial and temporal scales (Boyd, 2010), further complicating the challenge of characterizing and projecting into the future the spatial and temporal human and ecological impacts from the DWH spill.

Ideally, one would like to have a fully developed and proven "end-to-end" ecosystem model that explicitly describes all important interactions. However, ecosystem models capable of incorporating complex system dynamics are still early in their evolution (Allen and Fulton, 2010). Such models do not exist for most ecosystems including the Gulf of Mexico. While complete ecosystem models might be ideal, they are not essential for making progress on evaluating ecosystem services. As a practical matter, reasonable estimates of ecosystem services can be made with simpler existing models that focus on particular aspects of ecosystems. Even though these models will omit some interconnections, if done in a thoughtful manner they may be able to capture the most important linkages and generate reasonable estimates of ecosystem service provision and value. The committee will explore these models in the final report.

In addition to understanding the provision of services, understanding the value of services in terms of human well-being also poses a number of issues. Economic approaches to valuation offer the promise of measuring benefits from ecosystem services in a common metric (money). However, some ecosystem service benefits are extremely difficult to accurately assess in monetary terms (e.g., spiritual, cultural, and aesthetic values). There are additional concerns over distributional equity: who benefits and who is harmed by changes in ecosystem conditions? Making the public whole via restoration is not simply a matter of making sure that aggregate net benefits with restoration are greater or equal to aggregate net benefits before the oil spill. Making the public whole also involves making sure that aggregate net benefits to various groups within society do not decline. Since many services emanate from public resources, for example national parks for recreation and oyster beds for food, it is important that the benefits of ecosystem services are enjoyed by as many as possible without excluding or negatively impacting one segment of the population.

An ecosystem services approach focuses not only on the restoration of damaged resources, but also on maintaining the usefulness of those resources to the public. On the other hand, an ecosystem services approach that restores the value of the services but does so via human-engineered substitutes (e.g., building a dyke or water filtration plant) will not result in making the environment whole. Some portions of the public may not view such actions as adequate restoration even though the value of services is made equivalent. There is also the danger that an ecosystem services approach will focus on a small subset of services and may not restore the full suite of ecosystem services valued by the public given the difficulty of valuing the complete set of ecosystem services (NRC, 2005a). To the extent that the public values the existence of habitat and species, regardless of the extent that these lead to provision of other ecosystem services beyond existence, the gap in practice between restoring ecosystem services and restoring habitat and species will be reduced. High existence values may mean making the environment whole would be necessary for making the public whole.

We also caution that our discussions have not touched on the issue of public involvement or review of any potential restoration project. It is clear that for the DWH spill public involvement and review will be a key element of decisions on restoration projects. It is likely that the value placed on particular habitats, restoration projects, or natural resources will vary with the community involved, which will add complexity to the overall process. Furthermore, improvements that increase the benefits from one ecosystem service may come at the expense of another ecosystem service. What may be acceptable to one community may not be acceptable to another, and what is valued as a project by one state agency may not be valued in the same way by another. Much has been written about how best to make environmental decisions that affect broad communities within society (e.g., Cash et al., 2003; NRC, 2005b, 2008). Technical analyses of the value of ecosystem services should fit within a larger consultative process that involves affected communities.

Despite these limitations, shortcomings and uncertainties, the committee believes that attempts to incorporate an ecosystem services approach to understanding the impacts of the DWH spill would inevitably offer a much more comprehensive and realistic assessment. The tremendous amount of data that has been and will continue to be collected in connection with the DWH spill will facilitate such attempts. While the toolbox is not complete, especially for the complexities of the DWH oil spill, techniques and models are available to value ecosystem services, and research and application of new approaches are ripe for development. The committee will continue to explore the issues associated with potential benefits (and shortcomings) of applying an ecosystem services approach to damage assessment, as well as those associated with restoring (and perhaps increasing) ecosystem resilience for GoM, will be a focus in the production of its final report.

