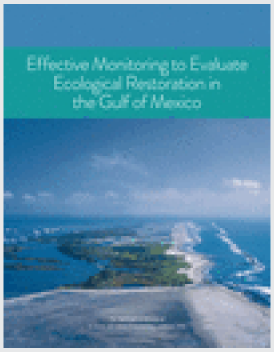

Effective Monitoring to Evaluate Ecological Restoration in the Gulf of Mexico

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Effective Monitoring to Evaluate Ecological Restoration in the Gulf of Mexico

Committee on Effective Approaches for Monitoring and Assessing Gulf of Mexico Restoration Activities

Ocean Studies Board
Water Science and Technology 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. 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 process. We wish to thank the following individuals for their review of this report:

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Shelby Walker, Oregon State University
Joy Zedler, University of Wisconsin-Madison

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the report's conclusions or recommendations, nor did they see the final draft of the report before the release. The review of this report was overseen by The review of this report was overseen by Holly Greening (Coordinator), Executive Director, Tampa Bay Estuary Program, and Dr. David M. Karl (NAS, Monitor), Director, Daniel K. Inouye Center for Microbial Oceanography, University of Hawai'i, they 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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PREFACE

The Macondo Well Deepwater Horizon (DWH) rig explosion in the spring of 2010 resulted in the largest accidental oil spill in U.S. history, impacting vast areas of ocean, seafloor, and coastal ecosystems and exacting a heavy toll on the region's natural resource-dependent communities. Legal settlements in the wake of DWH led to the provision of approximately $16 billion in restoration funds administered through three major programs: the Natural Resource Damage Assessment (NRDA) Trustee Council, the National Fish and Wildlife Foundation (NFWF) Gulf Environmental Benefit Fund, and the Resources and Ecosystems Sustainability, Tourist Opportunities, and Revived Economies of the Gulf Coast States (RESTORE) Trustee Council. These programs will support a wide range of restoration projects with objectives ranging from coastal and offshore habitat restoration to recovery of species of concern to stormwater management, water quality improvement and land acquisition. Monitoring will be an integral part of these programs to document restoration progress and outcomes, to gain new knowledge to inform future project design and management, and to inform the restoration programs and public on whether funds are being spent effectively.

Also as part of the post-DWH legal settlements, the federal government requested that the National Academy of Sciences (NAS) establish a new program – the Gulf Research Program – to fund and conduct activities to enhance oil system safety, human health, and environmental resources in the Gulf of Mexico and other oil and gas producing regions of the U.S. continental shelf. This report was produced at the request of the Gulf Research Program. The Committee was asked to identify best approaches for monitoring and evaluating restoration activities. Over the course of one year the Committee held three public meetings, two in Washington, D.C. and a third in New Orleans, LA as well as a closed meeting in Santa Barbara, California focused on report writing. The public meetings included oral presentations from representatives of the three Gulf restoration programs as well as other state, federal, and academic rest groups, and members of the public.

The Committee was careful not to overstep its charge. In particular, we did not address how to restore the species, habitats, and ecosystems of the Gulf of Mexico or what to restore them to. Rather, the Committee focused on providing guidance on best practices for monitoring, evaluation and adaptive management of restoration progress. Given the enormous scope of post-DWH restoration efforts, the Committee also deliberately confined the range of topics and ecological systems to address, as summarized below.

Restoration occurs in the larger context of coupled ecological and social systems where social goals and policies drive and are driven by ecosystem condition and trends. A comprehensive restoration monitoring approach arguably requires joint monitoring of both ecological and social outcomes of restoration actions. At its outset the Committee discussed with the sponsor whether to tackle both ecological monitoring as well as socioeconomic monitoring of ecosystem services and the associated resilience of Gulf Coast communities. Based on the guidance by the sponsor, but also given the expertise of the Committee, the group decided to confine the report to the ecological dimensions of restoration monitoring. However, the

Committee recognizes the need for monitoring of socioeconomic outcomes of gulf restoration and their coupling to ecological outcomes.

Those familiar with the Gulf of Mexico will appreciate the enormous diversity and complexity of the region's ecosystems. The Committee elected to focus on delivering key principles and approaches for restoration monitoring that would apply to environmental restoration projects in general, and to provide specific guidance only for a limited set of widespread and important nearshore habitats and species that are the targets for much of the restoration funding. Restoration monitoring of offshore and deeper water benthic habitats was excluded because of the dearth of experience with those ecosystems, and monitoring of commercial fish stocks was excluded because of the monitoring mechanisms already in place for those resources. The Committee did not take up water quality monitoring except in the context of restoration monitoring for specific habitat types.

This report captures the collective wisdom of some of the nation's leadings experts in ecological restoration theory and practice. I want to express my deep appreciation to every member of the Committee for his or her attention, thoughtfulness and hard work, as well as their wonderful collegiality.

On behalf of the entire Committee I would also like to thank our superb NRC staff for their excellent support and many contributions to the project. Study Director Claudia Mengelt, Senior Project Officer Stephanie Johnson, Postdoctoral Fellow Heather Coleman, and Senior Program Assistant Payton Kulina were instrumental in keeping the project on course and in producing the final report. Working with this team has been a pleasure and a privilege.

Frank W. Davis, Chair
Committee on Effective Approaches for Monitoring and Assessing Gulf of Mexico Restoration Activities

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Part I

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SUMMARY

Gulf Coast communities and natural resources suffered exte nsive direct and indirect damage as a result of the largest accidental oil spill in US history, referred to as the Deepwater Horizon (DWH) oil spill. Notably, natural resources affected by this major spill include wetlands, coastal beaches and barrier islands, coastal and marine wildlife, seagrass beds, oyster reefs, commercial fisheries, deep benthos, and coral reefs, among other habitats and species. Losses include an estimated 20% reduction in commercial fishery landings across the Gulf of Mexico and damage to as much as 1,100 linear miles of coastal salt marsh wetlands.

This historic spill is being followed by a restoration effort unparalleled in complexity and magnitude in U.S. history. Legal settlements in the wake of DWH led to the establishment of a set of programs tasked with administering and supporting DWH-related restoration in the Gulf of Mexico. The largest programs include the Natural Resource Damage Assessment (NRDA) Trustee Council, the Gulf Coast Ecosystem Restoration Council and (known as the RESTORE Council), and the National Fish and Wildlife Foundation (NFWF) Gulf Environmental Benefit Fund. These entities administer the majority of approximately $16 billion in restoration funds, which provides an unprecedented opportunity—and a responsibility—to accomplish substantial environmental restoration throughout the Gulf.

Parts of the DWH legal settlements funded a number of restoration science programs, including the Gulf Research Program (GRP) of the National Academies of Sciences, Engineering, and Medicine (the Academies). The GRP operates over 30 years with $500 million to support research, education and training, and environmental monitoring in the Gulf with the goal of improving understanding of the region's interconnecting human, environmental, and energy systems.

Based on discussions with some of the restoration and science programs, the GRP recognized a common need for restoration monitoring and assessment guidance. Therefore, the GRP asked the Ocean Studies Board of the Academies to convene a committee to advise restoration funding programs regarding monitoring and evaluation of restoration activities in the Gulf of Mexico. In particular, the Committee *Effective Approaches for Monitoring and Assessing Gulf of Mexico Restoration Activities* (the Committee) was asked to identify best practices (i.e., existing, proven, cost-effective approaches) for monitoring and evaluating restoration activities to improve the performance of restoration programs and increase the effectiveness and longevity of restoration projects. The Committee's work was to identify (the full statement of task can be found in Chapter 1):

- Current, effective approaches for developing initial and long-term monitoring goals and methods.
- Approaches for determining essential baseline data needs.
- Essential elements of a long-term monitoring framework (including baseline information).

- Additional novel approaches to augment current best practices that could increase effectiveness, reduce costs, ensure region-wide compatibility of restoration monitoring data, and advance the science and practice of restoration.
- Options to ensure that project, or site-based, monitoring could be used cumulatively and comprehensively to provide region-wide insights and track effectiveness on larger spatial and longer temporal scales.

The high-level goals of the above-mentioned restoration programs are similar, particularly as they relate to restoring habitats, species, and living coastal and marine resources. While NFWF focuses solely on restoring habitats and associated living resources, both the NRDA Trustee Council and the RESTORE Council also aim to improve water quality, along with some socio-economic components. The NRDA Trustee Council's socio-economic goals include enhancement of recreation opportunities, whereas the RESTORE Council's goals include enhancing community resilience, as well as revitalizing the Gulf's overall economy. Notably, only the NRDA Trustee Council explicitly lists a provision that includes restoration monitoring and adaptive management as high-level goals.

In this report, the Committee provides general guidance for restoration monitoring, assessment, and synthesis that can be applied to most ecological restoration supported by these major programs given their similarities in restoration goals. The Committee considered project-level monitoring (monitoring associated with site-specific or localized restoration activities), monitoring to evaluate restoration outcomes for highly mobile species (e.g., marine mammals, turtles, and birds) over large spatial areas such as watersheds and regional assessments, and monitoring to support larger spatial scale programmatic evaluations across multiple states and sub-regions. Although the release of oil during the DWH spill was mostly offshore in deep water, most restoration activities are along the coast. Because of the breadth and diversity of these coastal habitats and associated species subject to restoration or restoration plans, the Committee could not address best practices for monitoring and assessment of all possible Gulf habitats, species, and ecosystems. Instead, Part II of this report provides specific guidance for a subset of restoration monitoring efforts, including oyster reefs, tidal wetlands, and seagrass habitats, as well as wide ranging birds, sea turtles, and marine mammals. Effective monitoring practices for these habitats and species are addressed in detail, but it is important to note that these sections only represent a subset of the many habitats and species that are in need of restoration attention within the Gulf of Mexico.

Project objectives provide the specificity necessary to realize overarching restoration goals. However, in reviewing the major funding administrators' programs, the Committee found that specific, measurable restoration objectives were generally not well delineated or identified. Instead, program goals were frequently linked directly to restoration actions without an explicit description of what the overall program intends to accomplish. Measurable objectives, related metrics, and research-based targets for habitat and species restoration are required to reliably assess programs and improve restoration effectiveness. Thus, the absence of clearly articulated, specific, measurable objectives could hinder effective program management in the Gulf. **Therefore, the Committee concludes that restoration programs need to develop clear and measurable ecological and, where appropriate, socio-economic objectives at project and program levels to guide monitoring plans and against which to evaluate restoration progress.**

Restoration Monitoring Is Imperative for Ensuring Restoration Effectiveness and Demonstrating Restoration Progress

The need for restoration monitoring is widely acknowledged, but most restoration projects in the U.S. and elsewhere often have lacked monitoring or the monitoring efforts have been insufficient to generate rigorous, decision-relevant, or publically accessible information. For example, the National River Restoration Science Synthesis, one of the few endeavors to objectively evaluate restoration efforts, found fewer than half of all restoration projects had measurable objectives and collected quantitative data to evaluate a given project's outcomes. Previous attempts to conduct meta-analysis and synthesis across restoration projects point to a broad range of issues hampering adequate monitoring and evaluation including lack of sufficient funding, inadequate monitoring designs, and poor data management. Monitoring budgets are required for a wide array of tasks including long-term ecological monitoring, data collection, scientific oversight, training, data management, quality assurance and reporting. Restoration monitoring serves three primary purposes: (1) to assure projects are built or implemented and are initially functioning as designed (*construction monitoring*); (2) to assess whether restoration goals and objectives have been or are being met (*performance monitoring*); and (3) to inform restoration management, to improve design of future restoration efforts, and to increase ecosystem understanding (*monitoring for adaptive management*).

Without timely monitoring and analyses, restoration programs in the Gulf of Mexico will not be able to demonstrate to the public whether restoration progress and programmatic goals have been achieved and whether restoration funding has been well invested. Furthermore, since restoration funds are spent on behalf of society, funding administrators are responsible for connecting the effects of bio-physical changes resulting from restoration activities to outcomes for societal well-being. Knowledge gained from restoration monitoring and related assessments can improve the overall effectiveness of restoration, which has the potential to translate into savings in restoration cost. Monitoring also engenders transparency and facilitates communication among stakeholders and practitioners concerned with how projects and multi-state programs are affecting natural resources across the Gulf region as a whole.

To provide assurance to funders and the public of the benefits derived from restoration investments, monitoring should be viewed as an integral part of restoration projects, and detailed monitoring plans should be required by restoration programs at the time of restoration proposal submission.

Therefore, the Committee recommends that all restoration administered by the Gulf Coast Ecosystem Restoration Council (known as RESTORE), National Fish and Wildlife Foundation Gulf Environmental Benefit Fund, Deepwater Horizon Natural Resource Damage Assessment Trustee Council, and the Gulf states be accompanied by a strategic monitoring effort.

Such a monitoring strategy must enable assessment of progress relative to the restoration objectives articulated by the projects and programs. When appropriate, monitoring should also support adaptive management.

Informative, cost-effective restoration monitoring can be challenging to design and requires thoughtful planning and execution. **At a minimum, all restoration projects should include construction and performance monitoring, which includes an in-depth assessment to determine whether a given project was constructed or implemented as planned and has**

met its stated objective(s).The Committee recommends that adequate monitoring plans be considered a prerequisite for restoration funding and that those plans contain the following essential elements, at minimum:

- Clearly articulated, measurable restoration objectives (from the project plan);
- Identify well-articulated management questions that monitoring and evaluation seek to address using conceptual system and causal models that link ecological and socio-economic drivers and stressors with both biophysical and ecological processes to outcomes such as populations, habitats, ecosystem, ecosystem service, and human well-being (as appropriate) (derived from a given project plan);
- Explicitly identify appropriate metrics, targets and criteria for addressing the management questions such as measuring ecological, and where appropriate, social and economic restoration outcomes;
- Evaluation of available baseline data appropriate to a given project objectives and/or plans to collect new baseline data if needed;
- Appropriate sampling and analysis designs, including consideration of reference and/or control site(s), sampling locations, timing, frequency, and sample size;
- Well-documented and, where possible, standardized sampling protocols;
- Rigorous data management plan (see below for details);
- Anticipated methods for data analysis and associated evaluation;
- Realistic project budgets and staffing to support the appropriate level of monitoring, study design, data acquisition via monitoring, data analyses, modeling, scientific oversight, training, data management, quality assurance, and reporting, etc.; and
- Monitoring program management plan (including timely reporting and communication plan) to assure that the applied monitoring program is efficient, accountable and transparent at all phases of a given effort.

The importance of clear and measurable restoration objectives cannot be over-emphasized, because they set the framework and targets against which to monitor and assess restoration progress.

Coordinating Monitoring Efforts Will Benefit Gulf Restoration

The current magnitude of funds and efforts being invested in restoration in the Gulf of Mexico provides an unprecedented opportunity to solve these challenges and advance the science of restoration, as well as to improve cost-effectiveness and outcomes of restoration projects. Because some projects may take decades before they become self-sustaining and fully restored and individual projects interact with other projects, monitoring beyond the duration and scale of individual projects is needed to understand whether the Gulf of Mexico region's ecosystem is recovering. Partnerships and coordination has the potential to reduce the cost of monitoring to individual programs.

For example, coordination could reduce environmental monitoring costs and improve evaluation by jointly producing critical baseline data and a network of reference sites. As the number of local restoration activities increases, there is the potential for reference sites to inform multiple projects, as demonstrated by Louisiana's Coast-wide Reference Monitoring System. Establishing networks of reference sites for different habitat types would allow sharing of baseline information and reference condition data, while also promoting the adoption of a set of standardized variables and related protocols for restoration monitoring. Many long-term monitoring efforts are already underway in the Gulf that could be leveraged in developing these reference monitoring networks. Restoration programs benefit from coordinating with existing environmental monitoring efforts to establish or expand existing monitoring networks and ensure data are shared.

Thus, the Committee concludes that restoration programs (i.e., the NRDA Trustee Council, the RESTORE Council, and NFWF) and Gulf research programs (i.e., the NAS Gulf Research Program, NOAA RESTORE Act Science Program, and Centers of Excellence for each Gulf state) would greatly benefit from working together to identify strategic opportunities in the Gulf of Mexico to maximize the effectiveness and utility of monitoring while also reducing the overall cost of long-term monitoring across the Gulf region. Examples of such opportunities for leveraging resources include:

- Explore opportunities for a system of restoration reference sites across the Gulf of Mexico for several types of habitats to be restored;
- Identify potential long-term ecological monitoring sites that could be paired with ecological research to improve the effectiveness of restoration approaches;
- Monitoring mobile species may require comparison beyond static reference sites, such as using reference populations or seasonal reference points; and
- Jointly identify the most pressing research needs, objectives, and questions that would inform and improve restoration effectiveness.

Although it will require additional time and resources, coordination among restoration funders and practitioners is critical to ensure that monitoring informs both project-level performance and progress toward regional or Gulf-wide restoration objectives set by funding allocation programs (e.g., the NRDA Trustee Council, RESTORE Council, NFWF). Collaboration and coordination on monitoring designs, selection of metrics, and the development of standardized protocols for restoration study design, monitoring, and data stewardship will enhance consistency and utility of the data both within and across projects and programs, increase opportunities for merging information for regional synthesis, and improve the quality of the data collected. **Gulf restoration programs should work together to assemble teams of restoration scientists, managers, and practitioners to identify critical subsets of metrics and protocols that should be standardized for a given restoration type (ecosystem, habitat, or species). These coordination efforts should identify standardized monitoring protocols and information management approaches (regarding, for example, sampling design, identification of reference or control sites, metrics, laboratory procedures, metadata standards, non-spatial and geospatial, data and metadata archiving and access).**

Especially in states where long-term data sets may exist using a variety of protocols, it might pose some challenges to develop and implement standardized sampling protocols. Nevertheless, there is likely a critical subset of restoration-specific data to be collected where the benefits of consistently sampled data at a program scale justify the additional costs. For example, many restoration projects aim to improve a given coastal habitat with the objective of also enhancing numerous living resources such as sea turtles, fishes, invertebrates, marine mammals, and birds. Assessing the impacts of habitat restoration on living marine resources, including biodiversity, will require monitoring beyond the project-scale, and would be more efficient and effective if done using standardized Gulf-wide monitoring efforts.

Data Stewardship Is Essential to Gulf Restoration Monitoring and Assessment

The Committee views restoration monitoring data as a valuable and lasting product of Gulf restoration funding and believes good data stewardship greatly enhances the value of restoration monitoring and enables assessment of progress towards restoration goals. To ensure that these data retain their value through time data stewardship should be made a high priority by the funding agencies at the outset of all restoration efforts and require the use of a well-conceived standards-based data management system. **To ensure that data stewardship is addressed appropriately, the Committee recommends that all restoration projects be required to include a written data management plan and deliverables as a condition for funding restoration proposals. Those plans should:**

- Identify roles and responsibilities of the data providers, data management personnel, and end users.
- Describe the flow of data including any transformations.
- Describe and apply appropriate data QA/QC and cite the authoritative guides that will be followed.
- Identify and apply appropriate community standards for metadata content and controlled vocabularies that will be applied to the datasets. Where gaps exist in community standards, the project should adopt, adapt, or extend other existing standards.
- Identify appropriate long-term trusted digital repositories where the full body of data and metadata will be submitted. Data can be submitted to the repository by the originator or by a portal or cooperative on behalf of the originator. This will likely require the restoration funding programs to provide support for new facilities or to supplement or expand existing facilities;
- Consider how to design and incentivize compliance, as well as to possibly enforce standards, with such policies at the beginning of a project; and
- Publish datasets using digital object identifiers (DOIs).

Data publishing and archiving is currently facilitated by existing data portals, data cooperatives, and data repositories. Examples from the Gulf of Mexico include the Gulf of Mexico Coastal Ocean Observing System (GCOOS) Data Portal, the Gulf of Mexico Research Initiative Information and Data Cooperative (GRIIDC), NOAA's National Centers for Environmental Information and other NOAA units. Such cyberinfrastructure makes data archiving feasible and practical for all parties engaged in restoration monitoring. **Restoration programs should require that monitoring data are archived with an entity that has long-term support to ensure managed open data-access for the next several decades**.

Open access to restoration monitoring data will enable the evaluation of restoration progress over space and time scales larger than individual projects. It will also enable cost-effective sharing of lessons learned (from both successes and failures). Monitoring data are also essential for synthesis activities seeking to understand differences within and among project outcomes while also improving the design of future projects. More broadly, readily accessible restoration monitoring data will support research to advance the scientific understanding of Gulf species and ecosystems and post-spill recovery processes. Because data quality is improved through use, early data sharing and synthesis activities need to be strongly encouraged. **Restoration programs should establish clear policies early on for archiving and sharing of restoration monitoring data, and enforce these policies to ensure open access in the long-term**.

Synthesis and Integration Will Advance the Effectiveness of Gulf Restoration

Synthesis will be important to connect ecological restoration efforts and associated monitoring with investments in Gulf communities and societal outcomes. In recent years, analysis and synthesis of existing data have dramatically increased as a means of accelerating scientific discovery and improving the generalization of information gained from monitoring or research. For Gulf restoration, such synthesis activities are not only desirable, but are necessary for observing restoration progress beyond individual projects and to evaluate restoration outcomes for wide-ranging species such as marine mammals, sea turtles, and birds. Synthesis activities can also inform restoration programs on progress towards achieving their overall goals and objectives, while aiding to identify necessary changes to future project design and management. Moreover, synthesis efforts can reveal opportunities for better coordination of restoration activities, monitoring, adaptive management, data management, and dissemination.

Gulf synthesis efforts will confront challenges such as integration of heterogeneous data collected at multiple spatial and temporal scales, and the need for robust statistical and process-based modeling approaches to analyze monitoring data over larger spatial and temporal scales. The challenge of data integration will be compounded by the diversity of organizations involved in restoration monitoring, each with potentially different objectives, sampling designs, monitoring protocols, and metrics. Some of these challenges can be avoided or reduced by insuring that efforts are coordinated in regard to restoration planning, monitoring, and those data management activities emphasized above.

Some efforts have been made to promote data synthesis research—for example by the Gulf Research Program of the National Academies of Sciences, Engineering, and Medicine—but the capacity for synthesis activities among the organizations engaged in Gulf restoration is uneven at best. **Because meta-analysis of projects and synthesis of monitoring data is required for evaluating restoration progress beyond individual projects and gulf-wide restoration outcomes, Gulf restoration programs should consider creating a specific, dedicated enterprise for synthesis activities in support of Gulf restoration.** Restoration programs and research programs should jointly formulate plans to develop the appropriate organizational approach(es) for a synthesis and integration enterprise. Such an enterprise could be comprised of a center or multiple centers, a virtual consortium, and/or a grant-making program to fund synthesis efforts. The enterprise would provide the necessary infrastructure for collaborative synthesis projects, notably facilities for face-to-face and virtual meetings, technical and scientific staff to assist with data integration and analysis, training to build capacity for Gulf synthesis, and funding to support synthesis working groups. Synthesis and integration should be initiated as soon as possible and need to be undertaken in close collaboration with management activities and agency and organization staff. These activities need to take advantage of, inform, and contribute to restoration database development.

Restoration Evaluation and Learning Can Inform Adaptive Management

The complexity, large scale, and extended timeframe of Gulf restoration provide invaluable opportunities for improving the effectiveness of restoration through monitoring, evaluation and adaptive management. Knowledge gained through these efforts can be applied to improve the performance and cost-effectiveness of ongoing or future restoration activities. **The Committee concludes that as greater uncertainties or resources are involved, monitoring to enable adaptive management becomes critically important.**

Because of the complexity of the environment that restoration aims to manipulate, all restoration efforts will face some level of uncertainty and associated risk of negative or undesirable project outcomes. Uncertainties arise due to uncontrollable environmental variability as well as incomplete knowledge regarding how species, habitats, ecosystems, and people respond to restoration activities. Pre- and post-restoration construction and monitoring can be deliberately designed in ways that allow for restoration to proceed despite unresolved uncertainties. Although adaptive management may not be appropriate or necessary for all restoration projects, particularly those where the response is well known or the time scales of a given response are lengthy, adaptive management becomes more important when greater resources or uncertainties are involved. Adaptive management increases the likelihood that restoration goals will be achieved while decreasing the likelihood of undesirable outcomes. It also enhances the ever-important communication that is required among scientists, managers, and stakeholders.

Several Gulf restoration programs have stated their intent to use adaptive management in Gulf restoration, notably the NRDA Trustee Council. This provides an important opportunity to accelerate Gulf restoration practices and related science, but only if those programs provide strong guidance and adequate funding to ensure that adaptive management is included in restoration and monitoring plans and activities. Based on experience of other large restoration programs, adaptive management requires a strong commitment to a dedicated organizational structure that supports adaptive management planning, identifies and prioritizes key uncertainties, learns by analysis and synthesis of monitoring data, and makes adjustments to restoration projects based on new information in a timely fashion. **To improve long-term restoration effectiveness, and where the restoration program managers deem it appropriate, Gulf restoration programs should implement adaptive management at the program- and project-level. To implement adaptive management, projects or programs need to commit to the:**

- Careful determination of critical uncertainties, prioritized by the potential for adaptive management to improve future restoration decision making and reduce risk;

- Development of project-level adaptive management plans that formalize the key steps and responsible parties throughout the adaptive management process;
- Institutional support for synthesis and evaluation in support of decision making;
- Development of a decision-making process in advance for making adjustments to restoration projects;
- A clear financial and procedural commitment to adaptive management, which will likely require a dedicated organizational structure and additional planning and monitoring beyond typical restoration projects; and
- Coordinated guidance for implementing adaptive management for Gulf restoration efforts.

Conclusion

The unparalleled magnitude of both the DWH oil spill and the restoration funding available provide an unprecedented opportunity to accomplish substantial ecological restoration throughout the Gulf of Mexico region. Given this historic opportunity, programs have the responsibility to demonstrate in a transparent fashion how dollars are allocated, whether ecological restoration objectives are accomplished, and what is learned from restoration outcomes. Only statistically rigorous monitoring, well-designed data stewardship, and coordinated synthesis efforts will enable programs to evaluate restoration outcomes and draw conclusions with high confidence. To undertake such a monitoring and evaluation effort and to ensure restoration efforts are effective and resilient, the Committee recommends the following:

1. **Gulf restoration programs need to develop clear and measurable ecological and, where appropriate, socio-economic objectives at project and program levels to guide monitoring plans and against which to evaluate restoration performance.**
2. **All restoration administered by the NRDA Trustee Council, RESTORE Council, NFWF, and the Gulf states should be accompanied by a strategic, rigorous monitoring effort, described in a monitoring plan, that enables an assessment of progress relative to the restoration goals and objectives articulated by the programs and projects.**
3. **Gulf restoration programs should coordinate their efforts to ensure that monitoring data are as consistent and comparable as possible across the Gulf by (a) assembling teams of restoration scientists, managers, and practitioners that will identify critical subsets of metrics and protocols that should be standardized for a given restoration type and (b) coordinating with existing or related environmental monitoring efforts to establish or expand existing reference site networks.**
4. **Gulf restoration programs should ensure data are publically available by establishing and enforcing clear policies for archiving and sharing of restoration monitoring data and ensuring that monitoring data is archived with a portal that has long-term support and can be trusted to provide open data-access for the next few decades. This can be accomplished by contractually requiring data management plans with explicit deliverables as part of the restoration proposals.**

5. **Gulf restoration programs should consider creating a specific enterprise for synthesis activities in support of Gulf restoration, because synthesis of monitoring data is required for evaluating restoration performance beyond individual projects and restoration program outcomes for wide-ranging species such as marine mammals, sea turtles, and birds; and**
6. **Where it is deemed appropriate, all Gulf restoration programs should apply knowledge gained through analysis and synthesis of monitoring data by implementing adaptive management to improve restoration effectiveness.**

CHAPTER 1

INTRODUCTION

The 2010 Macondo Well Deepwater Horizon (DWH) rig explosion in the Gulf of Mexico claimed the lives of 11 people and resulted in the largest accidental oil spill in U.S. history – an estimated 134 million gallons of oil DWH NRDA Trustees, 2016. The oil spill contaminated an estimated 180,000 km^2 of ocean, 148 km^2 of seafloor, and 2,113 km of coastlines, beaches, and estuaries along the shores of Louisiana, Mississippi, Alabama, Florida, and Texas (Rabalais, 2014; Nixon et al., 2016). Natural resources suffered direct or indirect damage, notably offshore and coastal wildlife, migratory species, deep sea fauna, submerged aquatic vegetation and shellfish, coastal beaches, and wetlands (NRC, 2013; Rabalais, 2014; Nixon et al., 2016; see Figure 1.1). Gulf Coast communities were also negatively impacted because multiple benefits that people receive from the environment, generally referred to as ecosystem services (MEA, 2005), were also damaged. Losses include an estimated 20 percent reduction in commercial fishery landings across the Gulf of Mexico and potential damage to 1,770 km of coastal salt marsh wetland that help improve water quality, provide nursery habitats for commercial and recreation fishery species, and protect coastal towns and cities from storm surge and flooding (NRC, 2013).

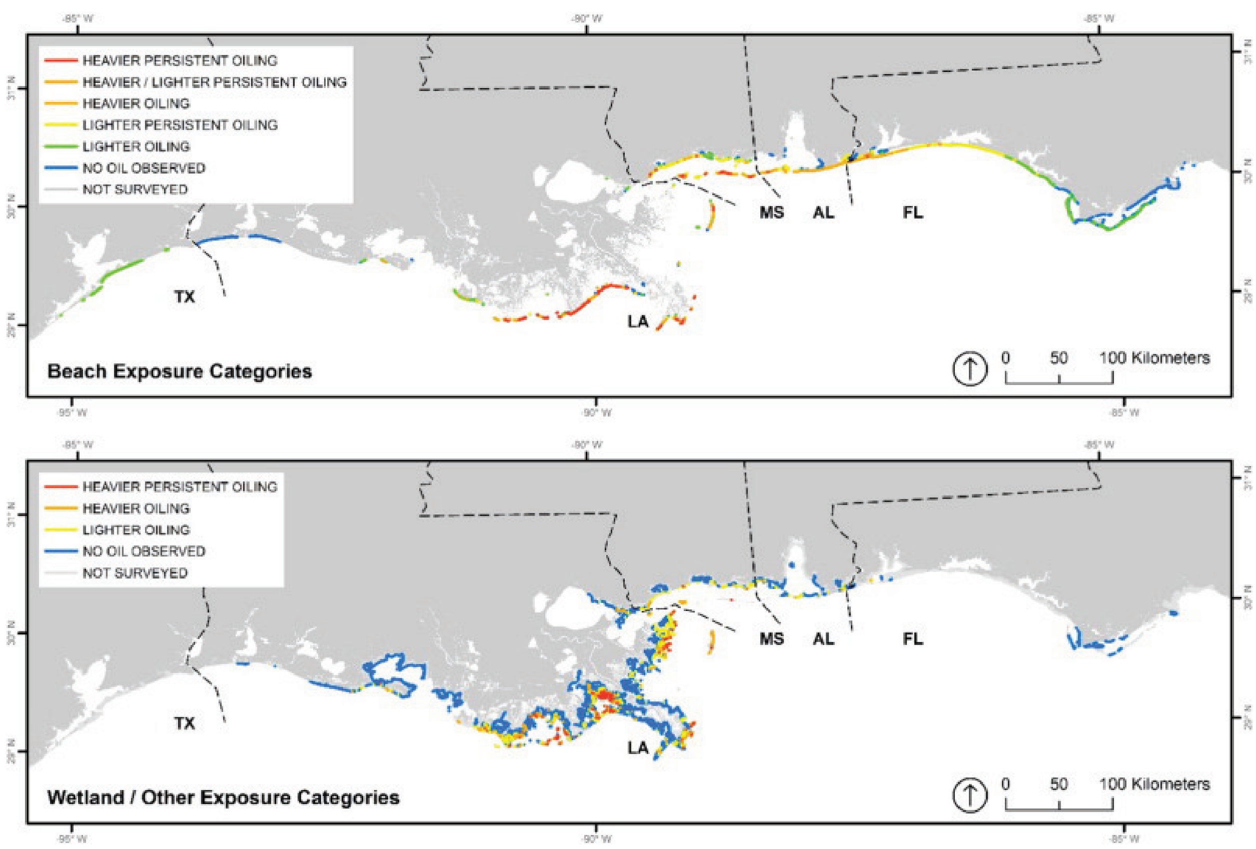

Figure 1.1 Map of oil exposure for beaches (46% of oiled shoreline; shown in the top image), and coastal wetland (52% of oiled shoreline) and other shoreline habitats (2% of oiled shoreline; shown together in the bottom image) after the largest marine oil spill to-date (measured by length of shoreline oiled) resulting from the Deepwater Horizon explosion. SOURCE: Nixon et al., 2016. Data are publicly available at http://gomex.erma.noaa.gov.

In the wake of the DWH oil spill and associated legal settlements between the responsible and injured parties, multiple large restoration efforts are being planned and initiated (see Chapter 2). Although the release of oil during the DWH spill was mostly offshore in deep water, many activities are focused on coastal restoration. The massive scale of investment in these restoration efforts underscores the high stakes and associated high expectations to demonstrate damage recovery and restoration progress (Hobbs, 2007; Palmer, 2009; Nilsson et al., 2016). The Gulf region's coastal and marine ecosystems support some of the nation's most productive fisheries (Upton, 2011; Sumaila et al., 2012) and many protected species, including marine mammal, turtle, and migratory bird populations. However, these restoration efforts are complicated by the fact that they occur within the context of other ongoing human activities and interconnected environmental change. Almost half of US domestic gas and one-fifth of domestic oil production are extracted from the Gulf, and seven of the nation's ten busiest ports can be found along the Gulf coast (EIA, 2015). The Gulf region is subject to intense development, industrial pressure, and pollution streams from the third largest drainage system on Earth—the Mississippi watershed—leading to potentially extensive ecosystem degradation. For example, hypoxia has been expanding in the Gulf of Mexico for decades (Turner et al., 2008), oyster biomass has declined by more than 80% over the past century (zu Ermgassen et al., 2012), areal coverage by wetlands in the Gulf decreases at a rate of nearly 1.6% per year (Dahl and Stedman, 2013), and depending on the location along the Gulf coast, 20-100% of seagrass habitat has been lost over the past 50 years (Handley et al., 2007).

Large-scale restoration has been shown to improve biodiversity and human well-being, but the state of restoration practice would benefit from improvements in both its effectiveness and cost efficiency (Alexander et al., 2016). The large infusion of new funding marks an unprecedented opportunity—and a responsibility—to accomplish substantial restoration progress in the Gulf. A key part of this responsibility will be documenting and demonstrating the accomplishments from this sizeable investment in restoration, which depends upon the development of a rigorous, coordinated, and consistent set of monitoring and evaluation approaches (Chapman, 1999; Chapman and Underwood, 2000).

Study Focus

Recognizing the need for guidance on monitoring and evaluating restoration progress during the early stages of investment in Gulf restoration, the Gulf Research Program of the National Academies of Sciences, Engineering, and Medicine sponsored this study to inform monitoring and evaluation of restoration activities in the Gulf of Mexico. An independent Academies' Committee was asked to identify best practices (i.e., existing, proven, cost-effective approaches) for monitoring and evaluating restoration activities to improve the performance of restoration programs and increase the effectiveness and longevity of restoration projects. The Committee was asked to identify:

- Current, effective approaches for developing initial and long-term monitoring goals and methods.
- Approaches for determining essential baseline data needs.
- Essential elements of a long-term monitoring framework (including baseline information) that would support current and planned restoration activities in the Gulf of Mexico.
- Additional novel approaches to augment current best practices that could increase effectiveness, reduce costs, ensure region-wide compatibility of restoration monitoring data, and advance the science and practice of restoration.
- Options to ensure that project, or site-based, monitoring could be used cumulatively and comprehensively to provide region-wide insights and track effectiveness on larger spatial and longer temporal scales.

The report reflects the Committee's consensus findings, based on review of the technical literature, presentations, and discussions at its four meetings, and the experience and knowledge of the Committee members in their respective fields. The Committee received briefings and input from a range of experts, including restoration practitioners, academics, and representatives of non-governmental organizations and state and federal government agencies.

The Committee's task was challenging, given the range of habitats and species subject to restoration, the diversity in project-scale or of possible restoration objectives, and the inability to present best monitoring practices for all possible Gulf restoration projects. Thus, the report provides general monitoring guidance that applies across all types of restoration efforts (Part I) and presents more specific guidance for a subset of habitat and species restoration projects that most closely aligned with the Committee's expertise (Part II).

LESSONS FROM PAST RESTORATION PRACTICE

Resource managers have a long history of practicing restoration by manipulating the environment (e.g., SER, 2004[1]; Coleman et al., 2009; for definition see Box 1.1). Restoration practice relies on important assumptions about how a species, habitat, or ecosystem will respond and aims to reconstruct one or more critical elements of an ecosystem back to a more "natural" state to boost provision of some important service or good of that particular ecosystem. For example, an oyster restoration project might involve placing bags of dead oyster shells onto the seafloor to provide clean substrate for naturally occurring oyster larvae to settle based on the assumption that this will lead to the restoration of a self-sustaining oyster reef assuming adequate baseline conditions and larval supply (Coen and Luckenbach, 2000; Baggett et al., 2014).

[1] See also extensive resources made available by the Society for Ecological Restoration at: http://ser.org/resources.

Box 1.1

Definitions

Restoration: For this report, the Committee adopted a broad definition of *restoration* as "the process of assisting the **recovery** of an ecosystem that has been degraded, damaged, or destroyed" (SER, 2004). Restoration is assessed against the extent that recovery goals and objectives have been achieved. Such goals usually include establishment of a system that is resilient to future disturbances and no longer dependent on restoration assistance to maintain desired ecological conditions and associated human benefits. The term **restoration** is used broadly in this report to be inclusive of an array of activities such as creation, enhancement, rehabilitation, reclamation, conservation, protection, management, and compensatory mitigation, which may be elements of an overall strategy to improve the condition of an ecosystem.

Recovery: "An ecosystem has recovered - and is deemed 'restored' - when it contains sufficient biotic and abiotic resources to continue its development without further assistance or subsidy. It will sustain itself structurally and functionally. It will demonstrate resilience to normal ranges of environmental stress and disturbance. It will interact with contiguous ecosystems in terms of biotic and abiotic flows and cultural interactions." (SER, 2004, p.3)

Restoration monitoring: The systematic collection of data that can be used to characterize the condition (including abundance, structure, and function) of a particular population, habitat, ecosystem, or ecosystem service over time. Restoration monitoring aims to inform assessments about restoration progress and improve the restoration effectiveness as needed. Monitoring may occur at a range of spatial and temporal scales from local to Gulf-wide and over months to decades.

Despite vast resource investment in restoration of estuaries and coastal habitats in the past, it is not yet customary for projects to rigorously monitor, assess, and document whether restoration activities have met the restoration objectives (or failed to do so) (Ruiz-Jaen and Aide, 2005; Suding, 2011; Halldórsson et al., 2012; Wortley et al., 2013). Furthermore, formal evaluations or meta-analysis across restoration activities are rare (Nilsson et al., 2016). Attempts to learn from the growing number of restoration efforts nation-wide have uncovered major problems due to a pervasive lack of well-defined goals and objectives, statistically insufficient monitoring designs, difficulties in locating documentation about projects including monitoring data and metadata, and a range of other issues (e.g., Palmer et al., 2007; Kennedy et al., 2011). In general, monitoring is a dramatically under-funded activity, and very few environmental management programs, including restoration, monitor ecological or social outcomes (e.g., a global review of conservation programs showed only 20-26% of projects had established monitoring programs [Goldman et al., 2008]). Although restoration monitoring (Box 1.1) is an integral part of restoration, it is often given a much lower priority than the actual construction or environmental manipulation effort (Thayer et al., 2005).

There are multiple ways that restoration monitoring and assessment activities provide significant value (Groves and Game, 2015). When done well, monitoring and evaluation can describe the environmental, social, ecological, and economic benefits accrued from restoration (De Groot et al., 2013). Especially in the northern Gulf of Mexico, where ecosystems are affected by human activities, management efforts, species interactions, introduced species, and uncertain natural events such as hurricanes, progress of restoration efforts may be uneven and unpredictable from year to year. Considering the substantial investment, Gulf coastal communities and the general public deserve a thorough assessment of whether the stated restoration goals and objectives are achieved, how projects affect their livelihoods, sustenance, and well-being, as well as accountability for how restoration funds are spent (Stem et al., 2005).

Monitoring and evaluation can also help inform decisions about how to make restoration more effective (see Box 1.2; here and in subsequent chapters the Committee uses oyster restoration as an example to illustrate general statements). Learning from restoration monitoring can occur through trial and error or, more efficiently, through the structured process of monitoring and formal evaluation and associated adaptive management (see Box 1.3). Carefully designed monitoring can inform decision-making to improve future restoration planning and implementation in both the Gulf region and related coastal ecosystems worldwide (Stem et al., 2005).

Box 1.2

Example of How Monitoring Improves Restoration Effectiveness

The following illustrates how one example of monitoring of oyster reef restoration in the Chesapeake Bay informed site selection and restoration practice. Oysters build reef structures that yield a variety of positive ecological and human benefits (see Part II, Oyster habitat). With native unrestored oyster populations at perhaps 1% of historic abundance in the Chesapeake Bay due primarily to overfishing, disease, and physical conditions (Rothschild, et al., 1994; Lenihan, 1999; Wilberg et al., 2011; Powers and Boyer, 2014; Lipcius et al., 2015), many (often expensive) attempts have been made to restore reefs. Efforts to restore functioning and resilient native oyster reefs have not yielded well-documented progress throughout the US, in large part because of inadequate reference sites, methodologies, metrics, and success criteria (Coen and Luckenbach, 2000; Kennedy et al., 2011; La Peyre et al., 2014; Baggett et al., 2015). Some have even suggested that oyster restoration might not be possible in historically important estuaries given harvesting practices and loss and replacement rates of shell above and below sediment (Powell et al., 2012; Waldbusser et al., 2013). However, for those efforts that used adequate methods, durations, materials and monitoring as tools to assess restoration progress, researchers have been able to distinguish up to three main factors controlling native oyster recovery: fishing pressure, sufficient spatial scale of restoration, and vertical reef height (Lenihan, 1999; Schulte et al., 2009; Wilberg et al., 2013; Powers and Boyer, 2014; Lipcius et al., 2015). Monitoring restoration efforts has shown that reducing fishing pressure protects oyster reefs from physical disturbance and may enhancedisease resistance (Ragone Calvo et al., 2003; Hare et al., 2006; Carlsson et al., 2008; Powell et al., 2012). High relief reefs have historically dominated large portions of eastern US and Gulf of Mexican estuaries; and increasing reef height and three-dimensional structure in the absence of dredging enhances flow rates, which can raise oyster abundance and density, positively affecting future recruitment and ultimately restoration performance (Hargis and Haven, 1999; Lenihan, 1999; Schulte et al., 2009; Lipcius et al., 2015). Restoration monitoring has shown that low-relief reefs, and relatively small restoration footprints (<1 acre), both of which have formed the basis many past Chesapeake Bay restoration efforts by resource agencies, were insufficient given all of the other stressors to support resilient oyster populations for more than a few years. Although constructing reefs using rapid methods that deployed getting shell off of barges (using water cannons) were quicker and viewed as cost-effective, the results were often lower quality, non-directed, shorter-lasting, and ultimately inefficient for restoration.

In the Chesapeake Bay, multiple restoration designs were monitored to test methodologies that are commonly used, but rarely evaluated. Researchers used water pumped from cannons to deploy oyster shell from barges to construct low-relief reefs. By using more shells and dumping shell overboard from buckets, a more precisely placed substrate can produce high-relief reefs (D. Schulte, personal communication). These restoration activities resulted in dramatic density increase from fewer than 2 oysters/m^2 (typical of harvested reefs in the area) to over 250 oysters/m^2 on constructed low-relief and over 1000 oysters/m^2 on constructed high-relief reefs in 3 years (Schulte et al., 2009; see Figure 1.A). Furthermore, modeled results of a similar scenario predicted oyster abundance on high relief reefs to far exceed that of low relief reefs decades after restoration (Wilberg et al., 2013).

Researchers concluded that conservation and restoration actions need to be monitored and evaluated separately, and that monitoring information needs to be collected over a long enough timeframe to effectively evaluate whether restoration objectives have been achieved (Schulte et al., 2009). Also, employing alternative metrics (to shell size) was critical to assessing restoration progress (Coen and Luckenbach, 2000; Luckenbach et al., 2005; Powers and Boyer, 2014). Furthermore, pre-construction assessments coupled with long-term monitoring and modeling have demonstrated that while a variety of reef conditions may support restored oysters for a few years, both good initial site suitability and maintenance of fishing closures are crucial to achieving sustained recovery over decades (Luckenbach et al., 1999; Wilberg et al., 2013; Theuerkauf and Lipcius, 2016). Synthesizing this information has helped shape more effective practices, reduced the cost of restoration efforts, and dramatically improved the benefits of oyster restoration in the Chesapeake Bay.

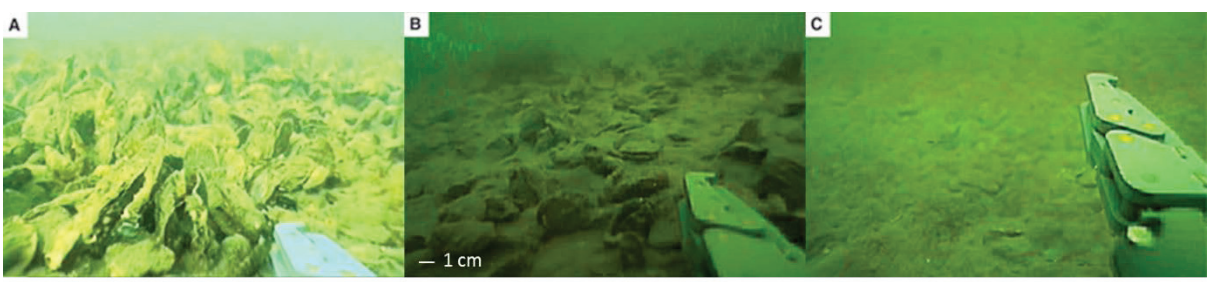

Figure 1.2 Photographs representing the average conditions found at each treatment reef: (A) shows high relief reef restoration results, (B) shows low-relief reef restoration results, and (C) shows unrestored bottom results, each three years after construction. The scale bar shown in (B) measures approximately 1 cm and applies to all three images. SOURCE: Schulte et al., 2009.

Box 1.3

Definition: Adaptive Management

Adaptive management (Holling, 1978) is a rigorous, systematic approach to ecosystem management that allows restoration to proceed in the face of uncertainties about how the ecosystem might respond to manipulations. Within adaptive management, monitoring and evaluation are carefully planned and implemented so that knowledge gained from restoration projects can be applied through flexible decision making to enhance ongoing or future restoration activities (see Figure 1.3.1; NRC, 2004). Management and restoration activities are treated as deliberately planned manipulations designed to reduce targeted uncertainties that are deemed to be the highest priorities to inform future decision making (Nyberg, 1998). As stated in NRC (2004), "careful monitoring of these outcomes both advances scientific understanding and helps adjust policies or operations as part of an iterative learning process." Adaptive management affords more efficient learning and improvements to decision making than through other implementation approaches, such as trial and error. The adaptive management process, and key elements necessary to implement it in Gulf restoration, are discussed further in Chapter 7.

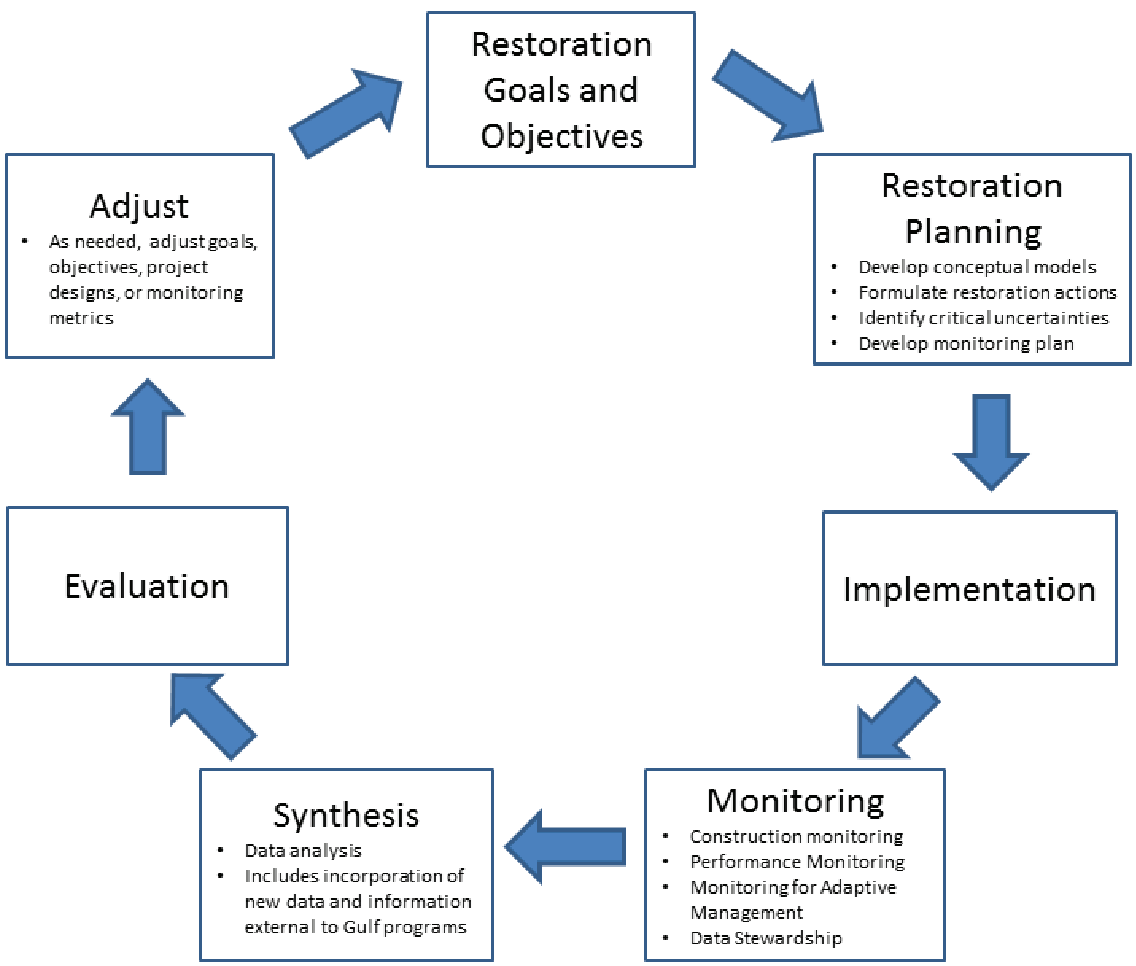

Figure 1.3 A conceptual diagram to illustrate the elements of restoration management and monitoring within an adaptive management framework. SOURCE: Committee.

Even with growing appreciation for its benefits and importance, conducting effective restoration monitoring and evaluation is difficult (see Box 1.4) and sometimes not considered part of the restoration process (Stem et al., 2005; Kondolf et al., 2007; Lindenmayer and Likens, 2009, 2010; Kennedy et al., 2011; Baggett et al., 2014). Thus, the Committee's report offers guidance in the subsequent chapters to overcome these difficulties. In Chesapeake Bay, Kennedy et al. (2011) reported that "of the more than 2,000 [oyster] restoration activities undertaken, a relatively small number were monitored," and where monitoring did occur, "the kinds and types of data required to determine explicitly the success of restoration were generally not recorded," severely limiting the authors' ability to evaluate the effectiveness of oyster restoration. The apparent reluctance to monitor restoration activities may stem from the misconception that monitoring comes at the cost of *doing* restoration. In contrast, monitoring could inform restoration such that *doing* restoration would become more cost effective (as described previously in Box 1.2). Without a commitment to rigorous monitoring, it will be impossible to assess the efficacy of the restoration activities and impossible to improve restoration practice to enhance effectiveness (Lindenmayer and Likens, 2010).

Box 1.4

Common Difficulties with Implementing Restoration Monitoring and Evaluation Efforts

Several reasons why monitoring and assessment activities are difficult to implement, difficult to learn from when they do occur, and consequently why this key component too often fails to follow restoration, are described below:

- Lack of political will and/or public support; [1]
- Lack of appreciation for the expense of monitoring and/or use of cost-effective measures; [2]
- Lack of sustained funding, patience, or effort; [2,3]
- Unclear, infeasible, or non-existent vision and program goals; [2]
- Unclear, untestable, or unbounded project objectives; [4,5]
- Metrics that are not tied to objectives or inappropriate performance criteria; [4,6,7]
- Insufficient baseline data and/or shifting baselines; [2,7]
- Unsuitable site selection and lack of control and/or reference sites; [7]
- Inadequate statistical sampling design; [4,8]
- Insufficient or non-existent data management, analysis, archiving, sharing, and/or broader synthesis; [2,3]
- Inaccurate understanding of ecosystem complexity, processes, and linkages; [2,7,9]
- Lack of clear spatial and temporal boundaries for ecosystems, natural processes, etc; [2,10]
- Inaccurate understanding of human effects (e.g., harvests) on species and ecosystems; [4]
- Inaccurate understanding of scaling inconsistencies and regional differences; [2,7]
- Lack of a clear understanding and statement of how monitoring information will guide management; [3,11]
- Lack of formal communication between practitioners and decision-makers to incorporate monitoring results; [3]
- Uncoordinated, ad hoc, multi-objective, and/or small-scale restoration under different authorities at multiple sites; [2,4,12]
- Ineffective program management, oversight, and accountability, and lack of clear guidance and requirements for large-scale monitoring; [2,4,11,12]
- Natural/human-induced disasters, disturbances, and unforeseen influences/interactions; [13] and
- Lack of attention to past successes and failures and unwillingness to adapt plans. [2,7,14,15]

Sources: (1) Baker and Eckerberg, 2013; (2) Manning et al., 2006; (3) Hutto and Belote, 2013 (and references within); (4) Kennedy et al., 2011; (5) e.g., SER, 2004; Tear et al., 2005; Allen et al., 2011; McKay et al., 2012; Convertino et al., 2013; (6) Neckles et al., 2002; Woolsey et al., 2007; Palmer & Wainger, 2011; Baggett et al., 2014; (7) Kusler & Kentula, 1990; NRC, 2001; NRC, 1994; Stelk et al., 2016; (8) Palmer et al., 2007; (9) e.g., Gross, 2003; NRC, 2003; Mazzotti and Barnes, 2004; Simenstad et al., 2006; (10) Charles 2012; (11) Kondolf et al., 2007; (12) Edwards et al., 2011; (13) Bulleri et al., 2008; (14) Stem et al., 2005; (15) Suding, 2011.

Past experience suggests that restoration practice can be greatly enhanced through properly-designed monitoring and evaluation efforts informed by the latest research in restoration ecology or conservation biology (Stem et al., 2005; Young et al., 2005; Suding, 2011;

Groves and Game, 2015). Although restoration ecology has much to offer to improve the efficacy of restoration projects, application of academic research from this relatively nascent field and its intersection with related disciplines—such as ecology, biology, geomorphology, hydrology, and others—is often lagging (e.g., Palmer et al., 2005, Baggett et al., 2014, Neckles et al., 2015). Furthermore, even when restoration is conducted with appropriate scientific considerations and rigor, restoration does not always achieve the stated objectives, for example reaching comparable biodiversity and ecosystem service provision found in non-degraded ecosystems (Benayas et al., 2009). The fact that many restoration projects lack any monitoring further illustrates the barriers between practice and monitoring and assessment of restoration (e.g., Ruiz-Jaen and Aide, 2005; Palmer et al., 2001; Kennedy et al., 2011). Improving the effectiveness and longevity of any current and future restoration projects relies on analyzing restoration practice and making results widely available (Palmer et al., 2007). Effective information exchange and stronger feedbacks between the practice and science of restoration monitoring will enhance the efficacy of restoration at a faster rate than either practitioners or researchers could accomplish alone (Young et al., 2005).

REPORT ORGANIZATION

The Committee's report includes discussion of the critical elements in the adaptive management process as it relates to restoration goals and objectives; restoration planning as it pertains to monitoring; monitoring including data stewardship; synthesis; evaluation; and adjustments (as depicted in Figure 1.3). In Chapter 2, the Committee reviews and summarizes the restoration goals and initial funding priorities of the major Gulf restoration programs, which are supported by Natural Resource Damage Assessment, Resources and Ecosystems Sustainability, Tourist Opportunities, and Revived Economies of the Gulf Coast States (RESTORE) Act, and National Fish and Wildlife Foundation funds. Chapter 3 addresses a major part of the Committee's task to identify best practices for monitoring and describes current, effective approaches for developing monitoring goals and methods as well as approaches for determining baseline data needs. Chapter 3 addresses this task by presenting general guidance on how to develop a project-level monitoring plan, based on a review of the literature. Important considerations that influence the design of the monitoring efforts are also discussed including recommendations on use of historical data and baseline information, statistical design for sampling, and impacts of scale. To supplement this general guidance, the Committee has prepared more specific guidance for restoration monitoring pertaining to a select sub-set of example habitats and species in Part II of the report. To address the Committee's task for long-term monitoring and approaches to augment best practices, in Chapter 4 the Committee considers monitoring approaches that go beyond the project duration or geographic scale. In particular, certain restoration efforts will benefit or require monitoring that extend well beyond the duration of the restoration project or beyond the geographic area of a single restoration project. In Chapter 5, the Committee presents information on effective data stewardship, including requirements for an effective data management system that provides timely, public data access via web portal. Subsequently, in Chapter 6, the Committee discusses how to ensure effective data synthesis and integration can occurs. Both Chapters 5 and 6 are important to addressing the last part of the Committee's charge, which has options to ensuring that project or site-based monitoring could be used cumulatively and comprehensively to track effectiveness at larger spatial scale. Chapter 7 discusses how the information gained from monitoring and synthesis can improve the effectiveness of restoration projects or programs (see Figure 1.3) and discusses adaptive management in greater detail. Finally, examples of good practices for monitoring select habitats (tidal wetlands, oyster reefs, and seagrass beds) and marine living resources (birds, sea turtles, and large marine vertebrates) are provided in Part II of this report.

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CHAPTER 2
GULF RESTORATION PROGRAMS

In this chapter, the major Gulf restoration programs are described to provide context for understanding monitoring and evaluation in light of various program mandates and goals. The chapter begins with a general discussion on setting restoration goals and objectives. Then the respective goals and monitoring plans for the major Gulf restoration plans are outlined, highlighting the importance of clearly defined measurable restoration objectives.

SETTING A VISION, GOALS, AND OBJECTIVES

Effective restoration programs benefit from a clear vision and well-defined goals and measurable objectives (NRC, 2005). A vision can simply be a statement, along with an artistic depiction of the end point conditions of the program, often developed in collaboration with stakeholders (e.g., Petts, 2006). The vision provides the guidance for development of clear sets of goals and objectives, which are critical to program efficacy and project design, implementation, and evaluation (Calow, 2009). Clear goals and objectives specify the desired future with restoration compared to existing conditions (NRC, 1992; SER, 2004; Beck et al., 2011). Restoration goals are typically broad and overarching, such as 'return to past ecological conditions,' 'address environmental damage,' or 'restore ecosystem services' (Baker and Eckerberg, 2016). Such goals are made operational through specific and measureable objectives.

Restoration objectives can be ecological or socio-economic or both. Ecological restoration objectives might focus on structural (i.e., pertaining to the physical or biological conditions at a project site, such as raising the beach and dune profile to pre-disturbance conditions or increasing marsh-dependent bird populations) and/or functional (i.e., focused on the processes provided by the restored habitat, such as providing suitable nesting conditions for threatened and endangered coastal birds) attributes of the system. Ecological objectives might also focus on restoring species numbers, such as in recovery plans for threatened and endangered species. Socio-economic objectives focus on the economic or social benefits to people gained from the restoration actions directly (such as employment in habitat construction) or from improved structure or function of the ecological system. In particular, another socio-economic objective could be the enhancement of ecosystem services supply through protecting and/or enhancing the bio-physical structure, function, and processes, and human well-being. This report focuses on monitoring for ecological restoration because the majority of the goals of Gulf restoration programs are primarily to undertake ecological restoration and because the Committee was asked by the sponsor to focus monitoring for ecological restoration. However, the monitoring and assessment of ecosystem services and other socio-economic are important to consider especially when explicitly listed as the project's objective (see NRC, 2012, Chapter 3; NRC, 2013, Chapter 5 for general reference).

Objectives for restoration are ideally chosen based on desired outcomes of a particular project, stakeholder values, and the feasibility and cost-effectiveness of achieving those objectives (NOAA, 2010). Moreover, restoration projects can often strive to achieve multiple objectives. For example, a coastal island can be restored to ameliorate erosion, improve habitat for a threatened species, mitigate pollution impacts, and dampen damaging storm surges for towns or cities onshore. However, some restoration objectives may be irreconcilable. For example, some stakeholders might want to restore a particular beach to provide suitable nesting sites for the conservation of a threatened coastal bird, which might require the exclusion of human access to the particular beach; others might want to restore the same beach for active recreational use. Thus, choosing well-defined guiding objective(s) for restoration is critical to achieving and evaluating the efficacy of a particular project. The importance of setting measurable objectives cannot be overemphasized. A common point of restoration project failure is the lack of an inadequate statement of goals and objectives (e.g., NRC, 1994; Diefenderfer & Thom, 2003; Calow, 2009; NOAA, 2010; Box 1.4). Objectives lead to associated actions (restoration efforts), and the environmental and socio-economic responses to restoration actions are monitored to determine whether the objectives are being met (see Chapter 7).

GULF RESTORATION PROGRAMS

Resolution of natural resource damage, civil and administrative, and criminal claims resulted in the disbursement of funds to a number of councils and programs to administer funds for Deepwater Horizon (DWH)-related restoration in the Gulf of Mexico (Figure 2.1): (1) the Natural Resource Damage Assessment (NRDA) Trustee Council; (2) the Gulf Coast Ecosystem Restoration Council (known as the RESTORE Council); and (3) the National Fish and Wildlife Foundation (NFWF) Gulf Environmental Benefit Fund. These major funding pools are administered separately by programs with different legal frameworks and goals. Despite their differences, these programs strive to support environmental restoration projects in a complementary manner within and across the five Gulf states and in the offshore environment. DWH-related restoration, monitoring, and research funds are also distributed through the North American Wetlands Conservation Fund, the National Academies of Sciences, Engineering, and Medicine's Gulf Research Program, the Gulf of Mexico Research Initiative, the National Oceanic and Atmospheric Administration (NOAA) RESTORE Act Science Program, and Gulf state Centers of Excellence (ELI and Tulane, 2014; CRS, 2015; USDOJ, 2016; see sources of Figure 2.1 for more information).

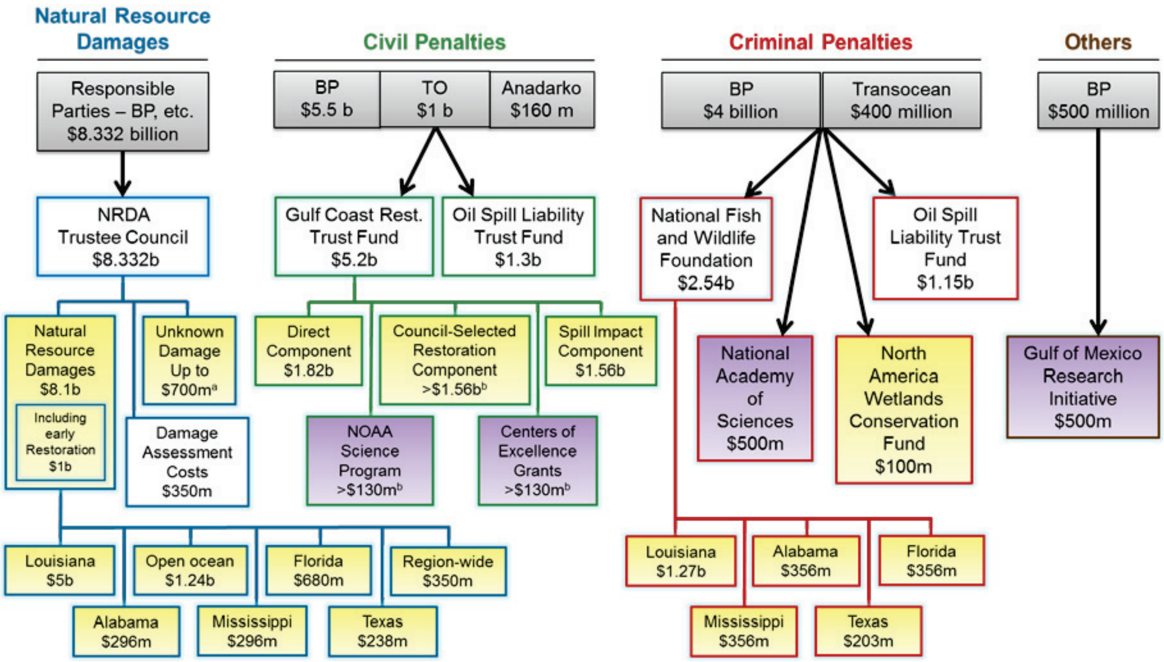

FIGURE 2.1 The funding landscape for Deepwater Horizon settlements and penalties, including funds for Gulf restoration efforts (shaded in yellow, note that the Gulf Coast Restoration Trust Fund (known as the RESTORE Council) Direct Component funds are partially dedicated to restoration) and Gulf science programs (purple).[1]. Abbreviations: BP Exploration and Production, Inc. (BP), Transocean, Ltd. (TO),Natural Resource Damage Assessment (NRDA), and National Oceanic and Atmospheric Administration (NOAA), million (m), billion (b). SOURCES: http://response.restoration.noaa.gov/about/media/who-funding-research-and-restoration-gulf-mexico-after-deepwater-horizon-oil-spill.html, http://www.justice.gov/opa/file/780696/download, http://eli-ocean.org/wp-content/blogs.dir/2/files/Funding-DH-Restoration-Recovery.pdf, http://eli-ocean.org/gulf/agreement/, https://www.fas.org/sgp/crs/misc/R42942.pdf.

Legal Frameworks for the Restoration Programs

Deepwater Horizon NRDA Trustee Council

Under the Oil Pollution Act (1990), natural resource trustees can recover the costs of damage assessment, restoration, and loss of use from potentially responsible parties in response to an oil spill. A natural resource damage assessment is conducted to identify and evaluate injury to natural resources from the release of oil, and the results are used to procure funds from the responsible party to restore damaged resources to the condition that would have occurred if the

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[1] Additional Notes on Figure 2.1: This figure does not include $90 million in payments from MOEX Offshore 2007, LLC to the Oil Spill Liability Trust Fund and Gulf states for civil penalties and Supplemental Environmental Projects.
[a] Unknown NRDA damage includes $232 million plus interest on the $8.1b payment.
[b] The Comprehensive Plan Component is supplemented by 50 percent of the interest on RESTORE funds, and the remaining interest is split between the NOAA Science Program and the Centers of Excellence grants.

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spill had not happened and to compensate the public for lost natural resources. In October 2015, the Department of Justice announced a settlement with BP Exploration and Production, Inc. (BP) that included $8.1 billion (including $1 billion in early restoration funds) to address natural resources damages and up to an additional $700 million (partly funded from the interest on the $8.1 billion) to address damages that are currently unknown but may be detected in the future. In April 2016, a consent decree from New Orleans federal court resolved civil claims against BP in the largest single-entity federal settlement in US history for a sum of $20.8 billion.[2] The *Deepwater Horizon* NRDA Trustee Council[3] therefore acts on behalf of the public to restore natural resources that were directly or indirectly harmed by the oil released into the Gulf of Mexico and compensate the public for their lost use of these resources.

RESTORE Council

The RESTORE Council was created by Congress through the RESTORE Act (2012)[4] and charged with overseeing 60% of all civil and administrative penalties related to the DWH oil spill under the Clean Water Act (1972)[5] through establishment of the Gulf Coast Restoration Trust Fund (see Figure 2.1). Of the $6.6595 billion settlement (BP, Transocean, and Anadarko), the RESTORE Council manages two categories of restoration funds—the Council-Selected Restoration Component and the Spill Impact Component. The Council-Selected Restoration Component (~$1.6 billion; 30 percent of funds plus interest) directs funds toward ecosystem restoration projects according to goals and objectives developed in the Initial Comprehensive Plan (RESTORE Council, 2013). The Spill Impact Component ($1.6 billion; 30% of funds) funds implementation of projects developed according to approved individual State Expenditure Plan (SEP) under the RESTORE Act[6]. In addition, the Direct Component divides $1.9 billion equally among the states for "ecological restoration, economic development, and tourism promotion." The RESTORE Act defines the geographic scope for restoration, which includes the coastal zone (i.e., the coastal waters and adjacent shore land) of the Gulf Coast states, including federal lands; any adjacent land, water, and watersheds within 25 miles of the coastal zones; and all federal waters in the Gulf of Mexico. The Act does not specify a timeframe for expenditure of the funds, but allows the Secretary of the Treasury to decide the amounts to be spent and invested each year from the Trust Fund (CRS, 2015).

NFWF Gulf Environmental Benefit Fund

NFWF was awarded $2.5 billion derived from criminal penalties from BP and Transocean to "fund projects benefiting the natural resources of the Gulf Coast that were

[2] Department of Justice consent decree: https://www.justice.gov/enrd/deepwater-horizon.
[3] The DWH NRDA Trustee Council is comprised of the five Gulf states, the National Oceanic and Atmospheric Administration, the Department of the Interior, the Environmental Protection Agency, and the U.S. Department of Agriculture.
[4] The Resources and Ecosystems Sustainability, Tourist Opportunities, and Revived Economies of the Gulf Coast States Act was signed into law in 2012 to establish the Gulf Coast Restoration Trust Fund in the U.S. Treasury Department: https://www.treasury.gov/services/restore-act/Pages/home.aspx.
[5] The Clean Water Act was reorganized in 1972 to establish the basic structure for regulating pollutant discharge into United States waters and regulating surface water quality standards: https://www.epa.gov/laws-regulations/summary-clean-water-act.
[6] https://www.restorethegulf.gov/sites/default/files/NOFA_SEPs_Final_Draft_ver20160524.pdf.

impacted by the spill" and, specifically, to support projects focused on physical restoration of habitats and ecological functions. Half of the funds are directed for projects in Louisiana to create or restore barrier islands or expand wetland habitat through river diversion projects. The remaining funding is allocated toward natural resources projects in Mississippi, Alabama, Florida, and Texas (see Figure 2.1) to "remedy harm" from the oil spill. As a result of the different legal frameworks and origins of these three major restoration programs, they have different restoration objectives and monitoring requirements.

Goals of the Restoration Programs

These three restoration programs have similar high-level restoration goals[7]. All three programs aim to restore and conserve habitat as well as replenish and protect living coastal and marine resources. In addition, the NRDA Trustee Council and the RESTORE Council aim to restore water quality and include some socio-economic components. The NRDA Trustee Council aims to enhance recreation opportunities and the RESTORE Council aims to enhance community resilience and revitalize the Gulf economy. Notably, only the NRDA Trustee Council explicitly lists the provision for monitoring and adaptive management as one of its high-level goals (see below for additional details on monitoring plans).

Although the broad goals articulated in these high-level plans appear similar, the restoration goals established by the RESTORE Council are broader than those set forth by the Oil Pollution Act (1990). The RESTORE Council has the flexibility to fund projects that restore the environment more generally and it is not limited to only ameliorating injury from the DWH oil spill. The RESTORE Council can choose to restore resources injured by the spill, restore degraded ecosystem(s) more broadly (independent of what caused the degradation), or be more forward looking and consider responding to predicted future global changes. The RESTORE Council's plan also describes fundamental core values underlying the restoration program, including a commitment to "science-based decision-making" and "delivering results and measuring impacts." The NRDA Trustee Council can support projects that restore or replace injured resources directly injured by the spill, as well as projects that provide resource services of the same type and quality, and of comparable value as those directly injured (OPA 1990 Section 990.53(b-c)). The *Deepwater* Horizon NRDA Trustee Council has adopted monitoring and adaptive management as one of its foundational goals, and can also support monitoring and adaptive management activities; including data collection, analysis, and modeling, that support the planning, implementation and evaluation of restoration for resources injured by the spill. The mission of the NFWF Gulf Environmental Benefit Fund is to conduct or fund projects "to remedy harm and eliminate or reduce risk of future harm to Gulf coast natural resources…where there has been injury to, or destruction of, loss of, or loss of use of those resources resulting from the Macondo oil spill."[8]

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[7] The Deepwater Horizon Trustee Council's Programmatic Damage Assessment and Restoration Plan and Programmatic Environmental Impact Statement: http://www.gulfspillrestoration.noaa.gov/restoration-planning/gulf-plan/; The RESTORE Council's Comprehensive Plan: https://www.restorethegulf.gov/sites/default/files/Final%20Initial%20Comprehensive%20Plan.pdf.; NFWF's Gulf Environmental Benefit Fund Funding Priorities: http://www.nfwf.org/gulf/Pages/fundingpriorities.aspx.

[8] NFWF's mission: http://www.nfwf.org/gulf/Documents/bp-oil-spill-agreement-12-1120-v2.pdf.

STATES' PRIORITIES AND STRATEGIES

The Gulf States differ substantially in their range of coastal ecosystem types, DWH-induced damage to these ecosystems, state government goals and priorities for restoration, and experience with developing restoration monitoring protocols. Funding allocations from criminal, civil, and natural resource damage assessment penalties differ among states as well, with some funds distributed equally and others distributed by a specific formula based on the oil-spill impact (see Figure 2.1).

Louisiana

Of the five states, Louisiana coastlines received the majority (65%) of oiling, and 95% of the Gulf's oiled wetland shorelines are within its borders (Nixon et al., 2016). Louisiana operates under the Coastal Protection and Restoration Authority, which integrates a range of state agencies and developed a comprehensive restoration plan (Louisiana's Comprehensive Master Plan for a Sustainable Coast; CPRA, 2012). This restoration plan prioritizes the state's investment in restoration toward marsh creation, sediment diversion, barrier island restoration, and hydrologic restoration. In support of the Master Plan, Louisiana has made substantial investments in baseline and reference site monitoring, monitoring protocols, model development, and data management. From 2016 to 2018, Louisiana anticipates spending $35 million of state and federal funds to implement its System-wide Assessment and Monitoring Program, $7.4 million for barrier island comprehensive monitoring, and $6.7 million for data management (CPRA, 2012). The state's Master Plan also requires spending about $3 million per year on restoration planning efforts, and the Plan itself must be updated every five years to incorporate improvements in scientific and technical understanding gained from research and ongoing projects. Louisiana's restoration efforts are supported by the Federal Coastal Wetlands Planning, Protection and Restoration Act,[9] which was passed in 1990 and mandates to evaluate the effects of specific projects as well as the cumulative and regional effects on the coastal landscape. This restoration program also funds the state's Coastal Reference Monitoring System,[10] which provides data on multiple reference sites across a range of conditions that can be used when evaluating the results of wetland restoration projects.

Alabama

The Alabama Gulf Coast Recovery Council has determined restoration priorities to include restoration and mitigation of damage to natural resources, ecosystems, fisheries, marine and wildlife habitats, beaches, and coastal wetlands.[11] All proposed state-sponsored RESTORE restoration projects have a strong monitoring component, a monitoring plan is attached to the projects, and monitoring is a line item in the budget for at least five years.

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[9] CWPPRA legislation: http://lacoast.gov/new/About/.
[10] LA Coastal Reference Monitoring System: http://lacoast.gov/crms2/home.aspx.
[11] The Alabama Gulf Coast Recovery Council: http://www.restorealabama.org/.

Florida

The state of Florida is sponsoring ecological and economic/recreational restoration projects, and is focusing on their Ocean Observing System, benthic mapping, non-point source pollution, fisheries-independent monitoring (potentially expanding data collection to other states), and technique effectiveness monitoring. Florida requires monitoring for restoration at (1) project (through permits and grants), (2) medium (e.g., through long-term catalogues and databases), and (3) larger scales (e.g., through geographic information system [GIS] change analysis and modeling). As an example of institutional coordination, The Florida Gulf Consortium[12] formed as an agreement among its 23 Gulf coast counties to help meet requirements of the RESTORE Act and develop a State Expenditure Plan.

Mississippi

Mississippi's restoration priorities emphasize the beneficial use of dredge material to restore eroding beaches, dunes, and coastal islands. The state recently released a restoration plan relying on monitoring data and stakeholder engagement, and funded by NFWF, as well as the Comprehensive Ecosystem Restoration Tool (MCERT Explorer) to support science-based decision making based on landscape, marine, and water quality conditions.[13]

Texas

Early restoration priorities in Texas include land conservation, wetland creation and restoration, coastal island restoration to enhance bird habitat, and coordinating across state lines and with federal agencies. Monitoring programs in support of these restoration programs are under development.[14]

Restoration Funding Priorities

Based on the early restoration plans and investments from each program, the Committee attempted to assess and compare the relative funding allocated to different habitats and living resources in the Gulf of Mexico (see Figure 2.2). For example, the NRDA Trustee Council identifies in the Programmatic Damage Assessment and Restoration Plan 13 different habitats or resources, referred to as Restoration Types, and allocates funding to each in specified regions, referred to as Trustee Implementation Groups (or TIGs, which are the five Gulf States, the open ocean, and region-wide[15])(PDARP; DWH NRDA Trustees, 2016). The majority of funding ($4.2 billion) is allocated toward wetlands, coastal, and nearshore habitat restoration, and $4 billion of those funds are directed toward projects in Louisiana. However, $1.2 billion has been allocated toward restoration and monitoring in the open ocean, including projects to improve the condition

[12] The Gulf Consortium is a public entity created in 2012 by inter-local agreement: http://www.fl-counties.com/advocacy/gulf-consortium.
[13] Mississippi Gulf Coast Restoration Plan: http://www.restore.ms/mississippi-gulf-coast-restoration-plan; MCERT Explorer: http://msrestoreteam.com/NFWFPlan2015/#p=1.
[14] Coastal Restoration Funding for Texas from the Deepwater Horizon Oil Spill: https://www.restorethetexascoast.org/.
[15] The term "region-wide" is defined as the Gulf of Mexico regional ecosystem (see PDARP page 3-2)

for marine mammals, sea turtles, sturgeon, birds, and deep benthic communities. An additional $350 million have been set aside for region-wide projects. An agreement in 2011 enabled early restoration for $1 billion to begin as part of the NRDA restoration process to restore injured resources. In December 2015, the RESTORE Council announced the approval of $156.6 million for the first allotment of restoration and planning, described by the Initial Funded Priorities List (RESTORE Council, 2015).

States are also developing expenditure plans for the ~$1.6 billion in RESTORE Spill Impact Component allocation funds, which are available to the states for approved plans according to a specified formula, described in federal regulation.[16] Proposed projects must restore and protect Gulf Coast natural resources or economies by undertaking at least one of the activities listed in Box 2.1. NFWF has collaborated with state and federal resource agencies to identify priority categories of restoration, and will continue to refine them as conservation planning and implementation proceeds. As of February 2016, the Gulf Environmental Benefit Fund has allocated over $480 million to support 73 projects, and nearly one-third of the funds have been directed toward barrier-island or beach and dune restoration projects. In Louisiana, NFWF has funded the Coastal Protection and Restoration Authority to conduct seven projects to date in accordance with their comprehensive Coastal Master Plan (CPRA, 2012). Approximately one-fourth of the funding to date has supported wetland restoration projects, with additional funding for coastal habitat improvements, watershed management projects, land conservation, and oyster reef restoration.[17]

Box 2.1

Projects Eligible for Funding Under the RESTORE Spill Impact Component

The RESTORE Act (2012) describes the scope of activities eligible for funding under the Spill Impact Component of funding. These activities can include the following:

- Restoration and protection of the natural resources, ecosystems, fisheries, marine and wildlife habitats, beaches, and coastal wetlands of the Gulf Coast region;
- Mitigation of damage to fish, wildlife, and natural resources;
- Implementation of a federally approved marine, coastal, or comprehensive conservation management plan, including fisheries monitoring;
- Workforce development and job creation;
- Improvements to or on State parks located in coastal areas affected by the Deepwater Horizon oil spill;
- Infrastructure projects benefitting the economy or ecosystem resources, including port infrastructure;
- Coastal flood protection and related infrastructure;
- Planning assistance;

[16] https://www.justice.gov/enrd/deepwater-horizon
[17] List of funded NFWF projects: http://www.nfwf.org/gulf/Pages/gulf-projects.aspx.

- Administrative costs of complying with the Act;
- Promotion of tourism in the Gulf Coast region, including recreational fishing; and
- Promotion of the consumption of seafood harvested from the Gulf Coast region.

Restoration Monitoring

NRDA Restoration Monitoring Guidelines

The Programmatic Damage Assessment and Restoration Plan (PDARP, DWH NRDA Trustees, 2016) embraces the development of carefully designed monitoring programs to support adaptive management and restoration decision making: "Given the unprecedented temporal, spatial, and funding scales associated with this restoration plan, the Trustees recognize the need for a robust monitoring and adaptive management framework to measure the beneficial impacts of restoration and support restoration decision-making. In order to increase the likelihood of successful restoration, the Trustees will conduct monitoring and evaluation needed to inform decision-making for current projects and refine the selection, design, and implementation of future restoration. This monitoring and adaptive management framework may be more robust for elements of the restoration plan with higher degrees of uncertainty or where large amounts of restoration are planned within a given geographic area and/or for the benefit of a particular resource" (DWH NRDA Trustees, 2016, Appendix 5E). The DWH NRDA Trustees (2016) state that monitoring guidelines will be developed in support of restoration, including "the establishment of a suite of core parameters and monitoring methods (i.e., minimum monitoring standards) to be used consistently across projects in order to facilitate the aggregation of project monitoring results and the evaluation of restoration progress for each restoration type."

Project monitoring is required by the Oil Pollution Act of 1990 for restoration activities funded by NRDA to ensure compliance with applicable environmental statues, evaluate project success, and assess the need for correction. According to the Oil Pollution Act (OPA 1990), DWH NRDA monitoring plans must include the following elements: (1) "measurable restoration objectives that are specific to the injury and the desired project outcome"; (2) "performance criteria that are used to determine project success or the need for corrective actions"; and should include (3) information on "duration and frequency, sampling level, reference sites, and costs." To encourage improved monitoring, NRDA Trustees supported Early Restoration projects with monitoring frameworks and conceptual plans developed by project type.[18] Due to the unprecedented temporal, spatial, and funding scales of the restoration that will be undertaken following the DWH oil spill, the NRDA Trustee Council has provided a more robust monitoring and management framework for long term restoration than that common in prior NRDA cases (DWH NRDA Trustees 2016, Appendix 5E). This framework includes monitoring the function of restoration projects and determining the need for corrective actions, setting monitoring and data standards to encourage consistency across projects, and supporting targeted data collection to inform restoration decision-making (DWH NRDA Trustees 2016, Appendix 5E). Restoration frameworks provide information and lessons learned that will be used to develop guidelines for standardized monitoring, including consistent parameters and methods to enable project

[18] [F32] For more information, please see DWH NRDA Trustees (2016). For a list of the 13 NRDA restoration project types, see http://www.gulfspillrestoration.noaa.gov/2016/02/update-on-the-comprehensive-restoration-plan-for-the-gulf-of-mexico/.

aggregation by restoration type, as well as plans for adaptive management and resource-specific strategies (DWH NRDA Trustees, 2016, Appendix 5E).

RESTORE Council Restoration Monitoring Guidelines

Based on the Initial Comprehensive Plan (RESTORE Council, 2013), a range of monitoring can be anticipated for the RESTORE Council's restoration efforts. In addition to supporting science-based decision making and measuring restoration impacts, monitoring will be necessary to meet the RESTORE Council's annual reporting required by Congress and the public. The applications to the RESTORE Council for funding are required to include methods for measuring, monitoring, and evaluating the outcomes and impacts of funded projects, programs, and activities. In December 2015, the RESTORE Council approved funding for a $2.5 million project to conduct an inventory and gap analysis of existing data and monitoring systems; develop and provide recommendations to the Council for common standards and protocols; establish metrics needed to measure influence of water quality and habitat restoration; establish baseline conditions; and provide recommendations to the Council on how to address gaps and future needs. The project is a partnership between NOAA and the USGS, and actively incorporates all five states' Council Members. In addition, the Council is funding another project through the state of Alabama for the Gulf of Mexico Alliance (GOMA) to further develop a Monitoring Community of Practice using expertise from existing GOMA Priority Issue Teams. These two Council-funded projects are closely connected and involve other government agencies, states, academia, non-governmental/non-profit organizations, business, and industry, to develop "basic foundational components for Gulf region-wide monitoring in order to measure beneficial impacts of investments in restoration."[19] While the RESTORE Council is committed to adaptive management (RESTORE Council, 2013), no guidance is currently in place with regard to adaptive management for RESTORE Council-administered projects.

NFWF Restoration Monitoring Guidelines

NFWF requires pre- and post-project monitoring to assess performance and achievement of specific goals proposed by applicants, as well as to inform adaptive management for each project and as a contribution to regional efforts, if possible (J. Porthouse, personal communication). Thus, projects funded by the Gulf Environmental Benefit Fund primarily need monitoring components to include evaluation of project construction/implementation, effect(s) on identified stressors, and ecological outcome(s). Secondary and more long-term purposes are to support adaptive management, provide lessons learned for similar projects, inform programmatic evaluation, and contribute to the understanding of regional baseline conditions (J. Porthouse, personal communication). All projects are expected to include pre- and post-implementation monitoring and adaptive management plans that are consistent with other regional programs such as the NRDA and RESTORE programs. Restoration projects are also expected to plan for data storage, make the data available to the public, and archive data for future use. Adaptive management plans for projects need to either be included in a proposal or are prepared with project development funding from NFWF. In addition, all data collected in

[19] RESTORE-funded Council Monitoring & Assessment Program Development project: https://www.restorethegulf.gov/sites/default/files/FPL_FINAL_Dec9Vote_EC_Library_Links.pdf (p.228).

association with Gulf Environmental Benefit Fund projects is expected to be publicly available as soon as possible after collection and quality assurance/quality control (J. Porthouse, personal communication).

RELATED SCIENCE PROGRAMS

Civil and criminal penalties from the DWH disaster were also paid by responsible parties to fund science programs that can inform restoration practice in the Gulf of Mexico (see purple-highlighted boxes in Figure 2.1). The National Academies of Sciences, Engineering, and Medicine's Gulf Research Program; the National Oceanic and Atmospheric Administration (NOAA) Gulf Coast Ecosystem Restoration Science, Observation, Monitoring, and Technology Program (known as the NOAA RESTORE Act Science Program); the RESTORE Act state-based Centers of Excellence; and the Gulf of Mexico Research Initiative will therefore work to enhance relevant science available to the restoration programs described above, to restoration researchers, and to the Gulf community in general. Another science program operating with DWH-related funds is the Gulf of Mexico Universities Research Collaborative (GOMURC),[20] which coordinates over 80 research institutions to support science and education.

Gulf Research Program

The Gulf Research Program operates over a 30 year timeframe (2013-2043) to support studies, projects, and other activities; and is focused on enhancing oil system safety, human health, and environmental protection in the Gulf of Mexico (as well as other US outer continental shelf areas). The organization seeks to "improve understanding of the region's interconnecting human, environmental, and energy systems and fostering application of these insights to benefit Gulf communities, ecosystems, and the Nation."[25] The Gulf Research Program will address this mission by supporting research and development, education and training, and environmental monitoring. Its strategies are therefore to pursue opportunities to enhance "long-term, cross boundary perspectives; science to advance understanding; science to serve community needs; synthesis and integration; coordination and partnerships; and leadership and capacity building."[25] Initial funding has supported early-career research fellowships, science policy fellowships, and exploratory grants, as well as projects to build capacity in Gulf communities, enhance local resilience and well-being, and synthesize environmental monitoring data. The Gulf Research Program has also held a number of workshops to identify funding opportunities, and produced subsequent reports on community resilience and health, monitoring ecosystem restoration and deep water environments, and middle-skilled workforce needs.[21]

NOAA RESTORE Act Science Program

The NOAA RESTORE Act Science Program does not have a specified timeframe of operation. The Program's mission is "to carry out research, observation, and monitoring to support, to the maximum extent practicable, the long-term sustainability of the ecosystem, fish stocks, fish habitat, and the recreational, commercial, and charter-fishing industry in the Gulf of

[20] GOMURC engages academia in response to and recovery from the DWH spill: http://gomurc.usf.edu/.
[21] Gulf Research Program: http://www.nationalacademies.org/gulf/index.html.

Mexico." NOAA administers the program with the U.S. Fish and Wildlife Service and the RESTORE Council to provide the science in support of "healthy, […] sustainable […] habitats and living resources (including wildlife and fisheries)." Program parameters allow for funding towards the following research activities and species: (1) "marine and estuarine research, ecosystem monitoring, and ocean observation; (2) data collection and stock assessments; (3) pilot programs for fishery independent data and reduction of exploitation of spawning aggregations; (4) cooperative research; and (5) eligible fish species including all marine, estuarine, and aquaculture species in State and Federal waters of the Gulf of Mexico." The Program especially values long-term projects, collaborative efforts, and partnerships within the Gulf region, as well as coordination with related research activities and existing federal and state science and technology programs. The Program operates according to its Science Plan,[22] which details ten long-term research priorities that will guide its support for future science funding opportunities, along with mission alignment, stakeholder input, topics addressed by other funding programs, and new advancements.[23] Recent investments from the first federal funding opportunity ($2.7 million) have been allocated to seven projects to date that will evaluate indicators of ecosystem conditions and services; identify data gaps; develop conceptual ecological and ecosystem models to assess the monitoring and management utility of observation networks; and assess and develop monitoring recommendations in the Gulf.[24]

RESTORE Act Centers of Excellence

The Gulf Coast Restoration Trust Fund also supports the Centers of Excellence Research Grants Program for the five Gulf states with 2.5 percent of the civil penalties deposited into the fund plus 25 percent of interest earned. Funds can be used to establish Center(s) through awards to educational institutions, nongovernmental organizations, and consortia; and by the Centers to advance science, technology, and monitoring efforts. Eligible disciplines include "(1) coastal and deltaic sustainability, restoration, and protection, including solutions and technology that allow citizens to live in a safe and sustainable manner in a coastal delta in the Gulf region; (2) coastal fisheries and wildlife ecosystem research and monitoring in the Gulf Coast region; and (3) offshore energy development, including research and technology, to improve the sustainable and safe development of energy resources in the Gulf of Mexico, sustainable and resilient growth, economic and commercial development in the Gulf Coast region; and/or Comprehensive observation, monitoring, and mapping."[25]

Gulf of Mexico Research Initiative

The Gulf of Mexico Research Initiative (GoMRI) was created as an independent research program with funds directly from BP to better understand the effects of oil pollution and related stressors on ecosystem and public health in the Gulf. Its main themes are physical movement of

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[22] NOAA RESTORE Act Science Program Science Plan: http://restoreactscienceprogram.noaa.gov/wp-content/uploads/2015/05/Science-Plan-FINAL-for-website.pdf.
[23] NOAA RESTORE Act Science Program: http://restoreactscienceprogram.noaa.gov/.
[24] Research funded by the NOAA RESTORE Act Science Program: https://restoreactscienceprogram.noaa.gov/research.
[25] Centers of Excellence Research Grants Program, administered by the U.S. Department of the Treasury: https://www.treasury.gov/services/restore-act/Pages/COE/Centers-of-Excellence.aspx.

oil and dispersants, degradation and ecosystem interaction, environmental effects, and technology to improve response, remediation, and human health effects. The initiative is committed to "investigate the impacts of the oil, dispersed oil, and dispersant on the ecosystems of the Gulf of Mexico and affected coastal States in a broad context of improving fundamental understanding of the dynamics of such events and their environmental stresses and public health implications. The GoMRI will also develop improved spill mitigation, oil and gas detection, characterization and remediation technologies." Regardless of the source of funds, GoMRI research results will be published in peer-reviewed journals with no BP approval requirement.[26]

Conclusions and Recommendations

As discussed in detail above, the structure established to administer funds for projects and programs that are designed to restore and monitor species, habitats, and ecosystems after the DWH disaster (see Figure 2.1) delineates three major Gulf restoration programs.[27] A number of related science programs are also playing important roles in support of informed restoration and monitoring efforts. These organizations intend to work in a coordinated manner to foster collaboration and further efforts to synthesize knowledge and practice that can help improve the condition of the Gulf. Each funding program answers to different mandates and as a result has slightly different, but clearly articulated, broad restoration goals.

However, specific, measurable restoration objectives were not as well delineated or identified. Instead, program goals were frequently linked directly to restoration actions, without an explicit description of what the overall program intends to accomplish. For example, "restoring 100 acres of tidal marsh to increase marsh bird abundance by 10% in 5 years" is a hypothetical, measurable objective. Other illustrative examples of measurable objectives are provided in Part II of this report. Measurable objectives are required for program assessments and for improving restoration effectiveness (Kentula et al., 1992; NRC, 2005; Kapos et al., 2010; NRC, 2016). Thus, the absence of clearly articulated, measurable objectives could hinder effective program management in the Gulf. A notable exception is found within the PDARP (DWH NRDA Trustees, 2016), which included separate, more-specific, often measurable restoration "goals" for each of the thirteen restoration types in addition to the five broad restoration goals noted previously in this chapter. Furthermore, NFWF has awarded funds for the Florida Fish and Wildlife Conservation Commission and the Florida Department of Environmental Protection to develop an "integrated, far-reaching planning effort" for restoration and conservation for Florida's coastal, natural resources.[28] It appears that this "science-based" planning effort will develop the needed goals and objectives against which restoration progress can be assessed. As discussed in Chapters 3 and 7 of this report, specific, measurable restoration objectives are needed, particularly for the RESTORE Council and NFWF, to support performance assessment and support adaptive management. For specific examples of such objectives and metrics, see Part II of this report.

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[26] In 2010, BP committed $500 million over a 10-year period to create GOMRI: http://gulfresearchinitiative.org/.
[27] See the following documents for information on project funding: DWH NRDA Trustees (2016), RESTORE Council (2015), NFWF list of funded projects (http://www.nfwf.org/gulf/Pages/fundingpriorities.aspx).
[28] Florida Gulf Environmental Benefit Fund Restoration Strategy: http://www.nfwf.org/gulf/Documents/fl-restoration%20planning-15oc.pdf, last accessed June 17, 2016.

Moreover, in addition to ecological outcomes, when appropriate, measurable objectives area also needed for socio-economic outcomes. For example, NRDA, RESTORE, and some state programs have high-level goals that suggest intended outcomes for ecosystem services, such as commercial and recreational fishery benefits, improved recreational opportunities at beaches and other habitats, improved water quality for coastal communities and increased community resilience to storms and floods. The degree to which these human benefits will be targeted and monitored can be significantly clarified by the development of specific objectives targeting socio-economic outcomes, in addition to those developed for environmental outcomes.

Therefore, the Committee concludes that Gulf restoration programs need to develop clear and measurable ecological and, where appropriate, socio-economic objectives at project and program levels to guide monitoring plans and against which to evaluate restoration progress. Given the similarities in the strategic goals of the Gulf restoration programs, restoration objectives need to be considered holistically across these three programs to ensure compatibility of efforts and to ensure that restoration and restoration monitoring efforts can yield the greatest synergies.

CHAPTER 3
RESTORATION PROJECT MONITORING

Effective restoration monitoring and evaluation depend on understanding how monitoring results can be used to address management questions for a given restoration project and/or program levels and developing appropriate monitoring designs that address those questions with sufficient statistical rigor, i.e., with acceptable confidence in decisions (Michener, 1997; Lindenmayer and Likens, 2010; Groves and Game 2016).[1] In this chapter, the Committee addresses a major part of the its charge "to identify best practices … for monitoring" and describes "current, effective approaches for developing monitoring goals and methods" as well as "approaches for determining baseline data needs." To address this task, this chapter presents general principles for developing a project-level monitoring design. Chapter 4 discusses needs for monitoring beyond the project-scale, and Chapter 5 introduces guidance for data stewardship and sharing. Chapters 6 and 7 discuss how synthesis and assessment of monitoring data can inform project and program management. Part II of this report discusses good practices for monitoring specific restoration project types.

PURPOSES OF RESTORATION MONITORING

Monitoring and evaluation efforts that are conducted for different restoration management needs often require different approaches (Stem et al., 2004). Restoration project monitoring involves systematic collection of data for three primary purposes: 1) to determine whether a particular project was completed as specified in the restoration plan (*construction monitoring*); (2) to evaluate the performance of a restoration project relative to the project objectives (*performance monitoring*); and 3) to learn from the restoration effort in structured ways to enhance the effectiveness of restoration efforts over the long-term (*monitoring to support adaptive management*; see also Chapter 7). These three project-level monitoring purposes are most readily associated with an individual project site but can also apply at larger scales (e.g., across multiple sites within a larger project or across multiple projects within a watershed or region). The Committee recognizes that data are required to assess the need for restoration; however, it does not consider collection of those data to be part of the purview of this study. In some cases, programs may require additional monitoring to address specific project or program-level information needs. Each of the three primary purposes of monitoring is discussed in general below, as well as in terms of species-specific and habitat-specific restoration in Part II of this report.

Construction monitoring, performance monitoring, and monitoring to support adaptive management are not specific types of monitoring, as much as the purposes behind the development of specific monitoring designs. Similar metrics may or may not apply to all three purposes, but the monitoring designs appropriate for each purpose are likely to vary depending on the questions being addressed.

[1] For a more complete definition of scientific rigor, please see: http://atlasti.com/rigor-social-science-research/.

Construction Monitoring

Restoration typically involves an intentional manipulation of the physical and biological ‘environment’ to achieve an intended ecological result. Construction monitoring provides the data necessary to aid in the determination of whether a project was constructed or implemented as designed and in accordance with applicable regulations and is, therefore, essential for all restoration projects ([Hutto and Belote, (2013) also referred to as “Implementation Monitoring”. Projects that do not involve construction will still require monitoring to assess whether projects were implemented as designed. Many projects entail structural changes to the ecosystem (e.g., building islands, grading to appropriate elevations, planting native vegetation) that set the stage for the interplay of physical, chemical, and biological processes intended for restoration (Powers and Boyer, 2014). Construction monitoring in such cases could include monitoring before (as part of the site-selection process), during, and immediately following construction to ensure that design specifications are met, any structures and machinery are functioning as expected, and activities comply with the Endangered Species Act, Coastal Zone Management Act, and other relevant statutes.[2]

Monitoring the manipulation to ensure that it is implemented and functioning as intended is critical because the initial design and related construction (restoration or creation) phase is often the main component of the environmental manipulation (Thayer et al., 2003) and involves for the majority of the restoration funds to be expended. Careful oversight and related monitoring will go a long way to insuring a positive outcome (e.g., Weinstein et al., 1997, 2014; NRC, 2003; Clewell et al., 2005; Palmer et al., 2005, 2011; Clewell and Aronson, 2013; Weinstein, 2014). Construction monitoring may also provide useful information for elucidating critical uncertainties related to the implementation and interpretation of the results of the related ecological performance monitoring (Downs and Kondolf, 2002).

Monitoring in advance of the restoration project implementation can inform the restoration site-selection (also for BACI designs) and provide critical baseline and historical information. Careful site-selection will enhance the likelihood for restoration objectives to be achieved. For example, salinity is an important factor for oyster restoration and selecting an oyster restoration site(s) in a suitable salinity range can improve restoration outcomes (Pollack et al., 2012; Baggett et al., 2014). In addition, the best understanding of the biology and ecology of a given site(s) and/or species involved in the restoration effort needs to be analyzed in a timely fashion to be able to inform early on project design choices (e.g., Mitsch, 2014).