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A

Committee and Staff Biographies

COMMITTEE

Larry A. Mayer (*Chair*) is the Director of the Center for Coastal and Ocean Mapping, Co-Director of the Joint Hydrographic Center, and Professor of Earth Science and Ocean Engineering at the University of New Hampshire. His research interests include sonar imaging, remote characterization of the seafloor, and advanced applications of 3-D visualization to ocean mapping challenges. Dr. Mayer received his Ph.D. from the Scripps Institution of Oceanography in marine geophysics in 1979, and graduated magna cum laude with an Honors degree in geology from the University of Rhode Island in 1973. At Scripps his future path was determined when he worked with the Marine Physical Laboratory's Deep-Tow Geophysical package, but applied this sophisticated acoustic sensor to study the history of climate. Dr. Mayer has participated in more than 50 cruises and has been chief or co-chief scientist of numerous expeditions, including two legs of the Ocean Drilling Program. Recently he has been involved (both at sea and in the lab) with the visualization of environmental data from the Deepwater Horizon incident and the application of acoustic techniques to monitor wellhead integrity and the subsurface environment in the region. He brings a strong set of spatial analysis skills and tools to this committee that will be valuable in mapping the affected areas of the Gulf and understanding impacts. Dr. Mayer served on the President's Panel for Ocean Exploration and chaired the 2004 National Research Council's *Committee on National Needs for Coastal Mapping and Charting*.

Michel C. Boufadel is Professor and Chair of the Department of Civil and Environmental Engineering at Temple University. Dr. Boufadel's expertise includes investigating the offshore transport and fate of oil, original and dispersed, since 2001. He is very familiar with the Regional Ocean Modeling System (ROMS) and the various windcast and wave models, such as the Joint North Sea Wave Project (JONSWAP). Furthermore, Dr. Boufadel has developed a strong understanding of the physics of waterflow, oil transport, and oil transformation (with and without dispersants), and has a strong understanding of the role of oil viscosity, surface tension, emulsion, evaporation, droplet formation (i.e., dispersion), and breakup under various energy levels. Dr. Boufadel's skills will be essential when the committee addresses the question of where the oil went and what it will likely do under a broad range of marine and coastal conditions. Dr. Boufadel earned a Ph.D. and a M.S. in environmental engineering from the University of Cincinnati in 1998 and 1992, respectively, and a B.S. in civil engineering and hydraulics from the Jesuit University at Beirut, Lebanon, in 1988.

Jorge Brenner is currently the Associate Director of Marine Science at the Nature Conservancy. Dr. Brenner is interested in ecosystem services health assessment, valuation models, and spatial dynamics of biodiversity. He is also working on marine conservation and sustainability sciences. Dr. Brenner has experience working on related issues in Mexico, the Mediterranean, and the Gulf of Mexico regions. He brings an international perspective to the committee in addition to his strength in identifying the relevant ecosystem services that the committee will need to quantify for valuation. He earned a Ph.D. in marine sciences from the Catalonia Polytechnic University in 2007, and a M.S. in environmental engineering and a B.S. in biochemical engineering and aquatic resources from the Monterrey Technology Institute University in 1997 and 1995, respectively.

Robert S. Carney is a Professor in Louisiana State University's Department of Oceanography and Coastal Sciences. Dr. Carney's primary research expertise is in deep-ocean biological oceanography, but he is also familiar with shallow systems having directed the Coastal Ecology Institute of LSU for 9 years. He has been awarded numerous grants for his research since 1978, including multiple awards from the Minerals Management Service and National Oceanic and Atmospheric Administration to support the new sampling as well as reanalysis of archival deep Gulf of Mexico data. He is a PI in the Alfred P. Sloan Foundation Census of Marine Life and co-directs international research on continental margin ecosystems. He is a founding member of INDEEP (International Network for Scientific Investigation of the Deep Sea) which will begin funding by Foundation TOTAL in 2011. In addition to basic science, he has published on the design of oil-related impact studies and information needs of deep ocean management. Dr. Carney will provide critical insights regarding the effects of the spill on benthic biota in the Gulf, particularly in the deeper waters near the blowout. In 1977 Dr. Carney earned a Ph.D. in oceanography from Oregon State University; he also earned a M.S. in oceanography from Texas A&M University in 1971 and a B.S. in zoology from Duke University in 1967.