Construction monitoring also enables critical learning about the manipulation itself, creating a knowledge base for future improvements. For example, as part of the Biscayne Bay Coastal Wetlands Project, the South Florida Water Management District constructed four of 10 planned culverts in the L-31 E Canal to divert water to the east, towards Biscayne Bay to rehydrate coastal wetlands. The goal of these four culverts was to divert 4% of water available for diversion every year. Post-construction monitoring revealed that this design criterion was not always met for several reasons. Remedial actions were taken to retrofit the culverts that included re-establishing downstream sump depths to design criteria and installing debris barriers to prevent clogging on the upstream side. In a second phase of this project, plans called for the installation of a pump to move water into the L-31 E canal from an adjacent but unconnected

[2] All restoration projects will require an environmental compliance review—seesee also http://www.gulfspillrestoration.noaa.gov/environmental-compliance/

canal. Monitoring of the remedial actions indicated that pumping maintained water at an optimal stage for delivery through the culverts to the east (Charkhian et al., 2015). Thus, ultimately the restoration project pump design was verified and culverts adjusted based on the post-construction monitoring. Further examples of good practices for construction monitoring of several restoration types are discussed in Part II of this report. Information gathered from construction monitoring can be an element of performance monitoring and is required for monitoring for adaptive management.

Given the large investment in restoration and the invaluable benefits to improving outcomes of restoration, the Committee concludes that construction monitoring should be required for every project.

Performance Monitoring

Performance monitoring provides the information necessary to assess whether a project (or set of projects) as built or implemented has achieved its stated objectives in terms of desired biological and the larger ecosystem structure, composition, and/or ecosystem services provided (see also Hutto and Belote, 2013). Performance monitoring and evaluation inform the public and funding agencies of benefits realized from the restoration investments and provide accountability. As such, performance monitoring is also essential for all restoration projects. As discussed in Chapter 2, clear restoration objectives are needed to determine performance and to identify an appropriate monitoring program. The preferred approach to assessing restoration performance involves monitoring of pre-project baseline conditions at a restoration site and appropriate reference and/or control sites (see Box 3.1), so that restoration-related responses can be distinguished from other environmental factors (see Figure 3.1). Development of effective performance monitoring requires consideration at both temporal and spatial scales because the ecological interactions that are needed for habitat development and restoration of associated ecosystem services may take a very long time to develop (decades in some instances), and depend on environmental drivers operating at scales well beyond the project boundaries and duration. For a description of drivers of coastal change used by the Louisiana System-wide Assessment and Monitoring Program,[3] see Hijuelos et al. (2013).

[3] The System-Wide Assessment and Monitoring Program (SWAMP) ensures a comprehensive network of coastal data collection activities to support coastal protection and restoration across Louisiana: http://cims.coastal.louisiana.gov/RecordDetail.aspx?Root=0&sid=11471.

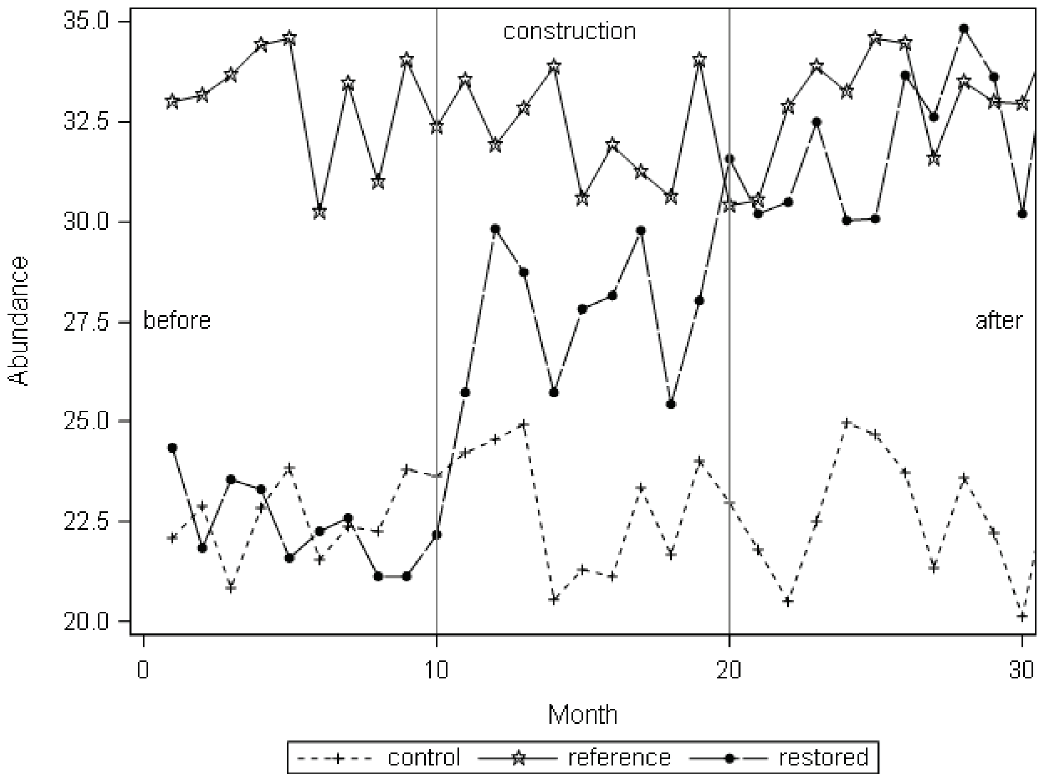

Figure 3.1 Hypothetical example of performance monitoring data using baseline and post-construction monitoring at a degraded control site (similar to the restored site, but without restoration), a restored site, and a reference site (with conditions that serve as the restoration target) to distinguish restoration response from natural variability (see also Box 3.1). Note that this graph shows an aspirational (hypothetical) outcome of restoration, not actual data. SOURCE: Committee.

Box 3.1

Matched Reference and Control Sites

Baseline information: Information collected before or at the start of a given project that provides a basis for planning and/or evaluating subsequent progress and related impacts.

Matched reference sites are sites or areas that are physically and biologically similar to the area being restored (according to pre-determined characteristics) but that do not require restoration (Kennedy and Sanford, 1999; Beck et al., 2011; zu Ermgassen et al., 2012a; Baggett et al., 2014). These sites provide a benchmark of how much progress is needed to achieve adequate restoration progress and help control for effects of broad scale natural disturbances when assessing restoration progress. The differences between the restoration project site(s) and the matched reference site(s) are expected to be relatively large before restoration and increasingly small after restoration (see Figure 3.1). Reference sites can also provide information on the effect of naturally occurring disturbances and expectation with respect to natural variability. In the Gulf of Mexico, as in other areas experiencing natural oil seepage and sustained oil drilling, even reference sites may be contaminated with oil and petroleum breakdown products given the Gulf's 914 distinct seep zones (MacDonald et al., 2015) and large number of oil spills occurring each year (NOAA responded to 44 large actual and potential spills in 2014 in the Gulf of Mexico[4]).

Control sites, in contrast, are degraded to a similar degree as the planned and matched restoration project sites, but have no planned restoration activities. Control sites with similar physical characteristics and species can provide useful comparison data for interpreting a restoration response. It would be impractical and unnecessary to require selection of a control site with characteristics or population abundances identical to restoration sites. The purpose of control locations is to represent the range of habitats that resemble a restoration site (Underwood, 1994). The difference between a well-matched control and restored site, as it proceeds into the future after restoration, is then the isolated effect of restoration (see Figure 3.1). The difference between conditions at control and restored metrics are expected to be small initially, then increase with restoration progress.

With appropriate and timely data management and synthesis described in subsequent chapters, analysis of the performance monitoring data at the project and program level can inform project managers about the progress toward the restoration objectives. Baseline and existing and new historical information are critical for the purpose of performance monitoring.

For example, performance monitoring of a coastal marsh restoration with the objective of providing enhanced wildlife habitat would likely include measuring metrics such as marsh elevation, soil organic matter content, native and invasive plant distribution, and targeted wildlife abundance, density, and biodiversity (see Table II.3 in Part II for details). These monitoring data would be collected both before and for several years after restoration and compared to similar sampling at carefully selected control and/or reference sites (discussed in more detail later in this chapter). Performance monitoring of a restoration effort to enhance resident marsh bird populations would likely build on many of those marsh habitat metrics and also include nest success, fecundity, and survivorship (see Table II.4 in Part II for details).

The synthesis or simple aggregation of performance monitoring data across restoration projects and across a region can also inform restoration program managers about the overall progress toward programmatic goals (see also Chapter 5). For example, with consistent monitoring of oyster restoration projects and proper data stewardship, a program review could aggregate the areal extent of oyster reef restored across the Gulf of Mexico coastline and compare it to programmatic objectives, such as the RESTORE Trustee Council's goal "to restore and conserve habitat."

Without the performance monitoring, it would not be possible to conclude whether the investment in restoration resulted in the desired outcomes and whether the intended objectives were achieved. **Therefore, the Committee concludes that performance monitoring, as in construction monitoring, should be a requirement for each restoration project.**

[4] Waters off the Gulf of Mexico experience the most oil spill responses by NOAA of any US region: http://response.restoration.noaa.gov/about/media/information-about-oil-spills-your-fingertips.html.

Monitoring to Support Adaptive Management

The third restoration monitoring purpose—monitoring for adaptive management—provides the greatest potential to improve the performance of a given restoration project or programs and to increase the effectiveness and longevity of that restoration project. The principles of adaptive management (see also Box 1.3), its potential benefits to Gulf restoration, and steps necessary to implement adaptive management effectively in the Gulf are discussed in detail in Chapter 7.

Monitoring in support of adaptive management is deliberately designed to address well-defined restoration management questions and uncertainties (see Glossary for definition of uncertainty). The results of this monitoring (and subsequent evaluation efforts) are intended to inform and enhance restoration decision-making by identifying weaknesses in the planning, implementation, and/or monitoring phases of restoration that can be improved upon in the future (Nilsson et al., 2016). The findings from monitoring for adaptive management could potentially trigger adjustments to a restoration project to improve the likelihood of achieving its objectives, and they could inform the design of other similar projects (Thom, 2000; Simenstad et al., 2006; LoSchiavo et al., 2013; RECOVER, 2015). The Committee distinguishes this monitoring effort from performance monitoring by the fact that it aims to not only assess performance but also inform critical uncertainties of a restoration project that might hinder it from achieving its objectives. For example, this monitoring effort might be applied to resolve why a certain objective was not achieved or how restoration effectiveness could be enhanced. In contrast, performance monitoring aims to understand only ‘what’ the restoration outcomes are and whether stated restoration objectives were reached.

Restoration uncertainties addressed through monitoring in support of adaptive management are uncertainties of knowledge—in contrast to statistical uncertainties about whether a response can be detected amidst natural variability—and can stem from several sources. For example, there may be uncertainty related to which of several restoration designs produces the largest ecosystem benefits or the extent to which restoration site selection influences performance. (See Chapter 7, Box 7.2 for an example of an adaptive management program to identify the optimal oyster cultch quantity for reef restoration efforts in the Gulf.)

Monitoring in support of adaptive management also improves the understanding of the causes of restoration outcomes and project performance thereby improving ongoing as well as future restoration planning and decision making. How such monitoring improves restoration effectiveness through the adaptive management process is discussed in Chapter 7. For example, in a tidal marsh restoration, test plots could be designed and monitored to assess the impact of soil surface elevation in the restored marsh on native and invasive plant distribution; wildlife abundance, density, and diversity; and ecosystem resilience in the face of storm events. This information could be used to enhance the design of future marsh wetland restoration projects in the Gulf or change the emphasis of restoration at the programmatic level. Monitoring may also support the development of predictive models to aid management actions. For example, models may be used to predict the effect of different management actions on shorebird nesting success. A monitoring program may be designed to reduce uncertainty associated with model predictions. See Part II for additional examples of monitoring to support adaptive management.

PROJECT-LEVEL MONITORING PLAN

This section provides an overview of key inputs and design decisions to be made in the development of a project-level monitoring plan (Figure 3.2). A variety of literature is also available on the design and analysis of restoration monitoring activities (Michner, 1997; Block et al., 2001; Thom and Wellman, 2003; Roni et al., 2005) and habitat- and species-specific considerations in the development of a monitoring plan are provided in Part II.

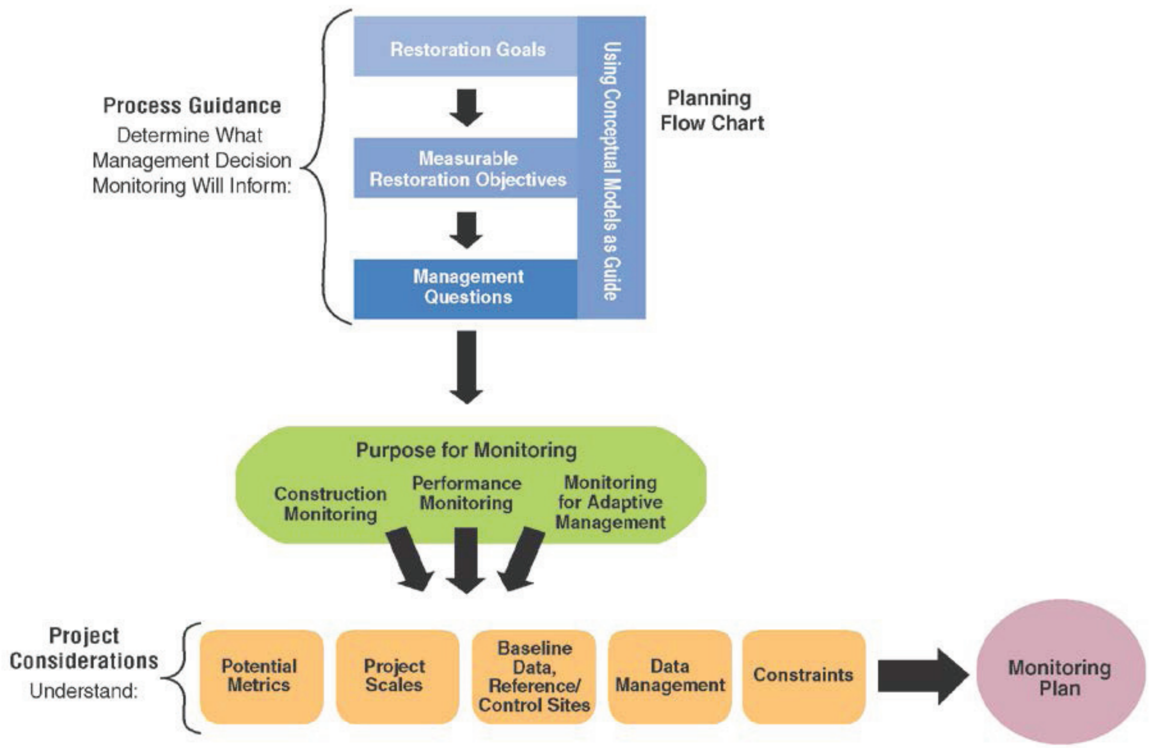

Figure 3.2 Planning process for developing a monitoring plan. The initial steps determine the managers' information needs and what management decisions to be informed. These management questions then determine whether construction and performance monitoring is sufficient or whether the project would benefit from adaptive management (thus requiring monitoring for adaptive management). Based on the purpose of the monitoring effort and a range of considerations about potential metrics, project scale, available baseline information, and various constraints, the monitoring plan can be developed and decisions about statistical design and required metrics, for example, can be made. SOURCE: Committee.

Overarching Considerations for the Development of a Project-level Monitoring Plan

In the development of a monitoring plan, there are overarching inputs that may apply to all Gulf restoration efforts of a particular type (see Figure 3.2). These include a conceptual model for a given habitat type or species being restored, associated restoration objectives, and management questions to be addressed by the monitoring program. In the Gulf restoration, these

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are likely to be developed at the program level, prior to the design and implementation of the monitoring plan. However, if these elements have not already been developed, they will need to be established to support the design of an appropriate and effective monitoring program.

Conceptual Models

A conceptual model provides a visual and/or narrative framework that connects key environmental and social factors to ecosystem structure and processes (Thom 2000). Conceptual models can be used for a range of problem-solving situations and take a variety of forms (Argent et al., 2016). On this range of application for conceptual models the Committee refers to two types of models that serve somewhat distinct needs in restoration planning and management:

1. Systems models, which are used in initial stages of restoration planning to understand better the current socio-ecological context for restoration, and
2. Causal models, which are related and used in later stages of planning and implementation to document how a planned restoration actions are expected to change specific targeted socio-ecological elements of the system.

Conceptual systems models. Conceptual systems models show known or assumed causal linkages that occur at a broad scale between different biophysical, ecological, social, and economic elements of a given system. These models needs to represent the best understanding of the systems biological, chemical, physical, social, cultural, and economic elements and processes. This broad conceptual systems model helps ensure that restoration planners have the most complete view possible of the system, including where restoration project manipulations might impact or be impacted by ecosystem processes. The model may be a simple verbal description, a simple box and arrow conceptual diagram, or a visual representation of a detailed numerical model (Williams et al., 2009; Tallis et al., 2010).

Conceptual models can be produced through various means, including situation analysis (Foundations of Success, 2009); application of the driver, pressure, state, impact, and response (DPSIR) framework (Mateus and Campuzano, 2008; Tapio and Willamo, 2008; Tscherning et al., 2012), or use of the press-pulse dynamics framework (Collins et al., 2010). Figure 3.3 shows a generic representation of the DPSIR framework, which depicts hypothesized linkages between drivers of environmental change, specific stressors that are foci of societal concern, ecological and societal responses to those drivers and stressors, and endpoints that can be measured to provide information on ecosystem state and responses to restoration and management activities (; Gentile et al., 2001; Harwell et al., 2015). The framework shown in Figure 3.3 is being adopted and further developed as part of the Gulf of Mexico Report Card initiative.[5] Conceptual models have been widely applied to wetland restoration efforts in the Gulf region and elsewhere (e.g., Barnes, 2005; Ogden et al., 2005; Kelble et al., 2013). System-specific and regional models served an important role in identifying indicators in the Comprehensive Everglades Restoration Plan (LoSchiavo et al., 2013). Similarly, conceptual ecological models were integral to

[5] Gulf of Mexico Report Card initiative:http://harteresearchinstitute.org/newsletter/docs/gulfofmexico_reportcard_brochure.pdf.

development of an integrated modeling and monitoring system for Louisiana's Coastwide Reference Monitoring System for Wetlands[6] (Twilley, 2003; Steyer et al., 2006).

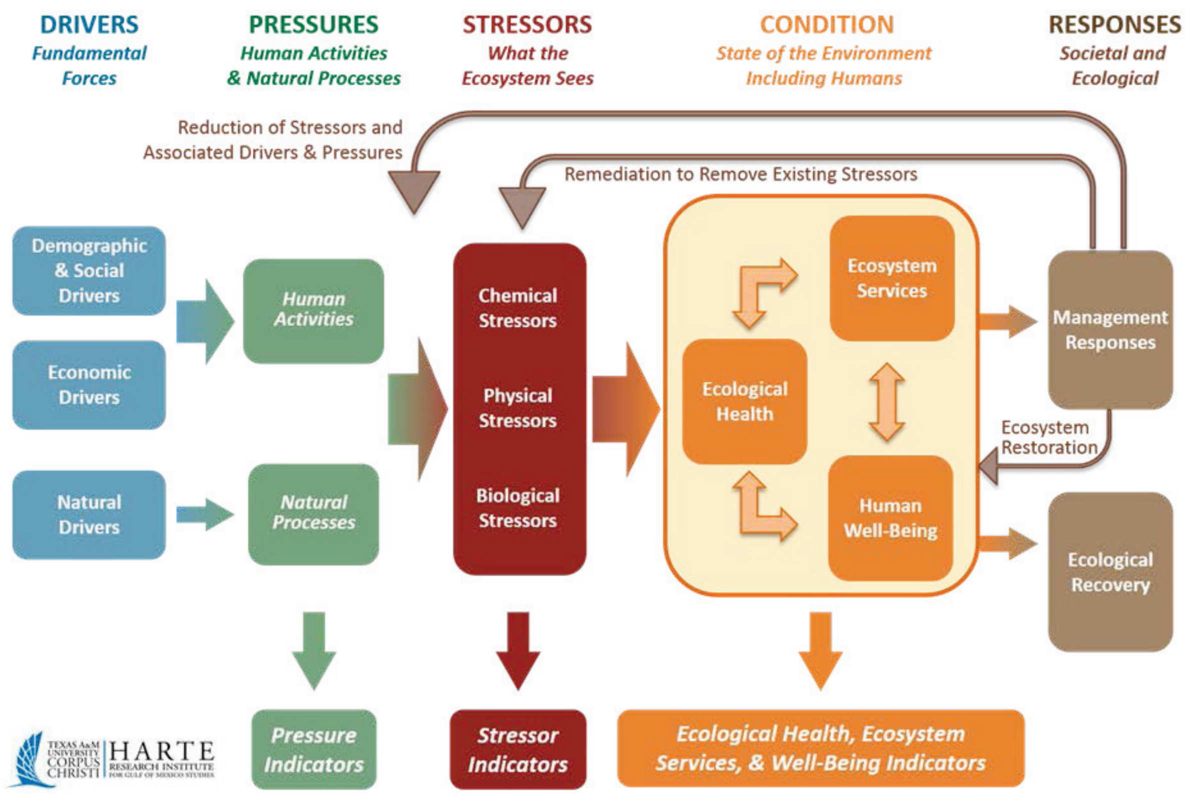

Figure 3.3 A generic framework of drivers, pressures, stressors, condition, and responses that is being developed as a basis of the Gulf of Mexico Report Card initiative. SOURCE: Harwell et al., 2015.

Conceptual models (both systems and causal models) can be used to identify and highlight key uncertainties that inform monitoring design choices and adaptive management planning, and linkages with weak evidence can be probed through experimental implementation (Schreiber et al., 2004; Ogden et al., 2005; see also Chapter 7). Conceptual models can also identify indicators used to assess the outcome of restoration activities and the metrics that best quantify the response of the indicator to management intervention and/or stressors (Bormann et al., 1999; Rumpff et al., 2011). They also serve to communicate the science underpinnings of restoration to a broader audience.

Conceptual models both inform and are informed by the development and application of process-based, quantitative ecological models (Swannack et al., 2012). Some conceptual models simply show linkages without indicating the sign or strength of the relationships, whereas more

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[6] Louisiana Coastwide Reference Monitoring System (CRMS): http://lacoast.gov/crms2/Home.aspx.

complex models may include the hypothesized direction and shape and/or strength of the relationship between stressor and response variable (e.g., linear, non-linear, threshold-like) (Suding and Hobbs, 2009). Both conceptual and numerical models can be revised over time as new information becomes available.

Conceptual systems models developed for ecological restoration commonly focus on the biophysical and ecological elements of a system without including connections to specific social and economic systems beyond immediate drivers of change (sometimes called “threats”) (e.g., Davis et al., 2005; Montagna et al., 2013; Fischenich and Barnes, 2014; White et al., 2014; Wingard and Lorenz, 2014; Tempest et al., 2015; Vasslides and Jensen, 2016). Because several restoration programs in the Gulf have explicit restoration objectives that include socio-economic outcomes, for those restoration projects that include socio-economic objectives broader socio-economic conceptual models that capture these additional elements and processes within the system need to be built (e.g. Grant and Griffin, 1979; Olander et al., 2015; Tomlinson et al., 2015; Nair et al., 2016).

Causal models. Once the broad system being targeted for restoration is captured in a systems model, the causal model focuses on a subset of the overall system to show how a specific restoration action is expected to improve the system. Generally, such conceptual models start with a description of an undesirable state and detail the causal pathway by which a specific restoration action is expected to lead to a desired restoration objective. This type of conceptual model may be called a causal model, results chain, theory of change, or logic model (for example, see Foundations of Success, 2009; Thorne et al., 2015). Such causal models are often developed as part of alternative management strategy evaluations, where different possible management actions are considered and compared. Simply put, these models show how a system is expected to change in response to a given restoration action or set of actions. Figure 3.4 provides a simplified example of a causal model for a hypothetical oyster reef restoration project, showing the expected effects on environmental conditions, oyster populations, and associated ecological and economic outcomes. As with systems’ conceptual models, the strength of evidence can be summarized and included in the model, as is shown in Figure 3.4.

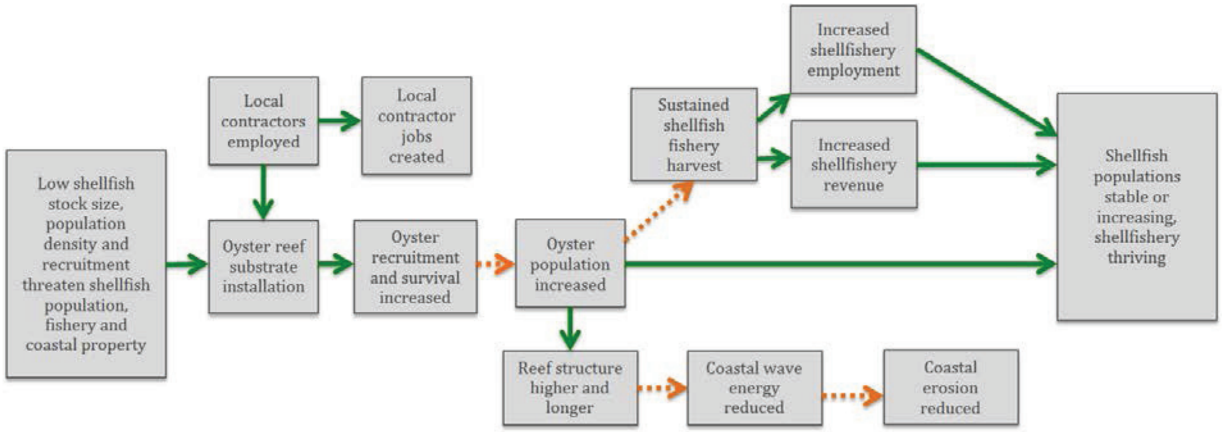

Figure 3.4 Hypothetical causal model for a proposed oyster reef restoration project. Colored arrows represent the strength of evidence for each causal assumption along the pathway from undesired state to desired state. Green arrows reflect strong evidence and orange/dashed arrows reflect average or moderate evidence. The model reflects direct socio-economic outcomes from the restoration (local contractor jobs created), direct environmental outcomes (oyster recruitment and survival increase), and indirect socio-economic outcomes (increased shellfishery employment). Metrics for any link between the restoration intervention and a socio-economic outcome are benefit-relevant indicators, suggested as best practice metrics when there are socio-economic restoration goals. SOURCE: Committee.

Both positive and negative potential ‘non-target’ outcomes are typically included in the causal model to reflect plausible risks and co-benefits. Even when a restoration project does not have social or economic objectives, consideration of unintended social and economic outcomes ought to be included. Expanding the causal model to capture non-restoration drivers that are likely to affect the desired outcome(s) is a common way to identify risks. Consideration of these drivers is especially important in larger scale restoration projects where the restoration action is likely to be only one of many forces acting on the focal system at a time (Loschaivo et al., 2013; Rose et al., 2015). The system conceptual model can be very helpful in identifying these other drivers. In the oyster reef example, high shellfish harvest rates could counteract the potential benefits of adding more oyster substrate. These additional factors can also be reflected directly in the causal model (e.g. drawn in as additional boxes in Figure 3.4).

Restoration Objectives

As discussed in Chapter 2, restoration programs are often driven by management goals that are broad and non-specific. At a project or subregional (i.e., watershed) level, these broad goals need to be translated into specific, measurable objectives so that project performance can be quantitatively assessed relative to its objectives (Palmer et al., 2007; Kennedy et al., 2011). For example, an oyster restoration project objective may be to increase adult oyster populations twofold to improve oyster harvests through enhancement, or to stabilize shorelines (see Part II:

Oyster Reef Restoration Objectives). In situations where there are multiple objectives, for example to restore a number of bird species, objectives may be dynamic because species co-occurrence can change as a restored habitat undergoes succession (Tulloch et al., 2016).

Objectives may be expressed as basic physical or structural design conditions for a site, such as a specific elevation profile and the desired grain size distribution for an island restoration, and/or functional characteristics, such as population size. Quantitative objectives (also termed restoration targets; see Glossary) are often determined, where feasible, using historical data (prior to particular disturbances) or data from reference sites (undisturbed habitats that are similar to restoration objective conditions). The rationale for using reference sites to define a restoration target is that a location being restored will be affected by both the restoration action(s) and natural environmental conditions that change during and after restoration effort occurs (see Figure 3.1 and Box 3.1). Therefore, reference sites can help determine how much of the changes detected via monitoring in one or more restored area(s) are due to restoration action(s) rather than natural changes or effects from other (non-restoration) actions. Setting biodiversity-based targets is often a challenge due to ecological data gaps, as well as to social, economic, political, legal, and ethical considerations. These elements elevate target setting for populations (i.e., articulating how much restoration is enough) beyond a purely scientific exercise by expressing acceptable risk (Wilhere, 2008); guidance exists for setting restoration targets and alternative methods of conservation and restoration (e.g., Tear et al., 2005; Sanderson, 2006; Carwardine et al., 2009).

A helpful concept borrowed from systematic conservation planning is complementarity, or using multiple management areas to protect the target values of a set of biodiversity features together as a network (Margules and Pressey, 2000; Ardron et al., 2010). Applied to restoration practice, this idea suggests that targets to can be achieved across a network of project sites in a coordinated and complementary fashion, rather than attempting to meet all project objectives within one restoration site, by one entity, or by independently implementing multiple ad hoc sites (Manning et al., 2006; Ikin et al., 2016). Because areas with individually high species richness may not maximize diversity on a landscape scale, setting targets for complementary attributes such as age, size, shape, species structure, and landscape context over a set of sites may achieve restoration objectives in a more cost-effective manner and with less of an overall footprint than site-specific target setting. For example, Ikin et al. (2006) realized higher landscape-scale bird diversity by planting complementary sets of species assemblages than planting to maximize local biodiversity at each restoration site.

Causal models (e.g., Figure 3.4) can also help guide the selection of quantitative restoration objectives. Evidence synthesis (see Chapter 6) can indicate not only how much support there is for a given link, but how large a change can be expected through a given pathway. For example, a project may have a restoration objective to triple local harvestable oyster abundance over five years, but review of available science shows that the largest increase the proposed action has caused in other cases is a doubling of abundance, and a 30%population increase over the same time period is the median result. This information can inform restoration design, indicating that additional actions are needed if the 300% increase is to be achieved, or that a much lower restoration objective ought to be set. Modeling can also be used to establish quantitative restoration targets and help include considerations for how the social and political context may influence the choice of targets (Eden and Tunstall, 2006; Baker and Eckerberg, 2013).

Questions to Be Resolved

Ultimately, monitoring provides information that informs future restoration decisions, and therefore, key questions to be addressed are important overarching inputs to monitoring designs. Restoration program managers' questions could include:

- Was the project constructed adequately and as designed?
- Did the restoration project meet its stated objectives?
- What realized ecological benefits and/or costs were derived from the project (see Table 6.1)?
- What are the potential impacts, including benefits and costs, to society (e.g., jobs, ecosystem services)?
- What design elements could or should be adjusted in the future (or in other projects) to improve performance and efficiency in terms of overall cost?
- How will project monitoring data and information be managed and communicated?

Monitoring can also help improve a conceptual model and resolve the relative importance of various stressors (e.g., salinity, water quality, hydrologic conditions) on ecological response at a restoration site. In a monitoring design, restoration managers' questions need to be developed into testable questions, or statements that may be evaluated based on appropriate monitoring data. Questions that are clear, testable, limited in scope, and consistent with available information are more likely to lead to sound monitoring, analysis, learning, and restoration decisions (Thom and Wellman, 1996; Keeney and Gregory, 2005; Kennedy et al., 2011; Moore and Runge, 2012).

Project-Related Inputs to Monitoring Design

When moving from the broad conceptual model and restoration objectives to a project-level monitoring design, specific project-related factors need to be explicitly defined. These include potential metrics, temporal and spatial scales, the availability and appropriateness of baseline or reference site data, and other constraints.

Potential Metrics

Metrics are measureable parameters that can be used to evaluate testable hypotheses and address restoration managers' questions (as discussed in the previous section). Metrics might involve a single directly measurable quantity, such as animal or plant abundance, or a derived quantity based on multiple measures, such as a specific indicator of biodiversity. Metrics can also act as surrogates by representing other parameters that are either too numerous, challenging, or expensive to measure; for example, monitoring just a few species of birds can provide an indication of a plethora of co-occurring species (e.g., Tulloch et al., 2016). Metrics may also measure specific ecological processes, services, or functions (Short et al., 2000; Wortley et al., 2013; Palmer et al., 2014).

The suite of potential metrics for a given project and other parameters with the ability to affect those metrics can be identified from conceptual models or from existing guidance documents (e.g., Conway, 2011; Roman and Burdick, 2012; Baggett et al., 2014; Neckles et al., 2015; ; see also Part II). For example, a conceptual model for restoration of sea turtle populations may suggest reducing beach predation as a means of achieving the objective of increasing the survival of hatching sea turtles (see Figure II.5 in Part II). The numbers of nesting females, hatchlings produced, and predators controlled (or predator-exclusion corrals constructed) could be measured across a suite of beaches during relevant time periods compared to reference or control sites (see Box 3.1). Other related metrics potentially affecting survival might also be important to consider, especially for causative modeling, and may require different sampling regimes depending on the type of predator (terrestrial versus aquatic) or other stressors of interest. For example, artificial lighting that could cause hatchling disorientation may also need to be measured, which requires sampling at different temporal and spatial scales than sampling for predation intensity. See Part II for further discussion of metrics for different habitats and species restoration efforts.

Temporal and Spatial Scales Necessary to Address Questions

Restoration monitoring can occur at multiple spatial scales including at the individual project-level; over multiple projects within a hydrologic basin; or at the landscape- or regional-level to evaluate cumulative restoration effects (see also discussion on scaling in Chapter 6). Spatial scale is especially important for restoration projects that have widely ranging species, such as projects with the objective of improving the health and abundance of coastal bird populations or marine mammals (see Chapter 6). The design of a project-level monitoring plan needs to consider the spatial scale that it aims to inform and whether aggregation across multiple projects or even across subregions is intended. The appropriate scale need to be evident in the management questions to be addressed, and monitoring needs to occur at the spatial scale(s) at which relevant metric(s) operate.

The spatial extent of a monitoring plan may influence selection of specific metrics and associated model to assess restoration progress (Palmer et al., 2005). A regional monitoring program might use a landscape-level metric, such as connectivity, that would not be informative at the local scale. Spatial extent may also limit the ability to make inferences about the influence of naturally varying environmental factors. For example, abundance of a desired plant species might naturally vary widely over the entire Gulf of Mexico due to estuary scale factors such as salinity and nutrients but may not naturally change much over smaller areas if these factors are relatively constant. Hence monitoring these factors may not be necessary at a local scale but may be important at a regional scale.

Temporal scales of restoration responses and the time scales of other stressors are important considerations when developing a monitoring plan and prioritizing restoration objectives. When monitoring to determine the performance of a restoration project, a considerable amount of time may be required before progress toward some objectives can be observed (e.g., carbon storage, marine mammal population change, density of oysters), and their assessment will require a variety of measurements over appropriate spatial and temporal scales. Restoration objectives would ideally include measuring ecosystem attributes that respond within short to moderate time-scales to provide near-term indications of restoration performance and to reduce long-term monitoring costs. In this case, too, monitoring needs to occur at the temporal scale at which relevant metric(s) operate.

Availability of Baseline Data and Reference and/or Control Sites

The availability of historical information that is collected prior to restoration and possibly prior to a disturbance prompting restoration can provide valuable information for evaluations of restoration performance (e.g., Coen et al., 2004; Burrows et al., 2005). For example, the condition measured at the site in need of restoration, but prior to initiating the restoration project, provides a measure of the baseline conditions against which to assess restoration progress (see Figure 3.1 and definitions in Box 3.1). In addition, historical information at or near a given restoration project site may provide quantitative targets for restoration in the absence of available reference sites. Therefore, it is important to determine the availability of baseline monitoring data at a restoration site and assess the value of the data for evaluating restoration performance. If existing baseline data are lacking, additional pre-project data collection will likely be needed.

Baseline data collected prior to restoration may be insufficient for a rigorous evaluation of restoration performance, because natural variability and unanticipated environmental effects may confound measures of restoration response. Comparative methods using reference and control sites can help address this concern especially when matched to the restoration project site (Nichols and Williams, 2006; Stoddard et al., 2006; Hiers et al., 2012). Different strata within a restoration site may also provide information to guide and evaluate restoration actions (Nichols and Williams, 2006). It is important to note, however, that no two locations are truly identical, and there is no guarantee that progress in restoration will result in a restored site matching a reference site, especially over long time periods (Palmer et al., 2013; Mebane et al., 2015;). The availability of appropriate reference sites may be limited, and sites along a gradient of impacted conditions may be appropriate.

In some locations, control sites (sites that are similarly degraded but are not being restored; see Box 3.1) offer the only source of data on comparative environmental responses. As example, with subtidal oyster reef restoration in the Chesapeake Bay (or elsewhere), all similar habitats to the restoration site are significantly degraded and no suitable reference sites exist (Coen and Luckenbach, 2000).

The state of Louisiana and the U.S. Geological Survey began developing the Coastwide Reference Monitoring System in 2003 to encourage consistent monitoring parameters and facilitate the comparisons between restored and reference or control sites. The program developed 390 reference sites along a range of ecological conditions in Louisiana coastal wetlands, providing hydrologic, vegetation, and soil data for each site (USGS, 2010; Hijuelo et al., 2013). This system-wide view was developed to help track changes over time and attribute change to natural variability vs. restoration given the large scale of restoration planned for the coast of Louisiana. Chapter 4 further discusses the benefits of such a system-wide view to enable an assessment of restoration progress at a larger scale.

Components and Design Decisions of a Project-level Monitoring Plan

The inputs discussed above inform decisions and choices associated with sampling and monitoring designs. These decisions include identifying targets, criteria, and hypotheses that may be quantitatively evaluated to address management questions, metric selection, identifying specific sampling design elements such as sample size and the timing and extent of sampling, identifying sampling and analysis protocols, and determining strategies for data analysis evaluated with a formal test or pre-determined decision rule. Quantitative analysis focuses on supporting management decisions through hypothesis testing and predictive modeling. From a statistical perspective, two approaches have emerged that are useful in restoration monitoring. The first approach is based on specifying a target through a statistical hypothesis that is then evaluated with a formal test. The second relies on using a model or multiple models for evaluating data and hypotheses and using information theory and predictive analysis for addressing decisions and uncertainty (Anderson et al., 2000, Stephens et al., 2007).

Identifying Quantitative Questions

Management questions need to be translated into specific, testable hypotheses or measurable questions that can be addressed in a quantitative manner through a data collection process. In the case of oyster reef restoration, managers may want to know whether the project objective for increased abundance was obtained. To evaluate this objective quantitatively would require the selection of a target related to abundance, the time period for evaluation, and when the decision criteria is reached or exceeded. One hypothesis might be that the difference in abundance relative to a pristine reference site is greater in the period before restoration than in the period after restoration. A more specific hypothesis ties restoration outcome to a criterion associated with a numerical quantity in a specified time period (e.g., that the average abundance of oysters exceeds 100 oysters per m^2 by the end of 5 years). In monitoring project performance, careful science-based evaluation requires defining restoration progress and choosing metrics and targets well-connected to that definition. In adaptive management, questions may focus on hypothesis evaluation or involve testing of predictive models. For example, causal models are used to embed hypotheses about the system behaviors and enables managers to predict and test for the impacts of their activities. Monitoring then focuses on testing these hypotheses or the predictive models, which provides the basis for learning and adaptive management. For example, human disturbance is known to be a factor affecting shorebird survival and abundance. If human activity can be controlled at various restoration sites, modeling might be useful to address when and by how much activity ought to be reduced to improve shorebird survival (Williams et al., 2009).

Selecting Metrics

Selecting the appropriate metrics to monitor is critical to rigorous assessment of restoration projects and management actions. Several factors influence the choice of the best metrics for a given restoration effort. Foremost, metrics need to provide data necessary to resolve the identified hypotheses, questions, and objectives (Coen et al., 2004; Kennedy et al., 2011; Baggett et al., 2014). For example, for performance monitoring, metrics need to facilitate an evaluation of progress toward the project objectives. A wetland restoration project with the primary objective of restoring native plant habitat may be assessed by distinctly different metrics than a project with an objective of land-building to counter sea-level rise (see Part II of this report for examples of objective-metric linkages). Restoration is often expected to develop along a path, termed a restoration trajectory (Zedler and Callaway, 1999), and different components may progress toward the intended target along different trajectories and require different timeframes, necessitating monitoring of several different structural and functional metrics (Burdick et al., 1997; Craft et al., 2003; Thayer et al., 2005). For example, some marsh fish species have been shown to return almost immediately after restoration (Simenstad and Thom, 1996; Dionne et al., 1999) and others repopulate within a year (Dibble and Meyerson, 2012). Vegetation typically requires several years to regrow, with fast-growing seagrasses coming back relatively quickly, followed by higher-altitude marsh grasses, and eventually mangrove forests (Short et al., 2000). Longer still, development of marsh nutrient and carbon pools and cycling processes can take over 20 years to reestablish (Craft et al., 2003). Restoration performance indices are sometimes used to integrate a number of structural and functional metrics into one assessment score that is comparable across projects (Chmura et al., 2012). Additional detail and examples of such metrics for different restoration contexts are described in Part II of this report.

Project-specific conceptual or causal models (see Figures 3.3 and 3.4) can help identify the most appropriate metrics (Bormann et al., 1999; Ogden et al., 2005; Rumpff et al., 2011). Any metrics that correspond to an element or assumption along the causal pathway will be useful in understanding whether a restoration project is producing the expected impact(s). The more specific the causal model, the easier metric selection becomes. For example, the oyster case shown in Figure 3.4 has identified specific elements of the oyster population known to be important for long-term population viability—oyster recruitment and post-settlement survival rates. Extensive monitoring on natural and restored subtidal (e.g., Puckett and Eggleston, 2012; Soniat et al., 2012) and intertidal (e.g., Bartol and Mann, 1997; Harding et al., 2012) reefs has shown that oyster recruitment rates can be quite variable both spatially and temporally (Roegner and Mann, 1995; Coen and Humphries, 2016; Hanley et al., 2016). These elements suggest specific metrics to track such as rates of recruitment, post-settlement survival, and density. The specificity of the model rules out other metrics such as oyster reef area or oyster percent cover when assessing long-term population viability. Additional measures would be needed to track benefits for erosion reduction, the most direct measure being adjacent shoreline erosion rates. Olander et al. (2015) provide detailed guidance on how to use causal models to derive benefit relevant indicators that capture the connection between ecological elements or processes and people that use or enjoy those elements.

Although it is difficult to identify the ideal set of metrics, criteria for good metrics include responsiveness to restoration, measurement variability (signal-to-noise ratio), ability to directly measure desired endpoints that are in a conceptual model, cost effectiveness, and ease of measurement (Neckles et al., 2013; Schlacher et al., 2014). The choice of metric also requires information about constraints and existing baseline data, and there are a variety of documents suggesting selection procedures. Schlacher et al. (2014) used a ratings-based approach to select metrics based on specific criteria. Neckles et al. (2013) describe a structured decision-making approach to aid in designing a monitoring program for salt marsh restoration that is based on reducing the number of metrics by eliminating redundant metrics, organizing management decisions, and evaluating the power of metrics to address management questions (i.e., through a priori statistical power analysis). Such activities are extremely valuable as they bring together different groups and lead to consistent, scientifically sound approaches to metric selection. Although it is best to connect metrics with conceptual models and restoration objectives, a variety of sources provide lists of recommended metrics for different restoration projects. For example, Baggett et al. (2104) provide a list of reef, environmental, and service-related metrics to consider for oyster restoration; Palmer et al. (2011) provide a list to consider for non-tidal wetland restoration monitoring. Part II of this report provides a committee-synthesized set of potential metrics that can guide monitoring according to example objectives that pertain to oyster reef, tidal wetland, seagrass, bird, sea turtle, and marine mammal restoration (see Tables II.1-II.6).

Spatial and temporal factors may impact the restoration metric effect size and the choice of metrics. The restoration metric effect size is a statistical (numerical) measure of change in the metric that is viewed as significant from a scientific or restoration perspective. For example, consider a marsh restoration with a performance objective of a 20% increase in the relative abundance of a particular species compared to the baseline. Given information about the variability in the metric, it is then possible to evaluate if this amount of change may be detected given the sample size, monitoring design, and evaluation criteria. Spatial and temporal scales are important, as the variability in a metric might change with scale. Standardized effect size (i.e., change relative to the variability) might increase over time for some metrics if the variability due to restoration decreases. Hence the expected change in a metric, as well as expected variability and timeframe, become important considerations in the choice of metric.

Careful selection of the metric(s) to be used in restoration monitoring is critical so that monitoring funds will be used efficiently (Kondolf et al., 2007; Lindenmayer and Likens, 2009, 2010; Kondolf et al., 2007). It is important to recognize that a long list of metrics is not required for many programs and need to be discouraged unless there is sufficient justification. As noted by Thom and Wellman (1996), "The primary function of the monitoring program is *to assess progress and to indicate the steps required to fix a system that is not meeting expectations*. Hence, it is not necessary to develop a large number of complex measures if a small, simple set of measures will suffice."

One of the common problems with metric selection is selecting too many metrics only to find that the monitoring program cannot sustain the level of monitoring required to measure them all. For example, in the case of the Comprehensive Everglades Restoration Plan,[7] the number of "performance measures" was originally about 150 and was eventually reduced to 53 (NRC, 2012). However, even after this optimization of the monitoring plan, sharp budget cuts caused further cuts to system-wide monitoring. Such problems occur when there is a lack of long-term planning and commitment of funding for monitoring and the lack of prioritization to develop limited suites of objectives and metrics. Therefore, it is critical to monitor only what is to answer the most critical management questions and knowledge uncertainties.

Determining the Sampling Design to Provide the Desired Statistical Power or Certainty

Once the testable hypotheses are defined, design inputs determined, and the metrics selected, an appropriate monitoring design can be identified, including details on sampling locations, sampling timing and frequency, and sample size appropriate for the desired statistical power or level of certainty in the results (Caughlan and Oakley, 2001; Sanderlin et al., 2014). The overall monitoring design needs to be selected to produce reliable estimates of the metrics and to be able to draw strong inference based on the monitoring data collected. The choice of a specific design also depends on other inputs (e.g., costs and other constraints, availability of suitable reference/control sites) and other design decisions (e.g., the metrics selected, the statistical approach associated with the analysis of the monitoring data).

[7] Comprehensive Everglades Restoration Plan: http://www.nps.gov/ever/learn/nature/cerp.htm.

Sampling locations and reference sites. Decisions on sampling location involve selecting reference and/or control sites (see Box 3.1), as well as selecting sampling locations within sites. Careful selection of reference and control sites is critical for assessing the progress of restoration actions relative to natural variation, as reference sites provide the target from which performance criteria can be derived and control sites provide the comparison against which progress towards targets can be measured (Underwood, 1991, 1994; Thom and Wellman, 1993; Coen and Luckenbach, 2000; Powers and Boyer, 2014).The decision of what to use for reference and control sites is partly philosophical, as there are often several valid alternatives, although there may be practical constraints based on the availability of data or physical access to the site (Baggett et al., 2014). Environmental conditions are continually changing in the Gulf of Mexico, and thus it is often not straightforward to select a reference or control site where metrics will respond in the same way as the restored site over the time period of assessment. Given that natural events occurring over the long term will likely alter the course of restoration, the use of a single reference or control site is likely to create difficulties with evaluation of progress. Multiple reference sites may better capture the natural variability in the ecosystem and in response to other stressors (Chapman and Underwood, 2000; Block et al., 2001; Maccherni et al., 2014).

Additionally, sampling control and/or reference sites at the same frequency and intensity as restoration site(s) will aid performance assessment (Shaw and Mitchell-Olds, 1993; Schwarz, 2015). Historically, many types of sampling occurred only during daylight hours, on weekdays, in suitable weather, or at an insufficient frequency. Real-time deployed sensors can help assess environmental impacts by gathering data during atypical events, and reporting these data in near real-time allows for appropriate responses to events soon after they occur. Importantly, one needs to sample monitoring parameters at sufficiently high frequencies that are biologically as well as environmentally relevant, and that are appropriate given the significant parameter variability, regardless of project objective(s). One way to enhance sampling frequency through existing efforts is to incorporate requirements for DWH restoration efforts into the Gulf of Mexico Coastal Ocean Observing System (GCOOS).[8] See Tables II.1-II.6 for details on recommended sampling parameters such as temperature (often inexpensively logged near continuously), salinity, dissolved oxygen, etc. Monitoring a set of these parameters will be invaluable for assessing ocean acidification and related problems for shell-forming marine organisms like plankton, mollusks, echinoderms, and corals (Doney et al., 2009, 2012; Waldbusser and Salisbury, 2014).

When determining the sampling locations within a restored site, probabilistic selection of sampling sites is often recommended as part of the design because it has the potential to reduce bias from site selection (Gilbert, 1987; Baggett et al., 2014). The basic probabilistic approach uses simple random sampling or stratified random sampling design based on known criteria (e.g., depth, slope, proximity to other habitats, etc.). Variation in sampling design occurs based on known biological attributes (e.g., mobile or sessile organisms), the habitat or species being restored or sampled (birds, vegetation, etc.), gradients, or confounding properties of the physical units. Other sampling strategies may result from a desire to reduce variability in population estimates (see for example, Exxon Valdez Oil Spill Trustee Council, 1993; Thayer et al., 2005; Baggett et al., 2014). Simulation modeling, a method of quantitatively or computationally

[8] Gulf of Mexico Coastal Ocean Observing System (GCOOS) is one of a series of Regional Coastal Ocean Observing Systems that are part of the U.S. Integrated Ocean Observing System (US IOOS). GCOOS portal: http://data.gcoos.org. See also http://gcoos.tamu.edu/products/index.php/oil-gas/oil-spill.

evaluating the behavior or performance of a system over time and/or under different conditions using a simplified representation of the system (see below), can also aid in sample site selection (Newbold, 2005; Steyer, 2010). See the recent review by Widis et al. (2015) and report by the Louisiana Coastal Protection and Restoration Authority (Hijuelos and Hemmerling, 2015) for further details on site selection.

Sample timing and frequency. Temporal sampling is often not selected randomly but is typically set at regular intervals (e.g., annual or quarterly) because of seasonal or interannual variability. The temporal spacing of sampling is important, so that factors affecting restoration performance (the signal) are captured, whereas the noise associated with temporal variability is avoided (Block et al., 2001).[9] For example, in the case of oyster restoration, Baggett et al. (2014) suggest that for important metrics related to oyster populations (mean density, size, size frequency), sampling needs to be tied to the end of the maximum oyster recruitment or growth (e.g., autumn; high and low temperatures significantly impact growth rates at temperate or subtropical sites). Various methods exist for determining the spatial and temporal scale for sampling units (Hill et al., 2005; Krebs, 2009). Spatial and temporal sampling considerations are discussed in Part II for specific restoration types.

The duration of project-level monitoring is also an important consideration, and is best determined by taking into account the metrics to be used, level of relevant uncertainties, sampling frequency, constraints, and other relevant factors described in this chapter. For some Gulf restoration projects, short-term monitoring (over the duration of a particular project) may be adequate to evaluate performance. However, substantially longer-term monitoring may be required to adequately determine progress toward some objectives (although sampling frequency may decrease over time) and responses to stochastic events (e.g., storms) or longer-term drivers (e.g., sea-level rise). This need raises important questions regarding the responsibility, feasibility, and cost-effective approaches for monitoring once the implementation and funding duration of a project ends. These challenges are further discussed in Chapter 4. For example, Konisky et al. (2006) found that in salt marshes physical factors rebounded rapidly with increased flooding and salinity levels after about one year, especially for culvert projects, but biological responses were less definitive and occurred over longer timeframes. This suggests that some metrics might be removed after a certain time period or monitored with lesser frequency. In long-term monitoring efforts, the integrity of the time-series data collected is important (Lindenmayer and Likens, 2009, 2010). If there is information on how a metric might change over time or space, sampling frequency might be adapted to better measure that change. One strategy might be to sample frequently over one season and less frequently over others (Underwood, 1993). Alternatively, projects might require a long-term monitoring plan and associated funding that lasts well past the project's construction or implementation phase.

Sample size. Quantitative design choices, such as sample size, are usually linked with data variability, which is expressed as statistical uncertainty or as statistical power. Uncertainty in an estimated parameter is described by the confidence interval, which provides a range of values over which the true value of the parameter is expected to occur at a stated degree of confidence. A power analysis is a statistical procedure that provides information on the adequacy of sample size in testing or comparative situations. The goal of the exercise is not just to

[9] Understanding the temporal cycles in data is critical in sampling temporal data to avoid problems associated with aliasing (i.e., if a signal is undersampled, the signal that is estimated from the sample has a pattern that is different than the original signal) and may result in false trend determination (Mudelsee, 2014, p. 196).

determine a sample size but also to determine if the sampling and decision process is feasible. For example, in evaluating coastal wetland restoration, it is common to assess whether a performance metric is "approach[ing] reference conditions" (Palmer et al., 2011). When the variability is high or the sample size is small (or both), the restored site and the reference site comparison might result in the incorrect conclusion that there is no difference (i.e., the non-rejection of the null hypothesis of) due to the high natural variability. Therefore, sample size evaluation and study design selection become critical because the metric selection and monitoring plan ought to be designed to avoid the decision error of "not rejecting" a hypothesis test due to inadequate sample size or high variability (Block et al., 2001). Sample size estimates may be based on exact or simulation methods (Hijuelos and Hemmerling, 2015). Power analysis programs are available from standard statistical packages (for example, Benedetti-Cecchi, 2001; Schwarz, 2015).

The power analysis approach is useful for hypothesis-based approaches to restoration evaluation when there is a specific numerical target or a comparison with a reference/control (Hijuelos and Hemmerling, 2015). In other cases, where the emphasis is on the use of more complex models and the focus is prediction, a simulation-based approach is required (e.g., Sanderlin et al., 2014). Where predictive modeling is more of a focus, it is necessary to establish that candidate models and associated model parameters will have sufficient certainty to decide amongst competing models. Without attention to sample size and design, monitoring may not produce useful information and there is the potential for an excess of model uncertainty, resulting in weak inference.

Basic monitoring study designs to assess restoration performance. Depending on the historical conditions and reference data available and management questions to be resolved, several basic designs are available for restoration monitoring. The design that is recommended as the "gold-standard" is the "before-after-control-impact" (BACI) design, where data are collected before and after restoration (Figure 3.1) at the restoration site and at a matched reference site (or multiple reference sites) (Stewart-Oaten et al., 1986, 1996). Such an approach has been recommended for oyster restoration projects, comparing relatively healthy unharvested natural reefs with the restored oyster reef (Coen et al., 1999; Baggett et al., 2014) as well as tidal wetlands (Konisky et al., 2006). The design requires pre- and post-construction monitoring at both reference and restored sites that is sufficient to detect performance toward structural and functional restoration objectives. The BACI design assumes that the sampling is done on the same frequency, and if different frequencies are used, there may be loss of statistical power (and hence ability to make strong inference based on the data). It is also valuable to have data on one or more matched control sites—sites that are similar to the restoration project site but still requiring restoration. These sites provide a means to compare how much progress a restoration project has made.

A second, simpler but less powerful approach is to monitor specific metrics at a project site before and after restoration, and compare pre-restoration baseline data with the trajectory of a site after restoration action(s) (a "before-after" design; Michener, 1997). This approach essentially ignores the effects of non-restoration factors, which may be appropriate in some situations when the effects of these other factors are small compared to the effects of the restoration action. An example could be a large diversion event, which would be expected to dominate short-term responses on the local area. In some situations, other data or models can be used to adjust for the effects of other factors after the restoration action (Michener, 1997).

Another variation would only use post-construction data (when there is little or no information about the site prior to restoration). This approach might also be feasible for restoration projects that create new habitat rather than restore existing habitat. However, these approaches may result in less defensible conclusions.

A third approach relies heavily on modeling of complex systems to analyze the performance of a restoration project, in light of many influencing factors that may vary over time. Simulation modeling can be used to predict the direction of restoration, and when combined with monitoring data, can be used to estimate the probability that a restored site is converging to the project objectives (Roman et al., 1995; Lirman and Miller, 2003). With simulation modeling, a monitoring design would be intended to provide data to help refine a model, better understand the effects of various factors and provide data to compare actual measurements against model predictions (SAIC, 1996; Meselhe et al., 2015). For example, an assessment of bird population responses needs to consider many complex factors in addition to restoration projects underway. Linked ecological and hydrological models can be used to interpret monitoring results in light of other factors, such as river flooding and climate variability, that may influence population numbers. Progress in these cases is measured by comparing future scenarios with and without restoration. Monitoring data are used to reduce uncertainty in future predictions, which can help evaluate the effects of management actions and facilitate adaptive management.

Coordination of monitoring strategies. In creating a monitoring design, it is important to recognize how the information that is collected might be used in other decision processes to balance practical with statistical and quantitative considerations. Monitoring information might not only be used for local but also for regional assessments. This consideration suggests it is important for different agencies to collaborate on prioritizing metrics, sampling frequencies, sampling and analysis protocols, and establishing and maintaining reference and control sites across multiple restoration projects. The efficiency gain for restoration funding agencies through enhanced data consistency and usability of such collaboration is potentially huge. For example, if data are collected at a restored site by one agency and at a reference site by a second agency, there needs to be collaboration on the monitoring design and timing of sampling. Uniformity of design will lead to better opportunities for combining information into regional decision making and analysis, improved quality of data, and quicker release of information to stakeholders. Enhanced collaboration could also reduce sampling redundancies for commonly sampled parameters.

Identifying Sampling and Analysis Protocols

Protocols are documents that detail the data collection and measurement process. The purpose of the protocol is to reduce uncertainty associated with data collection by providing specific information about sampling methods, transportation, and laboratory analysis processes. Such factors affect the bias and variance of the measurements and hence the accuracy and sensitivity of the metric. Establishing a uniform approach to sampling reduces the decisions that need to be made by personnel and laboratories and can help ensure consistency across projects and changes in personnel. If different laboratories are used, there needs to be comparison with spiked samples (samples with known concentrations) to evaluate differences between laboratories. If different sampling methods are used, there may be the need for calibration of measurements. Monitoring program pilot studies can prove useful in certain restoration projects to better understand how different choices affect data variability, to evaluate the protocols, and assess the ability to make conclusions based on the probable results.

Protocols are commonly used in many monitoring programs such as bird programs or marsh monitoring programs (Conway. 2011; Folse et al., 2014). Protocols are especially important with citizen monitoring and have been successfully implemented for various restoration projects (Drociak and Bottitta, 2005).

Given that restoration projects and monitoring will be implemented by multiple agencies, it is important that some standardization of protocols be considered, developed in a coordinated fashion, and documented. The lack of a consistent protocol (sometimes at least partially due to a lack of documentation) makes it difficult to make coherent regional evaluations of multiple restoration projects. Konisky et al. (2006) note that effective regional assessments require common ecological data sets that are collected using a standardized approach. For the Gulf, this implies a need to use interagency teams with representatives from multiple disciplines and backgrounds collaborate in the development and evaluation of protocols.

Protocols ought to also be treated as information and considered part of metadata that are collected in the monitoring process (see also Chapter 5 as it relates to data stewardship). Experience shows that protocols can change over time for a variety of reasons. Results from other restoration projects may lead to protocol revisions to improve future restoration evaluations. New technologies may render existing protocols obsolete. When protocols change, how they changed needs to be documented. Ideally this documentation includes an experimental inter-comparison of the new protocol with the other to allow a quantitative interconversion. Adequately documenting changes in protocols is part of metadata and is critical for reducing uncertainty associated with these changes.

Data Analysis and Assessment

The process for assessing the data from restoration monitoring follows from the chosen questions or hypotheses and the sampling design. The three general approaches are the comparative approach, the trend approach, and predictive modeling assessment.

In the comparative approach, data collected at a restored site is compared statistically or graphically with data associated with the target. In the case of construction monitoring, the comparison may be with a fixed target (a numerical value) while in the case of restoration progress, the comparison may be with data collected before and after restoration (see previous discussions of basic monitoring designs). In case a BACI design was chosen for progress monitoring, monitoring data at the restored site can be compared to conditions at the reference site. Similarly, assessing progress toward mobile species restoration often use the comparative approach against a pre-determined restoration target.

The second assessment approach is based on trend or changes in parameter estimates through time. While not ideal, such approaches often occur when there are not matched reference sites available for comparison. For example, with mobile animals such as fish or marine mammals, a restoration objective might be to increase abundances or densities of species, and there might not be reference areas for comparison (Dias and Garrison, 2015). In these cases, with sufficient temporal information, a trend can be evaluated after a restoration project is implemented and compared to trends during a pre-project period. Trend analysis is highly dependent on the temporal scale of measurement and requires a sufficient timeframe to measure performance, as well as an understanding of the temporal cycles to assess outcome. Long-term monitoring (10 years or more) may be required for some ecological and environmental metrics. Evaluating trends in long-lived populations such as marine mammals, birds, and turtles will require a multi-decadal timeframe for evaluation given their lifespan.

Both frequentist and Bayesian methods may be useful for the above analysis. Bayesian methods treat parameters (e.g., means, slopes) as random, and model these parameters with distributions. The Bayesian approach starts with prior distributions representing prior knowledge of parameters and updates these distributions based on the data and associated statistical likelihood. The Bayesian approach has advantages as it is typically simulation-based and effective with more complex models (Duncan and Vesk, 2013; Scheuerell et al., 2015).

A third evaluation approach occurs when the focus is on model predictions, and monitoring data collection is used to inform a more complex model. For example, the Louisiana Coastal Protection and Restoration Authority relies on "Future Without Action" predictions to provide a baseline for decision-making (e.g., to minimize coastal flooding damage) considering modeled future project outcomes.[10] This approach is often necessary for assessing large-scale restoration progress amidst many other complex influences, particularly if there are no good reference sites for comparison. Future conditions are simulated without the restoration project, but with anticipated changes in other factors and including the effects of other projects. Then the model is rerun with all conditions repeated but with the project of interest included. Thus, the difference between results is the anticipated effects of the restoration, after accounting for likely changes in non-restoration factors and other projects that could influence the effects. For example, the model LaVegMod (Visser et al., 2013) uses Louisiana Coastwide Reference Monitoring System data selected using probabilistic sampling and simulation to estimate the degree to which objectives are achieved for wetland vegetation restorations at spatial sites given information on hydrology, salinity, subsidence, sea-level rise, and nutrients over a 50-year time frame.

It is important to note that restoration projects usually fall into a statistical category called "quasi-experiments" (Eberhardt and Thomas, 1991). The restoration project site and the reference site act as treatments; however, these are treatments that have not been randomized as would be expected in a manipulative experiment (i.e., there is only one replicate of the treatment). Results, therefore, are project-specific and apply to the specific location and time but may not be generalizable to other locations and times (Green, 1979; Hurlburt, 1984; Block et al., 2001). Nevertheless, conclusions from such monitoring efforts can inform passive adaptive management. Classical experimentation requires replication of experimental units (i.e., sites that are restored)—not repeated sampling of a single experimental unit. A test that compares reference and restored sites actually is comparing the single restored site with the single reference site. Hence it is to be expected that if more measurements are made, small differences that may not be ecologically significant can become statistically significant. It is therefore important that both statistical as well as management criteria be used for the evaluation of progress (Johnson, 1999).

[10] Louisiana Coastal Protection and Restoration Authority Future Without Action: http://coastal.la.gov/whats-at-stake/fwoa/.

In adaptive management, it is sometimes possible to use a randomized control design. This design would use random allocation of a potential restoration treatment(s) to sites or spatial units and use a control site (no treatment or standard treatment) to evaluate effects of the treatments and possibly determine "best" restoration methods. With replication, such a design would be considered a true experiment and would provide strong evidence for selection of restoration methods. This approach would enable active adaptive management (see Chapter 7 for additional discussion on active adaptive management) and provide important opportunity to learn about restoration efficacy and impacts.

Analysis of monitoring data may require comparison of multiple models that change as new data are collected or information is gained. Such comparisons often involve information criteria and predictive approaches for evaluation. Multiple models may be used to gain an overall predictive analysis (Anderson et al., 2000), and the use of classical statistical hypothesis tests may not be useful (for discussion, see Lukacs et al., 2007; Stephens et al., 2007).

What is critical to understand from the management perspective is that the strength of a statement about restoration progress, regardless of the inference method, depends on the quality of the data from the monitoring design, the certainty in the underlying statistical or computational model, and the connections among the design, model, and cause and effect. Monitoring design affects the strength of inference from the analysis of monitoring data regarding a specific restoration result. What can be stated about restoration and the strength of the statements is linked to the information from the monitoring program.

VALUE OF INFORMATION: LINKING MONITORING DESIGN WITH RIGOR OF ASSESSMENT CONCLUSIONS

When designing the monitoring effort, the plan needs to consider: how much the conclusions will be valued; and how important the strength of the conclusions will be (Table 3.1). The target audience or the decision-maker determines the statistical rigor and confidence needed to answer the management questions. Thus, the rigor of the statistical monitoring design determines the strength of the conclusion (statistical inference). The strength of the conclusion needs to be reflected in the reporting of restoration results. This assures that credit for restoration progress is allocated based on projects with rigorous monitoring, and that statements of progress are appropriately cautious for those with only anecdotal data or poorly designed monitoring programs. For example, most of the 62 biodiversity monitoring efforts analyzed by Kleijn and Sutherland (2003) were too poorly designed to determine whether projects had met their objectives, often lacking statistical analysis and unbiased methodology. Table 3.1 lists examples of possible conclusions and related strength of inference that can be associated with different types of monitoring designs: Conclusions associated with the strongest inference stem from the BACI and "before-after-control-reference-impact" (BACRI) designs, which yield the most certain findings, including attribution to specific restoration actions. Conclusions from sites with pre- and post-restoration monitoring control or reference site cannot provide attribution as the restoration results observed could be due to many, uncontrolled factors. It is important to recognize that while most restoration projects will have varying degrees of uncertainty associated with the outcome, it is possible to reduce some of that uncertainty through proper design of monitoring. Through this approach, stronger statements about the progress and value of restoration projects are possible.

Table 3.1 Level of confidence possible from statistical conclusions, based on statistical rigor of the chosen monitoring design.

	Strength of the Conclusion and Required Monitoring Design		
Level of confidence possible	**Sample Statement Possible from Chosen Monitoring Design**	**Monitoring Designs**	**Caveats**
Certain (high rigor, experimental testing, causal link,)	• The project has increased recreation activity at this site by 25% over a 2-year period. • The project's wetland restoration reduced nutrient loads in the project region by 10% and improved water quality in 45 stream miles to below total maximum daily load requirements.	• Before-after-control-impact (BACI) design. • Before-after-control-reference-impact (BACRI) design. • Randomized control study.	• If a single reference site is used, there may be natural differences between reference and restored areas that change over time. Natural factors may result in the reference and restored sites becoming more similar.
Somewhat certain (medium rigor. correlation,)	• Recreation activity at this site has increase by 25% over the project period, and Project X has invested in recreation infrastructure at the site. Increased visitation may be related to the decreased rain during the summers post restoration. • Nutrient loads have declined and water quality has improved in the project area where Project Y restored wetlands.	• Control-impact design. • Before-after design. • Trend assessment.	• The effect that is observed may not be a result of the restoration actions. In the before-after design, the result may be due to an environmental factor that changed in the after period. In the control-impact design, the effect may partly be due to site differences. Natural factors may result in the reference and restored sites becoming more similar.
Cautious (low rigor, anecdotal,)	• People in the area of the project have seen more people using the site for recreation, and they think it is because of Project X. • There are more wetlands in the Project Y area than in other similar areas.	• Restoration site construction monitoring. • Sampling at a single time or location.	• The conclusions may be affected by biases associated with individuals reporting and conditions such as weather. • The monitoring provides no evidence of project performance

When formulating a restoration monitoring plan it is important to consider all constraints that limit the ability of carrying out the restoration monitoring plan over the duration specified in the monitoring plan. As discussed in Box 1.3, constraints are usually associated with cost, societal, political, organizational, monitoring design, or ecosystem complexity. In addition, there may be constraints associated with the sampling process such as restrictions on when and where samples can be taken, spatial restrictions (e.g., site access), equipment and/or resource restrictions, and personnel limitations. Understanding the boundaries associated with a given restoration project are critical in refining the scope of potential monitoring decisions such that the monitoring plan is practical and can be implemented and sustained over the required time-frame. Ultimately, deliberate decisions need to be made to meet the decision-makers' need for information and degree of confidence in the conclusion. It is also important to recognize that constraints are sometimes controllable through advanced planning.

The cost of conducting a monitoring program can be substantial and one of the most difficult elements of a restoration program to estimate. An assessment of restoration projects conducted through the early 1990's showed that monitoring cost averaged 13% of the total project cost, but ranged from 3 to 67% (Shreffler et al. 1995). Recently, the San Francisco Bay Shoreline Study, which covers an area of 15,100 acres of restoration of salt ponds and tidal marsh, estimated that it would require $8.7M for adaptive management monitoring over a 10–year period (South San Francisco Bay Shoreline Study 2015). The Glen Canyon Adaptive Management Program ($11M per year), Sacramento-San Joaquin River Delta Plan ($11M per year), Columbia Estuary Ecosystem Restoration Program ($4M per year) provide examples of level of effort devoted to monitoring in larger systems. These costs can include focused uncertainties research (Thom et al., in revision).

Larger restoration programs with federal support, especially by the Corps of Engineers, have provided guidance regarding monitoring costs and duration (Thom et al., 2004). The following describes the guidance for monitoring within the Comprehensive Everglades Restoration Plan (CERP): "Monitoring and assessment activities prior to and during construction should include costs for sampling, project (contract) management and associated QA/QC costs, analysis, documentation, reporting, and entry of data into approved data storage. Any cost of monitoring performed during the period of construction shall be included in project construction costs and any cost of monitoring performed after the period of construction shall be included in project Operations, Maintenance, Repair, Replacement and Rehabilitation (OMRR&R) costs…Monitoring costs for ecosystem restoration cannot be cost-shared longer than 10 years post-construction of a particular component. If required to be maintained beyond 10 years for a particular component, it will be 100% non-Federal." (CERP Guidance Memorandum 040.02, page 5).

Costs for monitoring include a wide array of tasks, some tasks of which may not be adequately funded. Caughlan and Oakley (2001) concluded that the majority of costs for long term ecological monitoring are often allocated to data collection, while critical aspects such as scientific oversight, training, data management, quality assurance and reporting are often neglected. Thus budgeting for all program costs is a key factor in a program's longevity. They also found a close relationship between statistical issues and cost. For example, estimating costs associated with sampling design, replication and power, and comparing those costs for various alternative designs was a way to streamline the work and develop a well-planned and realistic monitoring budget.

As discussed above, a "value of information" framework (Paulsen, 1995) could be operationalized in the context of monitoring the effectiveness of restoration actions (Thom and Wellman 1996). Here, the incremental improvement in information gain relative to questions central to the monitoring program can be weighed against cost. Decisions can then be made regarding the value of that increment on decisions. The most common evaluative approach is to use some form of a cost-effectiveness model (Orth, 1994). This approach facilitates the comparison among alternative monitoring methods or levels of monitoring effort, and allows decision-makers to build a set of cost-effective actions that highlight the higher marginal costs associated with conducting additional sampling.

The assessment of cost for monitoring restoration projects is affected by complexity and duration of the project. Thom and Wellman (1996) suggested that, in order to make a decision on what to include or exclude in a monitoring program, the overall requirements of the program needs to be kept in mind. The monitoring program needs to accomplish the following:

- Be cost-effective
- Target restoration project goals and performance criteria
- Develop defensible information and data
- Facilitate decisions on midcourse corrections.

Hence, the elements included in the monitoring program are best assessed against these requirements by: (1) prioritizing these requirements; (2) listing potential monitoring components and a rough estimate of cost; and, (3) trimming down the list based upon the prioritization of the requirements. A critical element of refining costs is developing clear linkages between factors that will be changed by the action to the factors that control the development of the ecological response factor. Conceptual models and numerical models can be essential tools in ascertaining these linkages.

CONCLUSIONS AND RECOMMENDATIONS

To provide assurance to funders and the public of the benefits derived from restoration investments, monitoring should be viewed as an integral part of restoration, and detailed monitoring plans should be required by restoration programs at the time of restoration proposal submission. Therefore, the Committee recommends that all restoration - administered by the RESTORE Council, NFWF's Gulf Environmental Benefit Fund, and NRDA Trustee Council, and the Gulf states - be accompanied by a strategic monitoring effort, described in a monitoring plan.

Project-level monitoring is required to assess restoration progress toward individual project objectives. To assess restoration progress at the program-level and Gulf-wide, a strategic monitoring effort is required that can aggregate and synthesize across projects (see Chapters 4-6 for detailed guidance). Effective construction monitoring ensures that a given project was completed in accordance with its design and applicable regulations and allows construction problems to be corrected quickly. Performance monitoring provides the information necessary to assess whether the restoration project has achieved its biological and ecological objectives. Performance monitoring requires careful design so that site level restoration-related responses can be distinguished from natural variability and changes associated with other environmental factors. Project-level monitoring may also provide support for structured learning and adaptive management.

Informative, cost-effective restoration monitoring can be challenging to design and requires thoughtful planning and execution. The restoration programs might consider providing guidance, training, and/or expertise to the grantees with regard to developing the appropriate monitoring plan including a review team with expertise in monitoring, formal evaluation, and statistics. **At a minimum, all restoration projects should include construction and performance monitoring, which includes an in-depth assessment to determine whether a given project was constructed or implemented as planned and has met its stated objective(s)**. **The Committee recommends that monitoring plans be considered a prerequisite for any restoration funding and that those plans contain the following essential elements, at minimum:**

- Clearly articulated measurable restoration objectives (from the project plan);
- Identify well-articulated management questions that monitoring and evaluation seek to address using conceptual system models and causal models that link ecological and socio-economic drivers and stressors with both biophysical and ecological processes to outcomes such as populations, habitats, ecosystem, ecosystem service, and human well-being (as appropriate) (derived from a given project plan);
- Explicitly identify appropriate metrics, targets and criteria for addressing the management questions such as measuring ecological, and where appropriate, social and economic restoration outcomes;
- Evaluation of available baseline data appropriate to a given project objectives and/or plans to collect new baseline data if needed;
- Appropriate sampling and analysis designs, including consideration of reference and/or control site(s), sampling locations, timing, frequency, and sample size;
- Well-documented and, where possible, standardized sampling protocols;
- Rigorous data management plan (see Chapter 5 for details);
- Anticipated methods for data analysis and associated evaluation;
- Realistic project budgets and staffing to support the appropriate level of monitoring, study design, data acquisition via monitoring, data analyses, modeling, scientific oversight, training, data management, quality assurance, and reporting, etc.; and
- Monitoring program management plan (including reporting and communication plan) to assure that the applied monitoring program is efficient, accountable and transparent at all phases of a given effort.

Careful planning of a monitoring design is needed to ensure that monitoring addresses key management questions with sufficient statistical rigor. A monitoring design should be informed by overarching program-level input from the conceptual socio-ecological model, restoration objectives, and management questions and by site-level considerations including project scales, available baseline and reference sites, and potential constraints. These inputs are essential considerations to the monitoring design decisions. Decisions on testable hypotheses; metrics; sampling locations, timing, and frequency; sample size; and basic design all affect the statistical power or level of uncertainty of the results. Modeling tools are available to test the impacts of various monitoring designs to determine if they are adequate for evaluation of restoration performance with known confidence. Once data are collected and analyzed, communicating the results and associated level of confidence should accurately reflect the rigor of the monitoring program.

Lack of consistency in sampling methods, design, and analysis can significantly diminish the usefulness of the data for assessing restoration performance. Consistent monitoring designs and standardized protocols enhance consistency and usability of the data both within and across projects, increase opportunities for combining information for regional analysis, and improve the quality of data collected (see additional discussion in Chapters 5, 6, and Part II). **Gulf restoration funding agencies should work together to ensure that monitoring data are as consistent and comparable as possible across the Gulf by assembling teams with expertise in restoration science, statistics, program management, monitoring & evaluation, and restoration practice that will identify critical subsets of metrics and protocols that should be standardized for a given restoration type. As much as is feasible, restoration funding agencies should also strive to create standardized metrics and protocols across all restoration types to facilitate the aggregation and synthesis of restoration data collected from distinct but interconnected restoration projects across Gulf ecosystems (see additional guidance in Chapters 4 and 6).** Although standardized sampling protocols may pose challenges, especially in states where long-term data sets may exist using other protocols, there is likely a critical subset where the benefits of consistent data at a program scale justify the costs. All protocols should be well documented in the metadata reported in the monitoring process.

CHAPTER 4
MONITORING BEYOND THE PROJECT SCALE OR DURATION

Restoration of the Gulf of Mexico is a complex endeavor taking place over a vast spatial scale and extended timeframe, and affecting many habitats and species. So far, the Committee has focused discussion on how project-level monitoring can improve restoration effectiveness. However, assessing progress toward restoration program goals may require monitoring and assessment beyond the project duration and area. To address the Committee's task to assess approaches for long-term monitoring using site-based measurements cumulatively to assess region-wide insights, and to augment best practices, this chapter discusses monitoring approaches that go beyond the temporal or spatial scale of individual projects.

SENTINEL SITES FOR LONG-TERM, BROAD-SCALE MONITORING OF RESTORATION OUTCOMES

Long-term restoration monitoring is an important but often ignored component of restoration programs. As discussed in previous chapters, local project monitoring rarely extends more than a few years beyond completion of construction. In contrast, ecosystem restoration at the scale of most Gulf restoration projects could require decades to develop effectively (Thom et al., 2010). Documenting and understanding long-term dynamics of restoration sites will be especially important given the possibility for powerful regional drivers of local restoration outcomes such as sea-level rise, climate change, extreme weather events, and species invasions. Moreover, individual projects can interact with and influence other projects in the same region, resulting in cumulative restoration effects that can only be understood through coordinated long-term observations (Steyer et al., 2003). Ultimately, state and federal restoration programs require information from long-term monitoring to know whether restoration investments are having a durable beneficial or negative effect on Gulf ecosystems and the services they provide to society (see also synthesis and integration in Chapter 6).

Although long-term restoration monitoring is not financially feasible or practical for every restoration site, a deliberately selected set of "sentinel sites" could provide reference site information for multiple restoration projects. These sites could be selected as dynamic "target reference sites" that have limited negative impacts from human activity (see Chapter 3) and that do not require restoration. These reference sites provide a quantitative target for each monitoring metric against which to compare restoration progress; thus when restoration site conditions reach the reference site values, the relevant objective(s) have been achieved. Despite the need for two or more target reference sites to reliably evaluate restoration outcomes (Ruiz-Jaen and Aide, 2005), a recent review of 301 restoration articles found that only 44%of the studies actually used a target reference site for comparison with a restoration site (Wortley et al., 2013). Instead, 30% only used a control site that shared the same baseline as the restoration project sites but received no restoration treatment, and 26% did not include a reference or control site (see discussion on implications for rigor of conclusions in Chapter 3). As a result, the meta-analysis by Wortley et al. (2013) could not draw strong conclusions about the effectiveness of restoration given the lack of rigorous monitoring.

Clearly, including target reference and/or control sites significantly increases the cost of project monitoring. Ideally, a network of sentinel sites could provide reference information for many projects, releasing funds for other purposes. Designing such a system would require close attention to relevant scales of variation in ecological processes. For example, each estuary has a tendency to be somewhat unique (Montagna et al., 2013). Also, seagrass beds vary systematically from the eastern to western regions of the Gulf, with those in the north-central and north-western regions lacking abundant meadows of turtlegrass (*Thalassia testudinum*) and manatee grass (*Syringodium filiforme*). These seagrass species occur most often in high salinity, clear waters of the eastern and southern Gulf and uncommonly in the turbid, low salinity waters of the north-central and north-western Gulf (Eleuterius, 1987), and it would be beneficial for the deployment of sentinel seagrass sites to account for this variation.

Some restoration programs have embraced the concept of a system of reference sites. A good example is the Louisiana Coastwide Reference Monitoring System[1] (CRMS), a comprehensive monitoring network that was specifically designed to support restoration planning and assessment. Implemented under the Coastal Wetlands Planning, Protection, and Restoration Act, which mandated 20 years of restoration project monitoring, CRMS now involves standardized, long-term monitoring at roughly 390 locations (USGS, 2010; Hijuelo et al., 2013). Also, the National Oceanic and Atmospheric Administration (NOAA) and partner coastal states launched a program to coordinate 28 National Estuarine Research Reserve System (NERRS) sentinel sites in 2011. For example, the Northern Gulf of Mexico Sentinel Site Cooperative maintains a set of reference sites to track and predict sea-level rise, changing salinity, effects on oyster beds and marsh productivity, and habitat suitability modeling. The NERRS uses a System Wide Monitoring Program protocol to conduct standardized, long-term monitoring on water quality, weather, habitat, species, and land-use/cover.[2] Many other long-term monitoring efforts are already underway in the Gulf to provide a starting point for a network of restoration sentinel sites (Love et al., 2015; see Chapter 6).

In addition, a subset of restored and control sites could be monitored beyond the initial duration of a typical project (~3-5 years). Such long-term monitoring of restoration performance could also provide the opportunity for additional hypothesis testing in the case of unexpected outcomes. Similarly, as further discussed below, such long-term monitoring sites could become the location for ecological research that could improve the understanding of key knowledge uncertainties (see also Chapter 1). The concept of pairing long-term ecological monitoring with rigorous ecological research has been previously implemented by several programs such as the National Science Foundation's Long Term Ecological Research Network[3] (the largest and oldest continuous ecological network in the US), the U.S. Fish and Wildlife Service's National Wildlife

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[1] Louisiana Coast-wide Reference Monitoring System (CRMS): http://lacoast.gov/crms2/home.aspx.
[2] National Estuarine Research Reserve System (NERRS): http://nerrs.noaa.gov/research/, http://oceanservice.noaa.gov/sentinelsites/gulf-of-mexico/.
[3] The Long Term Ecological Research (LTER) Network was created in 1980 to conduct research on ecological issues that can last decades and span huge geographical areas: www.lternet.edu.

Refuge System,[4] the U.S. Environmental Protection Agency's National Estuary Program,[5] and the National Park Service's National Seashores[6] and other types of properties.

Monitoring to improve the efficacy of Gulf restoration is an important component to better enable adaptive management in the region. However, the Committee recognizes that active adaptive management to reduce uncertainty can be expensive and technically demanding (see Chapter 7). Adaptive management can also require long-term active management and monitoring. For restoration efforts that must confront similar, decision-critical uncertainties, a designed set of management experiments and accompanying long-term monitoring effort at a set of sites across the Gulf could offer a means to cost-effectively accelerate production of restoration knowledge for multiple projects and increase the possibility of success.

MONITORING AND ASSESSMENT OF MOBILE LIVING RESOURCES

Restoration projects often aim to improve the quality of habitat for living resources. This type of monitoring effort will require performance monitoring to be designed at the scale at which a particular habitat is assumed to affect target resources. This design becomes increasingly complex when attempting to restore species with large spatial ranges such as birds, fish, sea turtles, or marine mammals. It is often not known if the aggregated outcomes of many small projects can have an effect on species at larger scales. Monitoring the benefits, potential harm, and cumulative effects from a variety of restoration projects on mobile living resources, therefore, requires special consideration. In particular, such monitoring efforts will need to consider approaches to monitor across the range of a particular species.

Understanding restoration benefits for bird populations, for example, requires a dedicated monitoring program that would be long-term, standardized, well-coordinated, geographically broad, taxa-wide (i.e., many multiple bird species), and multi-indicator (according to the rationale, metrics, and methods described in Part II). Such an effort would span decades and potentially extend beyond the limits associated with the funding programs described in Chapter 2. It would be based on a conceptual ecosystem understanding (Lindenmayer and Likens, 2010) and include elements discussed in this report, such as a robust and rigorous design (see Chapter 3) and data management effort (see Chapter 5). It would focus on determining population-level impacts of bird-specific ecological processes, possibly through synthesis (see Chapter 6), and on improving common restoration/management techniques employed across the Gulf of Mexico region, possibly through adaptive management (see Chapter 7).

Because restoration aims to enhance or repair ecosystem structure and/or function, it is often assumed that habitat restoration will benefit fish and wildlife in a particular ecosystem being restored. "This assumption is rarely tested, but it should be" (Block et al., 2001). For example, habitat selection criteria for bird species can be so complex that simply restoring the habitat might not be sufficient (Ahlering and Faaborg, 2006). This assumption can also fail when restoration projects have negative impacts on non-target fish and wildlife (Wilson et al., 1999). A

[4] The National Wildlife Refuge System is a designation for protected areas in the U.S. including 562 national wildlife refuges and 38 wetland management districts: https://www.fws.gov/refuges/.
[5] The National Estuary Program works to improve the waters, habitats, and living resources of 28 estuaries across the country: https://www.epa.gov/nep.
[6] A set of 10 National Seashores are currently in places to preserve the national coastline while supporting water-based recreation, for example Gulf Islands and Padre Island in the Gulf of Mexico.

number of potential unintended consequences of restoration projects on birds, sea turtles, and marine mammals are illustrated in Table 4.1, and monitoring to uncover these effects as well as to consider appropriate tradeoffs and informed management decisions is described by Hutto and Belote (2013).

Table 4.1 Examples of how various restoration projects can have direct and indirect positive and/or negative effects on marine mammals, sea turtles, and coastal birds.

Restoration practice	**Potential impacts on mobile species**	**Monitoring for adaptive management and marine mammal restoration**	**Monitoring for adaptive management and sea turtle restoration**	**Monitoring for adaptive management and coastal bird restoration**
Use of alternative fishing gear to reduce bycatch	Reduced number of stranded, incidentally captured, and entangled animals; reduced mortality	Monitor data from targeted observer program tied to fishery; stranding network surveillance	Monitor data from targeted observer program tied to fishery; stranding network surveillance; measure sea turtle population trends on nesting beaches and in water	Monitor mortality data through targeted observer program tied to commercial fishing; determine species- and age-specific annual survivorship
Increase enforcement to reduce illegal killing	Reduced number of stranded animals with signs of human interaction	Number of man hours working marine mammal related enforcement; stranding network surveillance	-	-

Management of fisheries to ensure sustained prey base	Changes in prey quality, abundance, or distribution causing changes in species distribution, reproductive success, and survivorship	Monitor coastal dolphin health through live animal health assessments and stranding network surveillance; monitor marine mammal reproductive rates, survival, abundance and distribution using photo identification, line transects and passive acoustic monitoring	Monitor sea turtle health through live animal health assessments and stranding network surveillance; measure sea turtle population trends on nesting beaches and in water	Monitor species-specific abundance and distribution, community diversity, and demographic parameters; monitor bird population trends for 10+ years at state, regional, and/or Gulf-wide scales
Barrier island restoration	Increase in available bird habitat causing distribution and abundance shifts, and increased reproductive success and survivorship			Monitor species-specific abundance and distribution, community diversity, and survivorship at paired restoration and reference sites for at least 10+ years; monitor bird population trends for 10+ years at state, regional and/or Gulf-wide scales

Beach renourishment	Increase in available bird habitat causing distribution and abundance shifts, and increased reproductive success and survivorship			Monitor species-specific abundance and distribution, community diversity, and survivorship at paired restoration and reference sites for at least 10+ years; monitor bird population trends for 10+ years at state, regional and/or Gulf-wide scales
Hydrologic flow modifications	Altered estuarine salinity resulting in skin damage and impaired organ function in coastal dolphins; changes in distribution and abundance of mammals, turtles, birds, and their prey	Monitor coastal dolphin health through live animal health assessments and stranding network surveillance; monitor dolphin distribution, reproductive rate and survivorship using photo identification	Monitor sea turtle health through live animal health assessments and stranding network surveillance; measure sea turtle population trends on nesting beaches and in water	Monitor species-specific abundance and distribution, community diversity, and demographic parameters; monitor bird population trends for 10+ years at state, regional, and/or Gulf-wide scales
Salt marsh restoration	Changes in prey distribution and abundance	Monitor coastal dolphin health through live animal health assessments; stranding network surveillance; monitor dolphin distribution, reproductive rate and survivorship using photo identification	Monitor sea turtle health through live animal health assessments and stranding network surveillance; measure sea turtle population trends on nesting beaches and in water	Monitor species-specific abundance and distribution, community diversity, and demographic parameters of paired restoration and reference sites for at least 10+ years

Construction of boat ramps and structures for recreation	Increased noise during construction and use causing disturbance and masking of dolphin communication; increased human disturbance causing boat strikes and affecting migration, reproductive success, distribution and abundance, survivorship, and behavior of many species	Monitor coastal dolphin health through live animal health assessments and stranding network surveillance; monitor marine mammal reproduction, survival, abundance and distribution using photo identification, line transects and passive acoustic monitoring	Monitor sea turtle health through live animal health assessments and stranding network surveillance; measure sea turtle population trends on nesting beaches and in water	Monitor species-specific abundance and distribution, community diversity, and demographic parameters at paired construction and reference sites for at least 10+ years; monitor bird population trends for 10+ years at state, regional and/or Gulf-wide scales
Dredging to restore coastal habitat	Disturbance of coastal dolphins and manatees; release of contaminants; enhanced harmful algal blooms; incidental capture and mortality of sea turtles; alteration of physical habitat and prey sources; interruption in sea turtle migration and nesting behavior and reduction in reproductive success; interruption in bird foraging and loafing; shift in distribution and abundance; decrease in bird survivorship	Monitor marine mammal health through live animal health assessments and stranding network surveillance	Monitor incidental sea turtle captures during dredging operations; capture and relocate sea turtles from dredging site to other areas; monitor sea turtle health through live animal health assessments and stranding network surveillance	Monitor species-specific abundance and distribution, community diversity, and survivorship at paired dredging and reference sites for at least 10+ years; monitor bird population trends for 10+ years at state, regional and/or Gulf-wide scales

Although many restoration activities will not aim to restore marine mammals, they may influence ecosystem parameters or stressors that, in turn, impact these animals. Some restoration activities have the potential to benefit marine mammals through habitat and water-quality enhancements and the restoration of submerged aquatic vegetation that would replenish prey. Other activities could potentially have adverse effects, such as sediment dredging, beach nourishment, construction of coastal defense (or other) structures, and hydrologic river diversions. For example, dredging of contaminated sediments can temporarily re-suspend pollutants and nutrients into the water column, potentially exacerbating harmful algal blooms (Van Dolah, 2000; Martins et al., 2012). River diversions may benefit construction activities while potentially harming commercial oyster harvest (Caffey et al., 2014). Beach nourishment and maintenance activities can destroy feeding grounds and alter animal behavior at target and adjacent sites (Speybroeck et al., 2006; OSPAR Commission, 2009). Disturbance from construction activities nd associated vessel traffic can increase noise and mammal ship strikes, and disrupt behavior and habitat use (Nowacek et al., 2001, 2004; Wells et al., 2008; Bechdel et al., 2009). Restoration activities that reduce salinity in specific coastal areas can affect inshore dolphin skin health, electrolyte balance, stress levels, prey abundance, and/or exposure to infections and contaminants (Barros and Odell, 1990; Wilson et al., 1999; Hart et al., 2012; Meager and Limpus, 2014; Mullin et al., 2015).

Sea turtles may be adversely affected directly and or indirectly by restoration projects that take place on land and at sea (see Table 4.1). Beach armoring and nourishment projects can reduce sea turtle nesting habitat and decrease sea turtle nesting success by altering beach habitat so that it is unsuitable for adult females and their eggs (Lutcavage et al., 1996). Restoration project activities that use heavy equipment to traverse the beach may compact sand and decrease sea turtle nesting success, as well as potentially crush eggs, hatchlings, and nesting females (NMFS et al., 2011). Construction behind beach dunes may also threaten sea turtles if the activities alter dunes or erect structures with lights that can disorient nesting females and emerging hatchlings (Witherington and Bjorndal, 1991; NMFS et al., 2011). Dredging in nearshore waters where sea turtles forage and migrate is also a significant threat (NRC, 1990; Lutcavage et al., 1996). In addition to capturing and killing sea turtles, dredges can indirectly cause adverse impacts by altering important sea turtle habitat (NMFS et al., 2011). Dams and water diversions may also adversely impact sea turtles by reducing prey availability in certain locations. Some of the sea turtles that inhabit Gulf of Mexico waters are benthic feeders during their adult years (e.g., loggerhead and Kemp's ridley sea turtles). These turtles feed on crabs and other invertebrates (Shaver, 1991; Plotkin et al., 1993) whose abundance may be affected locally by changes and disruptions to freshwater inflows (NMFS et al., 2011).

The Gulf of Mexico is used by many species of migratory birds that make wide-ranging seasonal movements throughout their annual cycles, and can also be inadvertently affected by a number of restoration and/or management actions (see Table 4.1). Pending restoration activities across the Gulf of Mexico will likely provide vital habitat for these species at some point during their movements in and around the Gulf region. Perhaps best known of the highly mobile bird taxa include shorebirds, wading birds, and waterfowl, all of which typically require use of multiple wetlands to satisfy different aspects of their life history (Haig et al., 1998). Movements may include 'prospecting' to inspect potential breeding areas (Boulinier et al., 1997), use of foraging areas away from nesting sites (Bildstein et al., 1990), post-breeding dispersal (Erwin et al., 1996), and shifts in site use during migration or the winter (Farmer and Parent, 1997).

Pelagic seabirds in the Gulf of Mexico are poorly known with little work focused on this highly mobile group (Duncan and Havard, 1980). Both biological and physical factors appear to affect Gulf-wide seabird distributions (Ribic et al., 1997), with presence in the Gulf of Mexico varying by season (Hess and Ribic, 2000). Unfortunately, there are some gaps in understanding the linkages between nesting colonies and at-sea foraging areas throughout annual cycles; nor has adequate monitoring data been collected to describe linkages and movements among colonies. This lack of information hampers our understanding of how restoration might benefit or impact these highly mobile species. Due to the lack of distribution and abundance data, their highly mobile character, and the uncertainties outlined above, we suggest broad geographic-focused seabird survey efforts integrated with surveys for marine mammals and sea turtles as an initial monitoring effort. We also stress the need for efforts focused specifically on monitoring movements of seabirds within and among colonies, as well as near and offshore movements throughout the annual cycle. As discussed later in this chapter, the Bureau of Ocean Energy Management (BOEM) and other agencies are planning a Gulf-wide monitoring effort targeting birds, sea turtles, and marine mammals.

Coastal fish species provide another example to illustrate the need to assess restoration effects on wide-ranging animals. The situation for coastal fish is generally different from marine mammals, sea turtles, and birds in that many restoration actions are targeted to specifically improve conditions for fish. Restoration of wetlands leads to increased habitat for many stages of ecologically and economically important fish species (Beck et al., 2001). Many coastal and marine fish and shellfish (e.g., penaeid shrimp) species use wetlands for part of their life cycle, but spend time in other habitats (Able, 2005), which may themselves also be the target for restoration actions or act as stressors for fish and shellfish species. In addition, fish and shellfish populations show wide annual fluctuations due to the effects of environmental and climate variation, changes in predation pressure (Houde, 2008), and for some species, changes in their management (Anderson et al., 2008).

To understand and document the effects of restoration targeted at one habitat and a subset of life stages (e.g., increased wetlands affecting juvenile fish) in contrast to the effects of other habitats and environmental variation on other life stages, monitoring needs to extend beyond the local and project levels. Similar considerations are needed for highly migratory fish species, such as tuna as well, which transverse even wider geographic areas. Understanding these linkages (or testing assumptions) between restoration actions and various life-history stages and specific life-history requirements is critical and typically relies on conceptual ecological models to design the appropriate sampling scheme, as well as on ecological or ecosystem modeling to test assumptions (see Chapter 6). Only when the full life cycle of fish and shellfish populations, the multiple habitats, and the mix of stressors and drivers (Krausman and Harris, 2011) are considered, can the effects of restoration actions be assessed at scales beyond the life stages monitored at the project-level.

The need for cross-scale synthesis of monitoring data to understand cumulative restoration effects (NRC 2003b; Krausman and Harris, 2011) on wide-ranging animals argues for developing an integrated and coordinated approach to monitoring marine mammals, sea turtles, birds, and fish in the Gulf of Mexico. Furthermore, informing cumulative effects analysis with coordinated monitoring for unintended consequences could assist federal agencies with legal challenges (Smith, 2006; Schultz, 2010; Hutto and Belote, 2013). Even then, assigning causation will be challenging in such a large and dynamic system that is affected continually by multiple stressors. Monitoring, research, and data coordination in the Gulf of Mexico will be essential, as most protected species monitoring is performed by federal agencies[46] (Koontz, 2002), whereas state or county agencies or their contractors are being awarded most of the habitat restoration project funds (e.g., by the Natural Resource Damage Assessment [NRDA] Trustee Council and National Fish and Wildlife Foundation [NFWF][47]).Plans are underway to develop a Gulf of Mexico Marine Assessment Program for Protected Species (GoMMAPPS)[48] becaue of the gaps in research and monitoring data available to assess mobile living marine resource abundance, distribution, habitat use, and behavior in offshore waters (Love et al., 2015; Stelk et al., 2016). The program is modeled after the ongoing Atlantic Marine Assessment Program for Protected Species (AMAPPS)[49] and will monitor effects of oil and gas activities, as well as cumulative impacts from other anthropogenic and natural stressors. Collecting broad-scale data using aerial and vessel-based surveys over multiple years on seasonal distribution and abundances of pelagic seabirds, marine mammals, and sea turtles to mitigate and monitor impacts of human activities, especially oil and gas related, is the primary goal of this program. GOMMAPPS also plans to collect data at finer scales at specific sites, employ tag telemetry studies, and collect related habitat characteristics to gather information on seasonal distribution, residence time, abundance, life history, behavior, and habitat use and frequency. GOMMAPPS will involve working groups for marine mammals, sea turtles, and seabirds, whose work is scientifically reviewed and integrated, and coordinated across partnering agencies. These efforts will operate from nearshore waters to the U.S. exclusive economic zone (200 nautical miles offshore) across the Gulf, and may include Gulf-wide surveys encompassing Mexican waters as well. Ultimately, GOMMAPPS intends to develop tools and models to collaboratively produce and share spatially-explicit seasonal density estimates of protected species that incorporate habitat characteristics, which fills a substantial monitoring and assessment need for the region (R. Green, personal communication). As these efforts focus on offshore regions, a monitoring gap may exist for coastal mobile species potentially affected by state-driven restoration projects. It remains to be seen how comprehensive this monitoring effort will be, how many representative target species within each taxa will be monitored, and how many gaps will remain regarding monitoring of mobile species.