Cortis K. Cooper currently serves as Fellow with Chevron Energy Technology Company, a position he has held since 2002. Prior to beginning his service as Fellow, Dr. Cooper was employed as Scientist/Engineer at Chevron Exploration Technology for 12 years. In this position, he was primarily tasked with quantifying winds, waves, and currents for operation and design of offshore facilities worldwide including measuring and modeling oil spill fates; modeling hurricane alleys in the Gulf of Mexico; modeling sea level in the Caspian Sea; forecasting the Loop Current and associated eddies in the Gulf of Mexico; supervising major ocean current models in the Gulf of Mexico, West Africa, Northeast Atlantic, and Northwest Australia; leading a $1.6 million, 32-company joint industry project (JIP) to improve ocean towing; and leading a $2 million, 24-company JIP to investigate the fate of oil and gas from deepwater blowouts. Dr. Cooper was a member of the 2003 National Research Council's Committee on Oil in the Sea: Inputs, Fates, and Effects, which initiated and led a field experiment in 2000 that simulated a deepwater blowout off Norway. He has studied the physical oceanography of the Gulf of Mexico for 25 years. Dr. Cooper brings a wealth of relevant skills to the committee, but his grasp of industry standard operating procedure and his understanding of oil dispersion under various oceanographic conditions will be most useful. He earned a Ph.D. in environmental engineering from the University of Maine in 1987, and a M.Sc. and B.S. in civil engineering from the Massachusetts Institute of Technology in 1977 and 1975, respectively.

Jody W. Deming (NAS) holds the Walters Endowed Professorship in the University of Washington's School of Oceanography. She has also served as Director of the University of Washington's Marine Bioremediation Program. Dr. Deming has made major contributions to the understanding of life in deep-sea and polar environments. As a marine microbiologist, Dr. Deming has focused her research efforts on the behavior of bacteria under conditions of extreme temperatures, pressures, and salt concentrations. She has used a combination of observational, experimental, and modeling approaches to explore the role of bacteria in the flow of carbon through deep-sea ecosystems, including in the Gulf of Mexico. Dr. Deming's expertise on marine microbial communities and their role in ecosystem functioning will be essential as the committee assesses the impact of the oil on the lower trophic levels of the Gulf food web. Dr. Deming earned a Ph.D. in microbiology from the University of Maryland, College Park in 1981, and a B.A. in biological sciences from Smith College in 1974. She was elected to the National Academy of Sciences in 2003 and is a current member of the OSB.

David J. Die is an Associate Professor at the University of Miami's Rosenstiel School of Marine and Atmospheric Science and the Associate Director of the Cooperative Institute for Marine and Atmospheric Studies. Dr. Die's research focus is on the quantitative evaluation of fishery management strategies and his current portfolio includes collaborative development of a fishery ecosystem model for the Gulf of Mexico. He also has strong links to the Gulf of Mexico Fishery Management Council and was the founding director of the Center of Independent Experts, a central part of the peer review process for the National Marine Fisheries Service. Dr. Die is the current chair of the big-eye tuna working group of the International Commission for the Conservation of Atlantic Tuna and has recently been asked to serve on the international panel synthesizing tuna and billfish science for the International Union for the Conservation of Nature. He has extensive knowledge of both the ecology and population dynamics of upper trophic levels in the Gulf of Mexico ecosystem and the fishing pressures, and management regimes, to which they are subject. He will bring an international perspective and a strong understanding of the impacts of the spill on the fishing industries in the Gulf. Dr. Die received a Ph.D. in biology and living resources from the University of Miami in 1989, and a B.Sc. in zoology and marine biology from the Universidad de La Laguna (Spain) in 1982.

Josh Eagle is an Associate Professor of Law at the University of South Carolina School of Law and is affiliated with USC's Marine Sciences Program and its School of Earth, Ocean and Environment. His expertise is in ocean and coastal law, natural resources law, environmental law, and property law. He has testified before Congress and the Interagency Ocean Policy Task Force on legal issues related to ocean zoning and the siting of offshore energy facilities. Mr. Eagle's expertise in pertinent laws and regulations, including the Natural Resource Damage Assessment (NRDA) process, will help the committee understand the legal implications of various definitions and assessments of ecosystem services. From 1990 to 1995, Professor Eagle served as a trial attorney for the United States Department of Justice in Washington, DC. From 1997 to 1998, he was wildlife counsel in the policy office of the National Audubon Society in Washington, DC. Mr. Eagle received a J.D.

from Georgetown University Law Center in 1990, an M.S. in Forest Sciences from Colorado State University in 1996, and a B.A. from Johns Hopkins University in 1985.

Joseph R. Geraci is Professor in the Department of Pathology and in the Program of Comparative Medicine at the University of Maryland's School of Medicine. His research over the past 40 years has focused on understanding how biological and environmental factors underpinning marine mammal health break down to affect the viability of the individual or population. Dr. Geraci has led research teams from the Arctic to the tropics, on studies of factors governing the health of marine mammals and their environment. He has published extensively on the effects of oil on marine mammals. In addition, Dr. Geraci has served as marine mammal health and program advisor to the U.S. Department of Agriculture; Department of Justice; Marine Mammal Commission; National Marine Fisheries Service; U.S. Navy; Canada Department of Fisheries and Oceans; the governments of Argentina, Brazil, Ecuador, Australia, New Zealand, Japan, Spain, and the Caribbean and Pacific Rim nations; the International Whaling Commission; United Nations Environment Program; International Atomic Energy Agency; and non-governmental organizations, aquariums, and research laboratories internationally. Working with the National Marine Fisheries Service, he has played a founding role in developing U.S. regional marine mammal stranding-recovery programs into a nationwide network with international reach. Dr. Geraci will provide an important set of skills in assessing the pathologies and mortalities of megafauna (like marine mammals and sea turtles) that are attributed to the oil spill. Dr. Geraci has a V.M.D. from the University of Pennsylvania, a Ph.D. from McGill University in Montreal, Canada, and a B.Sc. from Suffolk University in Boston.

Barbara A. Knuth is Vice Provost, Dean of the Graduate School, Professor of Natural Resource Policy and Management, and Associate Director of the Human Dimensions Research Unit in the Department of Natural Resources at Cornell University. Dr. Knuth's research focus, through theory-development and empirical studies, advances understanding and practice related to the human dimensions of natural resource management, particularly related to fisheries and wildlife resources, and aims to foster integration of social science and natural/physical science information within natural resource management and policy decision-making processes. Dr. Knuth's expertise will help the committee accurately identify and quantify the relevant ecosystem services that have significant societal importance. She earned a Ph.D.

in fisheries and wildlife sciences from the Virginia Polytechnic Institute and State University in 1986, an M.En., a B.Phil., and a B.A. from Miami University in 1982 and 1980, respectively.

Kenneth Lee is the Executive Director of the Centre for Offshore Oil, Gas and Energy Research (COOGER), part of Fisheries and Oceans Canada. At COOGER he is responsible for the identification of priority research needs and the coordination and implementation of collaborative national and international research programs with government and academia to provide scientific knowledge and advice pertaining to the potential environmental impacts associated with the development of Canada's offshore oil and gas, and ocean renewable energy sector. Dr. Lee's research and project management activities include studies to link organic and inorganic contaminants, marine noise, and alterations in hydrodynamic processes to effects on biota, including commercial fisheries species; chemical/microbiological studies on the biotransformation and biodegradation of contaminants; development of novel approaches to assess the impact of organic pollutants by the development and validation of toxicity assays based on advances in genomics, microbial ecology, and biochemical analysis; coordination of multidisciplinary studies including the application of numerical models to predict the risk of industrial activities and contaminants on ecosystem health. Dr. Lee is one of the world's leading experts on the effects of dispersants and other spill response technologies: This expertise will be most useful as the committee assesses the impact of the 1.8 million gallons of dispersants used in the DWH spill. He received a Ph.D. and M.Sc. in botany/environmental studies from the University of Toronto in 1982 and 1977, respectively, and a B.Sc. in biology from Dalhousie University in 1975.

James T. Morris is the Director of the Belle Baruch Institute for Marine and Coastal Sciences, Professor of Biological Sciences, Distinguished Professor of Marine Studies at the University of South Carolina, and an AAAS Fellow. Dr. Morris has authored more than 80 peer-reviewed publications, largely focused on coastal wetlands. He has served on numerous committees and panels for various agencies, including the U.S. National Science Foundation (NSF), the Irish National Science Foundation, the National Research Council, and the IndoFlux committee of India. Dr. Morris has a long history of funding from NSF for research at North Inlet, South Carolina on the effects of sea-level change on coastal wetlands. Dr. Morris will help the committee assess the impacts of the spill (and spill responses) on the Gulf wetlands—arguably the most critical and complex habitat responsible for many of the ecosystem services under review with this study. He earned a Ph.D. in forestry and environmental studies and a M.S. in biology from Yale University in 1979 and 1975, respectively, and a B.A. in environmental sciences from the University of Virginia in 1973.