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[46] [A57] For example, the National Oceanic and Atmospheric Administration (NOAA) and U.S. Fish and Wildlife Service (USFWS) administer the Endangered Species Act of 1973 as well as the Marine Mammal Protection Act of 1972 (the latter with the Marine Mammal Commission). A group of federal agencies is also planning the Gulf of Mexico Marine Assessment Program for Protected Species (see below).
[47] NRDA early restoration allocation: http://response.restoration.noaa.gov/about/media/nrda-trustees-announce-1-billion-agreement-fund-early-gulf-coast-restoration-projects.ht; NFWF Gulf Response Grants: http://www.nfwf.org/gulf/Pages/projectlist.aspx.
[48] Gulf of Mexico Marine Assessment Program for Protected Species (GoMMAPPS) will be administered by BOEM, NOAA, USGS, and USFWS.
[49] The Atlantic Marine Assessment Program for Protected Species (AMAPPS) is a partnership and joint research program between BOEM, NOAA, USFWS, and Navy that organizes monitoring of a variety of taxa including North Atlantic right whales, sperm whales, bottlenose dolphins, and pilot whales in the southeast Atlantic and Gulf of Mexico: http://www.nefsc.noaa.gov/psb/AMAPPS/.

PARTNERING RESTORATION MONITORING WITH RESEARCH

There is often a strong reluctance to fund restoration monitoring other than construction or performance monitoring (described in Chapter 3), partly because it often is assumed that it comes at the cost of doing restoration, is an ongoing/long-term activity that is not guaranteed to provide useful results (or be cost-effective), and is not framed with a clear purpose and plan (Mazzotti et al., 2007; Tamarisk Coalition, 2014). However, without adequate investment in long-term restoration monitoring to inform future management actions, low levels of certainty will sustain reluctance to fund new projects (Perillo et al., 2009). The magnitude of restoration as well as the influx of research funding currently occurring and planned for the Gulf of Mexico presents a unique opportunity to ensure that the collective impact of restoration projects is maximized. For that reason, targeted research alongside monitoring efforts has the potential to greatly enhance restoration effectiveness.

As discussed extensively in Palmer (2009), application of the latest research is often lagging and conversely, restoration ecologists might not be answering the most relevant questions for which practitioners need answers. Also, a great majority of restoration-related studies do not specify policies that could be informed by results of their research, nor use terminology that is accessible to policy makers. Considering this, restoration research and restoration efficacy would both benefit from explicitly integrating research, policy, and/or public outreach (Groffman et al., 2010; Jorgensen et al., 2014; Perring et al., 2015). The extent of restoration efforts planned combined with the fact that knowledge on the efficacy of ecological is still maturing, particularly for Gulf of Mexico ecosystems, presents a unique opportunity to bring together scientists and practitioners to formulate and address applied and basic research needs (Palmer, 2009; Bjorndal et al., 2011).

At the project- or sub-regional (watershed/estuary) restoration scale, there are several critical information gaps affecting restoration in the Gulf of Mexico. These information gaps result in increased uncertainty as to whether restoration projects will achieve their objectives. Considering the following examples of process uncertainties will aid monitoring in its role to improve the understanding of these processes and enable programs to improve future project design and implementation (The Water Institute of the Gulf, 2013; DWH NRDA Trustees, 2016):

- Restoration in the Gulf has and will occur across a grand geographic scale through individual projects, and the degree to which restoration activities affect species and habitats beyond the project footprint and the extent to which multiple nearby projects interact remain poorly understood.
- Sea-level rise, subsidence, and the periodic impact of tropical storms and hurricanes introduce considerable uncertainty in the outcome of restoration projects.
- There is an insufficient understanding of some of the target resources (e.g., deep benthic communities) that limits the development and implementation of certain restoration projects at a large scale.
- Some approaches to restoration may be untested or controversial (e.g., diversion of water and sediment to build land mass).
- Some restoration efforts depend upon voluntary participation by commercial interests (e.g., voluntary changes in fishing practices or gear to reduce bycatch), levels of

participation are difficult to predict, and factors that influence behavioral changes are not well understood.

Difficulties in bridging the gap between research and its application are not unique to restoration practice and many solutions are available, such as joint meetings and conferences between practitioners and scientists, cooperative research institutes, jointly developed research agendas, dedicated boundary organizations, and/or scientific review and evaluation of restoration studies. Several programs are in place that could bridge restoration research with its application and implement some of these solutions: the Gulf Research Program at the National Academies of Sciences, Engineering, and Medicine, NOAA Resources and Ecosystems Sustainability, Tourist Opportunities, and Revived Economies of the Gulf Coast States (RESTORE) Act Science Program, Centers of Excellence, and Gulf of Mexico Research Initiative. These programs could work jointly with the restoration programs to identify the most pressing research questions and identify restoration projects that would not only benefit from monitoring for adaptive management but also from targeted research experiments at the restoration sites, for example, to inform some uncertainties about the conceptual models.

In particular, more rigorous and extensive monitoring becomes most crucial when a project is associated with some known risk factors such as high scientific uncertainty associated with a conceptual model, novel restoration technique, large restoration scale, extensive potential socio-economic consequences, or long-term restoration. When projects are undertaken with some of these high-risk factors involved, monitoring for adaptive management may be needed (see Chapter 7 for further discussion). Knowledge gained from such restoration monitoring efforts could be further enhanced if research were undertaken alongside such restoration projects. Such joint efforts between restoration practitioners and scientists would not only advance restoration science, but also significantly enhance the practice of restoration by improving the knowledge base used to design restoration projects (NRC, 2003; Brumbaugh et al., 2006; Perring et al., 2015). Considering such partnerships might also be necessary when commitments to extensive, long-term monitoring are insufficient.

CONCLUSIONS AND RECOMMENDATIONS

The current magnitude of funds and efforts being invested in restoration in the Gulf of Mexico marks an unprecedented opportunity to solve the challenges currently faced, to improve cost-effectiveness and outcomes of restoration projects, and to advance science in support of restoration. Because some projects may take decades before they become self-sustaining and fully restored, and because individual projects interact with other projects, monitoring beyond the duration and scale of individual projects will be needed to understand whether the Gulf of Mexico region's ecosystem is recovering. **Thus, the Committee concludes that restoration programs (i.e., the NRDA Trustee Council, the RESTORE Council, and NFWF) and Gulf research programs (i.e., the NAS Gulf Research Program, NOAA RESTORE Act Science Program, and Centers of Excellence for each Gulf state) would greatly benefit from working together to identify strategic opportunities in the Gulf of Mexico to maximize the effectiveness and utility of monitoring while also reducing the overall cost of long-term**

monitoring across the Gulf region. The Committee recommends that the restoration and research programs develop long-term, broad-scale restoration monitoring in the Gulf due to the large restoration scale, slow anticipated recovery time for several species, novel restoration techniques, number and diversity of restoration projects, potential and intended socio-economic influences, and uncertainties associated with climate change and extreme weather.

The Committee recommends that restoration programs jointly with research programs (i.e., the Academies' Gulf Research Program, NOAA RESTORE Act Science Program, and Centers of Excellence for each Gulf state) consider the following options for leveraging program funds and needs:

- Explore opportunities for a system of reference sites across the Gulf of Mexico for several types of habitats to be restored (modeled after and expanded from CRMS);
- Identify potential long-term ecological monitoring sites that could be paired with ecological research to improve the effectiveness of restoration approaches;
- Monitoring mobile species may require comparison beyond static reference sites, such as using reference populations or seasonal reference points (e.g., GoMMAPPS will conduct a temporal, species-based version of sentinel site monitoring); and
- Jointly identify the most pressing research needs, objectives, and questions that would inform and improve restoration effectiveness.

CHAPTER 5
DATA STEWARDSHIP

Data from restoration monitoring efforts will form the basis for assessing restoration performance, progress toward goals and objectives, planning, and guiding actions. This chapter discusses the elements of a comprehensive data management system designed to produce high-quality future restoration and planning data suitable for analysis and synthesis to yield knowledge that can guide decision-making. The Committee was asked to identify "options to ensure that project or site-based monitoring could be used cumulatively and comprehensively to track effectiveness" at larger spatial scales**.** Data stewardship is an important element to ensure such synthesis efforts can assess restoration effectiveness at larger spatial scales. Good data stewardship also enables assessment and documentation of lessons learned from restoration outcomes. A well-functioning data management system can provide information on a timely basis to support adaptive management at the project and program scale.

This technical overview of data management covers good practices in aspects such as quality assurance and quality control, metadata, data publishing, and policies and platforms for data sharing. However, it does not provide specific guidance on implementation of these concepts since recommendations for specific situations will vary substantially among communities or science domains of practice. Furthermore, it is outside the scope of this report to recommend methods of ensuring that particular standards are adopted and followed, or the length of time that data needs to remain proprietary, for example.

THE IMPORTANCE OF A DATA MANAGEMENT PLAN AND DATA MANAGEMENT SYSTEM

The principal goal of data management is to preserve the usability of data and information through time. The challenges to achieving open sharing and long-term preservation of data are not unique to restoration monitoring and are documented for many fields of science (Wicherts et al., 2006; Reichman et al., 2011). The failures to make data publically available are so pervasive that an editorial in the journal Nature referred to it as "data's shameful neglect" (Nature editorial, 2009). Furthermore, accessing data after the publication of a manuscript becomes increasingly difficult (Vines et al., 2014), despite recognized benefits of data sharing for the particular research field and increased citation rates for the particular manuscript in which the data were originally published (Piwowar et al., 2007). Recognizing the importance and benefits of digital data availability, the White House Office of Science and Technology Policy (2013)[50] adopted an Open Data Policy and directed federal agencies to make federally funded research data available to the public in digital formats.

Data stewardship comprises behaviors, practices, and actions that ensure project and program data are of good quality, secure, available, understandable, and useable through time. Some agencies have developed guidance and policies to encourage good data management,

[50] https://www.whitehouse.gov/the-press-office/2013/05/09/executive-order-making-open-and-machine-readable-new-default-government;last accessed February 26, 2016.

stewardship, and data publication (e.g., USGS [51]). In contrast, the Committee finds that some frequently used restoration guides (e.g., Thayer et al., 2005; Baggett et al., 2014) failed to address the topic. Therefore, the Committee concludes that in the future such restoration guides should include discussions of good practices for data management as discussed in this chapter.

Restoration projects typically include a project manager, project scientists and engineers, technicians, and a range of skilled practitioners. While most project scientists and practitioners have a hand in data stewardship, experience shows that best results are achieved when data management activities and deliverables are included in the contractual requirements and in the project budget, and when data management needs are considered early in project cost discussions. Results are also improved when the proposal explicitly identifies the data manager responsible for project data management. These data management practices enable project managers to assess and report on project performance and help the funding agencies assess restoration activities and outcomes. Requiring restoration projects to include a data management plan helps ensure that data are preserved and public funds are more efficiently allocated by making data management a project priority at the outset rather than near the end. Whether the plan is developed by the project or imposed by the program is not as important as the need to have some plan.

A complete data management plan describes the full life cycle of project data from collection to archiving. The plan describes the roles and responsibilities of data providers, data management staff, and end users. Based on the Committee's review of best practices for data stewardship (NRC, 2003, 2007), a good data management plan describes some or all of the following elements that make up the data life cycle:

- the data to be created or collected,
- details of data collection and tracking (collection forms, procedures/protocols, sample labeling, chain-of-custody),
- details of any transformations (data averaging, filtering, or editing),
- quality assurance and quality control,
- data security and backup,
- identification of community standards to be employed (i.e., for metadata content, metadata encoding, controlled-vocabularies, units of measure, file formats, and encoding),
- data sharing and release policies,
- intermediate and long-term archiving (i.e., portals, cooperatives, trusted digital repositories), and
- the acquisition and use of digital object identifiers (DOI).

A data management system is a realization of the data management plan. It consists of human effort combined with hardware and software resources as well as community agreements on best practices, standards, and policies. A good data management system takes actions to ensure that data and metadata are sufficiently complete such that appropriately trained users will

[51] Guidance from the US Geological Survey is available here: http://www.usgs.gov/datamanagement/index.php.

have the information needed to comprehend what the data are, how, when, and where they were obtained, and what they represent without additional information (NRC 2007). A good data management system makes data easy to use. It does this by making data easy to discover, understand, access, and retrieve at selectable levels of granularity in user preferred forms and formats. Better data management systems offer online browsing capabilities that help users determine if the data are likely to be fit for a particular purpose before retrievals are initiated, and support remote sub-set services in cases where only small parts of larger data sets are desired (NRC 2007). A data management system incorporates community agreements on standards and best practices. Standards include descriptions of how information is encoded (e.g., file formats, measurement units, vocabularies) and what pieces of auxiliary information are required or optional (i.e., metadata content standards).

GUIDANCE FOR THE MOST CRITICAL ELEMENTS OF THE MANAGEMENT PLAN

The following sections provide some additional details regarding important considerations when developing or implementing the data management plan to help ensure that high-quality data are accessible for analysis and synthesis into the future.

Quality Assurance and Quality Control

Quality assurance (QA) and quality control (QC) are essential elements of a quality data management program.[52] QA refers to taking actions before data are collected to prevent data defects (e.g., proper selection and placement of sensors and their settings for the application). QC refers to corrective steps taken after the data are collected (e.g., flagging, removing, or replacing wild-points, out of range values, and data contaminated by sensor fouling or equipment failure). Guidance on QA/QC often exists for the type of measurements being made and/or the specific equipment used. For example, the U.S. Integrated Ocean Observing System (IOOS) Quality Assurance of Real-Time Oceanographic Data Program has produced a series of documents for wind, water level, optics, temperature and salinity, dissolved oxygen, nutrients, surface waves and *in situ* measurements of ocean currents, and others are planned. These manuals describe required and recommended QA activities and QC checks based on advice from numerous leading experts in the various communities of practice. The QA/QC process for ecosystem restoration is discussed by Stapanian et al. (2015). One of the best ways to improve data and uncover flaws is through data sharing and synthesis activities prior to the end of a project. Once data are submitted to a long-term repository, it is unlikely that further improvements will ever be made.

[52] IOOS Quality Assurance of Real-Time Oceanographic Data manuals are available here: http://www.ioos.noaa.gov/qartod/welcome.html.

Metadata

Documenting metadata is central to data and information preservation. Metadata provide information about what data were collected, where and when they were collected, by whom, and the method(s) used. There are three common difficulties associated with producing metadata: 1) the person who collected the data and is in the best position to create metadata, typically does not have a need or the expertise to cast metadata into standard forms; 2) the beneficiaries of good metadata are unknown future users and it is difficult to anticipate what auxiliary information would be important to them; and 3) the creation of good metadata is tedious and labor intensive, and often this work is not budgeted for (Michener, 2006; NRC, 2007). Consequently, and all too often, metadata creation is delayed with the result that metadata are non-existent, incomplete, or become separated from the data. Metadata are more useful when they adhere to published standards for content, vocabularies, and schema. Standards specify what additional pieces of information (content) are required or optional, what words are used to express the information (controlled-vocabularies), and how they must be written (encoding schemas) so that computers can process them. Adherence to standards enables computerized search and machine-to-machine exchanges without loss of information. A wealth of information on metadata standards is given by the Federal Geographic Data Committee (FGDC, 2012).

Content Standards

An important aspect of metadata development is to anticipate what information is important to record. Because gathering "additional information that may be important to all future users of the data" is an unbounded task, some informed consensus on what needs to be recorded is needed. For this reason, metadata content standards have been developed by user communities that articulate what information is required to enable comprehensive data use within their subject areas. Community metadata content standards are lists of information that a community has deemed to be required and/or optional. Standards can be built by adopting smaller blocks of standards for elements common across many communities (e.g., blocks for date-time, address or location, people and organizations, personnel and labs, species, sensors, and platforms).

For data that have significant geospatial content, i.e., any data for which a latitude and longitude are generally recorded, which is likely true for most restoration data, there are two widely-used content standards: 1) a standard produced and promulgated by the Federal Geographic Data Committee (FGDC) and many federally-funded programs have required its use; and 2) the International Standards Organization (ISO) 19115 family of standards for geographic metadata.[53] The metadata content standard for a particular project can be built-up by combining or extending standards. There are many such existing standards; for example, Dublin Core is a set of standards for objects that might be found on the web (web pages, documents, etc.). It is the basis for Darwin Core, which is a standard for sharing information on biological diversity. The Ocean Biogeographic Information System developed a schema that extends the Darwin Core to better capture the geographic aspects of observations of the species occurrence.

[53] FGDC standards facilitate the development, sharing, and use of geospatial data: https://www.fgdc.gov/standards.The ISO family of geographic information/geomatics work aims to establish a structured set of standards for information concerning objects or phenomena that are directly or indirectly associated with a location relative to the Earth: http://www.isotc211.org/.

The Ecological Society of America developed a metadata specification for ecological data that builds on Dublin Core, FGDC, and elements of ISO called the Ecological Metadata Language.[54] A wealth of information about marine-related metadata and content standards for many disciplines is available from the Marine Metadata Interoperability website, the International Oceanographic Data and Information Exchange, and other sources.[55]

Controlled-Vocabularies and Ontologies

Vocabularies are terms used within a language to name objects and concepts, but the same word can have a different meaning depending on the context or community. For example, the term “current” has a different meaning to a marine scientist than it does to an electrician. A controlled-vocabulary (CV) is a carefully selected and curated vocabulary designed to support the unambiguous interpretation of shared data objects and concepts for a particular community. For example, the numerical weather modeling community developed a CV called the Climate and Forecast Set of Standard Names,[56] which is a list of commonly used terms with exact spellings, definitions, and units. These conventions have been widely adopted for exchanging observed data as well as model outputs. The Marine Metadata Interoperability website[57] hosts CVs for a number of domains and provides guidance on how to select a good CV. Like content standards, CVs can be constructed for a particular project by combining one or more CVs, borrowing a few terms from a CV, or extending an existing CV.

An ontology supplements the terms in a CV by describing classes, attributes, and relationships of the vocabulary’s objects and concepts.[58] Encoding these additional pieces of information can greatly improve computer-aided search results (e.g., searches for “sea surface temperature” and “SST” would return the same information, searches for salinity would return conductivity data, searches for “remotely sensed sea surface temperature” would return satellite data but not buoy data). Constructing ontologies is relatively difficult and is usually done by experts. However, by adopting an existing CV, one often gains an existing ontology as well and thereby greatly increases the potential for data discoverability. It is for this reason that data managers are strongly encouraged to find a CV and use those terms to name their data. Ontologies can be used to map terms among different CVs and content standards, allowing automated searches to occur across data systems that employ different standards.

Schemas

Schemas are rules for encoding metadata in a useful and consistent ways that computer algorithms expect. Like content standards and CVs, schemas can be built by combining other

[54] Ecological Metadata Language EML is a metadata specification developed for the ecology discipline: https://knb.ecoinformatics.org/#external//emlparser/docs/index.html.
[55] Marine Metadata Interoperability content standards: https://marinemetadata.org/conventions/content-standards; International Oceanographic Data and Information Exchange guidelines (data management plan updated in March 2016: http://www.iode.org/index.php?option=com_oe&task=viewDocumentRecord&docID=16859).
[56] The Climate and Forecast Set of Standard Names: http://cfconventions.org/standard-names.html.
[57] Marine Metadata Interoperability is available here: https://marinemetadata.org/conventions/vocabularies.
[58] Ontologies are constructed to improve computer searches. Classes are kinds of things such as “remotely sensed” data and “*in situ”* data. Attributes are characteristics such as a name, unit of measure, or numerical value. Relationships are logical constructs between objects that describe equivalence and subordination.

schemas. For example, the ISO 8601 standard requires date-time to be encoded in UTC as "2015-08-29T04:30Z." Other schemas exist for geographic locations, organizations, and many other common types of metadata. If the data originator or data manager follows published schemas, then someone at a later date will not need to invest time to make data more transportable and suitable for automated processing.

Data Publishing

Data publishing is the mechanism by which data are made available to others. For example, a small project may send a DVD or hard drive containing their data to an archive at the conclusion of the project and leave publishing to the archive. In contrast, a large or lengthy project may expect to service recurring requests for data during the course of the project. They may want to deploy their own data portal or subcontract such services. The type of services one might expect in a data portal or similar entity include: a catalog or registry offering multi-faceted searches, an online browsing capability offering views of the spatial and temporal coverage of the data inventory and plots of data subsets to help users decide if the data are fit for their purpose, a way for the user to mark the selected data for download or other access, choices of output formats, and support for data transfers from the portal to the user.

A relatively new option in scientific publishing is the ability to cite or reference a specific digital dataset using a digital object identifier (DOI). A DOI is a unique character string that points to data on a host somewhere. DOIs are issued (sometimes called minting) by DOI Registration Agencies like DataCite[59] and others. If the dataset were to move to a new host, the DOI would remain the same, i.e., it would persist but the information behind the DOI would be updated by the registration agency to point to the new host. While many journals support DOIs, conventions for citing or referencing the DOI varies by journal. For example, a citation might simply say DOI: 10.1006/jmbi, but this resolves to a permanent URL with the prefix http://dx.doi.org/. Thus the actual URL is http://dx.doi.org/10.1006/jmbi.

Policies for Data Release, Data Sharing, and Data Use

Policies governing data release and sharing typically specify the timing of data releases, define who may receive data, and set procedures for initiating, processing, and fulfilling data requests. In 2013, the Office of Science and Technology Policy stated that the data upon which a scholarly conclusion in a scientific publication is based must be made available online at the same time the scientific manuscript is made available to the public.[60] Many proposals to NOAA require adherence to NOAA's Data and Publication Sharing Directive for Grants and Contracts,[61] and some scientific journals require data to be submitted to a repository as part of the publication process. Policies might require that a formal written data request be submitted to a funding agency manager who might deny early release to the press but grant early release to a cooperating restoration project. It is important to anticipate possible scenarios and build policies

[59] DataCite is available here: https://www.datacite.org.
[60] Office of Science and Technology Policy Open Access memo: https://www.whitehouse.gov/sites/default/files/microsites/ostp/ostp_public_access_memo_2013.pdf.
[61] NOAA Data and Publication Sharing Directive for Grants and Contracts version 3.0: https://nosc.noaa.gov/EDMC/PD.DSP.php.

into the funding opportunity documents. Generally, the environmental community is moving towards open data sharing policies that allow the principal investigator adequate time to have the first and best opportunity to work with the data but require the data be made available to the public on a timely basis free of charge. Experience shows that data quality improves with repeated use, for example by leading to the discovery of errors, especially when the data are combined and considered along with other datasets. This typically occurs in the analysis phase of a project, and there can be merit in delaying data submittal to long-term digital repositories until the most likely opportunities to improve the data have been exhausted.

While the funding agency sets policies, the data provider needs to prepare and publish a data use policy.[62] A data use policy covers what the data user may expect of the provider's data and the provider, and what behavior the provider expects of the user. For example, a data use policy may express caveats and disclaimers on the accuracy, validity, and fitness for purpose of data in an attempt to absolve the data provider of liability for negative outcomes resulting from the use of the data. If data usage is tracked, the policy may state how the provider will use the user's tracking data with respect to privacy issues. The data use policy may ask that any publications based on the data include a citation or other acknowledgment or suggest the courtesy of a conversation with the principal investigator. As discussed in Chapter 1, despite data publishing policies, it is often difficult to ensure that data are made publically available in a reasonable time-frame. Thus, the Committee concludes that it is important to carefully consider how to design and incentivize compliance, as well as to possibly enforce standards and penalize non-compliance, with such policies at the beginning of a project.

Trusted Digital Repositories, Data Portals, Data Cooperatives, and Cyberinfrastructure

Restoration work will generate data having value well beyond the end of the individual projects and overarching programs. This value will be realized only if the data are preserved and re-used. This poses two questions: where data reside to best ensure preservation? and where data reside to best facilitate use?

Clearly, preservation of digital data begins immediately after data collection when project-staff make and distribute backup copies of the data to local and remote sites. However, long-term archival of digital data is best handled by a "trusted digital repository." "A trusted digital repository is one whose mission is to provide reliable, long-term access to managed digital resources to its designated community, now and in the future" (RLG, 2002). An important attribute of a trusted digital repository is its longevity, which is related to institutional viability. Several principal trusted data repositories for earth and ecosystem science data in the US are funded by the US Federal Government solely to provide this service; their longevity is reasonably well assured. Some trusted repositories reside in Universities such as the Macaulay Library of the Cornell Lab of Ornithology, which has been curating and distributing analog (and now digital) recordings of bird and other animal (e.g., whale) vocalizations since 1929. Trusted digital repositories generally serve one or more science domains (e.g., oceanography) and do not accept data from other science domains. Thus, the choice of where to submit data for long-term archiving is often dictated by the type of data. In some cases, a repository for a particular

[62] For example, see the NOAA Restoration Center Guidelines for Data Sharing Plans: http://www.habitat.noaa.gov/partners/toolkits/ffo/example_data_sharing_plans_noaa_rc.pdf.

type of data (e.g., dispersants) is not available. These so called "orphan" datasets tend to get lost over time. In such cases, alternatives to trusted digital repositories need to be considered.

Data portals and data cooperatives are repositories where data from projects and programs tend to aggregate over the program's lifetime. These repositories hold data types from all of the science domains that the programs cover and serve a smaller but broader community than the long-term repositories. Data portals and data cooperatives tend to persist only as long as the programs they serve. While they are not long-term solutions, there is a benefit to submitting data to both intermediate and long-term archives in the same way as making and distributing multiple copies to local and remote sites.

Facilitating data use is achieved by providing services that make data easy to discover and acquire in desired forms and formats. Typically, users search for data at known data-aggregation sites or portals, cooperatives, and repositories. Thus, submitting data to such sites will promote data-use. The specific entity/entities selected to receive project/program data will depend primarily on the types of data they specialize in and the services they offer.

Although there is considerable overlap between what portals, cooperatives, and repositories do, there are subtle differences. *Data Portals* aggregate similar types of data received in various forms from both affiliated and unaffiliated sources; these data are transformed and published in uniform forms and desirable formats. *Data Cooperatives* aggregate data of various types received from their membership and publish the data as received. *Data Repositories* aggregate similar types of data from myriad sources for long-term preservation and publish the data as received. Portals strive to make data easier to use and persist as long as they are able to find funding. Cooperatives serve their membership community and persist as long as the community support persists. Repositories are primarily concerned with long-term preservation and are expected to persist indefinitely. These three functions can exist in one entity, such as the USGS's National Water Information System,[63] which aggregates data in a uniform way with a high likelihood of information longevity. USGS also manages ScienceBase,[64] a collaborative data cataloging and management platform that serves hundreds of environmental communities. Louisiana's Coastwide Reference Monitoring System[65] manages short- and long-term restoration of coastal wetlands within the state, and enables assessment of the cumulative effects of these activities (Steyer et al., 2003). See Part II for references to other habitat and taxa-specific platforms, such as eBird.[66]

A few major data aggregating entities in the Gulf of Mexico that accept a broad range of environmental data types from a large number of data originators include the Gulf of Mexico Coastal Ocean Observing System (GCOOS) Data Portal,[67] the Gulf of Mexico Research Initiative Information and Data Cooperative (GRIIDC),[68] the National Oceanic and

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[63] The National Water Information System (NWIS) aggregates decades of similar types of data that have been acquired in various forms and formats from their regional members and offers uniform data through standards-based web services: http://waterdata.usgs.gov/nwis.
[64] ScienceBase provides a common platform for discovering data and associated products, and requires submission of metadata along with data (preferably in common and open formats): https://www.sciencebase.gov/catalog/.
[65] The state Louisiana's Coastwide Reference Monitoring System (CRMS) gathers information from a suite of sites that encompass a range of ecological conditions across its coast: http://lacoast.gov/crms2/home.aspx.
[66] eBird is an international real-time checklist program that collects information on bird abundance and distribution at a variety of spatial and temporal scales: http://ebird.org/content/ebird/.
[67] Gulf of Mexico Coastal Ocean Observing System (GCOOS) portal: http://data.gcoos.org.
[68] Gulf of Mexico Research Initiative Information and Data Cooperative (GRIIDC) database: http://data.gomri.org.

Atmospheric Administration's National Centers for Environmental Information (NOAA/NCEI),[69] NOAA's Office of Response and Restoration (ORR), and the U.S. Environmental Protection Agency (EPA).

The GCOOS Data Portal aggregates near real-time and historical physical oceanographic, marine meteorological, biogeochemical, and selected biological data from federal sources and both funded and unfunded non-federal sources and re-distributes these data in common formats through standards-based interfaces conforming to IOOS's sanctioned standards and best practices. GCOOS will submit near real-time and historical data not already residing in NCEI to NCEI. GCOOS was established in 2005 and has secured funding through mid-2021.

GRIIDC is the data management arm of the Gulf of Mexico Research Initiative, which administers environmental ecosystem and oil spill research funded by BP for the ten year period of 2010 through 2020. GRIIDC's holdings include a wide range of physical, chemical, and biological data, including data on petroleum and dispersants derived from over 240 projects and almost 3,400 researchers. The platform assists researchers in the process of submitting data, and tracks datasets to ensure proper archiving. GRIIDC re-distributes data in the originator's formats through their website and will archive data in appropriate long-term digital archives including NCEI. GRIIDC is actively seeking other funding opportunities to ensure their database continues to be available well beyond 2019.

In 2015, NOAA's National Oceanographic Data Center, National Geophysical Data Center, and National Climatic Data Center were consolidated into NCEI. NCEI and its preceding components all exhibit the characteristics of a long-term trusted digital repository, which include administrative responsibility, organizational viability, and financial sustainability, among others. NCEI is primarily concerned with preserving access to original data without loss of information through continual migration across changes in information technology. NOAA/ORR developed a nation-wide series of data portals, the Environmental Response Management Application (ERMA)[70] to support regional responses to environmental disasters. Following the Deepwater Horizon event, in addition to supporting response efforts, ORR was tasked with building a portal for the environmental data (including photographs, telemetry, field observations, instrument data, and laboratory results for tissue, sediment, oil, and water samples) supporting the Natural Resource Damage Assessment litigation. These data can be queried, visualized, and downloaded through the Data Integration Visualization Exploration and Reporting (DIVER) explorer tool.[71] ORR has expressed interest in continuing to aggregate DWH restoration data if possible and in 2016 devoted significant resources to improving and enhancing their system.

The EPA has developed the STOrage and RETrieval and Water Quality eXchange (STORET/WQX) system to house and exchange terrestrial and near coastal water quality and

[69] National Centers for Environmental Information (NCEI) site: https://www.ncdc.noaa.gov/news/national-centers-environmental-information.
[70] The Environmental Response Management Application (ERMA) is an online mapping tool that integrates both static and real-time data: http://response.restoration.noaa.gov/maps-and-spatial-data/environmental-response-management-application-erma.
[71] NOAA ORR public Natural Resource Damage Assessment data: https://dwhdiver.orr.noaa.gov.

pollution data for US states, tribes, and federal agencies. By the above definitions, STORET/WQX is a cooperative long-term repository.[72]

Cyberinfrastructure is a term coined by the National Science Foundation (NSF) to describe the infrastructure composed of computers, networks, software, and community agreements that enable the automated discovery and delivery of distributed data to distributed users without loss of information. In abstract discussions, cyberinfrastructure is often cast as resources and services. Resources are hardware, networks, data, and people. Services are community agreements expressed in the form of software codes that enable user-driven system-to-system exchanges of information. Most of this software operates at the interfaces between systems. All contemporary portals, cooperatives, and repositories have incorporated current cyberinfrastructure into their systems to varying degrees.

Cyberinfrastructure has co-evolved along several lines in the past decade. The Open Geospatial Consortium (OGC) establishes and/or sanctions standards and best practices for data with strong geospatial content. Their guidance documents[73] include high-level abstract specifications on functionality and sufficiently detailed implementation standards such that developers can independently build interoperable software systems. Much of the OGC work has been incorporated into the standards sanctioned and used by large commercial software companies for Geographical Information Systems as well as by federal systems. The IOOS Program is the US contribution to the Global Earth Observing System of System, which seeks to harness the myriad of globally-distributed near real-time observations of environmental parameters in support of many societal benefits. The IOOS Program office is also the organizing entity for the 11 Regional Associations that span US territorial waters, of which GCOOS is a member. The IOOS focus is on quasi-operational delivery of data and model output.

The NSF has sponsored a number of initiatives such as Geoscience Network (GEON), National Ecological Observatory Network (NEON), Ocean Observatories Initiative (OOI), and others designed to develop cyberinfrastructure that unifies open science data systems including portals, cooperatives, and observing systems. The NSF focus is research-oriented and seeks to develop intelligent interfaces and more capable search facilities. Currently, the Data Observation Network for Earth (DataONE) program[74] has gained considerable traction in the research community. DataONE consists of three coordinating nodes and a growing number of member nodes. The coordinating nodes replicate member node catalogs and optionally their data holdings. Member nodes benefit because their data holdings are more easily discovered by a broader community. DataONE also provides a number of resources designed to help new data collection programs develop data management plans and learn about best practices that cover the whole data life cycle. Both GCOOS and GRIIDC are becoming member nodes in DataONE, making their data more accessible to the broader research community.

Another NSF initiative, EarthCube,[75] seeks to inspire collaborations between geoscientists, informaticists, and cyberinfrastructure developers who will lead community development of capabilities for interoperable sharing of data. It is also an opportunity to educate

[72] EPA STORET/WQX data: http://www3.epa.gov/storet/.
[73] The Open Geospatial Consortium archive: http://www.opengeospatial.org/docs/is.
[74] The Data Observation Network for Earth (DataONE) program is available here: http://dataone.org.
[75] EarthCube is available here: http://earthcube.org/.

scientists in data stewardship and digital scholarship. The NOAA/NASA analog to NSF's EarthCube is the Federation of Earth Science Information Partners (ESIP).[76]

Prominent cyberinfrastructure groups influencing data system development in the Gulf include IOOS, a federal interagency program led by NOAA,[33] and DataONE. The Committee concludes that requiring data submission is the best way to ensure that data collected at great expense and effort are preserved as a lasting legacy.

CONCLUSIONS AND RECOMMENDATIONS

In general, data from research and from restoration monitoring, in particular, are often not made publically available. Lack of data access makes it difficult or impossible to evaluate retrospectively whether restoration objectives were achieved for many restoration projects, even when monitoring occurred. To overcome this barrier to restoration evaluation and enable restoration programs to document and demonstrate progress toward restoration objectives, good data stewardship is essential. Data stewardship preserves data for current and future use.

To increase the likelihood that data from restoration monitoring will become publicly available, data stewardship should be a priority in restoration monitoring from the onset and should employ a well-conceived data management plan. **To ensure that data stewardship is addressed appropriately, the Committee recommends that all restoration projects be required to include a written data management plan and deliverables as a condition for funding restoration proposals. Those plans should:**

- Identify roles and responsibilities of the data providers, data management personnel, and end users.
- Describe the flow of data including any transformations.
- Describe and apply appropriate data QA/QC and cite the authoritative guides that will be followed.
- Identify and apply appropriate community standards for metadata content and controlled vocabularies that will be applied to the datasets. Where gaps exist in community standards, the project should adopt, adapt, or extend other existing standards.
- Early data sharing and synthesis activities conducted prior to data archiving should be encouraged because data quality is improved through use.
- Develop data sharing policies and establish them in writing prior to project implementation and collection of any data.
- Identify appropriate long-term trusted digital repositories where the full body of data and metadata will be submitted. Data can be submitted to the repository by the originator or by a portal or cooperative on behalf of the originator. This will likely require the restoration funding programs to provide support for new facilities or to supplement or expand existing facilities; Along with the previous consideration, restoration funder

[76] The Federation of Earth Science Information Partners (ESIP) is an open, networked community that brings together science, data, and information technology practitioners: http://www.esipfed.org/.

support for this recommendation will facilitate synthesis of data that describe separately implemented but interconnected restoration efforts (see Chapter 6).

- Publish data using Digital Object Identifiers (DOIs).
- Consider how to design and incentivize compliance, as well as to possibly enforce standards, with such policies at the beginning of a project.

Data publishing and archiving is currently facilitated by existing data portals, data cooperatives, and data repositories. Examples from the Gulf of Mexico include the Gulf of Mexico Coastal Ocean Observing System (GCOOS) Data Portal, the Gulf of Mexico Research Initiative Information and Data Cooperative (GRIIDC), NOAA's Data Integration Visualization Exploration and Reporting (DIVER) Explorer, and EPA's STOrage and RETrieval and Water Quality eXchange (STORET/WQX)[34] data systems. Such cyberinfrastructure makes data archiving feasible and practical for all parties engaged in restoration monitoring. **Restoration programs should require that monitoring data are archived with an entity that has long-term support to ensure managed open data-access for the next several decades**.

Finally, the Committee considered whether to recommend that all restoration data be submitted to a single central facility, and if so whether that facility should be a new facility or an existing facility. Given that it takes years for a new activity to become fully-established and well-functioning, we felt that using an existing facility was the more reasonable approach. The Committee saw merit in choosing a single facility but none of the existing facilities in the Gulf are of sufficient size to take on all the work expected to come out of this massive restoration and monitoring push, and none currently offer the full scope of capabilities required. The existing groups are complementary and all could play a role together in serving the broader community and the coming synthesis efforts (see Chapter 6).

CHAPTER 6

SYNTHESIS AND INTEGRATION

Individual restoration projects can be extremely valuable, but the cumulative effects of multiple ad hoc, small-scale efforts are unlikely to regain large ecosystem function without coordination (Manning et al., 2006). Indeed, much essential knowledge from Gulf restoration monitoring can only be gained by integrating disparate data and information from multiple sources into a cohesive interpretation of specific issues or topics. The Committee refers to such activities as "synthesis" to distinguish them from data analysis and reporting activities that would be routinely performed to assess implementation and progress of local restoration projects. Examples of synthesis activities include:

- Aggregation and analysis of monitoring data from multiple localities to assess resource-specific restoration progress over larger spatial scales and longer time periods;
- Compilation, integration, and analysis of local biological survey data and environmental monitoring data to evaluate restoration effects on wide-ranging organisms such as fish, birds, and marine mammals;
- Aggregation and analysis of physical and biological data over multiple projects and years to identify key ecological factors and interactions affecting restoration outcomes for specific species and habitat types; and
- Transdisciplinary analysis of integrated environmental monitoring data and socio-economic data to determine ecosystem service benefits of environmental restoration to human communities.

Synthesis can thus serve many important purposes. Synthesis of monitoring data at both project-level and across multiple projects is needed to provide the Gulf states, Congress, and the public with regular, synoptic reports on restoration progress. Synthesis is also needed to inform better program management in terms of where to deploy resources, as well as opportunities for improved restoration design and management (see also Chapter 7). Synthesis activities will accelerate progress in scientific understanding that underpins all Gulf restoration efforts. For these reasons, the Committee concludes that synthesis and integration of restoration monitoring data are essential to guide restoration efforts in the Gulf of Mexico region toward achieving their high-level goals.

This chapter presents the rationale for incorporating synthesis as an integral component of Gulf restoration monitoring programs. Together with Chapters 4 and 5, this chapter addresses the Committee’s task: “to augment current best practices that could increase effectiveness, reduce costs, ensure region-wide compatibility of restoration monitoring data, and advance the science and practice of restoration;” and “to identify options to ensure that project, or site-based, monitoring could be used cumulatively and comprehensively to provide region-wide insights and track effectiveness on larger spatial and longer temporal scales.” Special consideration is given to the issue of integrating and analyzing data across multiple spatial and temporal scales, or "scaling."[77] Some key methodological elements necessary to support effective synthesis using Gulf monitoring data are also discussed. The chapter concludes by considering possible organizational models to support synthesis for Gulf restoration.

RATIONALE FOR SYNTHESIS AND INTEGRATION

Ongoing and planned Gulf restoration projects span a wide range of space and time scales as well as ecosystem and habitat types, from local site restoration to restoration of multiple sites within a *landscape* or *watershed* or multiple restoration activities in a larger region. Some single restoration actions can affect entire habitats and regions, and may enhance or diminish the effects of other restoration activities (Allison and Meselhe, 2010; see Table 4.1). These potential project interactions make not just monitoring, but synthesis of monitoring data, critical to effective multi-faceted restoration.

For Gulf restoration, a concerted effort will be needed to support synthesis both within large individual "projects" where multiple restoration activities are monitored by single organizations or collaborative entities, and for activities that integrate monitoring data from multiple smaller and possibly unrelated projects across several organizations. An example of an organization scaling up wide-ranging restoration monitoring activities is Louisiana's Coastwide Reference Monitoring System[78] (for wetlands) and System-Wide Assessment and Monitoring Program (for barrier islands and open water areas),[79] which together ensure consistent monitoring parameters and provide reference sites (see Chapter 3) to evaluate individual project and overall program effectiveness, as well as to assess landscape change across the state (Hijuelos et al., 2013). Other relevant cases include the Saltmarsh Habitat & Avian Research Program[80] collaboration that aims to advise management actions for tidal-marsh birds and their habitats across the Northeast U.S. (and provides a potential model for monitoring the effects of sea-level rise and upland development in the Gulf; e.g., Elphick and Field, 2014; Elphick et al., 2015), and the Atlantic Marine Assessment Program for Protected Species[81] (see Chapter 4). Examples of restoration data synthesis drawing from multiple monitoring projects and organizations across a region are rare, but framing synthesis in terms of ecosystem services may help provide restoration investment rationale and may feed back into better informed restoration design (Alexander et al., 2016). Some important lessons have been learned from efforts to synthesize across oyster restoration projects (Kennedy et al., 2011) and on river restoration projects (Palmer et al., 2014). The latter synthesis effort was conducted through the National Center for Ecological Analysis and Synthesis.

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[77] The term "scale" is often used to refer to spatial or temporal resolution (sometimes referred to as "grain" or "measurement scale"), for example, "fine scale" vs. "course scale." But the term is also used to refer to spatial or temporal extent (or "domain"), for example "local scale" vs. "regional scale." To further complicate matters, the term is often applied to levels of organization such as "ecosystem scale." Scaling as used here refers to the analysis of data at different resolutions and/or over different domains than the original data.
[78] The Louisiana Coast-wide Reference Monitoring System (CRMS): http://lacoast.gov/crms2/home.aspx.
[79] The System-Wide Assessment and Monitoring Program (SWAMP) ensures a comprehensive network of coastal data collection activities to support coastal protection and restoration across Louisiana: http://cims.coastal.louisiana.gov/RecordDetail.aspx?Root=0&sid=11471.
[80] The Saltmarsh Habitat & Avian Research Program (SHARP) is a collaboration among academic, governmental, and non-profit organizations: http://www.tidalmarshbirds.org/.
[81] Atlantic Marine Assessment Program for Protected Species (AMAPPS): http://www.nefsc.noaa.gov/psb/AMAPPS/

Large Gulf restoration projects will involve coordinated restoration of the same resource or habitat type at multiple sites in a landscape or watershed. For example, a single $3,750,000 oyster restoration project funded by the National Fish and Wildlife Foundation (NFWF) Gulf Environmental Benefit Fund aims to restore 600 acres of oyster reefs across multiple sites in Mobile Bay, Mississippi Sound, and Bon Secour Bay.[82] Moreover, many if not most of the projects currently in planning or early implementation stages will be part of larger coordinated restoration programs. For instance, in the funded priorities list published by the Gulf Coast Ecosystem Restoration Council in December 2015,[83] special consideration was given to large-scale projects that contribute to ongoing restoration programs in key watersheds and estuaries (Figure 6.1). As an example, the Jean Lafitte Canal Backfilling project in Louisiana will reclaim 16.5 miles of canals and spoil deposits to restore multiple habitats in an extensive freshwater wetland complex encompassing multiple habitat types. The key point is that both "project-level" monitoring data and data from multiple projects could require considerable cross-scale synthesis from individual sites to multiple sites in a landscape or watershed, and across multiple projects within a region or Gulf-wide.

Furthermore, because affected areas and mobile species within U.S. jurisdiction are part of a larger ecosystem, coordinating efforts to share restoration information internationally is important. The International Union for Conservation of Nature’s Working Group on the Gulf of Mexico has cautioned that “without a means to coordinate information and policies amongst the three Gulf national principals—the United States (including the state governments), Mexico and Cuba—the long-term restoration of the ecological health of the Gulf of Mexico cannot be achieved effectively” (Edwards et al., 2011).

[82] http://www.nfwf.org/gulf/Pages/GEBF-Alabama.aspx.
[83] https://www.restorethegulf.gov/council-selected-restoration-component/funded-priorities-list.

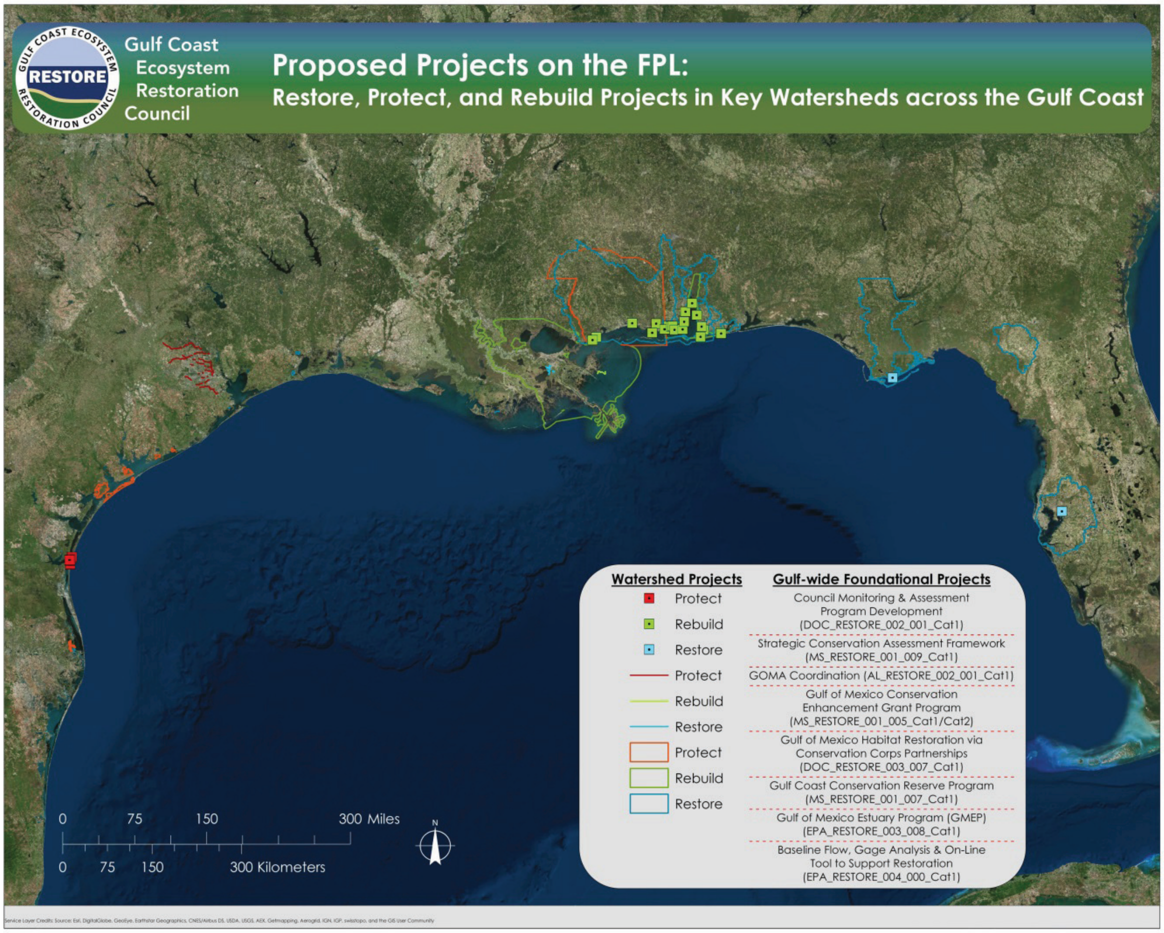

Figure 6.1 Approved restoration projects for funding on the Gulf Coast Ecosystem Restoration Council's Funded Priorities List (FPL) are organized by watershed. A single square represents a project that aims to protect (red), rebuild (green), or restore (blue) a given habitat or area. SOURCE: https://www.restorethegulf.gov/sites/default/files/FPL_forDec9Vote_Errata_04-07-2016.pdf.

Regular integrated assessments of restoration performance have been undertaken for other large restoration programs such as the Comprehensive Everglades Restoration Plan (CERP[84]). Since 2006, five CERP System Status Reports have been generated based on analysis and synthesis of data collected by the Restoration Coordination and Verification (RECOVER) Monitoring and Assessment Plan program (RECOVER, 2005, 2007, 2009, 2012, 2014). These reports are intended to explicitly link science to decision-making and provide reports to inform Congress of progress toward restoration objectives. Similarly, the Interagency Ecological Program (IEP) for the San Francisco Estuary has created a Management Analysis and Synthesis

[84] Comprehensive Everglades Restoration Plan (CERP): http://141.232.10.32/pm/ssr_2014/ssr_exec_sum_2014.aspx.

Team specifically for the purpose of synthesizing IEP monitoring data. That effort engages interdisciplinary teams and makes extensive use of scaling techniques, including conceptual and process models, for synthesis.[85] CERP and IEP synthesis activities have supported both learning and adaptation. For example, the 2014 CERP System Status Report connected research findings to restoration management and decision-making for oyster reefs, invasive species, fire, climate change, and sea level rise (NRC, 2014[86]).

For large restoration programs, an additional level of synthesis may be needed in order to communicate restoration progress to diverse stakeholders and decision makers. Since the 1990s, environmental report cards have become increasingly used for this purpose (Connolly et al., 2013). The report cards present the information in simple terms that are easily understood by the general public and elected officials (Stem et al., 2005) and they are especially valuable when assessments are tied to a legal framework or for communicating to decision-makers (Edwards et al., 2013). For example, since 2007, the Chesapeake Bay annual report card has provided an overall assessment of Chesapeake Bay "health" based on monitoring data for seven biological and water quality indicators.[87] Also, results obtained from Louisiana's Coastwide Reference Monitoring System for wetlands are displayed in a report card format, among other methods of visualization, to facilitate comparison among monitoring sites (Hijuelos and Reed, 2013; G. Steyer, personal communication).

Synthesis efforts may also inform programs about needs and opportunities for better coordination of project-level monitoring. Often, coordination appears to be adequate when viewed at the general planning and multi-agency committee levels. However, data integration efforts can expose limitations in the compatibility of various monitoring design and data management protocols (see Chapters 3 and 5). Furthermore, the prevalence of poorly designed monitoring efforts that lack statistical power to draw strong conclusions (see Table 3.1) may also hinder synthesis efforts (Kleijn and Sutherland, 2003).

Over the multi-decadal time span of Gulf restoration funding, the Committee stresses the importance of synthesis activities to promote communication, collaboration, and coordination of restoration planning and monitoring across the Gulf. These efforts will lead to more effective and efficient restoration at the project, regional, state, and Gulf scales. Restoration practice, as well as planning efficacy and monitoring efficiency, benefits from enhanced communication between the phases of restoration (planning, implementation, and monitoring) following evaluation within each phase. To maximize the likelihood of using lessons from past projects to inform future restoration, this communication would ideally include results that did and did not meet objectives, and would occur in formal, informal, oral, and written forms (Hulme, 2014; Nilsson et al., 2016).

Improved coordination would be especially valuable for the Gulf of Mexico, given the extensive ongoing and past monitoring efforts, and because coordinated restoration beyond the site scale can achieve objectives in a more cost effective manner (Ikin et al., 2006; see Chapter 3). The Ocean Conservancy recently catalogued 899 different existing and past long-term monitoring programs in the Gulf of Mexico concerned with at least one of 12 resource categories identified by the Deepwater Horizon Natural Resource Damage Assessment

[85] http://www.water.ca.gov/iep/pod/synthesis.cfm.
[86] Progress Toward Restoring the Everglades: The Fifth Biennial Review, 2014.
[87] http://ian.umces.edu/ecocheck/report-cards/chesapeake-bay/2013/.

(NRDA). While there are conspicuous monitoring gaps, notably for offshore species and environments, these monitoring programs provide an important foundation for a coordinated, Gulf-wide environmental monitoring network (Love et al., 2015). However, the Ocean Conservancy report does not assess issues related to data sharing and access, which would need to be resolved before monitoring efforts could yield data for the purpose of assessing Gulf-wide condition of natural resources. If a mechanism is developed to enable integration and synthesis of these monitoring programs (as a baseline) with restoration-related monitoring, these environmental monitoring efforts could support assessment of the effects of restoration at multiple scales. Leadership will be required to ensure that the large number of independent monitoring efforts develop a mechanism for effective data-sharing (see Chapter 5 for discussion on data stewardship).

APPROACHES TO SYNTHESIS AND INTEGRATION

Scaling from Data Points to Landscapes and Regions

Some management questions will require that data obtained directly from monitoring samples need to be scaled-up. Scaling-up can be thought of as interpolation and extrapolation from a single data point at a particular location (i.e., observations) to larger spatial units. Scaling in the temporal dimension (e.g., monthly to annual samples) often involves simple averaging, summing, or trend extrapolation. This section focuses on more complicated aspects of spatial scaling that often benefit from tools such as geographic information system (GIS) and remote sensing analysis (see Box 6.1).

Box 6.1

Geospatial Analysis

Single-point measurement at a given geographic location can be put into the larger geographic context of the sampling location through geospatial analysis using tools such as geographic information system (GIS) and remote sensing analysis. GIS is valuable at small scales, but can be especially useful for monitoring efforts when applied at large spatial and temporal scales. This readily available software allows practitioners to easily map changes in habitats, resources, and activities, and perform spatial analyses based on field surveys in conjunction with sonar, video, aerial imagery, real-time sensors, unmanned aerial platforms, and modeling efforts (Ferguson and Korfmacher, 1997; Chauvaud et al. 1998; Green et al., 1998; Wildish et al., 1998; Smith et al., 2001a,b; Grizzle et al., 2002, 2005, 2008; Hernandez-Cruz et al., 2006; Gambordella et al., 2007; SCDNR, 2008; Baggett et al., 2014; Le Bris et al., 2016). GIS, often coupled with remote sensing data has also been used to aid restoration and other conservation efforts (e.g., Chapman, 1999; Klemas, 2013; Riegel et al., 2013; Rose et al., 2015). The continued application of emerging tools and remote sensing techniques will be important in identifying the status and change of natural and restored habitats (e.g., oyster reefs, submerged aquatic vegetation, marsh), along with management intervention activities to maintain valued ecosystem services (Powell, et al., 1995; Bartlett and Smith, 2001; Riegl et al., 2005a,b; White and Fennessy, 2005; Gambordella et al., 2007; SCDNR, 2008; Holman and Haller, 2013; Baggett et al., 2014; Pettorelli et al., 2014; Barbosa et al., 2015). Restoration suitability indices are often derived from remote sensing and GIS analysis for numerous marine and estuarine habitats (Cake, 1983; Soniat and Brody, 1989; Bergquist et al. 2006; Volety et al., 2009; Pollack et al., 2012; Soniat et al., 2013; La Peyre et al., 2015)

When accompanied with *in situ* monitoring, remote sensing technologies can provide powerful opportunities for assessing relationships between short- and long-term environmental and biological change (e.g., land-use change, climate change, invasion biology, coastal zone management) at a variety of spatial and temporal scales (Ozesmi and Bauer, 2002; Powell, et al., 1995; Civille et al., 2005; Warren et al., 2007; Holman and Haller, 2013; Baggett et al., 2014; Lecours et al., 2015; Vivitskaia et al., 2015). Novel approaches for remote sensing (e.g., acoustic methods such as side scan and multibeam sonar, LiDAR; and aerial imagery such as satellite, multispectral, hyperspectral, three-dimensional global positioning system (GPS), real-time kinematic GPS, helicopters, drones), modeling, and high resolution real-time monitoring can enhance these efforts greatly (Morris et al., 2005; Christian et al., 2006; Wabnitz et al., 2008; Moore et al., 2009; Palumbi et al., 2009; Leifer et al., 2012; Sample, 2013; Blake et al., 2015; Schubert et al., 2015; Ventura et al, 2016). Real-time, *in situ* sensors can provide information on metrics such as primary production (photosynthesis and chemosynthesis) and respiration, nutrients (e.g., nitrogen and phosphorus), micronutrients, dissolved inorganic carbon, pH, and sulfide (Moore et al., 2009). Finally, critical to the application of remotely sensed data are ground-truthing, integration into a spatial GIS database, and the ability to access the imagery and related metadata (e.g., Coen and Grizzle, 2016; SCDNR, 2014).

There are several key scales for which information will likely be used to assess restoration activities in the Gulf. These scales are the immediate local areas surrounding the sampled locations, the larger project area, the relevant sub-region (e.g., estuary, watershed, or basin), state-wide scale (or other relevant jurisdictional boundary), and coast-wide scale. Furthermore, most scaling efforts can be categorized into classes based on the type of calculations used to interpolate and extrapolate to larger spatial and temporal scales.

Statistical Inference

The use of statistical hypothesis testing and strength of statistical inference associated with various monitoring design choices is described in detail in Chapter 3. In the context of synthesis, scaling via statistical inference is the common way sampled data are extrapolated. Methods include traditional univariate techniques (e.g., analysis of variance, regression), multivariate approaches (e.g., clustering), and methods designed specifically for time series (auto-correlated) data. Also, non-parametric and Bayesian versions of many of these techniques might in some instances provide a better statistical approach (e.g., Anderson, 2001; Lukacs et al. 2007). All of these methods require explanatory and response variables that are either directly measured or derived from measured variables. For example, one could use linear regression to examine the relationship between fish diversity (derived response variable) and the density of vegetation (example of other measured variables), and the fraction of the day a marsh is inundated (estimated from elevations and water levels from other sources). The variables in these analyses tend to be state variables (e.g., concentrations, quantities), rather than rates.

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Statistical methods need to be used in conjunction with exploratory (e.g., self-organizing maps – Chon 2011) and visualization techniques (Bryan 2003) in order to ensure robust results.

Basically, when samples from some population are taken in accordance with a specific design (e.g., based on the assumption that samples are representative of the 'target' population and are unbiased and 'random'), results can be extrapolated to the regional or population-level. In this case, scaling-up explicitly involves inferring a value for the response variable beyond the measurement scales (e.g., plant stem densities from a set of samples to the average stem density in an entire wetland area), and is often accompanied by an explicit expression of the variance of the scaled up estimate.

Formula Calculations

Scaling using a formula approach is a broad category that involves a series of calculations that presume samples are representative of larger areas, and invokes information for the extrapolation beyond the sampled data (i.e., not simply statistical inference). GIS analysis (see Box 6.1) can be used as a formal procedure for spatial scaling. A simple illustration of scaling used for wetlands restoration in the Columbia River is provided in Box 6.2.

Box 6.2

Formula-based Scaling of Particulate Organic Matter from Restored Marshes

Levees built around former tidal floodplain wetlands in the Columbia River estuary had resulted in the cut off about 80 percent of marsh area and the associated loss of export of marsh macrodetritus (i.e., particulate organic matter, POM) contributed by the marshes to the downstream estuary (Sherwood et al., 1990). This loss of POM input resulted in a shift in the downstream estuarine food web from one supported by marsh-derived organic matter to a food web dominated by phytoplankton and zooplankton transported into the estuary from the reservoirs upstream of Bonneville Dam. Other studies have shown that juvenile salmon survival is higher in the historical marsh-driven food web. Restoration was undertaken to reconnect the floodplain connection to the river so that the POM export from the marshes could be transported downstream to the estuary. Because hundreds of restoration projects are presently underway and are planned related to the reconnection and marshes, a set of formulas were employed to estimate the cumulative additive effects of the multiple projects on POM delivery to the downstream estuary. A simplified example of the calculations illustrates the formula-based approach to scaling. The actual calculations used more information and are described in Johnson et al. (2012).

Export of POM from a marsh can be roughly estimated as the difference between the live peak stranding crop in the summer and the late winter. POM export from one of the intensively studied restored sites (Kandoll Farm) was calculated to be: $447\ g\ dry\ wt\ m^{-2} \times 655{,}994\ m^2 = 293{,}229\ kg\ dry\ wt$. Studies in the estuary showed that a certain amount of the POM produced at marsh sites remains there and is re-mineralized, consumed or buried. Hydrodynamic modeling of particulate fluxes, combined with local measurements, showed that about 33% (0.33 x 293,229 kg dry wt = 96,766 kg dry wt) of the summer standing crop was actually exported from the Kandoll Farm.

Analysis of the detailed data collected at three intensively restored studied sites showed that restoration of the full 4050 ha of marsh that has historically been lost would result in the injection of 15.1mT dry wt of POM into the estuary. Using the same methodology but with the POM loss rate measured at reference marsh sites, showed that full restoration of the lost marshes would restore the export of POM to about 83% of what was historically exported from the original marshes.

A commonly used formula approach for scaling is habitat suitability index (HSI) analysis, which has been applied to a variety of restoration programs (e.g., Soniat et al., 2013; McManus et al., 2014; Nyman et al., 2013), although the term "suitability" is not always well-defined and models are rarely verified or validated (but see Theuerfkauf and Lipcius, 2016). HSI analyses involve specifying functions that assign values from zero to one over the range of each important environmental variable (USFWS, 1980; Draugelis-Dale and Rassa, 2008). Typically, process models (see below) are used to estimate the baseline values of environmental variables throughout the applicable spatial grid cells, and then again to estimate variables for baseline plus restoration actions. The functions are applied to the environmental variables cell-by-cell, and then the area of the cells is summed, and weighted by their overall suitability. Thus, one can compare the total weighted habitat area with and without the influence of restoration.

HSI analysis has many advantages but also some key weaknesses (Roloff and Kernohan, 1999; Ahmadi-Nedushan et al., 2006; Gore and Nestler, 2006). The main advantage to a habitat-based approach is cost savings due to a lack of need for new data collection when baseline data and/or expert elicitation is an option. Habitat suitability indices are also relatively easy to understand and explain. The HSI approach avoids some challenges associated with modeling population and community dynamics. Such models are typically subject to debate about the model formulations, are data-intensive, and can be highly uncertain. Habitat is critical to healthy and productive animal populations, and so determining how "restoration actions" will affect habitat relative to "no action" is an important step towards quantifying the ecological benefits and costs to biota of restoration actions. The major disadvantage to habitat-based approaches is simply that they lack complexity and they quantify habitat, which may or may not be directly correlated to abundance and provide little information on community level responses (Van Horne, 1983; Morrison et al., 2006). The issue is that creating more viable habitat does not mean that there will automatically be more fish (for example), only that the restoration action created the capacity for more organisms. Other issues related to using HSI analysis include challenges in formulating how multiple habitat variables interact to affect habitat quality and limits to the transferability of information from laboratory and limited field data to other locations that experience different combinations of environmental conditions. Ultimately, changes in HSI over time can be useful, even if a direct link to population demographics is tenuous (e.g., Jones-Farrand et al., 2009; Unglaub et al., 2015).

Process Modeling

Process modeling can be used, outside of the statistical analysis of monitoring data, as a method for scaling up monitoring results, enabling mechanistic understanding of the results, and forecasting (Clark et al., 2001; Peck, 2004). Process modeling computes the values of state variables (often the same as the response variables in statistical analyses) by representing the rates of change in key processes that affect these state variables. Thus, unlike the statistical and formula-based approaches, the equations of a process model are differential or difference equations, whose solution results in the values of the state variables (e.g., concentrations) over time and space.

An example would be simulating the number of fish in a location over time by representing the mortality rate and reproduction rate dependent on time-varying inundation and water levels of the wetlands in that location. Simulations that predict the total number of fish would be performed under identical conditions but with the wetlands in unrestored and restored states and the change in the number of fish (of a given age-class) attributed to the effects of the restoration.

There are process modeling approaches for almost all of the response and explanatory variables used in the analysis of monitoring data. For example, as part of the Louisiana 2012 Coastal Master Plan, there are process models for hydrodynamics, land building from diversions, fish and shellfish habitat responses to water quality and habitat changes, and the succession of wetland vegetation communities (Peyronnin et al., 2013). As part of the Master Plan, these models are linked with each other (output of one model becomes an input to another model), and used to determine estuary-wide responses to the implementation of multiple restoration actions.

Process modeling, in theory, enables more conditions to be simulated than statistical and formula-based analyses, and by representing the underlying mechanisms (to varying extents), can lead to the use of model-based hindcasting and forecasting. For example, a properly developed and tested process model can be used to provide hindcasts for situations when explanatory variables are available but measured responses are not, and for forecasting response variables under previously unobserved conditions. The monitoring data and its analysis provide critical inputs to the process model and enable the process model to be calibrated and validated.

Process models are especially well-suited to answer defined and specific questions. The more specific the questions, the more straightforward it is to develop an appropriately scaled and formulated process model. However, process models are limited by how well they represent the dynamics of their response variables. Rose et al. (2015) recently proposed a set of best practices for selecting and using fish-oriented models for evaluation of the ecosystem restoration. The role of the modeler's expert judgment in the design of the process model does not weaken the power and utility of ecological modeling, but it might weaken the strength specific inferences. The role of expert opinion highlights the importance of documenting and codifying the model selection process, the strategy and results of calibration and validation, and ensuring that the model is robust for the conditions dictated by model scenarios especially those involving possible future conditions. Great care must also be used in how data are used to inform model development and used in model evaluation (see discussion of data quality and metadata in Chapter 5).

Ecosystem Modeling

Ecosystem modeling can be valuable for taking a holistic approach, rather than the more focused approach (e.g., population dynamics, fisheries stock assessment) used with process modeling (Schirripa et al., 2013). For example, Ecopath with Ecosim models[88] have been applied to Gulf ecosystem-based fisheries management scenarios to improve understanding of fishing, management measures, and climate change on predation and competition (Chagaris et al., 2015). Also, an Atlantis ecosystem model and management evaluation tool,[89] based upon sub-models for major steps of biophysical, oceanographic, economic, social, and management dynamics, has been created to simulate Gulf conditions. Atlantis models now depict the food web matrix from bacteria to apex predators considering age structures, larval transport, habitat limitations, nutrient cycling, fisheries influence, and response to oil and other stressors (Masi et al., 2014; Ainsworth et al., 2015; Tarnecki et al., 2016). Ecopath with Ecosim, Atlantis, OSMOSE,[90] and other decision support tools can play a valuable role in integrated ecosystem assessments, particularly in steps such as developing metrics/targets and management strategy evaluation (Levin et al., 2009; Center for Ocean Solutions, 2011). The issues associated with process modeling become even more critical when using ecosystem models because of their coverage of many aspects of the ecosystem. Ecosystem models are very data-demanding and significant effort is needed to calibrate and validate these models to the point that they can be used for predicting dynamics under new conditions. Ecosystem models as described here are often best used for strategic evaluation of mixtures of management actions rather than for tactical decisions about whether a specific management action need to occur (Fulton et al. 2011).

Assessing Restoration Effects on Wide Ranging Animals

Cross-scale synthesis of monitoring data is essential to assess and interpret restoration outcomes for marine mammals, sea turtles, birds, fish, and other wide-ranging organisms whose population and community dynamics operate at Gulf-wide or larger scales subject to cumulative effects of multiple activities, including non-target forms of restoration (e.g., Bayne and Dale, 2011; Johnson and St.-Laurent, 2011). These organisms are often used as indicators of the success of large-scale restoration because they act as biological integrators of the health of the environment, exert a large influence on ecosystems, are highly valued by the public, and are often protected and/or regulated by state and federal laws (see Chapter 4). Because these species have complex life histories (i.e., they use many habitats and may migrate), are long-lived, and are subjected to multiple stressors (Rose, 2001), little about their response to restoration can be inferred from project-scale monitoring data examined in isolation (exceptions could include local habitat-use by wide-ranging species). Therefore, increasing the prevalence and consistency of monitoring,[91] and providing mechanism(s) for sharing data[92] on wide ranging animal response to restoration will help inform synthesis activities.

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[88] Ecopath with Ecosim (EwE) ecological/ecosystem modeling software: http://ecopath.org/.
[89] Atlantis ecosystem modeling software: http://atlantis.cmar.csiro.au/.
[90] Object-oriented Simulator of Marine ecOSystems Exploitation (OSMOSE) modeling software: http://www.osmose-model.org/. See Grüss et al. (2016) for an example.
[91] For example, through the Gulf of Mexico Marine Assessment Program for Protected Species (GoMMAPPS; see Chapter 4).
[92] For example, through the Environmental Response Management Application (ERMA) and the Data Integration Visualization Exploration and Reporting (DIVER) explorer tool (https://dwhdiver.orr.noaa.gov).

Assessing Restoration Efficacy across Multiple Projects in the Larger Ecosystem Context

Monitoring has tended to focus on particular habitats or species (or sets of species) in isolation, or sometimes on valuable species that also function as habitat (e.g., oysters) or mobile taxa that are intricately linked to fixed habitat (e.g., birds that rely upon certain wetlands; see Part II of this report for good practices for monitoring select habitats and species). This last case illustrates the beginning of a movement toward integrated monitoring (see Steyer et al., 2006), where formerly isolated efforts are conducted with awareness of other related but independently conducted types of monitoring. This idea goes beyond incorporating outside metrics into a particular monitoring scheme, for example a sea turtle-focused practitioner measuring seagrass density and turtle-related tourism along with sea turtle demographics. Integrated monitoring instead involves a number of practitioners each focused on monitoring different ecosystem components in a compatible manner in an effort to assess overall restoration progress in a complementary manner.

There are several challenges that need to be overcome to enable the synthesis of monitoring data and evaluation of restoration progress across the different restoration programs. Most importantly, there are varying objectives and a lack of communication across different restoration programs, state/municipal lines, government agencies, research collaborations, university affiliations, or project funding organizations (see Chapter 2). In addition, there is a need to build awareness of *how*, *what*, and at what *scale(s)* each type of practitioner already monitors and assesses (see Chapter 3 and Part II); to consider restoration (and potentially other management) activities on a larger, sometimes Gulf-wide, scale by accounting for potentially harmful effects of such activities on unrelated restoration efforts (see Chapter 4); and to promote a culture of data *compatibility* and *access* (see Chapter 5). The Gulf Coast Ecosystem Restoration Council (known as the RESTORE Council) has recently responded to the need for integrated monitoring by committing to fund a partnership[93] to build on existing capabilities and activities in the Gulf. This effort will catalogue historic and ongoing monitoring, identify data gaps, improve coordination, and develop consistency in methods and data standards applicable at scales from individual sites to Gulf-wide (G. Steyer, personal communication).

Meta-analysis is another approach to synthesize monitoring project outcomes to better inform restoration practice. Meta-analysis is a formal statistical approach for pooling results from multiple, independent experiments or studies to achieve greater generality and synthesis (Koricheva et al. 2013). For example, Benayas et al. (2009) evaluated the effects of restoration on biodiversity and ecosystem services across 89 published studies in various terrestrial and aquatic ecosystems. Using the response ratios of restored vs. unrestored and restored vs. reference ecosystems (i.e., ln(restored/degraded) or ln(restored/reference)) for metrics such as species richness and biomass, they inferred that ecological restoration increased provision of biodiversity and ecosystem services by 44 and 25%, respectively. Moreno-Mateos et al. (2012) conducted a meta-analysis of published studies of 621 wetland sites from throughout the world to document the long time needed for restored wetlands to recover to reference conditions. Based on response ratios for metrics such as plant community diversity and carbon storage, they concluded that even a century after restoration efforts, biological structure remained on average 26% and 23% lower, respectively, than in reference sites. Such quantitative meta-analyses

[93] RESTORE-funded Council Monitoring & Assessment Program Development project: https://www.restorethegulf.gov/sites/default/files/FPL_FINAL_Dec9Vote_EC_Library_Links.pdf (p.228).

would be invaluable in assessing restoration performance and outcomes in the Gulf of Mexico region.

CHALLENGES AND OPPORTUNITIES

Organizational Challenges

There are several commonly-encountered challenges with synthesis of large projects, such as insufficient human and financial resources, expertise, and access to quality data. These challenges are amplified for restoration in the Gulf of Mexico because of its broad spatial scale, long-time frame, diverse data types, and multiple organizations involved in the restoration and monitoring activities. Monitoring data are generated from construction, performance, and monitoring for adaptive management, use of existing data, and model outputs. Restoration will occur across the Gulf of Mexico and will involve a wide variety of projects, including wetland creation, barrier islands, river diversions, and fisheries management actions. These projects will be implemented in various locations over an extended time period.

Synthesis of Gulf restoration monitoring will be data-intensive and thus will require a commitment to good data stewardship and management practices, open access to well-documented data, and creation of integrated databases for analysis (Chapter 5). The latter activity usually needs to be done by the synthesis team, and can require extensive data error checking, data cleaning and harmonizing (e.g., cross-walking of species taxonomies), converting data to common units, data conflation (bringing data to common spatial and temporal scales and levels of precision), and data updating prior to analysis (e.g., Soranno et al., 2015). Most environmental scientists are not fluent in modern data management skills and best practices; therefore, data integration can be the most time- and resource-consuming step in synthesis (Michener and Jones, 2012). For this reason, synthesis centers generally employ scientific programmers and data technicians to assist and train working groups with data management and analysis.

Scientific inference (see Chapter 3) from analysis of large volumes of data, including data that were originally collected for other purposes, also has special challenges. In recent decades, a variety of powerful new methods have been developed to support "data-intensive" science, many of which will be unfamiliar to researchers trained in traditional field science and statistical analysis of field survey and experimental data. Examples include meta-analysis (Koricheva et al., 2013) and machine learning techniques such as boosted regression trees and artificial neural networks (Olden et al., 2008). Discussion of these methods is beyond the scope of this report, and they are mentioned here mainly to highlight the need for training, scientific support, and modern cyber-infrastructure of synthesis activities (as further discussed below).

Thorough synthesis can result in achieving or exceeding project objectives with efficient use of monetary resources. What typically limits effective synthesis is the lack of sufficient funding and staffing to ensure that restoration activities are monitored and data shared such that meta-analyses and syntheses can be conducted (see Kennedy et al., 2011). Given the enormous scale of restoration in the Gulf of Mexico, it will be difficult to rationalize, especially decades from now, a lack of a significant synthesis effort.

Organizational Approaches

Synthesis requires the delineation of a group of individuals that are given the responsibility for data synthesis, meta-analysis, and integration. Synthesis usually involves "team science," that is, collaboration of two or more individuals with different roles or responsibilities (NRC, 2015). Increasingly, team science involves both face-to-face and virtual interactions. Collaborative, team-based synthesis research has proven so effective for scientific progress that new centers have been created specifically to provide financial, logistical and technical support. Examples include the National Center for Ecological Analysis and Synthesis in Santa Barbara, California, the Socio-Environmental Synthesis Center in Annapolis, Maryland, the National Institute for Mathematical and Biological Synthesis in Knoxville, Tennessee, and the John Wesley Powell Center for Analysis and Synthesis in Fort Collins, Colorado.

Synthesis can occur in a variety of interactive venues (e.g., seminars, workshops, project teams) but the "working group" model is perhaps the most widely practiced when multiple organizations and disciplines are involved. This usually entails bringing together a small team (< 20 people) who meet for up to a week at a time in intense collaboration at a facility that can provide computational and logistical support. Groups may meet several times per year over multiple years, depending on the scope of the activity. Factors that contribute to working group effectiveness including face-to-face meetings, leadership, diversity (notably in expertise, gender, age, and career stage), and data management and computational support (Hackett et al., 2008; Woolley et al., 2010; Hampton and Parker, 2011). Immersion at a neutral, independent facility away from participants' daily workplaces is also associated with increased working group productivity and positive outcomes (Hackett et al., 2008; Lynch et al., 2015).

Multiple states, federal agencies, and organizations are involved in funding Gulf of Mexico restoration projects, imposing their own data reporting requirements on their projects (as discussed in Chapter 2). It is not clear to the Committee who has primary responsibility for data synthesis. Attempts at synthesis by the same personnel tasked with doing the actual restoration activities will not be successful. Expecting staff of funding and coordinating organizations to conduct synthesis is also unrealistic. Synthesis requires a significant effort by a group with certain skills, and is not effective when it is simply added to the duties of individuals already time-limited from restoration activities. There are a range of institutional approaches that can meet the need for the type of meta-analysis and synthesis required to assess restoration progress in the Gulf of Mexio. Given the complexity of the task and the broad range of restoration activities undertaken, the Committee presents a few options that could meet the need for and overcome the challenges of synthesis and assessment of restoration efforts in the Gulf of Mexico.

One organizational model for Gulf-wide synthesis activities would be to establish an independent center, similar to the aforementioned synthesis centers, whose mission is to advance Gulf restoration science, management, and policy solutions by analysis of available data. If such a center emulated existing models, if would not need to retain a large permanent research staff but would instead provide meeting facilities, cyberinfrastructure, and staff to support short-term and ongoing external working groups. Such a center could be tasked with producing regular assessments of Gulf-wide restoration progress. Additionally, such a center could promulgate data and metadata standards (see Chapter 5), serve as a data center or data hub, provide training in data management and data-intensive scientific methods, and communicate results to stakeholders and decision makers. There are now many successful models for synthesis centers that could help inform the design and operation of such a center.

An alternative model to the center concept could be a single institution or multi-institutional program whose mission is analysis and synthesis of restoration monitoring data to produce integrated assessments. For example, the Chesapeake Bay Report Card is produced by the University of Maryland's Center for Environmental Science. This model would depend more on permanent staff and less on collaborative teams comprised of scientists from different organizations. Given that fewer individuals would be involved in such a synthesis program, its scope would presumably be narrower than that of a synthesis center. Science programs that have been established with DWH funding (see Chapter 2) are currently and need to continue to contribute to the goal of data analysis and synthesis, for example by developing conceptual models, evaluating appropriate indicators of restoration progress, funding data synthesis grants, and publishing report cards. While useful for a non-technical audience, report cards and other integrated assessments are more limited in scope and explanatory power than other forms of synthesis needed to evaluate restoration as described in this chapter.

Another way to promote synthesis activities could be through a competitive contract and grant program to fund individual investigators and collaborating teams who propose and perform data synthesis within their existing organizations. This approach could be synergistic with and complementary to either a synthesis center or program. The National Academies' Gulf Research Program (see Chapter 2) currently operates such a program for data synthesis grants. Such projects would be at a small scale (a team of several people) and would allow a community to examine particular topics and analytical techniques. While one cannot guarantee what questions will be addressed and how, such a contract program benefits from multiple individuals and groups adding creativity and ideas to the general task of data synthesis. When appropriate, requests for proposals could be more specific to address a critical synthesis need or a key knowledge uncertainty as it relates to restoration efficacy. This small project approach could result in detailed insight into specific restoration actions or locations, and could generate ideas and approaches that are useful at larger scales. These three options are just a few of the organizational models, which could also be combined to form a synthesis center that also administers competitive grants for synthesis efforts.

CONCLUSIONS AND RECOMMENDATIONS

Synthesis for restoration efforts as large and complicated as planned for the Gulf of Mexico is a critical activity that promotes communication, collaboration, and coordination of restoration planning and monitoring. Without a significant commitment to synthesis, it would be impossible to promote integrative decision-making and to understand the effects of environmental restoration to human health and well-being and to the natural resources being restored at multiple scales.

Because meta-analysis of projects and synthesis of monitoring data is required for evaluating restoration progress beyond individual projects and gulf-wide restoration outcomes, Gulf restoration programs should consider creating a specific, dedicated enterprise for synthesis activities in support of Gulf restoration. These activities would include database development, research, and training. This enterprise could be jointly funded by Gulf restoration programs (e.g., the NRDA Trustee Council, RESTORE Council, and NFWF)

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and research programs (e.g., the Academies' Gulf Research Program) and could take the form of a new independent center, a dedicated program within an existing organization, or a new multi-agency synthesis program. The new Centers of Excellence in each Gulf state that are created under Resources and Ecosystems Sustainability, Tourist Opportunities, and Revived Economies of the Gulf Coast States (RESTORE) Act (2012) funding could play a significant role in supporting or hosting synthesis activities or a synthesis program. This would be especially powerful if the Centers in different states worked together.

The Committee recommends the following:

1. Restoration programs and research programs should acknowledge the importance of synthesis and integration into effective and efficient restoration, and recognize that synthesis and integration should be done by a group of tasked individuals (not simply added as an additional task to staff or those implementing the restoration), and commit sustained funding.
2. Restoration programs should jointly formulate plans to develop the appropriate organizational approach(es) for synthesis and integration, which can include working groups, a center for restoration science and synthesis (several models are available), and a complementary small grants program to encourage relatively high-risk/reward projects and innovative ideas.
3. Synthesis and integration should be considered as part of improving project-level actions, expanding project level restoration to broader scales, assessing restoration progress on regional and Gulf-wide basis, and ensuring that restoration effects are assessed on wide-ranging animals of conservation and commercial importance.
4. Synthesis and integration should be initiated immediately and should be done in very tight collaboration with management activities and agency and organization staff, and also be done in coordination with the development of all databases related to restoration.

CHAPTER 7

HOW MONITORING IMPROVES RESTORATION EFFECTIVENESS

A carefully designed monitoring program can improve the effectiveness of restoration efforts. Monitoring can inform restoration project design and site selection, measure progress towards restoration goals of an individual project as well as of a restoration program and further improve efficacy of the restoration process itself. In addition, monitoring an ongoing project can directly enhance restoration outcomes and improve future restoration decision-making. This chapter addresses the following part of the Committee's charge: "for monitoring and evaluating restoration activities to improve the performance of restoration programs and increase the effectiveness and longevity of restoration projects."

The first section of this chapter provides a general discussion of how monitoring can improve restoration effectiveness at the project and program levels and enhance restoration program management. Subsequently, the chapter describes adaptive management in support of enhancing restoration effectiveness, focusing on the project scale and beyond the project scale (such as at the scale of a tributary, estuary, program, region or basin-wide). The chapter also presents key steps necessary for application of adaptive management to Gulf-coast restoration and restoration monitoring.

Monitoring of restoration projects, the analysis and synthesis of monitoring data, and the evaluation of restoration projects and programs can contribute to the improvement of restoration design, effectiveness, and longevity. As discussed in Chapters 3 and 6, data from restoration monitoring can inform a range of critical decisions including the following:

- Prioritizing what actions need to be taken, and where, when, and how these actions need to be implemented;
- Selecting appropriate restoration sites;
- Determining, demonstrating, and communicating restoration progress toward objectives;
- Understanding why restoration (or elements of restoration) did not meet objectives;
- Informing program and project adjustments;
- Assessing and justifying expenditures;
- Advancing the state of restoration practice; and
- Improving conceptual and numerical computer models.

EVALUATING RESTORATION EFFECTIVENESS AT THE PROJECT AND PROGRAM LEVEL

Formal evaluations of *conservation* projects and programs have been growing in number and sophistication recently because of increasing recognition that "good project management is integrally linked to well-designed monitoring and evaluation systems" (Stem et al., 2005).

Formal evaluations[94] of restoration projects and programs have been lagging (Wortley et al., 2013; Nilsson et al. 2016) despite the long-standing practice of doing restoration. The committee considers the guidance developed for monitoring and evaluation of conservation programs applicable to the evaluation of restoration programs and a great resource (see also Groves and Game, 2016, for detailed guidance on monitoring and evaluation for conservation).

A range of approaches and systems for monitoring and evaluation have been employed in the field of conservation biology depending on the question the evaluation aims to inform. Such evaluation can take the form of a status assessment - based on, for example, population monitoring - performance assessment or impact assessments or systematic review (see Groves and Game, 2016 for a helpful classification for the types of evaluations and the questions they aim to answer). Status assessments and performance assessments are conducted at the project level. The status assessment informs decisions about the resource status in need of conservation (in this case restoration) and the performance assessment indicates whether the conservation intervention (or in this case restoration activity) yields progress toward the goals. The impact evaluation and the systematic review both look across multiple projects or even an entire program and are typically conducted by professional evaluators or researchers. Both of these latter evaluations inform adaptive management decision at the project and program level.

Lessons learned from formal evaluation of a project or program begin with an evaluation of whether the stated goals and objectives have been achieved (Kentula et al., 1992; NRC, 2005). As discussed in Chapter 2, many restoration programs' goals need to be articulated in terms of specific and measurable objectives. Subsequently, those ecological objectives or outcomes can be assessed at the project and program levels using three general categories metrics: structure, species abundance and diversity, and ecological processes (Thom et al., 2011; Wortley et al., 2013; NOAA, 2014). For example, a programmatic review by the NOAA Science Advisory Board found as part of its assessment of NOAA's restoration program that their projects generated significant economic benefits. However, the report noted that the *assessed* benefits did not extend to the goal of fisheries production. Furthermore, the review notes "to deliver measurable fisheries production benefits from restoration projects" the program would have to deliver fewer but larger projects."

As detailed in Chapter 3, how much can be learned from monitoring depends on the rigor and effort of monitoring employed. Here we briefly discuss how monitoring for different purposes can inform assessments, improve restoration outcomes, and how monitoring can be integrated into adaptive management.

ADAPTIVE MANAGEMENT TO ENHANCE RESTORATION EFFECTIVENESS

Because ecosystems are complex and are not fully understood, their responses to restoration efforts are often uncertain. However, as noted by the Gulf Coast Ecosystem Restoration Task Force (2011), "The dire state of many elements of the Gulf ecosystem cannot wait for scientific certainty and demand immediate action." Adaptive management provides a structured process that allows restoration to proceed in the face of uncertainties (Holling, 1978;

[94] While monitoring and assessment focus on ecological objectives and measures, a formal evaluation of a conservation program includes a review of whether the stated goals were adequate and the reasons for successes and failures (Kleiman et al., 2000). For the purpose of this report, however, we use the terms assessment and evaluation as synonyms and as defined by the Meridian-Webster dictionary.

also defined in Box 1.3). In adaptive management, monitoring and evaluation are carefully planned and implemented so that knowledge gained from restoration projects can be applied through flexible decision making to enhance ongoing or future restoration activities (NRC, 2004). Although adaptive management is implemented in a variety of ways, the process generally frames restoration implementation within a cycle of learning and adaptation. Key steps of adaptive management include setting restoration goals, planning restoration efforts (including identifying critical uncertainties that affect future decision making), implementation, monitoring, synthesis, evaluation, and adjustments to goals, project design, operations, or monitoring (see Figure 1.3.1) (Westgate et al., 2013; Fischenich et al., 2012; RECOVER, 2011; Williams et al., 2009; Conroy and Peterson, 2013).

Without a structured adaptive management program, performance monitoring may illuminate shortcomings of a restoration project, but performance monitoring alone is unlikely to be sufficient to determine the reasons for the project failure, resulting in little added guidance for future restoration decisions (also called trial and error). Unlike learning through trial and error, adaptive management supports more efficient learning and includes a targeted monitoring effort to resolve identified high-priority uncertainties (see also Chapter 3), thereby improving future restoration decisions.

The terms “active” and “passive “adaptive management are often used to distinguish two approaches to structured learning, although there is notable variability in the way these terms are used. In general, active adaptive management efforts emphasize rapid learning over other restoration objectives, while in passive adaptive management, learning is a useful benefit but not necessarily the highest management priority (Williams, 2011b). One common approach to active adaptive management allows simultaneous testing of two or more restoration designs or working hypotheses regarding predicted outcomes (Bormann et al., 1999; Hagen and Evju, 2013). Box 7.1 describes an active adaptive management project that examines oyster restoration effectiveness based on four different artificial reef heights in Apalachicola Bay. In contrast, passive adaptive management is characterized by management decisions informed by a single working hypothesis regarding predicted outcomes. Information gained through restoration monitoring is compared to model predictions, and improvements in expected outcomes may be examined by refining parameter estimates in a predictive model. Management actions (e.g., changes in restoration design or operations) may then be altered to conform to new predictions (Wilhere 2002; Schreiber et al., 2004; Gregory et al., 2006; Williams, 2011b). The Everglades Biscayne Bay Coastal Wetlands restoration project (USACE and SFWMD, 2012) presents a passive adaptive management plan in which a single restoration strategy is implemented and targets (or trigger values) for restoration responses (e.g., salinity, hydroperiod) are set that if not met, trigger the need to revisit the restoration goals, targets, and design alternatives (see Box 1.3). Active adaptive management generally leads to faster learning than passive strategies but can be expensive (Allen et al., 2011; Williams et al., 2009; Gregory, 2006).

Adaptive management is most commonly applied at the project scale (e.g. rehydration of an individual wetland), or over several closely linked projects. It is also possible to apply adaptive management at larger scales or at a program level (e.g. RECOVER, 2015), but identifying clear goals and objectives, developing system-wide conceptual models, and specifying critical uncertainties at the program scale that can be reduced through a deliberative monitoring and evaluation process is more challenging. Program-level synthesis, evaluation, and learning are discussed separately in Chapter 6.

Box 7.1

Adaptive Management of Apalachicola Bay Subtidal Oyster Fishery

Apalachicola Bay has until recently accounted for 90 percent of the wildstock Eastern oysters (*Crassostrea virginica*) harvested in Florida and 10 percent overall of the wildstock *C. virginica* from the entire Gulf of Mexico. Although the Apalachicola oyster fishery appeared to be resilient and sustainable over its >150-year history, it now appears to be at a tipping point, in terms of its continued sustainability as a wildstock fishery and potentially near collapse (e.g., Pine et al., 2015) as so many other oyster fisheries have succumbed (Beck et al., 2011; zu Ermgassen et al., 2012).

Prior to the DWH oil spill, but especially during the latter half of 2012, oyster landings declined precipitously. Numerous hypotheses for the observed declines were proposed, some related to fisheries management and some related to physical factors such as reduced freshwater inflows into the Bay. For example, it has been noted that two years of severe drought (2011-2012) occurred prior to the crash, resulting in increased salinity and potentially increased predation and disease rates within the Bay (e.g., Pine et al., 2015).

To expedite recovery, shell planting is being considered or has already begun (Figure 7.2.1). Recent modeling results suggest that 1000 acres of shell ("cultch"), could potentially be required for restoration of the fishery to regain past wildstock levels within the Bay (Havens et al., 2013). Two key restoration uncertainties--(1) what reef height (or shell volume/unit area, density) should be added to restore areas to promote oyster reef establishment; and (2) how fishery removals will affect oyster reef recovery given burial, shell removal, and decay processes--are the management questions to be addressed by an ongoing adaptive management project funded by the NFWF Gulf Environmental Benefit Fund.[a]

The project examines effects of different reef heights using varying amounts of cultch per unit area to restore historical subtidal reefs in the Bay. Three 10 acre reefs in different areas of the Bay each include five experimental 2 acre 'plots' planted with 0 (control), 100, 200, 300 or 400 yds^3 of fossil 'shell' from FL quarries each replicated three times. Monitoring includes measuring density of live and dead oysters, density of predators, density of shell/unit area, and mean size of live oysters. To measure oyster health, several types of condition indices are to be measured, as well as the prevalence and intensity of disease. Water quality parameters include temperature, salinity, turbidity, and dissolved oxygen. Once the oysters reach a harvestable size, plots will be open to experimental harvesting at controlled levels to determine a sustainable level of harvesting on a restored oyster reef. Ultimately, this project was intended to inform future large-scale oyster restoration projects and improve cost-efficiency and effectiveness with regards to restoration design as well as appropriate fisheries management practices (Havens et al., 2013, 2015).

Figure 7.A Placing oyster reef shell as part of an oyster reef restoration and adaptive management project in Apalachicola Bay. SOURCE: Alabama Marine Resources Division.

[a] See http://www.nfwf.org/gulf/Documents/fl-apalachicola-bay.pdf. The project is being conducted in partnership with the Florida Fish and Wildlife Conservation Commission, Florida Department of Agriculture and Consumer Services, Florida Sea Grant, and the University of Florida.

Benefits of Adaptive Management

Adaptive management offers numerous benefits. Through monitoring and evaluation, adaptive management allows learning and adjustments to restoration projects, thereby increasing the likelihood that restoration goals will be achieved and undesirable outcomes avoided. This flexible process allows adjustment guided by new knowledge at any stage (planning, design, construction, operation) during the lifetime of a project ensuring that restoration decisions are informed by the best available science on a continuing basis. Adaptive management allows restoration programs to prioritize what to do (and where and when) and make adjustments as new information is acquired. Adaptive management fosters dialogue between scientists, managers and stakeholders to interpret results of monitoring and assess progress towards goals. Adaptive management aims to develop the best results within the shortest amount of time, and it can reduce cost in the long-term (Fischenich et al., 2012). However, the adaptive management approach requires practitioners to examine proposed restoration activities and the uncertainties associated with outcomes at a considerable level of detail, necessitating a sizeable investment of resources for planning, monitoring, and evaluation.

When to Use Adaptive Management and When It Is Not Appropriate

Adaptive management is most suited for situations where natural resources will respond to a management intervention, but where there is considerable uncertainty (see Box 7.2) regarding the response; where reduction in that uncertainty could improve future restoration management and decision making (Allen et al., 2011; Williams, 2011a); or when stakeholder support and institutional capacity and commitment to sustain an adaptive program are present (Gregory et al. 2006). As detailed in chapter 3, there are four sources of uncertainty (environmental variation, partial observability, partial controllability, and knowledge uncertainty about the process). If the response of the system to restoration intervention is well known (low knowledge uncertainty), adaptive management is not needed. For example, as long as sites have been carefully selected, adaptive management of osprey nest platforms (NOAA, 2015) is probably not necessary. Also, if the system is unresponsive to management or if the response to the restoration is anticipated to be smaller than the natural variation in the system, then adaptive management is unrealistic (Allen et al., 2011; Peterson et al., 2003). Finally, time scale of response to restoration is an issue. If measurable indicators of change take many years or even decades to occur, adaptive management would be more challenging. A decision tree proposed by Williams et al. (2009) offers questions to help determine if adaptive management is appropriate to a specific project (see Box 7.3).

Active adaptive management, where several restoration alternatives are often tested simultaneously, is best employed when there are alternative management scenarios to choose between, uncertainty in system response is high, and improved understanding is needed quickly because moving forward with full-scale restoration without additional information poses a substantial risk. For example, restoration of oyster reefs will be a Gulf-wide endeavor, and implementation of the wrong strategy at such a scale would be costly as a result (e.g. Bormann et al., 1999; see also Box 7.1). Additionally, there must be suitable site conditions for implementing and testing the alternative management scenarios, and the responsiveness of the system to experimental manipulation need to be such that results are available in an acceptable time frame (Allen et al., 2011; RECOVER, 2010; Gregory et al., 2006).

Passive adaptive management is appropriate when uncertainty is low to moderate and projects are designed with sufficient flexibility to allow sequential adjustments to be made to the project or its operations. If there is so little flexibility in project design or operations that alternative scenarios cannot be implemented, adaptive management would not add value to long-term decision making.

Box 7.2

Critical Uncertainties and Approaches for Prioritization

By definition, *uncertainty* is used to describe a lack of sureness about something (i.e., a doubt about an event or outcome). A *critical* uncertainty inhibits making a sound decision, and typically involves moderate or high risk (i.e., the notion of negative or undesirable outcomes). For example, in an oyster restoration project, if the effect of cultch density on reef establishment is not understood, information is lacking to support decisions on the most cost-effective designs, with a substantial risk of wasted restoration funds or ineffective projects.

In Everglades restoration, the adaptive management planning team for the Central Everglades Planning Project (CEPP; USACE and SFWMD, 2014) identified several criteria for screening possible uncertainties, including:

- The uncertainty must be directly related to the project goals, objectives, or constraints.

- Reduction of this uncertainty must be relevant to inform project implementation, operations, or additional restoration actions necessary to meet the restoration goals.
- "The uncertainty needs at least one attribute that is measurable that will provide information to resolve the uncertainty, i.e. the attribute must be a trait able to change in the timeframe of the adaptive management plan, and one that is distinct from the 'background noise' of natural variability. Long-term changes need a faster responding surrogate-measure for the adaptive management plan."

Once the list of uncertainties was reduced by the screening process, they were further prioritized by knowledge, relevance, and risk to adaptive management to identify the most important uncertainties to serve as the basis for the adaptive management plan. These same criteria were used to prioritize program-level uncertainties in the CERP "Program-level Adaptive Management Plan" (RECOVER, 2015) :

- **Knowledge: "**What is the level of understanding (high, medium, low) of this uncertainty (i.e., how much is known about this uncertainty)?"
- **Relevance (Actionable): "**What is the level of confidence (high, medium, low) that addressing this uncertainty will resolve/improve design of CERP projects or enable a more ecologically effective approach to operations of the regional system?"
- **Risk: "**What is the risk (high, medium, low) of not meeting CERP restoration goals if this uncertainty is not addressed?"

SOURCE: USACE and SFWMD,2014; RECOVER, 2015.

Box 7.3

Determining Whether Adaptive Management Is Appropriate

The following questions are helpful to determine whether adaptive management is appropriate for restoration decision making in a specific project or program. If the answer to any of the questions is no, Williams et al. (2009) suggest that another approach is likely to be more appropriate.

1. Is some kind of management decision to be made?
   - No – decision analysis and monitoring are unnecessary when no decision options exist.
   - Yes – go to step 2.
2. Can stakeholders be engaged?
   - No – without active stakeholder involvement an adaptive management process is unlikely to be effective.
   - Yes – go to step 3.
3. Can management objective(s) be stated explicitly?
   - No – adaptive management is not possible if objectives are not identified.
   - Yes – go to step 4.
4. Is decision making confounded by uncertainty about potential management impacts?
   - No – in the absence of uncertainty adaptive management is not needed.
   - Yes – go to step 5.
5. Can resource relationships and management impacts be represented in models?
   - No – adaptive management cannot proceed without the predictions generated by models.

- Yes – go to step 6.

6. Can monitoring be designed to inform decision making?
   - No – in the absence of targeted monitoring it is not possible to reduce uncertainty and improve management.
   - Yes – go to step 7.
7. Can progress be measured in achieving management objectives?
   - No – adaptive management is not feasible if progress in understanding and improving management is unrecognizable.
   - Yes – go to step 8.
8. Can management actions be adjusted in response to what has been learned?
   - No – adaptive management is not possible without the flexibility to adjust management strategies.
   - Yes – go to step 9.
9. Does the whole process fit within the appropriate legal framework?
   - No – adaptive management should not proceed absent full compliance with the relevant laws, regulations, and authorities.
   - Yes – all of the basic conditions are met, and adaptive management is appropriate for this problem.

SOURCE: Williams et al. (2009).

KEY ELEMENTS NEEDED TO SUPPORT ADAPTIVE MANAGEMENT IN GULF RESTORATION

Several Gulf restoration entities have expressed a commitment to the use of adaptive management. The Gulf Coast Ecosystem Restoration Task Force (2011) recommended "establishing an effective adaptive management framework with critical research, modeling and monitoring elements to support adaptive management." The DWH NRDA Trustees identified monitoring and adaptive management support for restoration as one of the five overarching goals of the Programmatic Damage Assessment and Restoration Plan (DWH NRDA Trustees, 2016). The Louisiana Coastal Protection and Restoration Authority (CPRA) is implementing its Master Plan within an adaptive management framework (The Water Institute of the Gulf, 2013a), and the National Fish and Wildlife Foundation (NFWF) has funded CPRA to implement adaptive management in its river diversion and barrier island projects. NFWF expects all projects to include adaptive management plans in their proposals or be prepared to develop one (J. Porthouse, pers. comm., 2015).

Although there is clear support for the use of adaptive management in Gulf restoration (Gulf Coast Ecosystem Restoration Task Force, 2011; DWH NRDA Trustees, 2016), key components that are needed to facilitate effective implementation of adaptive management are currently lacking or not fully developed at a program level. These include careful determination of critical uncertainties, development of adaptive management plans, support for evaluation and synthesis of monitoring data, development of a process for adaptive management decision making, political will, and a financial and procedural commitment to adaptive management. Each of these elements is discussed in more detail below. Coordinated guidance from the major funding programs would help address these needs.