Stephen Polasky (NAS) is the Fesler-Lampert Professor of Ecological/Environmental Economics in the Department of Applied Economics at the University of Minnesota. His research interests include ecosystem services, natural capital, biodiversity conservation, endangered species policy, integrating ecological and economic analysis, renewable energy, environmental regulation, and common property resources. Papers authored by Dr. Polasky have been published in *Biological Conservation*, *Ecological Applications*, *Journal of Economics Perspectives*, *Nature*, *Science*, among others. He has served as co-editor and associate editor for the *Journal of Environmental Economics and Management*. He previously held faculty positions in the Department of Agriculture and Resource Economics at Oregon State University (1993-1999) and the Department of Economics at Boston College (1986-1993). Dr. Polasky was the senior staff economist for environment and resources for the President's Council of Economic Advisors (1998-1999). He was elected into the National Academy of Sciences in 2010. Also, he was elected as a Fellow of the American Academy of Arts and Sciences in 2009 and a Fellow of the American Association for the Advancement of Science in 2007. Dr. Polasky is a leader in the rapidly growing field of ecosystem services valuation, which is one of the core tasks for this study. Dr. Polasky received his Ph.D. in economics from the University of Michigan in 1986.

Nancy N. Rabalais is Executive Director and Professor at the Louisiana Universities Marine Consortium. Dr. Rabalais' research includes the dynamics of hypoxic environments, interactions of large rivers with the coastal ocean, estuarine and coastal eutrophication, and environmental effects of habitat alterations and contaminants. Dr. Rabalais is an AAAS Fellow, an Aldo Leopold Leadership Program Fellow, a National Associate of the National Academies of Science, a past president of the Estuarine Research Federation, a past vice-chair of the Scientific Steering Committee of Land-Ocean Interactions in the Coastal Zone/International Geosphere-Biosphere Program, and a past chair of the NRC Ocean Studies Board. She is a current member of the University-National Oceanographic Laboratory System (UNOLS) Council, the National Sea Grant Advisory Board, a Trustee for the Consortium for Ocean Leadership, a member of the Governing Board for the Gulf of Mexico Coastal Ocean Observing System, and an NRC committee member for Applying the Clean Water Act across the Mississippi River Basin. She received the 2002 Ketchum Award for coastal research from the Woods Hole Oceanographic Institution and shares the Blasker award with R.E. Turner. She was awarded the American Society of Limnology and Oceanography Ruth Patrick Award and the National Water Research Institute Clarke Prize in the summer of 2008. Her technical familiarity with the Gulf and the interface between the deep benthic habitats and habitats along the coastal and continental shelf will be useful in determining the impacts of the oil at various depths. Dr. Rabalais received her Ph.D. in zoology from the University of Texas at Austin in 1983.

Christopher M. Reddy is a Senior Scientist at the Woods Hole Oceanographic Institution. His research interests include marine pollution, marine natural products, and marine-based biofuels. He has studied numerous oil spills, including the *Florida*, *Bouchard 65*, *North Cape*, *Bouchard 120*, and *Cosco Busan* as well as natural oil seeps off the coast of Santa Barbara, California. Dr. Reddy has earned numerous awards and honors, including the Kavli Fellow in 2009 and 2010, which is awarded by the National Academy of Sciences as the premiere recognition for distinguished young scientists under the age of 45. He was also awarded the Henry L. and Grace Doherty Professor of Oceanography in the Massachusetts Institute of Technology/Woods Hole Oceanographic Institution's Joint Program. Among Dr. Reddy's many talents, his chemical forensics skills will be most useful in isolating the impacts of the DWH spill from other oil spills and seepage that frequent the Gulf region. He received a Ph.D. in chemical oceanography in 1997 from the University of Rhode Island and a B.Sc. in chemistry from Rhode Island College in 1992.