Defining Knowledge Gaps and Uncertainties

A primary step in the adaptive management process is identifying the critical uncertainty (or uncertainties) that will be the focus of targeted monitoring and evaluation (see Box 7.2). Defining what constitutes an uncertainty and what may make that uncertainty critical may be difficult, because uncertainty and risk are associated with virtually all restoration projects. Therefore, a systematic approach is needed to screen and prioritize project-related uncertainties. Box 7.2 describes criteria used in the Central Everglades Planning Project for screening uncertainties, and additional criteria for prioritizing them, which may be applicable to Gulf restoration projects. Screening criteria need to address the potential to improve future restoration decision making and reduce risk by reducing the uncertainty. In Gulf restoration, program managers would benefit from additional guidance from the program level to identify critical uncertainties. A coordinated effort among the large Gulf restoration programs would be the most efficient approach to identify and prioritize restoration uncertainties at both project and program scales.

Adaptive Management Planning

Although there is a demonstrated and acknowledged need for adaptive management in Gulf restoration, implementation and integration appears largely limited to Louisiana's Comprehensive Master Plan for a Sustainable Coast. For example, review of projects included in the RESTORE Council's Draft Initial Funded Priorities List (RESTORE, 2015), indicated that only those from Louisiana included as a deliverable, development of a plan for implementing adaptive management. Review of plans for projects identified in the Final Phase IV Early Restoration Plan (NOAA, 2015) also showed that consideration of uncertainties, corrective actions, and particularly the adaptive management process were largely lacking.

A requirement at the project-level to assess whether an adaptive management plan is needed would ensure that the benefits and costs of adaptive management are carefully considered and structured in the planning process. An adaptive management plan formalizes how the steps in the adaptive management process will be integrated into the implementation of a restoration project. Plans need to be scaled to reflect the size, cost, and complexity of the project. At the project scale, adaptive management plans inform decisions concerning project design, modification, and operation. Adaptive management plans at the sub-regional (i.e., watershed/estuary) scale involve multiple projects and would inform decisions concerning the sequence of project implementation and the potential need for additional project elements. Adaptive management plans at the sub-regional scale can also identify interactions between projects across time and space as uncertainties that need to be addressed.

In general, an adaptive management plan needs to address the following questions:

1) Why does the project require adaptive management?
2) What critical uncertainties may prevent the project from meeting its goals and performance criteria, and how could efforts to reduce these uncertainties improve future restoration decision making and reduce risk?
3) What monitoring strategies are necessary to address each critical uncertainty and what are the expected timeframes of response?

4) What level of project performance would trigger an evaluation of whether to implement a corrective action and how often will the criteria be evaluated?
5) If performance criteria are not met, what potential corrective actions should be considered?
6) Who is responsible for:
   - evaluating the monitoring data and quantifying performance criteria,
   - determining if a corrective or management action is required and what it should be,
   - planning and implementing the management action,
   - funding the program and any necessary corrective actions, and
   - communicating the results to interested stakeholders?

An example outline of a generic adaptive management plan adopted by the U.S. Army Corps of Engineers is given in Box 7.4. The Adaptive Management Framework for Coastal Louisiana (Water Institute of the Gulf, 2013a) and other references (Atkinson et al., 2004; RECOVER, 2010, 2015; Williams et al., 2009; Williams and Brown, 2012; Fischenich et al, 2012) provide guidance and recommendations for integrating adaptive management into coastal restoration projects and writing adaptive management plans.

Box 7.4

Example Outline for an Adaptive Management Plan

1. Introduction
    1.1 Authorization for Adaptive Management
    1.2 Rationale for Adaptive Management
2. Project Adaptive Management Planning
    2.1 Project Goals and Objectives
    2.2 Conceptual Ecological Model
    2.3 Sources of Uncertainty
    2.4 Performance Measures and Criteria for Action
    2.5 Potential Management Actions
3. Monitoring
    3.1 Rationale for Monitoring
    3.2 Project Monitoring Plan
    3.3 Analysis and Use of Monitoring Results
4. Data Management
    4.1 Description and Location
    4.2 Data Storage and Retrieval
    4.3 Analysis, Summarization and Reporting
5. Costs for Adaptive Management
    5.1 Adaptive Management Planning Costs
    5.2 Monitoring Costs
    5.3 Implementation Costs
6. Operating Procedures (How the Adaptive Management Plan is Implemented)
7. Assessment
    7.1 Assessment Process
    7.2 Frequency of assessment
    7.3 Variances and Success
    7.4 Documentation and Reporting
8. Decision Making
    8.1 Decision Making Process
    8.2 Criteria for Action
    8.3 Potential Adaptive Management Decisions
    8.4 Project Close Out
9. Communication Structure for Implementation

SOURCE: Adapted from Fischenich et al., 2012.

Facilitate Synthesis and Evaluation in Support of Decision Making

The results of monitoring and research necessitate periodic evaluation and synthesis to support adaptive management. The results are best reported in a systematic, clear, and concise manner to facilitate ease of use for decisions, with sufficient evidence provided to explain the major conclusions. The analysis of results needs to focus on how well the actions taken by the program are meeting the goals and objectives of the program and the degree to which critical uncertainties have been resolved. If the results are not as predicted, the reasons why need to be explained, if known. New recommendations for research and monitoring to resolve new questions, further reduce critical uncertainties, or improve models may be generated from the evaluation and synthesis process. Critical elements necessary to support synthesis and evaluation in the Gulf are discussed in more detail in Chapter 6.

The Platte River Recovery Implementation Program provides a good example of data synthesis of an extensive adaptive management program, with clear and relatively simple expressions of the results that are useful for stakeholders and decision makers (PRRIP, 2015). Table 7.1 summarizes major findings from the 2014 State of the Platte Report, including which critical uncertainties have been resolved and continue to be studied (highlighting information trends, if known). Additional supporting detail is provided for each “big question” in the report, along with possible adjustments that could be made for those questions that have been resolved.

Table 7.1 Synthesis of progress resolving uncertainties in the Platte River Recovery Implementation Program.

PRRIP Big Question	2014 Assessment	Basis for assessment
<u>Implementation</u> – Program Management Actions and Habitat		
1. Will implementation of SDHF produce suitable tern and plover riverine nesting habitat on an annual or near-annual basis?		Peer-reviewed Program synthesis concludes that SDHF will not produce suitable nesting sandbars.
2. Will implementation of SDHF produce and/or maintain suitable whooping crane riverine roosting habitat on an annual or near-annual basis?		Trending negative; Program synthesis chapters now in development will be discussed with the TAC and ISAC and peer reviewed in 2015; those synthesis chapters and published manuscripts related to the Program's vegetation and lateral erosion research will likely support a "two thumbs down" assessment in the 2015 State of the Platte Report.
3. Is sediment augmentation necessary for the creation and/or maintenance of suitable riverine tern, plover, and whooping crane habitat?		Trending positive; certainty about the sediment deficit; uncertainty about the role of that deficit in habitat creation and maintenance.
4. Are mechanical channel alterations (channel widening and flow consolidation) necessary for the creation and/or maintenance of suitable riverine tern, plover, and whooping crane habitat?		Trending positive; planform management manuscript now in development will be published and will likely support a "two thumbs up" assessment in the 2015 State of the Platte Report.
<u>Effectiveness</u> – Habitat and Target Species Response		
5. Do whooping cranes select suitable riverine roosting habitat in proportions equal to its availability?		A definitive assessment is expected by 2017 once peer review of data analyses (monitoring, telemetry, stopover study data, habitat availability assessments, IGERT research) is complete.
6. Does availability of suitable nesting habitat limit tern and plover use and reproductive success on the central Platte River?		Trending positive; three documents now in development will be peer reviewed and/or published and will likely support a "two thumbs up" assessment in the 2015 State of the Platte Report.
7. Are both suitable in-channel and off-channel nesting habitats required to maintain central Platte River tern and plover populations?		Trending negative; three documents now in development will be peer reviewed and/or published and will likely support a "two thumbs down" assessment in the 2015 State of the Platte Report.
8. Does forage availability limit tern and plover productivity on the central Platte River?		Trending negative; synthesis document related to tern forage (fish) will be peer reviewed that, in combination with the results of the Foraging Habits Study, will likely support a "two thumbs down" assessment in the 2015 State of the Platte Report.
9. Do Program flow management actions in the central Platte River avoid adverse impacts to pallid sturgeon in the lower Platte River?		Peer-reviewed Program stage change study concludes Program flow management actions will avoid adverse impacts.
<u>Larger Scale Issues</u> – Application of Learning		
10. Do Program management actions in the central Platte River contribute to least tern, piping plover, and whooping crane recovery?		By definition, implementation of the Program contributes to recovery of the target species. A definitive answer for this question can only be obtained by a broader analysis of the contribution of the central Platte to range-wide recovery.
11. What uncertainties exist at the end of the First Increment, and how might the Program address those uncertainties?		This question is a "parking lot" for uncertainties that could be addressed through adaptive management in an extended First Increment or new Second Increment.

SOURCE: PRRIP, 2015.

Develop a Process for Making Adjustments to Restoration Plans

Within the adaptive management process, decision makers take the information from research, monitoring, and evaluation and determine whether operations need to be changed, additional restorative actions need to be implemented, or future restoration plans need to be altered. The suite of decisions falls into three general groups (Thom 2000):

1. **No action** – do nothing because not enough time has elapsed since implementation;
2. **Do something** – implement adjustments to projects to improve effectiveness; or
3. **Change the goal** (i.e., performance metric) – that is, conclude that the project is performing as best as can be expected, albeit not optimal as was predicted, and that this performance is acceptable.

Often the suite of possible actions is large and some options may exceed the existing budget. Prioritization of actions can be facilitated through a structured decision-making process that considers benefits, costs, and other considerations in light of overall goals and budgets.

Determining in advance *who will decide what actions are taken, where, when, and for how long* is critical to an adaptive management program. Decision-makers may be appointed by agencies or come from independent stakeholder groups. Ideally, such a decision-maker would have a comprehensive understanding of the ecosystem, have a background in resolving complex issues involving science, engineering, and policy, and can translate complex, inter-disciplinary information to make solid informed decisions. The appointed decision maker needs to coordinate with a wide array of researchers and scientists, program managers, funding entities, and interested stakeholders. Many large projects utilize an independent science advisory panel to help in the prioritization process (Burns et al., in review).

Commitment to Adaptive Management

Because adaptive management requires more rigorous project planning, monitoring and management effort, it is more resource intensive. Therefore, a consistent, reliable commitment of monetary and human resources in support of the necessary science, monitoring, evaluation, and decision-making is required for successful implementation. Additionally, adaptive management is more likely to achieve its goals if the process is supported by a dedicated organizational structure (unit) within the agencies implementing restoration. That means that when adaptive management is determined to be appropriate to a project, the adaptive management framework and processes need to be embraced by the action agency. Although adaptive management is viewed as the pragmatic approach to restoration in many situations, the process can conflict with an agency's standard project implementation process. More work may be required upfront to identify and rank critical uncertainties and develop monitoring plans to address them. An adaptive management approach typically requires more monitoring funding than a typical project, and monitoring funding that is inconsistent or subject to major cuts can impact the effectiveness of the adaptive management process.

Coordinated Guidance

If adaptive management is to be implemented across the Gulf in a way that truly enhances the long-term effectiveness of restoration investments, additional program-level support for adaptive management is needed, including coordinated guidance for project managers. As previously discussed, coordinated program teams could identify high-priority uncertainties (see Box 1.2) for common project types and for the Gulf restoration program more broadly to provide guidance at the project level. Guidance is also needed to outline a framework for determining when adaptive management is (or is not) appropriate and a sound investment of resources in Gulf restoration efforts. The guidance could also identify effective adaptive management protocols and information required in adaptive management plans, describe program-le vel science resources to support project managers in these efforts, and outline strategies to coordinate adaptive management projects at scales larger than a single project.

CONCLUSIONS AND RECOMMENDATIONS

The complexity, large scale, and extended timeframe of Gulf restoration provide valuable opportunities for improving the effectiveness of restoration through monitoring, evaluation and adaptive management. Both construction and performance monitoring also provide opportunities for improving the effectiveness of restoration, although learning tends to occur more slowly. Adaptive management provides a structured process by which knowledge gained from monitoring restoration efforts can be used to reduce critical uncertainties and enhance ongoing or future restoration decision making. Adaptive management, therefore, increases the likelihood that restoration goals will be achieved and decreases the likelihood of undesirable outcomes, while enhancing communication among scientists, managers and stakeholders. Adaptive management is not appropriate or necessary for all restoration projects, particularly those where the response is well known or the time scales for ecosystem response are lengthy. However, with a well-conceived monitoring program and rigorous evaluation, adaptive management offers the potential to improve restoration performance over the long term and enhance cost effectiveness.

To improve long-term restoration effectiveness, and where the restoration program managers deem it appropriate, Gulf restoration programs should implement adaptive management at the program- and project-level. To implement adaptive management, projects or programs need to commit to the:

- Careful determination of critical uncertainties, prioritized by the potential for adaptive management to improve future restoration decision making and reduce risk;
- Development of project-level adaptive management plans that formalize the key steps and responsible parties in the adaptive management process;
- Institutional support for synthesis and evaluation in support of decision making;
- Development of a decision-making process in advance for making adjustments to restoration projects;
- A clear financial and procedural commitment to adaptive management, which will likely require a dedicated organizational structure and additional planning and monitoring beyond typical restoration projects; and
- Coordinated guidance for implementing adaptive management for Gulf restoration.

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PART II

GOOD PRACTICES FOR MONITORING RESTORATION OF SELECTED HABITATS AND SPECIES OF CONCERN

INTRODUCTION

While Part I describes the general process for effective monitoring and progress evaluation, Part II uses a few example habitats and species to illustrate how the general process guidance would be applied. The following descriptions draw on elements detailed in Part I of this report (e.g., identifying broad goals, measureable objectives, conceptual model(s), scales, metrics linked to objectives, targets informed by research, control and/or reference sites, applicable constraints, suitable sampling design, data management and sharing procedures). For some restored habitats and species, conceptual models are well-understood and can effectively frame restoration monitoring. For many, monitoring is currently guided by well-established methods. This part of the report draws upon many of the concepts discussed in Part I to provide examples of good practices for six habitats and species groups of concern in the Gulf of Mexico: oyster reefs, tidal wetlands, seagrasses, birds, sea turtles, and marine mammals.

The sections presented here are meant to act as a guide and reference, rather than a comprehensive manual, for restoration administrators and funders setting monitoring requirements and for practitioners tasked with monitoring habitat or species recovery. Although the release of oil during the DWH spill was mostly offshore in deep water, most of the restoration expertise and experience has been in coastal ecosystems. Therefore, Part II of this report focuses mostly on monitoring coastal restoration efforts, although these are not the only habitats and species in need of restoration attention. Guidance also exists for monitoring restoration of other habitats and species that may have been affected by the DWH spill. For example, beaches and barrier islands (e.g., Nelson, 1993; NRC, 1995; Brandon et al., 2013; Schlacher et al., 2014), coral reefs (e.g., Thayer et al., 2005; Precht, 2006; Edwards, 2010; Johnson et al., 2011; NOAA, 2014), deep sea habitats (e.g., Thayer et al., 2005; Shepard, 2014; Van Dover et al., 2014), mangroves (e.g., Field, 1999; Lewis, 2000; Thayer et al., 2005), offshore/marine fish (e.g., Peterson et al., 2003; Powers et al., 2003; Alford et al., 2014), and the water column (e.g., Thayer et al., 2005). Monitoring fisheries management is beyond the scope of this report; readers are advised to seek guidance from the National Marine Fisheries Service, for example on observer programs, electronic monitoring and reporting, or seafood safety monitoring,[95] and from the Gulf of Mexico Fishery Management Council.[96]

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[95] NMFS National Observer Program: http://www.st.nmfs.noaa.gov/observer-home/; NMFS Electronic Monitoring Systems information: https://www.st.nmfs.noaa.gov/advanced-technology/electronic-monitoring/index, http://www.nmfs.noaa.gov/sfa/reg_svcs/Councils/ccc_2013/K_FisheriesMonitoringRoadmap.pdf, http://www.nmfs.noaa.gov/sfa/reg_svcs/Councils/ccc_2013/K_NMFS_EM_WhitePapers.pdf; NMFS seafood safety surveillance: http://sero.nmfs.noaa.gov/deepwater_horizon/index.html.

[96] The Gulf of Mexico Fishery Management Council prepares fishery management plans to manage resources between state waters and the 200-mile limit of federal Gulf waters: http://gulfcouncil.org/. The Council guides fisheries management with10 key national standards applicable in all federal waters. Stock assessments are used to

Each of the sections provided here includes discussion on habitat or species-specific restoration objectives, uncertainties that currently hinder decision-making, elements of a project-level monitoring and assessment plan, and a table that provides a list of potential metrics that can be used to measure progress toward example restoration objectives. Guidance presented in the tables is based on available literature (or on the Committee's judgement, and indicated as such). In addition, the tables present guidance on broadly applicable project-level habitat or species[97] monitoring where there is a relatively high level of consensus in the literature on metrics that are best able to assess restoration for the purposes of construction, performance, and monitoring for adaptive management (see Chapter 3). Furthermore, as discussed in Chapter 4, assessing restoration progress at a regional or program-level will require monitoring to be undertaken in an integrated and coordinated fashion for each habitat type and species across the Gulf of Mexico. Manning et al. (2006) state that "large-scale, ambitious restoration projects will not happen by accident…and functioning ecosystems will not be reconstructed by chance through the cumulative effects of small-scale ad hoc restoration efforts."[98] Furthermore, creating a restoration vision that is shared by the larger Gulf-region funding agencies and programs, articulating that vision through explicit objectives, and coordinating monitoring metrics and data assessment protocols improves the chance of restoring large-scale ecosystem biodiversity, structure, process, function, and services. There is substantial benefit to be realized from monitoring the recovery of interconnected resources in an overlapping fashion with other restoration monitoring efforts.[99] To facilitate scaling up from project-level monitoring, the tables within each section below provide suggested metrics for each habitat and species that the Committee judges could be measured for coordinated restoration projects across the Gulf (see Chapter 4). Note that although the metrics in "program-level" columns may help assess restoration beyond the project scale, or across the Gulf itself, they may not provide priority information at smaller scales, depending on project objectives. For example, measuring the number of eggs produced per sea turtle in a given year improves understanding of status and trends beyond the scope of the project-level by indicating population- or species-level change and informing Gulf-wide sea turtles restoration efforts.

Many monitoring programs have not enabled larger scale restoration assessments specifically because they failed to employ necessary data management procedures, and very few have planned and provided adequate financial support for this consideration (Lindenmeyer and Likens, 2010; see Chapter 5). The sections that follow do not discuss data management and stewardship because the guidance is provided in Chapter 5 of the report and applies to all restoration monitoring independent of objectives or habitat type. It is critical to ensure that collected data will be managed, secured, and made available in a way that promotes their quality and suitability for restoration analysis, assessment, synthesis, and ultimately decision-support (see Chapters 6 and 7). Furthermore, this report (Part I and Part II) only briefly discusses monitoring for ecosystem services, because the Committee was asked to focus on ecological

monitor fish status, as required by the Sustainable Fisheries Act, are completed by NOAA, and inform Council management decisions on catch rates and allocation.

[97] In these sections, we refer to *species* as the subject of restoration monitoring, rather than populations, because restoration focus tends to be on species recovery. In particular, protected species have federal recovery plans that detail actions needed to increase their numbers in order to downlist or delist species from protected status.

[98] For example, see Hijuelos et al. (2013) for a description of Louisiana's cross-habitat and species restoration assessment framework, which includes monitoring atmospheric, land-based, water-based, and wildlife parameters.

[99] [E18] For example, monitoring seagrass habitat and prey (such as blue crab stocks) can help explain sea turtle response to restoration along with turtle-specific monitoring practices.

monitoring. However, monitoring for ecosystem services is important to consider as part of restoration monitoring and evaluation; see NRC (2012, ch. 3; 2013, ch. 5) for general reference, as well as Hijuelos and Hemmerling (2015) for a description of human systems sampling as well as information for Louisiana's sampling protocol for physical and biological metrics.

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OYSTER REEF RESTORATION MONITORING

Why Restore Oyster Reefs?

Healthy and well-developed intertidal and subtidal oyster reefs provide services to the ecosystems within which they reside, including habitat for numerous ecologically and economically important species; water filtration; reduction in nutrients, sediment, and harmful algal blooms; and shoreline protection or enhancement (e.g., Coen and Luckenbach, 2000; Coen et al., 2007; Grabowski and Peterson, 2007; Arkema et al., 2013; Baggett et al., 2014; Walles et al., 2015a, 2016a). Among other benefits, restoration improves commercial, subsistence, and recreational harvests of oysters and other valuable species. Wildstock oyster harvests in the Gulf of Mexico (the eastern oyster, *Crassostrea virginica*) are still some of the highest in the world, but their abundance within the Gulf of Mexico has declined by 50-99 percent based on historical records (Airoldi and Beck, 2007; Beck et al., 2011; zu Ermgassen et al., 2012).

Although intertidal oyster reefs are not generally harvested in the Gulf of Mexico, they were likely directly affected by oil and act as seed areas to populate harvested reefs, as well as provide a number of other valuable services. Therefore, both types of reefs are important to consider for restoration, and will be addressed in this report. Properly conducted restoration can enhance existing populations, in addition to creating new reefs that are comparable to historically well-developed natural reefs. Oyster restoration and related efforts in the Gulf have been shown to improve seafood harvests (potentially with even greater returns for dependent fisheries species than for oysters alone), support income and employment, and reduce coastal vulnerability to both natural disasters and small-scale erosion (e.g., Grabowski et al., 2012; Kroeger, 2012; Arkema et al., 2013). The good practices contained within this section are intended to better inform restoration and related monitoring efforts while providing overall consistency as much as possible across the Gulf of Mexico to better compare restoration outcomes.

Restoration Objectives

As mentioned above, common high-level goals that involve oyster restoration include creating/enhancing reef habitat, increasing oyster harvests, improving water quality and removing nutrients, increasing water clarity, enhancing adjacent habitats, and reducing coastal vulnerability. To assess progress toward any of these outcomes, a monitoring protocol must begin by translating restoration goal(s) into specific and measurable objectives with associated metrics (see Chapter 2). The main objectives for oyster reef habitat restoration have been described by Coen et al. (2004) in six categories: (1) enhancing resources to address the goal of improving harvests (Powers et al., 2009; Schulte et al., 2009; but see Coen and Luckenbach [2000] and Powers and Boyer [2014]); (2) creating broodstock sanctuaries to enhance areas with low recruitment (Southworth and Mann, 1998; Southworth et al., 2010); (3) enhancing nursery and feeding habitat (through predation effects) to increase critical habitat and secondary production (Coen et al., 1999b; Peterson et al., 2003; zu Ermgassen et al., 2016); (4) increasing filtration, nutrient cycling, and nitrogen, phosphorus, and /or carbon sequestration in tissues and shells to meet the goal of improving water quality or clarity (Dame and Libes, 1993; Nelson et al., 2004; Grizzle et al., 2008; Higgins et al., 2011; Kellogg et al., 2014; Smyth et al., 2016); (5) stabilizing shorelines (sometimes as part of what is referred to as creating living shorelines) by reducing wave energy and erosion (Meyer et al., 1997; Piazza et al., 2005; Walles et al., 2015a, 2016a), or by enhancing restoration of adjacent habitats (Milbrandt et al., 2015); and (6) promoting education to improve community involvement (Brumbaugh et al., 2000a, 2000b, 2006, Brumbaugh and Coen, 2009; Hadley et al., 2010).

Examples of common restoration objectives are provided in Table II.1, including oyster population enhancement, habitat enhancement for other species, water quality/clarity improvement, and adjacent habitat enhancement. Table II.1 also lists a set of measurable metrics (described below) that may help assess progress towards these objectives in many cases, depending on the relevant monitoring purpose (Note that example metrics to support monitoring for adaptive management are not included because of their inherent project/program-specificity).

Why Monitor Oyster Reef Restoration?

Practical and scientific understanding of oyster reef restoration is relatively advanced, and strong guidance exists to inform monitoring protocols and techniques depending on particular restoration objectives (e.g., Baggett et al., 2014). However, much of this progress is due to the focus of past activities on restoring oysters as a harvestable resource. Consequently, monitoring has largely focused on restoration with the objective on improving harvests and monitoring to improve restoration with other objectives has been lagging (Coen and Luckenbach, 2000; Kennedy et al., 2011; La Peyre, et al. 2014; Powers and Boyer, 2014; Coen and Humphries, 2016), although restoring oyster reefs to enhance ecosystem service provision is becoming more common (e.g., Coen et al., 2007).

As illustrated in Part I of this report (Box 1.2), monitoring oyster reef restoration can benefit restoration practice by demonstrating which factors contribute to effective restoration. However, few cases between 1990-2007 in the Chesapeake Bay were guided by clear goals and objectives, and only 43 percent of restoration recorded included **any** monitoring components. When monitoring did occur, it was usually inadequate to assess changes in oyster populations on constructed reefs due to a lack of replication, consistent and quantitative methodologies, and related sampling designs (Kennedy et al., 2011; Baggett et al., 2014; La Peyre et al., 2014). Similar analyses of smaller and more diverse datasets have been conducted in the Gulf of Mexico (La Peyre et al. 2014) with fewer than 25 percent of oyster reef restoration projects in the northern Gulf being monitored or even reported at all. Therefore, text below provides guidance and good practices for monitoring oyster restoration.

Decision-critical Uncertainties

Presently there are few, if any, rigorous (and general) conceptual models available for oyster reef restoration, or for that matter that apply specifically to the Gulf of Mexico (see Figure II.1). Most available models have addressed a subsection of possible restoration-related objectives, relating more to habitat suitability and site selection (e.g., Cake, 1983; Barnes et al., 2007; Pollack et al., 2012; La Peyre et al., 2015) in the Gulf of Mexico than to a more general model relating the functioning of oyster reefs within the larger ecosystems (e.g., Soniat and Brody, 1989; Coen and Bishop, 2015). Also, some models have been developed for specific estuaries (e.g., the Chesapeake Bay [USACE, 2012]; Louisiana diversions [Soniat et al., 2013]). They can be generalized for use here, but they typically include many parameters whose data are often unavailable or are too variable to apply throughout a single estuary, let alone the Gulf of Mexico (see Figure II.1, USACE 2012).

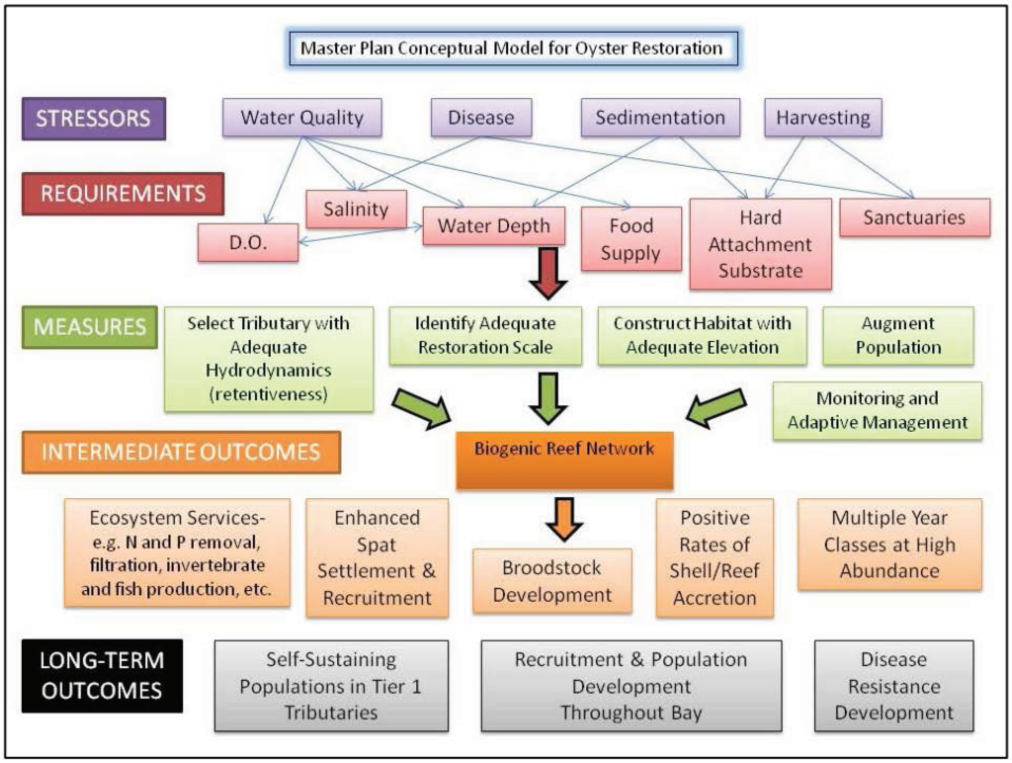

Figure II.1 Conceptual model for oyster restoration in the Chesapeake Bay. SOURCE: The U.S. Army Corps of Engineers, 2012. http://www.nab.usace.army.mil/Missions/Environmental/OysterRestoration/OysterMasterPlan.aspx.

Other restoration-relevant uncertainties include differences between U.S. East Coast and Gulf of Mexico estuaries and differences across parameters within the Gulf, for example, in typical temperature and salinity values from Texas (where subtidal reefs dominate) to Florida (where intertidal reefs dominate). However, conducting sensitivity analyses for these and other parameters can reduce some of these uncertainties (Beseres et al., 2012). In the Gulf, age and growth rates, settlement rates and early survival, natural mortality, disease rates, shell loss rates, reef growth and subsidence rates, and fecundity are often uncertain entries in region and population-specific models (e.g., Paynter et al., 2010; Casas et al., 2015). Resolving these uncertainties would inform future site selection and inform the assessment of restoration performance.

Restoration monitoring in the Chesapeake Bay has informed oyster reef restoration techniques. However, uncertainties still hinder effective restoration efforts in the Gulf of Mexico. For example, in some cases, simply restoring natural and historical hydrology to past flow regimes through removal of man-made impediments has been suggested as sufficient for the restoration process. Whether removal of impediments is a reasonable activity to restore oyster populations will have to be evaluated long-term under the same conditions proposed for typical restoration efforts (Craig et al., 2010; Milbrandt et al., 2015).

Project-level Monitoring and Assessment Plan Considerations

Recently, Baggett et al. (2014, 2015) and others (e.g., OMW, 2011, USACE, 2012; Coen and Humphries, 2016) have compiled relatively thorough handbooks on oyster restoration monitoring, including specific recommendations for the Eastern oyster, Crassostrea virginica. These handbooks build upon earlier efforts (e.g., Thayer et al., 2005; Coen et al., 2004; Leonard and Macfarlane, 2011) and understanding of restoration for the west coast Olympia oyster, Ostrea lurida (e.g., Peter-Contesse and Peabody, 2005; Wassen et al., 2014).

Monitoring Purpose and Project Objectives

One of the most important messages for any restoration and related monitoring efforts is the critical nature of developing objectives and related metrics *a priori*, and for the objectives to be explicitly followed for the various purposes of restoration monitoring. As defined in Part I of this report, the three primary purposes include the following: monitoring (1) to assure projects are built and are initially functioning as designed (*construction monitoring*); (2) to assess whether restoration goals and objectives have been or are being met (*performance monitoring*); and (3) to inform restoration management and to improve the design of future restoration efforts (*monitoring for adaptive management*). For performance monitoring and monitoring for adaptive management, it is good practice for all of the critical protocols to be documented as standard operating procedures and followed to the letter without changes. This protocol helps ensure that any observed changes are not the result of personnel changes or procedures, and thus facilitates comparison of results across projects and programs.

In addition to identifying the restoration objectives, the project needs to clearly identify the purpose of the monitoring effort (i.e. what questions the monitoring effort is to address). Without the stated objectives, the ability to effectively compare monitoring results and to assess progress towards oyster restoration objectives is significantly hampered (see Chapters 4 and 5; Coen and Luckenbach, 2000; Coen et al., 2004; Thayer et al., 2005; Kennedy et al., 2011; Baggett et al., 2014; La Peyre et al., 2014). Restoration project objectives need to be assessed against pre-determined targets and carefully selected and associated metrics (see Table II.1) using rigorous experimental designs (replication, independence, etc., see Chapter 3) and appropriate data management techniques (see Chapter 4). As part of the above, when possible, designs need to include: (1) baseline sampling of the proposed construction site(s) and historical datasets where available (termed "pre-construction" in Table II.1), along with (2) appropriate control and/or reference sites to compare with restoration site(s) progress (see Chapter 3; Coen and Luckenbach; 2000, Coen et al., 2004; Kennedy et al., 2011; Baggett et al., 2014).

Choose Suitable Metrics

Metrics and their corresponding targets to assess restoration success for both performance monitoring and monitoring for adaptive management, in conjunction with a project's proposed objective(s), are used to assess how a given oyster reef restoration project performs on initially short- and then longer-term timescales. For projects directed at restoring intertidal or subtidal Gulf of Mexico oyster reefs, it has been suggested that projects should at a minimum sample a limited suite of *universal* metrics that are used to assess reef, oyster, and environmental conditions as well as a project's performance regardless of its objective(s) (see below and Table II.1). Using an identical or nearly identical set of minimum, universal metrics and sampling protocols to assess different projects allows comparison among (a) projects in a limited area (within a program or a given area), (b) a larger spatial area, for example within the Gulf of Mexico, or (c) ocean basins (e.g., the Gulf of Mexico and western Atlantic Ocean), given the extensive range and conditions the eastern oyster occupies. Such universal metrics are summarized by Baggett et al. (2014, 2015), included in Table II.1, and described below.

Standardizing monitoring metrics and protocols are also critical to assess the extent to which restoration targets have been achieved, to promote learning and to improve restoration efforts (e.g., Kennedy et al., 2011; OMW, 2011; Baggett et al., 2014; La Peyre et al., 2014; Powers and Boyer, 2014). To illustrate this point, few restoration monitoring efforts in the Chesapeake Bay reported by Kennedy et al. (2011) employed good sampling designs, replication, and quantitative metrics (see Chapter 3); but even when studies were diligent in these aspects, the different methods of data collection (e.g., oyster recruitment and status measurements differing between states) made it impossible to adequately assess changes in oyster populations on constructed reefs. Understanding which metrics have high inherent variability is also important for reliable comparison within and across projects. Monitoring for adaptive management can incorporate this factor to improve resource (habitat) management by assessing restoration progress with a pre-determined recruitment target (see Chapter 7). For example, substantial spatial and temporal variability exist in oyster recruitment rates (e.g., Austin et al., 1996; Bartol and Mann, 1999; Harding et al., 2012; Baggett et al. 2014, Coen and Humphries, 2016). Planning restoration actions (e.g., planting shell as a recruitment substrate; see Box 1.2) before recruitment, and comparing oyster densities after multiple recruitment seasons to a target value will indicate whether additional restoration actions through monitoring and adaptive management (e.g., transplanting live oysters) are required. In many cases, a minimum set of metrics will be necessary, but not sufficient to track progress towards restoration objectives. Additional metrics need to be added to ensure progress is being made towards all objectives. For example, many researchers and managers are using objectives tied to specific ecosystem services derived from oyster restoration efforts to guide the choice of monitoring metrics (Coen and Luckenbach, 2000; NRC, 2004; Peterson et al., 2003; Coen et al., 2004; Grabowski et al., 2007, 2012; Pollack et al., 2013; zu Ermgassen et al., 2013a, 2013b). Baggett et al. (2014, 2015) refer to these performance monitoring metrics as "goal-based objective metrics," which serve to tie the objectives, design, and related sampling to one or more specific ecosystem services. For a given project, one or more restoration objectives are proposed *a priori,* and then explicitly evaluated as part of the restoration effort. Additional ancillary metrics were also presented by Baggett et al. (2014) and cited publications therein are included here (see Table II.1) to suggest a few additional metrics for monitoring across projects at the program-level scale.

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Universal, Minimum Metrics for All Oyster Restoration Activities

Regardless of project objective(s), a minimum set of parameters that should be sampled includes monitoring: (a) reef physical attributes; (b) oyster population attributes; and (c) a series of critical environmental parameters at intervals that are relevant given the spatial and temporal variability of estuarine systems (for example, see any of the National Estuarine Research Reserve's System-wide Monitoring Program water quality and atmospheric data[100]).

(a) *Reef Physical Attributes***:** A great deal of information is presented in Table II.1 to guide sampling parameters, frequency, timing, etc. for each monitoring purpose. Data gathered prior to reef construction can come from the pre-construction site and/or reference and control sites, and can possibly include historical fisheries-dependent or independent sampling data (Beck et al., 2011; zu Ermgassen et al., 2012). Briefly, for either reference or control reefs, or for newly constructed reefs immediately after material is deployed and through time, the most important parameters are *reef habitat attributes and status*. These include (i) reef footprint expansion (through initial spreading, resulting in decreased reef height) prior to reef material adhesion or growth, or contraction (via subsidence and material loss); and (ii) change in vertical relief (rugosity) of material above the substrate through time.

(b) *Oyster population attributes*: The most important metrics based on replicate sampling typically include (i) assessment of overall live (or dead) oyster size-frequencies; and (ii) mean density of live (or dead) oysters through time (Baggett et al., 2014, 2015). It is critical that monitoring for restoration projects with objectives that are not fisheries-related not rely on objective-inappropriate fisheries-employed metrics, such as the density of legal-sized oysters (e.g., Coen and Luckenbach, 2000; Luckenbach et al., 2005). Too often restoration projects whose focus is on other non-extractive services have been judged as to their success or failure inappropriately by using fishery metrics. For some restoration (e.g., Chesapeake Bay) efforts, a mix of the above metrics (including specific density of large oysters) and long-term datasets have been employed to judge success (e.g., OMW, 2011).

In addition to natural recruitment, restoration can also include amendments of live oysters from hatcheries, including seeding with larvae ("spat") or juveniles (for larger scales, see Southworth and Mann, 1998; Schulte et al., 2009). This is especially helpful when the natural recruitment rate is low or variable both spatially and temporally (e.g., Roegner and Mann, 1995; Brumbaugh and Coen, 2009; Soniat et al., 2012; Baggett et al., 2014; Coen and Humphries, 2016), one wants to 'jump start' reef restoration efforts (e.g., in the Chesapeake Bay or Hudson River estuary), sufficient funding is available, or time constraints favor these methods (e.g., Carbotte et al., 2004; Brumbaugh and Coen, 2009; Southworth et al., 2010; Leviton and Waldman, 2011; Starke et al., 2011; Baggett et al., 2014; Powers and Boyer, 2014). See Table II.1 and appropriate citations (Thayer et al., 2005; Coen et al., 2004; Powers et al., 2009; OMW, 2011; Baggett et al., 2014; Powers and Boyer, 2014; Coen and Bishop, 2015; Walles et al., 2015a, 2015b; Coen and Humphries, 2016; and references therein) for many additional parameters that would be necessary depending on, for example, variance from average disease levels, additive

[100] National Estuarine Research Reserve (NERR) Centralized Data Management Office information: http://cdmo.baruch.sc.edu/data/parameters.cfm.

recruitment densities, predator and competitor densities, fouling, sedimentation rates, or substrate losses.

(c) *Critical Environmental Parameters***:** Basic environmental metrics minimally include (i) temperature, which can be inexpensively logged near continuously, (ii) salinity, and (iii) dissolved oxygen, especially for deeper subtidal oyster reefs (see Table II.1). Good practice is for environmental metrics to be sampled at realistic frequencies that are both biologically and environmentally relevant. This means typically sampling at a much higher frequency than the above biological and reef characteristics, regardless of project objective(s) (Coen et al., 2004; Baggett et al., 2014). It is essential that these parameters be assessed at frequencies that are appropriate given their significant variability with rainfall, tides, and other weather events (Coen et al., 1999a; Van Dolah et al., 1999; Ringwood and Keppler, 2002; Coen and Bishop, 2015). It is essential that these parameters be assessed at frequencies that are appropriate given their significant variability with elements such as rainfall, tides, and other weather events (Coen et al., 1999a; Van Dolah et al., 1999; Ringwood and Keppler, 2002; Coen and Bishop, 2015).

Sustained long-term measurements are critical to our understanding of short- and long-term changes in estuarine and marine environments, especially given climate change and related impacts to oysters and other organisms (Waldbusser and Salsbury, 2014; Coen and Bishop, 2015; Ekstrom et al., 2015). During an initial monitoring period (often 1-2 years or longer), oyster densities and mean sizes ought to result in statistically greater mean densities of oyster or other filter feeding taxa (e.g., mussels), or other target species or functional groups on restored reef(s) through time as compared to pre-construction numbers. They ought to also show progress toward convergence with reference site and divergence from control site values. Successful oyster reef restoration has shown long-term continuation of these trends for a decade (for example, see Box 1.2).

In the past, sampling often only occurred during daylight hours, on weekdays, in suitable weather, and/or at a frequency that might only be monthly. To gather data during variable or atypical events, one needs to sample using newer methods and equipment. Synoptic sampling of these factors monthly is simply not sufficient to assess their effects on oysters, associated communities, and overall ecosystems. Reporting accessible data in near real-time allows for appropriate response times to assess events soon after they occur (e.g., the Gulf of Mexico Coastal Ocean Observing System[101] or Sanibel-Captiva Conservation Foundation's River, Estuary and Coastal Observing Network [102] see Chapter 4).

Habitat context can be quite different for intertidal and subtidal reef habitats (e.g., Grabowski et al., 2005; Coen and Bishop, 2015; Byer et al., 2015; Coen and Grizzle, 2015; Smyth et al., 2016) and need to be considered even in design of minimum metric selection. For example, effects on landward vegetated habitats (or living shorelines, as they are sometimes called) from oyster restoration, are typically derived from reefs or material that is near (either shallow subtidal or intertidal) or abutting marsh or mangrove shorelines. Deeper, subtidal reefs typically cannot protect or reduce shoreline erosion (Coen et al., 2007; Coen and Humphries, 2016). This context-dependent reef habitat function needs to be understood when discussing potential impacts (K. Arkema pers. comm., also see Arkema et al. [2013] for this type of

[101] Gulf of Mexico Coastal Ocean Observing System: http://gcoos.tamu.edu/.
[102] The River, Estuary and Coastal Observing Network: http://recon.sccf.org/index.shtml.

misperception). Similarly, as mentioned in TableII.1, low levels of dissolved oxygen is typically less of a concern for intertidal oysters than for subtidal oysters, but time of exposure and intertidal temperatures at exposures are important for intertidal oysters. Disease in *C. virginica* also appears to have different responses in the context of high temperatures and salinities for intertidal oysters than for those living subtidally (Coen and Bishop, 2015, and references therein).

Sampling Design and Protocols

Good monitoring practices typically include sampling protocols and methodology that have been successfully used before and are agreed to be effective (Baggett et al., 2014), unless a project seeks to explore novel or more cost-effective options, along with validated methods. Primarily, it is critical for sampling methods to ultimately be comparable across projects, states, programs, etc. Every state along the east coast of the U.S. or the Gulf of Mexico has used very different methods (and even measurements of bushel sizes) to assess oyster reefs (NRC, 2004; ASMFC, 2007; Keiner, 2010). For example, practitioners use any number of SCUBA diving techniques, dredges, patent tongs, or simply sample by walking along shorelines where intertidal oysters grow. Using different techniques will make it more difficult to compare the same metrics across project and statistical rigor of the conclusions will be lower.

Some restoration practitioners have suggested collecting at least one year (or through a given recruitment season) of pre-construction data, but this is often not possible and/or there is no applicable historical baseline (e.g., Coen et al., 1999a; Cranfield et al., 1999; Coen and Luckenbach, 2000; Coen et al., 2004; Beck et al., 2011; zu Ermgassen et al., 2012; Alleway and Connell, 2015). Paired natural (referred to as reference) sites can be used to assess trajectories of constructed oyster reefs through time (NRC, 1992; Coen et al., 1999a; Coen and Luckenbach, 2000; Baggett et al., 2014, 2015). This practice will greatly assist in the interpretation of restoration efforts early in reef development in terms of poor or atypical recruitment season(s) versus attributes related to a given constructed site or single effort.

Table II.1 Metrics considered good practice to monitor oyster reef restoration activities for construction, performance toward project objectives, and program-level or large-scale assessments.

NOTES: Examples are provided to illustrate linkages between restoration situations/objectives and appropriate metrics to assess progress. Example #1 (linkages shown in the table by “#1”) is to restore brood stock and enhance oyster population(s); Example #2 is to enhance habitat for other (non-oyster) species and adjacent habitats; Example #3 is to improve water clarity; and Example #4 is to protect adjacent habitat / living shoreline. Pre-construction denotes sampling to occur before restoration at proposed site(s) and control/reference site(s). Post-construction sampling should occur immediately after restoration to ensure site specifications. Metrics relevant for intertidal (I) and subtidal (S) oyster restoration are suggested by the Committee as appropriate to sample across multiple projects at a program, region, or Gulf-wide scale.

	Monitoring Purpose			
	Pre-Construction	**Post-Construction**	**Performance**	**Program-level**
Potential Monitoring Metrics	*Examples*	*Examples*	*Examples*	*Universal**
Habitat				
Reef areal dimensions (footprint)	#1, #2, #3, #4	#1, #2, #3, #4	#1, #2, #3, #4	I, S
Summed area of patches of living/non-living shell	#1, #2, #3, #4	#1, #2, #3, #4	#1, #2, #3, #4	I, S
Reef height(s) (vertical relief off bottom)	#1, #2, #3, #4	#1, #2, #3, #4	#1, #2, #3, #4	I, S
Percent cover of bottom by a given reef substrate			#1, #2, #3, #4	I, S[a]
Reef rugosity (finer scale micro-relief)	#1, #2	#1, #2	#1, #2	
Performance of material(s) employed			#1, #2, #3, #4	
Geomorphology/Hydrology				
Water temperature			#1, #2, #3, #4	I, S
Salinity	#1, #2, #3, #4		#1, #2, #3, #4	I, S
Dissolved oxygen	#1, #2, #3, #4		#1, #2, #3, #4	S
Air temperature at exposure	#1, #2, #3		#1, #2, #3, #4	
Duration of exposure	#1, #2, #3		#1, #2, #3, #4	
Dissolved nitrogen and phosphorus	#1, #3		#3	
pH	#1, #2, #3, #4		#1, #2, #3, #4	
Shoreline loss/gain	#4		#2	
Shoreline profile/elevation change	#4		#2	
Water transparency at submergence	#3		#3	
Light attenuation	#3		#3	
Typical wave energy regime	#1, #2, #3, #4	#4	#2, #3, #4	
Range of shear force at sediment surface	#1, #2, #3, #4		#1, #2, #3, #4	
Vertically-integrated water column current velocity through tidal cycle	#1, #2 ,#3	#2, #4		
Level of toxins related to microalgal blooms (before and during blooms)	#1, #2 ,#3		#1, #2 ,#3	
Soils/sediments				
Soil geomorphology	#4		#2 ,#3	
Soil/sediment organic content	#4		#1, #2 ,#3	
Soil/sediment grain size	#2, #4		#2 ,#3	
Sedimentation rate	#1, #2 ,#3		#1, #2 ,#3	
Subsidence rate of reef	#1, #2, #3, #4		#1, #2, #3, #4	
Sediment accumulation or change by vegetation (emergent or submerged)	#2 ,#3		#2 ,#3	
Upstream land use	#1, #2 ,#3		#1, #2 ,#3	
Adjacent Habitats				
Soil geomorphology	#4		#4	
Density and percent cover of emergent plants	#4		#4	
Density and percent cover of submerged aquatic vegetation	#3, #4		#3, #4	
Species, composition, percent cover of associated plants/algae on or adjacent to reefs	#2, #4		#2, #4	

	Monitoring Purpose			
	Pre-Construction	Post-Construction	Performance	Program-level
Potential Monitoring Metrics	*Examples*	*Examples*	*Examples*	*Universal**
Oyster Population Attributes				
Oyster density (annually)	#1, #2 ,#3	#1, #2 ,#3	#1, #2, #3, #4	I, S
Size-frequency distribution (annually)	#1, #2 ,#3		#1, #2, #3, #4	I, S
Disease prevalence and intensity	#1	#1, #2 ,#3	#1, #2 ,#3	I, S[a]
Oyster condition index	#1		#1	I, S[a]
Gonad development status	#1			I, S[a]
Oyster sex ratio	#1			I, S[a]
Shell biovolume, above-sediment hard substrate	#1, #2, #3, #4	#1, #2, #3, #4	#1, #2, #3, #4	I, S[a]
Adult oysters	#1,#3		#1	
Nearby reefs with large oysters	#1	#1	#1	
Nearby oyster reefs with recruits	#1, #2 ,#3	#1, #2 ,#3	#1	
Nearby reef size-frequency distributions	#1, #2 ,#3	#1	#1	
Oyster biomass	#1,#3		#1,#3	
Oyster post-recruitment survival	#1		#1,#3	
Oyster growth	#1		#1,#3	
Recruitment success	#1		#1,#3	
Mortality rates	#1		#1	
Associated Fauna/Flora				
Presence of predatory/pest/competitive species	#1, #2 ,#3		#1, #2, #3, #4	I, S[a]
Numbers and density of suite of selected species and/or faunal groups			#2	
Resident species composition, abundance			#2	
Transient species composition, abundance, density			#2	
Bird species composition, abundance, density	#2		#2	
Non-native species composition, abundance	#1, #2		#1, #2 ,#3	
Ecosystem Services				
Commercial oyster landings/revenue/employment			#1	
Commercial fishery closure frequency			#1	
Fishery market value	#1		#1	
Recreational oyster harvest rate at site			#1	
Secondary production from restored reefs	#2		#2	
Filtering capacity (chlorophyll *a* /seston concentration), sediment resuspension/erosion	#3		#3	
Microalgal concentrations at sites around reefs			#3	
Beach closure frequency near site			#3	
Public perception of water quality/clarity near site				
Public willingness to pay for oyster restoration				
Shoreline protection, erosion, adjacent vegitation	#4		#4	
Construction of shoreline armoring and other unnatural erosion prevention measures				
Nearshore wave height at site (moderate storms)			#4	
Wave attenuation by restored intertidal reef(s)			#4	
Coastal erosion rate			#4	
Value of adjacent coastal property damage from moderate storm events				

SOURCES: Lenihan et al., 1996, 1999; Lenihan and Peterson, 1998; Lenihan, 1999; Coen et al., 1999a,b, 2004, 2007; Coen and Luckenbach, 2000; La Peyre et al., 2003; Luckenbach et al., 2005; Piazza et al., 2005; Plunket and La Peyre, 2005; Brumbaugh et al., 2006, Brumbaugh and Coen, 2009; Plutchak et al., 2010; Piehler and Smyth, 2011; zu Ermgassen et al., 2012, 2013, 2016; Baggett, et al., 2014; Carroll et al., 2015; Coen and Bishop, 2015; Walles et al., 2015a,b, 2016a,b; Coen and Humphries, 2016; Margiotta et al., 2016.