Ralph G. Stahl, Jr., received his B.S. in Marine Biology from Texas A&M University (cum laude), his M.S. in Biology from Texas A&M University, and his Ph.D. in Environmental Science and Toxicology from the University of Texas School of Public Health. After receiving his Ph.D., he was a National Institute of Environmental Health Sciences Senior Postdoctoral Fellow in the Department of Pathology at the University of Washington in Seattle where he investigated the impact of genetic toxins on biological systems. Ralph joined the DuPont Company in 1984 and in the intervening years has held both technical and management positions in the research and internal consulting arenas. His research over the last 25 years has focused primarily on evaluating the effects of chemical stressors on aquatic and terrestrial ecosystems. Since 1993 Dr. Stahl has been responsible for leading DuPont's corporate efforts in ecological risk assessment and natural resource damage assessments for site remediation.

He has been involved with oceanographic studies in the Atlantic, Pacific, Gulf of Mexico and Caribbean Sea, biological and ecological assessments at contaminated sites in the United States, Europe and Latin America, and numerous toxicological studies with mammals, birds and aquatic organisms. He has been selected by the U.S. EPA, Army Corps of Engineers, SERDP, National Institutes of Environmental Health Sciences, National Academy of Science, the Water Environment Research Foundation, NOAA, State of Washington, State of Texas, and others to national or state peer review panels on ecological risk assessment, endocrine disruption in wildlife, or natural resource injury determination.

Dr. Stahl has served on the U.S. EPA's Science Advisory Board (Advisory Council on Clean Air Compliance Analysis, Ecological Effects Subcommittee), the Department of Interior's FACA Panel on Natural Resource Damages, and currently is active in the Society of Environmental Toxicology and Chemistry (SETAC), Ecological Risk Assessment Advisory Group. He is board certified in General Toxicology and is a Diplomate of the American Board of Toxicology. He has authored over 45 peer-reviewed publications on topics in environmental toxicology, ecological risk assessment, and risk management. He recently edited three books stemming from SETAC Education Foundation sponsored workshops, and currently serves on the Editorial Board of the journal *Integrated Environmental Assessment and Management*.

David Yoskowitz is the HRI Endowed Chair for Socio-Economics at the Harte Research Institute for Gulf of Mexico Studies, and Professor in the College of Business at Texas A&M University, Corpus Christi. Dr. Yoskowitz's interests include market and non-market valuation; ecosystem services; micro and small enterprise development; environmental and water markets; border economics; development microeconomics in Latin America; and socio-economic environment of the Gulf of Mexico region. Dr. Yoskowitz will bring a strong understanding of the Gulf ecosystem services and valuation, as well as a local appreciation of the smaller businesses and enterprises impacted by the spill. He received a Ph.D. in economics and a M.A. in economics from Texas Tech University in 1997 and 1994, respectively, and a B.A. in economics and finance from Bentley College in 1990.

STAFF

Kim Waddell is a senior program officer with the Ocean Studies Board. He received his Ph.D. in the Biological Sciences from the University of South Carolina and his B.A. in Environmental Studies from the University of California, Santa Cruz. Dr. Waddell recently rejoined the NRC after a 6-year hiatus during which he was a research associate professor at the University of the Virgin Islands and Texas A&M University working to build marine and environmental research capacity in the Caribbean region. During his previous tenure with the NRC, Dr. Waddell directed a number of studies for the Board on Agriculture and Natural Resources including California Agricultural Research Priorities: Pierce's Disease (2004), Biological Confinement of Genetically Engineered Organisms (2004), Animal Biotechnology; Science-based Concerns (2002), The Environmental Effects of Transgenic Plants (2002), Exploring Horizons for Domestic Animal Genomics (2002), and The Future Role of Pesticides in US Agriculture (2000).

Sherrie Forrest is an associate program officer with the Ocean Studies Board and the Board on Science Education at the National Research Council. She currently supports the work of several projects, including the Roundtable on Climate Change Education and the Effects of the Deepwater Horizon Mississippi Canyon-252 Oil Spill on Ecosystem Services in the Gulf of Mexico, and she previously worked on the Conceptual Framework for New Science Education Standards. She is also the study director on the Workshop on Climate Change Education in Formal Settings, K-14. She has a B.A. in English literature from Pepperdine University and an M.S. in biological oceanography from the Institute of Marine and Coastal Sciences at Rutgers University.

Jeremy Justice was a senior program assistant with the Ocean Studies Board from October 2008 to July 2011. He earned a B.A. in international and area studies from the University of Oklahoma in 2008. He is currently a program coordinator at the International Foundation for Electoral Systems (IFES) in Washington, DC.

Lauren Harding joined the Ocean Studies Board as a program assistant in August 2011. In 2011, she graduated from High Point University majoring in biology and minoring in chemistry. As an undergraduate, she conducted an independent research project on cave ecosystems. Prior to her position at OSB, Lauren was a marketing and accounting assistant with Webco General Partnership, a company of the U.S. military resale market.

Peter Thompson is a Christine Mirzayan Science and Technology Policy Graduate Fellow at the National Academies assisting with ongoing work with the Ocean Studies Board. He received his Ph.D. in Behavior, Ecology, Evolution, and Systematics from the University of Maryland where he used population genetics to study the natural history, dispersal, and deep evolutionary history of a single-celled parasite that is interfering with efforts to restore oyster populations in the Chesapeake Bay. Prior to enrolling in graduate school, Dr. Thompson was a research technician for ten years with the U.S. Food and Drug Administration where he studied virus-cell interactions and the development of novel hepatitis vaccines.

Christopher Prosser is a Christine Mirzayan Science and Technology Policy Graduate Fellow at the National Academies assisting with ongoing work with the Ocean Studies Board. He received his Ph.D. in marine science from the Virginia Institute of Marine Science, College of William and Mary, where he investigated multiple stressor interactions between toxicants and bacterial pathogens in the zebrafish (*Danio rerio)*. Prior to his dissertation studies, Dr. Prosser received a Masters in Environmental Management from Duke University and Bachelor of Science degrees in Biology and Marine Science from Coastal Carolina University.

B

Acronyms

AVHRR	Advanced Very High Resolution Radiometer
BOEMRE	Bureau of Ocean Energy Management, Regulation and Enforcement
CERCLA	Comprehensive Environmental Response and Compensation Liability Act
CFR	Code of Federal Regulations
CI	Continental Index
CRMS	Coastwide Reference Monitoring System
CVM	Contingent Valuation Method
CWPPRA	Coastal Wetlands Planning, Protection and Restoration Act
DO	Dissolved Oxygen
DOC	Dissolved Organic Carbon
DOM	Dissolved Organic Material
DWH	Deep Water Horizon
EEZ	Exclusive Economic Zone
EMAP-E	Environmental Monitoring and Assessment Program for Estuaries
EPA	Environmental Protection Agency
GC-MS	Gas Chromatography Mass Spectrometry
GIS	Geographic Information System
GoM	Gulf of Mexico
GOMFMC	Gulf of Mexico Fishery Management Council
HEA	Habitat Equivalency Analysis
HTCO	High-Temperature Catalytic Oxidation

LCE	Loop Current Eddy
LIDAR	Light Detection and Ranging
LME	Large Marine Ecosystem
LUMCON	Louisiana Universities Marine Consortium
MRIP	Marine Recreational Information Program
NAAQS	National Ambient Air Quality Standard
NCOM	Navy Coastal Ocean Model
NDBC	National Data Buoy Center
NGO	Non-governmental Organization
NOAA	National Oceanic and Atmospheric Administration
NOEP	National Ocean Economics Program
NRDA	Natural Resource Damage Assessment
OCPR	Office of Coastal Protection and Restoration
OMA	Oil-Mineral Aggregate
OPA	Oil Pollution Act
PAH	Polycyclic Aromatic Hydrocarbons
REA	Resource Equivalency Analysis
RS	Remote Sensing
RUF	Restoration Up Front
SAV	Submerged Aquatic Vegetation
SAY	Service Acre Year
SCOR	Scientific Committee on Oceanic Research
SeaWiFS	Sea-viewing Wide Field Sensor
SET	Surface-Elevation Table
SPM	Suspended Particulate Matter
TI	Tropical Index
USGS	U.S. Geological Survey
VOC	Volatile Organic Compound
WTP	Willing-To-Pay Survey