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TIDAL WETLAND RESTORATION MONITORING

Why Restore Tidal Wetlands?

Tidal marshes and mangroves historically covered vast areas of shoreline along the Gulf of Mexico. Losses to development, sediment supply and tidal flow restrictions, sea level rise, and more recently oil spills and hurricanes have collectively reduced habitat for wildlife and fisheries and have left coastal infrastructure and landward habitats more vulnerable to storm damage and impacts from climate change (LCWCRTF, 2006; Cretini et al., 2012; Gulf Coast Ecosystem Restoration Council, 2013). Continued losses of tidal marshlands and their interactions with other Gulf coast habitats are unraveling the remaining natural and human connections often referred to as ecosystem services. Human communities depend upon ecosystem services provided by the structure and functions of marshes and mangroves: protecting us from the flooding and erosion of storms, driving coastal food webs and fisheries, cycling nutrients, storing carbon and even maintaining themselves. Not only are healthy ecosystems more resilient to catastrophic disturbances, they allow socio-economic systems to resist and recover more quickly from such disturbances (NRC, 2013). Large-scale restoration efforts are needed to reverse these trends, and the Gulf Coast states have a unique opportunity with funding from the Deepwater Horizon (DWH) settlement to restore significant areas of tidal marsh, improve our understanding of tidal wetland interactions, and establish protection from direct and indirect impacts so that these systems can be self-sustaining as they move inland (see Kirwan et al., 2016).

A broad definition of “wetlands” may encompass many coastal and estuarine habitats, including beaches and dunes, sand and mud flats, beds of submerged aquatic vascular and non-vascular plants, and shellfish reefs. A variety of definitions exist, depending upon context and purpose, and range from regulatory[103] to pertaining to international conservation and sustainable use[104] (Mitsch and Gosselink, 2007). Gulf of Mexico restoration funding agencies tend to use narrow terms to define wetland restoration. Therefore to be consistent with Gulf terminology, in this report, “wetlands” are described as tidal marshes and mangrove swamps characterized by emergent vascular plants and strongly influenced by tidal hydrology. Included are marshes and mangroves from highly saline to fresh water systems as well as hybrid systems with artificial components such as those resulting from controlled river diversions and protected by artificial sills, as in living shorelines.

Restoration Objectives and Approaches

Gulf states and federal agencies have developed programs to restore emergent wetlands with the general goal of creating or reestablishing functional, self-sustaining marsh or mangrove ecosystems (Steyer et al., 2003; Twilley, 2003; Byrnes and Berlinghoff, 2011).[105] A critical step in establishing an effective monitoring protocol is translating restoration goal(s) into specific and measurable objectives (see Chapter 2). This section provides examples of such objectives, as well as examples of metrics that are frequently monitored to assess progress towards chosen

[103] Federal agency definitions: https://water.usgs.gov/nwsum/WSP2425/definitions.html, https://www.fws.gov/wetlands/Documents/classwet/wetlands.htm.
[104] Ramsar Convention definition: https://www.bgci.org/resources/article/0373/.
[105] Resources are also provided by the EPA: http://archive.epa.gov/gulfcoasttaskforce/web/html/resources.html.

objectives. For further guidance on moving from broad goal(s) to choosing appropriate monitoring metrics and other aspects of wetland restoration project assessment, see Roman et al. (2001), Neckles et al. (2002, 2015), and Steyer et al. (2003). For guidance on assessing a wetland restoration program, see Kentula et al. (1992).

There are a variety of potential restoration objectives for specific projects, and these objectives typically have connections to specific ecosystem services (Barbier et al., 2011). For example, emergent wetlands could be restored to provide habitat, either in general, or for specific aims like essential fish habitat to support fisheries or critical habitat to support threatened and endangered species. Restoration of emergent wetlands can also be used to provide storm and flood protection for local communities. Proposers of projects may also have narrower objectives like improved nutrient cycling, carbon storage, or reduced salt water intrusion. Examples of common restoration objectives are provided in Table II.2, including barrier beach marsh reconstruction for self-sustaining habitat, tidal marsh restoration to restore function and connectivity, and living shoreline restoration to prevent erosion. Table II.2 also lists a set of metrics (described below) that may help assess progress towards these objectives in many cases, depending on the relevant monitoring purpose (note that example metrics to support monitoring for adaptive management are not included because of their inherent project/program-specificity).

Tidal marshes and mangroves develop and exist within a set of conditions where plants interact with physical processes like tides, waves, and storms (Twilley, 2003). Losses of these habitats imply stressor(s), often associated with human activities, that need to be addressed and that usually influence the proposed restoration approach. As such, measuring stressors or their indicators need to be included in any monitoring plan. Restoration approaches that create functional habitat will establish emergent plants at appropriate elevations with regular tides that supply sediments, while limiting physical exposure. Note that some emergent wetland restoration projects will be designed to include adjacent, auxiliary habitats to protect the marsh edge from the erosional forces of waves. For example, a marsh or mangrove might be established landward of a restored barrier beach or a wetland may be armored along exposed edges by living oyster reef or artificial substrate (e.g., concrete, riprap; Sutton-Grier et al., 2015; NOAA, 2015b). Restoring tidal exchange to affected wetlands is another common restoration approach (Craig et al., 2010), as maintaining tidal flow is critical for maintaining marsh and mangrove habitat (Roman and Burdick, 2012; Turner and Lewis, 1997).As we learn more about emergent wetlands, new approaches may be developed and some may include novel ecosystems (as described by Morse et al., 2014).

Decision-critical Uncertainties

Losses of tidal marshes and mangroves along the Gulf Coast have provided many opportunities for large-scale restoration, however considerable uncertainties can hinder restoration activities. Common approaches to restoration include sediment deposition on subsiding marshes, re-establishment of tidal hydrology, re-creation of barrier islands with back barrier emergent wetlands, and re-building of emergent habitats in combination with grey/green structures that act as wave barriers and collect sediments (Turner and Streever, 2002; LCWCRTF, 2006; Gulf Coast Ecosystem Restoration Council, 2013). Restoration relies, to some extent, on knowledge of biophysical processes that support and sustain marshes over the long term (Twilley, 2003). A simple conceptual model shows a typical salt marsh in cross-section with physical drivers (in white boxes) interacting with biophysical attributes of the habitat (gray boxes) to result in changes in the surface elevation of the marsh (Figure II.2). In former wetlands where subsidence exceeded the marsh's ability to build (perhaps through mineral withdrawal or tidal restriction), restoration approaches and actions could be based on our understanding illustrated by this conceptual model.

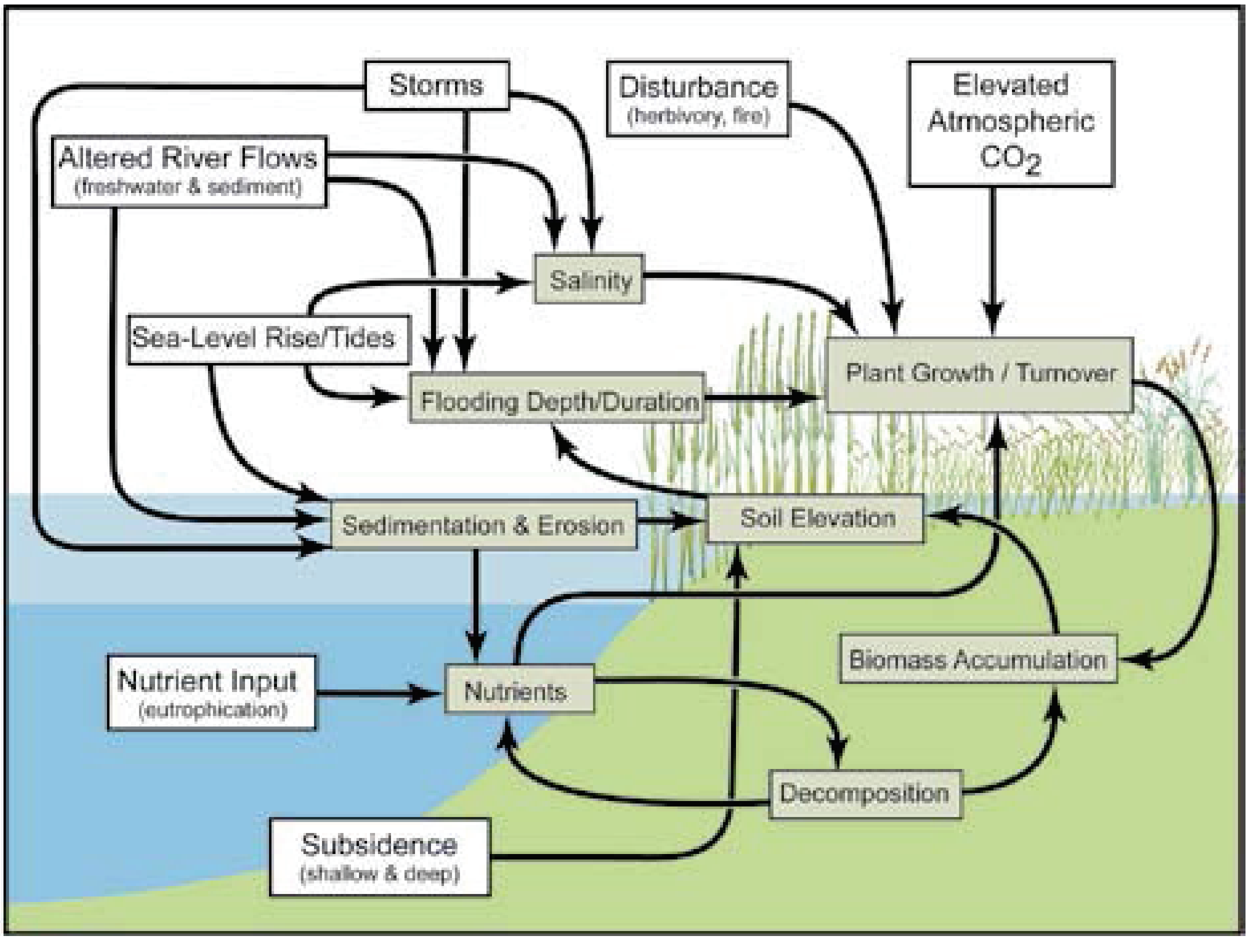

Figure II.2 Conceptual model of a tidal marsh in salt marshes with substantial tidal inputs of mineral sediment as influenced by environmental drivers and factors affecting accretion processes. SOURCE: Cahoon et al., 2009.

A critical uncertainty for managers conserving and protecting wetlands is predicting the rate of sea level rise at which significant portions of marsh will be unable to build as quickly and will convert to open water or tidal flats (Kirwan et al., 2010, 2016; Fagherazzi, 2013). Restoration, however, involves many more critical uncertainties because we know much more about natural than restored marshes. For example, in a barrier beach reconstruction project where a marsh is planned along the landward shore, critical questions include the following: What is the best grain size to use for a particular site? When will the fill become stable enough to plant? What is the optimal elevation of fill to create a self-sustaining marsh? A range of elevations and sediment fill textures may be planned to determine the most efficient combination of fill materials and elevations for a created marsh in a particular place or subject to a particular set of circumstances. This could be accomplished through a formal experimentation or simply by including variability in the design with respect to these variables. Another set of questions can help us understand the development of natural soil processes and the ability of a created marsh to grow and maintain elevation. By measuring soil conditions and elevation over time, we can answer when (and if) a created marsh begins to resemble reference marsh, and perhaps when it might be lost to sea level rise (Cahoon et al., 2009). Monitoring for adaptive management needs to be included in the monitoring plan when these questions are critical to restoring marsh function.

Note that the conceptual model (Figure II.2) may be more appropriate for marshes where mineral sediments are brought in daily by flood tides (mainly salt marshes), and less so for the large areas of brackish (mesohaline to oligohaline) marshes that comprise much of the Mississippi Delta where organic accumulation predominates (Kearney and Turner, 2015). Restoration efforts in less saline marshes or mangroves need to consider other models or modifications to the conceptual model example. For example, river diversions to supply wetlands with sediments may be better modeled with a strong seasonal component.

Project-level Monitoring and Assessment Plan Considerations

Information Needs Based on Monitoring Purpose and Project Objectives

As defined in Part I of this report, the three primary purposes of restoration monitoring include (1) assuring projects are built and are initially functioning as designed (*construction monitoring*); (2) assessing whether restoration goals and objectives have been or are being met (*performance monitoring*); and (3) informing restoration management, improving design of future restoration efforts, and increasing ecosystem understanding to improve restoration decision making (*monitoring for adaptive management*). The types of monitoring activities to assess restored marshes and mangroves will vary depending on restoration objectives, restoration approaches and stressors, construction requirements, uncertainties in the conceptual model used, desired learning objectives, and requirements established by specific funding agencies. The following sections provide detail and explanation for each monitoring purpose.

Construction Monitoring All habitat restoration projects entail some manipulation, typically to establish the habitat structure and biophysical processes necessary for development or enhancement of a self-maintaining habitat. Wetland construction monitoring assesses the manipulation(s) to determine whether contractors followed the design or plan. Types of information that are generally needed to assess construction monitoring include the restoration site location, areal extent, position of all the habitat components and structures developed for the project (including topographic heterogeneity), and materials (e.g., grain size, plant species) used. A contour plot of the site (especially if sediment is moved), tidal regime (if hydrology is altered), planting density and survival (if the site is planted), and cover of desirable plants (and undesirable plants for invasive plant removal projects) are all important to documenting restoration activity. It is good practice to assess these types of information by monitoring an applicable set of metrics (examples provided in Table II.2).

Performance Monitoring Performance monitoring is conducted to determine if a wetland restoration project is progressing toward specific objectives. Project objectives may range from re-establishing vegetation at a site, to developing a self-sustaining wetland that is resilient to specific storm intensities or sea level rise benchmarks, or providing ecosystem services such as coastal protection. Some objectives are not likely to be met immediately, but progress is expected as the marsh develops over many years (e.g., carbon storage). Performance monitoring typically includes assessment of plants, soil development and elevation, and perhaps faunal presence or support over appropriate spatial and temporal scales. For emergent wetlands, a restoration performance index can be used to integrate a number of structural and functional measurements into one assessment score that is comparable across projects (Chmura et al., 2012; Staszak and Armitage, 2013; Raposa, in review). Since objectives are often tied to some standard of marsh structure or function, establishing monitoring stations at one or more reference wetland(s) aid evaluation of progress toward objectives.

Monitoring for Adaptive Management For projects with uncertainties that might reduce performance or lead to failure, monitoring for adaptive management is appropriate. Monitoring activities can be designed to test the generality of a conceptual model for a project site or specific model component. For example, hydrologic models do not predict salinity well, so changes in salinity of the water column or porewater following hydrologic restoration can be a fruitful metric for adaptive management. Stressors that led to the initial wetland loss need to be assessed directly or by a proxy indicator. Sometimes restoration activities can change physical or biological processes at a site with unexpected results (Zedler, 2005). Other times specific project objectives may inexplicably not be met. Monitoring can help document and understand the causes of such phenomena so that we can learn more about these ecosystems and how activities might affect them. For example, if plants at lower elevations die despite a marsh being built and planted according to a recommended standard, then an assumption (e.g., plants at the low edge of a mature marsh would also be able to thrive in the restored marsh) must be wrong. It would be important to understand the probable reason(s) for such an unexpected result if we allow modification of the plan to accomplish the project objectives, or if funding agencies were to support similarly designed projects in the future. For these reasons, some monitoring may not directly support assessment of a project in meeting its objectives, but inform the restoration team of potential reasons for failures (e.g., incorrect assumptions or conceptual models). A judicious set of auxiliary measures (determined by stressors specific to the site or weakness in the restoration design) is considered good practice to support adaptive management.

Other Monitoring Finally, there may be occasions where a funder's requirements for monitoring are not fulfilled by monitoring the project-level metrics chosen by the project team to address project objectives and uncertainties. Because each agency or consortium has its own programmatic goals and is accountable for funds spent on restoration projects (see Chapter 2), several types of information will need to be collected for each project. Some of the requirements will be straightforward and already available, like project location, area restored, and approach used. However, others may require in-depth monitoring at specified spatial and temporal scales. For example, a funding agency may require an estimate of carbon storage for a restored marsh, which may necessitate an additional monitoring effort or only require an additional sampling step (e.g., adding bulk density to a soil sampling protocol that examines organic matter). Data developed from funder-required monitoring may also be used in conjunction with other data gathering efforts (e.g., highly mobile large vertebrates) to determine large-scale changes for Gulf-wide assessments of restoration benefits.

Choose Suitable Metrics

The metrics chosen for each restoration project, and at a larger scale for groups of projects, depend upon the objectives, financial resources, monitoring plan, and the team (see Chapter 3). Choices among specific monitoring metrics might depend on whether the team plans to use remote sensing tools, volunteers to collect data, an on-site monitor, or a team of seasoned professionals that only spends a few days at the site every year. Three examples of different restoration approaches follow with varying objectives, and a variety of metrics are suggested for each project and purpose for monitoring in the table that follows (Table II.2).

Example 1. Under the general goal of creating or reestablishing functional, self-sustaining ecosystems, a common wetland restoration scenario involves barrier beach reconstruction where a marsh (for example, 50 m wide by 1,000 m long) is planned along the landward shore. Specific, measurable objectives for the marsh component of the project could be

(a) to create an emergent marsh (Figure II.2) that

(b) provides habitat for birds, fish, and wildlife, and

(c) is self-sustaining (over the next 25 years).

Once the fill is stabilized at elevations appropriate to support a functional marsh (and remain within the acceptable limits of the construction design), it can be planted with elevation-appropriate species from the reach of the highest tides (high marsh) to the lower edge of the low marsh (typically planted with *Spartina alterniflora* [oystergass or smooth cordgrass]). Assuming there are no other restoration actions planned (see Table 4.1), natural processes needed to develop and sustain the habitat are allowed to proceed. Suggested monitoring activities for objectives are listed as [#1] are shown in Table II.2.

Construction Monitoring. Good practice is to include enough information to assure project directors that construction was implemented as planned, and will support development of the ecosystem and project objectives (Palmer and Allan, 2006). Metrics that are needed to address this objective include (1) the location and dimensions of the future marsh, (2) the elevations, once stabilized, that are appropriate, and (3) sediment texture. Once planted, the species, planting unit quality (e.g., size, shoot number, overall health), and density need to be assessed. In addition, post-construction monitoring (e.g., subsidence, plant survival at the end of the first growing season) may need to be performed at certain times to assess whether specified standards supplied in the restoration plan are met.

Performance Monitoring. The second type of monitoring described here focuses on meeting project objectives. For our case this entails plant and soil development for Objective A, so some measure of plant cover is needed. In addition, biomass just past the peak of the growing season can be measured to indicate production (Morris, 2007). Soil development might include percent organic matter and redox potential to determine whether the soil is reduced enough to begin to accumulate carbon. By adding bulk density to the soil collection protocol, we can calculate carbon storage (as a co-benefit, or perhaps information that is requested by project funders).

Objective B, to provide habitat, can be assessed through structural (are fish species and abundances similar to those found in the reference marsh?) and functional measures (do fish stomachs fill as fast in restored compared with reference marshes?). For this particular example, monitoring is limited to habitat for fish and birds in general, but if specific species are included in the project objective(s) (e.g., enhancing habitat for a threatened bird species), it is good practice to develop monitoring protocols for that species.

To address Objective C, creating a self-maintaining marsh, we need to know the marsh elevation and how fast is it building in elevation (Cahoon and Guntenspergen, 2010). Assuming local sea level rise is 1 cm/yr (i.e., in the Mississippi Delta region) and the marsh is building more slowly, how long will it take for the marsh to become so low in elevation that it ceases to exist? Over the short term (3-5 years), measures of marsh growth can be made using surface elevation tables (keeping in mind their limitations; see Stevenson and Kearney, 2009) and marker horizon stations, and compared to nearby sea level gauges installed for the purpose of post restoration monitoring (Folse et al., 2014; Cahoon, 2015). Over the longer term or at rapidly accreting sites, standard or more technologically advanced survey methods (e.g., Lidar or real-time GPS-based digital elevation models) could be used to show changes in features and the elevation growth of restored marshes (Roegner et al., 2009; Currin et al., 2012).

Monitoring for Adaptive Management. Restoration efforts that are monitored to promote learning and reduce uncertainty in a guiding conceptual model will often help explain unanticipated failure at a site and may reveal adaptive approaches to correct the problem(s) or improve understanding of how salt marshes function. For example, our conceptual model that directs data collection to support Objective 1C may not work well in created back-barrier marshes, and collection of these data at this (and perhaps other similar sites) will help identify limitations and improve the model for these types of projects. For our specific project, problems with plant survival may be caused by undesirable conditions or stressors than can be identified by high or low elevations and other soil measures (e.g., sulfides, pH). Another approach that can provide valuable data on specific flooding regimes is recording water level at both restoration and reference sites. Some monitoring may be instituted following clues pointing to herbivory, bioturbation, physical exposure, etc. to assess whether marsh plants are likely to persist.

Example 2. Another common wetland restoration scenario involves hydrologic restoration where a marsh has been cut off from regular, unrestricted tidal inundation. Typically the entire unit of marsh is restored if no human infrastructure is vulnerable to flooding, which is accomplished through culvert or bridge expansion or partial berm removal. Objectives for the marsh component of this type of project could be

(a) to restore tidal flushing and native vegetation to an emergent marsh that

(b) increases habitat connectivity for fish in support of fisheries, and

(c) stores carbon in soils for marsh sustainability and climate mitigation.

Once tidal flooding is re-established by restoration actions, measurements need to be taken to assure the correct tidal regime and level of flooding (relative to the marsh surface) is appropriate to support desirable marsh vegetation and access for fish, crabs, and shrimp throughout the tidal range. Assuming no other restoration actions are planned in this scenario, natural processes needed to develop and sustain the habitat are allowed to proceed. Suggested monitoring activities for construction and performance objectives are listed as [#2A, 2B, and 2C] in Table II.2.

Example 3. The final example considers a section of shoreline, once healthy marshland that has suffered significant erosion and submergence due to increased wave energy associated with boat traffic and local subsidence. The goal for such a project could be to preserve remaining marsh and restore some of the lost wetland through construction of a low sill to armor 2,200 feet of shoreline. This action is associated with adding mixed sediment (i.e., dredge spoil) behind the sill and as thin layer deposition on marsh areas that are too low in elevation, followed by planting. Objectives for the marsh component of the project could be

(a) to stop shoreline erosion and protect emergent marsh that

(b) will develop into healthy wetland as a mix of mangroves and grasses, and

(c) provide habitat for wading birds and recreational opportunities for birdwatching.

As the project includes an objective for birdwatching, and there are currently no access points or walking areas for birders to experience the restored marsh, the project includes construction of a boardwalk and birdwatching platform. Construction monitoring may focus on the establishment of these structures, sill placement, sill integrity, and other construction as well as sediment placement and depths, and planting units (e.g., grasses and mangroves). An opportunity presented for learning is to determine whether any erosion or change in grain size seaward of the sill might be associated with wave reflection. Other suggested monitoring activities for construction and performance purposes are listed as [#3A, 3B and 3C] in Table II.2.

Monitoring Planning Considerations

Appropriate Baseline Data. Several types of pre-restoration data need to be collected to improve planning for restoration. It is good practice to determine the elevation range and hydrologic regime of similar wetlands to the one(s) proposed as reference sites at several locations for all types of projects. Other baseline data can be collected to define the structure and function of the system prior to restoration so the initial conditions can be determined and net benefits can be estimated (e.g., a hydrogeomorphic approach to estimate the net value of different restoration options as mitigation for a development project; see Chmura et al. [2012]). In addition, it is good practice to collect pre-restoration data at project and reference sites in support of specific objectives for at least one year. Such data are needed for before-after-control-impact assessment designs (see Chapter 3). Specific metrics for data collection will largely depend upon the restoration approach, objectives, site conditions, processes, and stressors. For our Example 1, sediment samples of grain size, either within marsh peat or in adjacent unvegetated areas, might provide insight regarding appropriate grain sizes for the root zone of the restored marsh. Similarly, evidence of erosion at seaward marsh edges might alert observers to consider an erosion resistant design, so data on marsh edge erosion collected before project construction can be informative. Bird and birder visitation rate data at the site before restoration would also be valuable to support assessment of Example Objective 3C.

Appropriate Control / Reference Sites. It is good practice to select one or more reference site(s) (see Chapter 3). Reference site(s) will provide appropriate elevations or flooding regimes for comparison with the planned restoration, as well as targets for plant density, soil development, marsh elevation growth, support of fish and wildlife, etc. (Steyer et al., 2006). It is often difficult to find a “perfect” reference site, so the use of two or more, especially for larger projects where marsh restoration may encompass several sites, is recommended. Furthermore, multiple reference sites provide information on natural variability among sites and can aid in decision-making for adaptive management (Short et al., 2000; Steyer et al., 2006).

Develop a Rigorous and Robust Sampling Design. Where and when to sample is a much-debated topic, with good discussions provided for grasslands, marshes, and mangroves

(Elzinga et al., 1998; Roman et al., 2001; Thayer et al., 2005; Neckles et al., 2013). Construction monitoring has to be spatially comprehensive and provide estimates with narrow error to ensure adequate return on investment despite natural variability. Therefore, sampling protocols usually favor metrics are that are simple, quick to obtain, and unrelated to longer-term performance monitoring or monitoring for adaptive management.

Sampling for performance monitoring and monitoring for adaptive management may be needed before or after restoration construction for several years (perhaps up to 20 years for some metrics); typically sampling periods are chosen to coincide with the growing season or other biological cycles or seasonal patterns that might be important. Since much of performance monitoring involves establishing progress as the restored marsh approaches its reference with respect to specific objectives, a sampling design to examine trends (e.g., trajectories) is often chosen (Steyer et al., 2003). Permanent plot locations for plants and soils allow greater power per sample (see Chapter 3). A method that has been found to be applicable to a variety of restoration approaches considers a combination of metrics to assess: 1) the driving forces in the conceptual model used for a back-barrier salt marsh project (Example 1, Figure II.2: hydrology relative to elevation); 2) stressors (e.g., oil or sulfides); and 3) functional values, such as fish and wildlife use (Neckles et al., 2002; Steyer et al., 2003; Raposa et al., in review).

Transects perpendicular to the shore or elevation gradient that are established along the lower edge of the marsh (or along tidal creeks) are widely used to characterize each area or type of marsh to be sampled (Roman et al., 2001; Moore, 2013). Permanent markers are often installed at the ends of transects with random starting points and sample plots far enough apart to minimize autocorrelation (Elzinga et al., 1998; Roman et al., 2001). For relatively large projects along the Gulf coast, greater spacing may be desired. Based on vegetation patterns in New England marshes, 20 quadrats (1 m^2) will show how well vegetation development is progressing (Roman et al., 2001). Soil and porewater samples could also be collected a set distance from each vegetation plot (Neckles et al., 2002; Moore, 2013). Hydrology relative to elevation can be sampled as part of a robust sampling design using water level recorders tied into spot elevations (vegetation plots) or a digital elevation model (Moore, 2013; Neckles et al., 2013) or an array of surface elevation tables with marker horizons that will measure elevation change and surface accretion (Ford et al., 1999; Cahoon, 2015). However, the surface elevation table stations are relatively costly to establish and monitor, so resources may limit the number used.

Fish, birds, and other wildlife are characterized as highly mobile, unevenly distributed, and highly variable in diel, seasonal, and annual cycles. Therefore, this group is not only difficult, but often relatively expensive to measure at a scale and frequency that can provide meaningful results. Wildlife can be measured in a variety of ways, but species data are usually not coupled to the vegetation and soil plots (unless an assessment of common invertebrates that can be done visually is needed). Fish have been sampled using area-dependent gear in surface water features at low tides (Raposa, 2008; Neckles et al., 2013), on the marsh surface at high tide (Dionne et al., 1999), and along marsh edges (Rozas and Minello, 1997). Birds may be assessed from the air, through banding, using on the ground point counts, or specific repeatable vantage points and areas (Shriver and Greenberg, 2012). Birder visitation rates can be determined through point counts (as with birds, but counting people), by establishing a birder registration station, or by requiring permits for birder access. The importance factor for site-specific results is consistency and repeatability (with many repetitions over time), but for basin-wide and regional evaluation of restoration actions, it is good practice to agree upon a standard protocol that would work for most applications across funding agencies and states.

Table II.2 Metrics considered good practice to monitor tidal wetland restoration activities for construction, performance toward project objectives, and program-level or large-scale assessments.

NOTES: Examples are provided to illustrate linkages between restoration situations/objectives and appropriate metrics to assess progress. Example 1 (linkages shown in the table by "#1A, 1B, and 1C") is to reconstruct a barrier beach marsh; Example 2 is to restore a tidal marsh; and Example 3 is to restore a living shoreline and thin layer deposition marsh/mangrove. The "X" symbol indicates metrics that are suggested by the Committee as appropriate to sample across multiple projects at a program, region, or Gulf-wide scale.

	Monitoring Purpose		
	Construction	Performance	Program-level
Potential Monitoring Metrics	*Examples*	*Examples*	*Suggested*
Habitat			
Areal dimensions of restoration	#1, #3	#1A, #3A	X
Area of habitat types	#1, #3	#1A&B, #2B, #3A	X
Interspersion of habitat types (e.g., creeks)	#1, #2	#1B, #2B	
Location and timing of interacting management activities			X
Geomorphology/Hydrology			
Basemap with site location	#1, #2, #3	#1, #2, #3	X
Surface contours (digital elevation model)	#1, #2, #3	#1A,C, #2A, #3A	
Tides, currents	#2	#2A,B	
Flooding depth, duration, frequency		#2A, B	
Wave exposure/attenuation	#3	#3A	
Water quality: salinity, pH, DO, other			
Soils/Sediments			
Depth to water table			
Accretion/erosion/elevation change		#1C, #3A	
Porewater salinity		#2A	
Porewater sulfides, redox, pH			
Porewater metals concentration	#3		
Bulk density, organic matter (carbon storage)		#1C, #2C	X
Sediment texture	#3	#3A	
Sediment nutrients, carbon, nitrogen, phosphorus		#2C alternative	
Sediment metals			
Sediment organic pollutants			
Vegetation			
Plant density/survival	#1, #3		
Distribution/abundance of native/ invasive plants		#1A, #2A, #3B	
Primary production, above- to below-ground biomass ratio			
Stem density/height			
Stem growth (mangroves)		#3B	

	Monitoring Purpose		
	Construction	Performance	Program-level
Potential Monitoring Metrics	*Examples*	*Examples*	*Suggested*
Fauna			
Benthic species abundance/biomass/diversity			
Fish abundance/density/diversity		#1B, #2B	
Fish passage		#2B	
Fish length, biomass		#2B	
Bird abundance/density/diversity		#1B, #3C	
Mosquito abundance			
Ecosystem Services			
Provisioning			
Hunting (waterfowl, fur bearers)		#1B	
Total fishery landings / value			X
Landings / value in fishing grounds with known population connection to project site (seasonal)		#2B	X
Market price of relevant fish species			X
Regulating			
Rate of carbon sequestered		#2C	X
Wave attenuation, erosion protection		#3A	
Monetary value of adjacent property damage from moderate storm events		#3A	X
Supporting			
Flood storage		#2A	
Nutrient Cycling		#1C, #3B	
Habitat/refugia for biodiversity		#1B, #2A&B, #3C	X
Support of coastal food web		#1A&B, #2B, #3B&C	
Local or regional commercial fish larval dispersal patterns		#2B	
Adult recruitment to fishing grounds attributable to project site		#1A, #2B	
Cultural			
Travel cost and visitations		#1B, #3C	X
Recreational fishery permits sold (total or within grounds with known population connection to project site)		#1B, #2B	
Birder benefits (travel cost, species preferences, satisfaction, visitation)		#1B, #3C	
Hunter visitation rate to project site		#1B	
Fees from hunter permits sold for access to project site marsh (seasonal)		#1B	

SOURCES: Folk, 1974; Dionne et al., 1999; Roman et al., 2001; Neckles et al., 2002, 2013, 2015; Craft and Sacco, 2003; Steyer et al., 2003; Rozas and Minello, 1997, 2007; Morgan et al., 2009, 2015; Eberhardt and Burdick, 2011; Piehler and Smyth, 2011; Kauffman and Donnato, 2012; Mora and Burdick, 2013; Shriver and Greenburg, 2012; Moore, 2013; Staszak and Armitage, 2013; Kreeger and Moody, 2014; Howard et al., 2014; Lynch et al., 2015.

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SEAGRASS RESTORATION MONITORING

Why Restore Seagrass?

Shallow coastal waters contain numerous and exceptionally rich and productive habitats. Of special concern here, but less well-known and appreciated by the public, are the extraordinarily productive, biologically diverse, and economically valuable seagrass meadows that are abundant in coastal areas of all continents except Antarctica. Seagrass meadows provide valuable ecosystem services such as important habitats and food for a range of iconic species such as manatees, green turtles, and seahorses; providing nursery grounds for numerous economically important finfish and shellfish; sequestering carbon; improving water quality by intercepting the nutrients and organic matter carried by land runoff; stabilizing sediments and preventing erosion (Barbier et al., 2011). Despite these important services, seagrass meadows are among the planet's most threatened habitats, with their known global areal extent having declined by 29 percent since the late 1800s and losses rapidly accelerating in the last two decades (Waycott et al., 2009). On a global scale, this trend has significant ramifications because seagrass meadows have been estimated to provide ecosystem services for nutrient cycling alone valued at US$7,700 per acre annually (Constanza et al., 1997). Others value seagrass' contribution to enhanced fishery production in southern Australia at US$172,000 ha^{-1} yr^{-1} (Blandon and zu Ermgassen, 2014). Thus, the potential economic impact of seagrass loss is significant (Hyndes et al., in review).

Because of their occurrence in shallow coastal waters, these meadows are highly susceptible to human-induced perturbations, especially those that reduce the quantity and quality of light (Orth et al., 2006). Temperature changes also affect seagrasses profoundly (Fraser et al., 2014). Recent worldwide increases in sea surface temperature, along with the predicted rises during the coming decades (IPCC, 2013), raise concern for the long-term survival of seagrasses in many areas. Thus, seagrass meadows, most of which are already stressed and in decline (Waycott et al., 2009), are at further risk of declining in the areal extent and ecological function and as a result there will be a further decline in the ecosystem services they provide. There is thus a clear and compelling need to assess the roadblocks to seagrass recovery and restore conditions that are favorable for the regrowth and long-term persistence of seagrass meadows.

Restoration Objectives

Post-DWH restoration and recovery efforts in the Gulf of Mexico are providing opportunities to expand and enhance seagrass meadows in many locations. The general objective of these efforts is to facilitate the development of seagrass meadows whose areal extent, abundance, species composition, function, and provision of ecosystem services are assessed to be equivalent to those of reference meadows (see Chapter 3). Although most restoration activities aim to restore seagrass meadows simply to enhance this ecosystem type, efforts are often motivated by the intrinsic benefits that seagrass provide to hundreds of other species, and by their benefits to humans, such as nursery habitat for commercially and recreationally valuable species like shrimp, crab, and fish (Beck et al., 2001). Despite this objective of restoring seagrass to increase animal utilization, activities are rarely monitored to assess restored density of target species.

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It has long been known that these restoration objectives are most effectively achieved through improving environmental conditions, such as water clarity or nutrient availability, that enable seagrass to replenish and expand through natural processes or, less frequently, through transplantation (Fonseca et al., 1987; Fonseca et al., 1998). In general, replanting efforts have not often achieved their desired objectives in the Gulf of Mexico (Fonseca et al., 1987), although in one instance long-term monitoring of shoalgrass (*Halodule wrightii*) transplants showed slow increases in density over seven years in the improving nutrient and light regimes of Tampa Bay (Bell et al., 2014).

Decision-critical Uncertainties

Figure II.3 shows a conceptual model of some of the major factors that influence the areal extent, abundance, species composition, and functioning of seagrass meadows in the Gulf of Mexico, and in general, seagrass meadows wherever they occur. Ultimately, light is most often the resource limiting seagrass growth and survival, and it is given priority in these conceptual models. However, other environmental variables such as temperature, salinity, sediment type and biogeochemistry, as well as wave energy, can singly or interactively hamper seagrass survival in the Gulf of Mexico. These variables are less likely to determine the success of seagrass restoration activities, which will most often take place in areas that previously supported seagrass growth, and when conditions initially responsible for the demise of seagrasses have been restored to levels approaching their previous state.

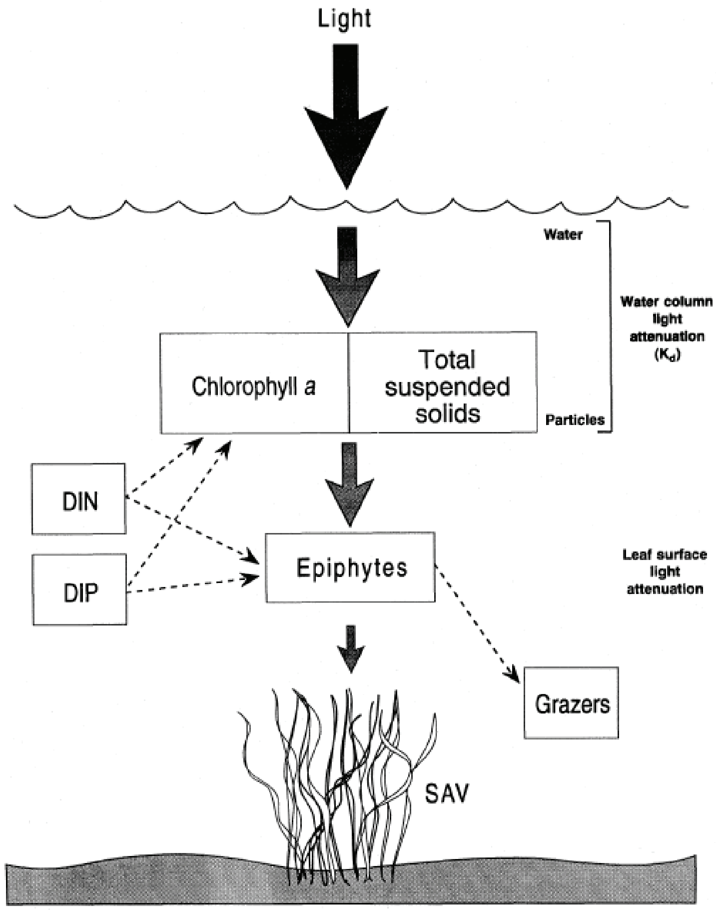

Figure II.3 Conceptual model showing light attenuation determining the amount of light availability for submerged aquatic vegetation (SAV). Abbreviations: dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP). SOURCE: Dennison et al., 1993.

In cases where action is taken to restore seagrass, the effectiveness of that action can be assessed using the methods below. Monitoring for adaptive management links the effect of the action on a particular stressor to the effects of the restoration actions and recovery patterns as strongly as possible. If the meadow does not recover, there must be a reason why. Therefore, good practice is to monitor parameters that are most likely to affect recovery rate (e.g., water clarity, salinity, sediment quality; see below) as appropriate. If monitoring for adaptive management (see Chapter 3), this sampling will allow adjustment of restoration actions to increase the probability that seagrass will recover.

Project-level Monitoring and Assessment Plan Considerations

Select Monitoring Types, Objectives, and Metrics

As defined in Part I of this report, the three primary purposes of restoration monitoring include (1) assuring projects are built and are initially functioning as designed (*construction monitoring*); (2) assessing whether restoration goals and objectives have been or are being met (*performance monitoring*); and (3) informing restoration management, improving design of future restoration efforts, and increasing ecosystem understanding (*monitoring for adaptive management*). A hierarchical strategy for seagrass monitoring can be used to assess or evaluate the construction and performance of restoration efforts. Where warranted the factors that establish quantitative relationships between physical and biotic parameters that ultimately control seagrass abundance, function, and persistence can be evaluated through monitoring for adaptive management. Also, monitoring certain parameters may enable scaling assessment ability up to a program, regional, and/or Gulf-wide level (see Table II.3). Given that planting of seagrasses will not usually achieve restoration objectives in the Gulf of Mexico, the following discussion focuses on restoration efforts that aim to improve environmental conditions for seagrass growth.

Monitoring protocols are primarily based on conceptual models (e.g., Figure II.3) that link: (1) light and nutrient availability to metrics of seagrass structure and function such as (a) shoot density and growth rates, and (b) landscape features, including patchiness and depth limit distributions; and (2) physicochemical stressors, including salinity, temperature, hydrodynamic processes, and human activities, to metrics of seagrass meadow condition. The hierarchical approach below follows a strategy adopted by several federal and state agencies, and it incorporates a multiscale monitoring protocol that integrates plant condition metrics with landscape features to detect and interpret changes in seagrass meadow structure and function. The program includes the following information needs:

- **Construction Monitoring**. An essential mapping component for status and trends documentation of seagrass meadow areal extent and patchiness before and immediately after the next primary growing season post-restoration;
- **Performance Monitoring**. An assessment program (cf. Neckles et al. [2012]) to evaluate achievement of restoration objectives using fixed stations that are sampled annually; and
- **Monitoring for Adaptive Management**. An optional, integrated approach that includes permanent stations and transects that are aligned with high resolution construction monitoring to examine the presumptive factors associated with changes in seagrass areal extent, depth limits, and patchiness.

See Table II.3 for monitoring metrics that are generally accepted to measure (“standardized”) for construction and performance monitoring of general seagrass restoration activities, and monitoring metrics that are suggested by the Committee to assess seagrass restoration efforts at a program, region, or Gulf-wide scale. Example ecosystem services, such as fisheries production through the provision of shelter and food, are provided in the table; see Costanza et al. (1997), Orth et al. (2006), and Barbier et al. (2011) for a more thorough discussion of recommended ecosystem service metrics for seagrass monitoring (note that example metrics to support monitoring for adaptive management are not included because of their inherent project/program-specificity).

Table II.3 Metrics considered good practice to monitor seagrass restoration activities for construction, performance toward project objectives, and program-level or large-scale assessments.

NOTES: Example objectives are not provided in this table because the typical seagrass restoration project is designed to expand and enhance seagrass meadows (as described in the Objectives section). The “X” symbol indicates metrics that are found in the peer-reviewed literature and generally accepted by the seagrass community as appropriate to sample for construction and performance monitoring. Program-level metrics are suggested by the Committee to enable comparison across multiple projects at a program, region, or Gulf-wide scale.

	Monitoring Purpose		
	Construction	Performance	Program-level
Potential Monitoring Metrics	*Standardized*	*Standardized*	*Suggested*
Habitat			
GPS location of restored reefs	X	X	X
Seagrass meadow areal extent	X	X	X
Light availability with depth			
Location and timing of interacting management activities			X
Geomorphology/Hydrology			
Water depth	X	X	
Water transparency	X	X	
Light attenuation	X	X	
Wave energy	X	X	
Water temperature	X	X	
Salinity	X	X	
pH		X	
Dissolved oxygen		X	
Water quality			
Soils/sediments			
Sediment type	X	X	
Sediment grain size distribution		X	
Sediment deposition			
Sediment nutrients			
Sediment chemistry, including sulfides			
Organic chemical contaminants (e.g., herbicides)			
Vegetation			
Seagrass species composition	X	X	X
Seagrass percent cover	X	X	
Seagrass patchiness	X	X	
Seagrass growth rate		X	
Biomass		X	
Seagrass shoot/stem density		X	
Seagrass maximum canopy height			
Seagrass condition index			
Seed reserves			
Leaf chlorophyll fluorescence			
Reproduction and demography			
Genetic diversity			
Above-ground biomass			
Below-ground biomass			
Epiphyte cover			
Abundance of drift macroalgae			
Fauna			
Abundance of seagrass grazers			
Abundance of epiphyte grazers			
Abundance of juvenile shrimp, crab, fish			
Density of juvenile shrimp, crab, fish			
Ecosystem Services			
Fisheries production		X	
Nutirent cycling		X	
Carbon sequenstration		X	

SOURCES: Thayer et al., 2005; Short et al., 2006; Moore et al., 2009; Dunton et al., 2010; Neckles et al., 2012; SeagrassNet: http://www.seagrassnet.org/seagrassnet-monitoring-summary; National Estuarine Research Reserve: http://nerrs.noaa.gov/research/.

Monitoring Planning Considerations

Best practices indicate using a grid of tessellated hexagons to select sampling locations for all levels of seagrass monitoring (Dunton et al., 2010). Within each hexagon, a randomly selected station can be permanently established in the restored seagrass meadow(s) to be monitored.

Baseline Monitoring Prior to Construction or Implementation (based on Dunton et al., 2010). The primary purpose of monitoring before implementing the restoration project is to characterize seagrass distribution over relatively large spatial scales. Best practice involves using remote sensing technology to compile status and trend maps for each study area (cf. Thayer et al., 2005; Neckles et al., 2012). Data are collected using remote sensing aerial imagery gathered by manned or unmanned vehicles, or by vessels using hydroacoustic mapping methods (Sabol et al., 2012; Chamberlain et al., 2009). Standard mapping methods are then used to identify the extent and configuration (patch structure) of the restored seagrass meadow(s). Thus, the approach includes acquisition of remotely sensed images, georectification of imagery, collection of ground-truthed data, interpretation of the images and delineation of vegetative areas, and importing the data into a geographic information system (GIS; see Box 6.1) format for accuracy assessment, change detection, and reporting (Thayer et al., 2005).

Performance Monitoring (after Dunton [2010] and Neckles et al. [2012]). Performance monitoring is conducted to assess whether restoration objectives are being achieved. In particular, the monitoring aims to address the following primary questions:

- What are the spatial patterns in the distribution of seagrasses over annual scales?
- What are the characteristics of these plant communities, including their species composition and percent cover?
- How are changes in seagrass percent cover and species composition related to measured characteristics of water quality and other relevant factors that control seagrass growth?

At each location, data are collected annually on seagrass species composition and abundance, and potential stressors. This can be done by visually estimating seagrass cover and canopy height in quadrats (although if visual surveys are not possible due to poor visibility, one core can be taken at each GPS-located sampling site). Data gathered to address restoration progress can include water depth, transparency, temperature, salinity, and dissolved oxygen, and measurements of photosynthetically active radiation (see Table II.3).

Below is a detailed recommended design for performance monitoring of seagrass meadows, adapted from Neckles et al. (2012):

- Annual sampling is performed during or shortly following peak seagrass standing crop (mid to late summer).
- For statistical rigor, use a repeated measures design with fixed sampling stations to maximize ability to detect change.
- Navigate to pre-selected stations with a GPS accuracy of 4 m or better.

- Define stations as the area within a 10 m radius of the GPS location.
- Collect hydrographic measurements prior to sampling.
- Determine the diffuse attenuation coefficient to evaluate water transparency
- Four replicate quadrat samples per station facilitate species composition and percent cover from each cardinal direction from the vessel (Neckles et al., 2012).
- Percent seagrass cover is estimated within quadrats using an underwater digital camera mounted to a quadrat frame, or in shallow water, through direct observation. If water transparency is extremely poor, direct *in situ* measurements and one core sample can suffice.
- When core samples are taken, morphometric data, biomass, shoot density, sediment characteristics, etc. are obtained.

Monitoring for Adaptive Management: One of the major objectives of monitoring for adaptive management is the elucidation of causal relationships between water quality stressors and seagrass response. Monitoring for adaptive management is typically conducted at a relatively small number of stations and consist of experimental studies and intensive sampling. This type of study is designed to address specific hypotheses relating to measured environmental change or changes in seagrass condition. Such studies can link the presumptive factors responsible for changes in seagrass structure and/or function to changes in water quality and/or seagrass condition indices. Monitoring occurs at least annually in mid-summer, but may also be conducted quarterly.

To assess **patch structure**, remotely sensed imaging at permanent stations can detect:

- patch formation, and
- advances and/or retreats from deep edges.

To assess **the abundance of drift macroalgae or algal epiphytes**, remotely sensed imaging or in situ sampling at permanent stations can detect:

- color changes, and
- percent cover changes.

To assess **water quality**, underwater sensors at permanent stations need to continuously/frequently measure:

- light attenuation,
- surface irradiance, and
- water transparency depth.

Best practice sampling design methods are generally consistent with either SeagrassNet,[106] a global monitoring program developed to investigate and document the status of seagrass resources worldwide (Short et al., 2006), or National Estuarine Research Reserve[107] protocols

[106] SeagrassNet global monitoring program: http://www.seagrassnet.org/global-monitoring.
[107] National Estuarine Research Reserve (NERR): http://nerrs.noaa.gov/research/.

(Moore et al., 2009, Figure II.3). For additional details, please see protocols provided by Dunton (2010) and Neckles et al. (2012).

An understanding of stress/response relationships is often best achieved through intensive, hypothesis-driven experimental studies. A fundamental understanding of the mechanisms and response metrics is required for monitoring for adaptive management studies, since measurements often occur across temporal and spatial scales. Monitoring could include the following additional parameters:

- seed reserves,
- growth,
- abundance of algal epiphyte grazers,
- sediment chemistry, including sulfides,
- organic chemical contaminants (e.g., herbicides),
- leaf chlorophyll fluorescence,
- reproduction and demography, and
- genetic diversity.

Ultimately, studies that include monitoring these additional parameters will enhance understanding of stress/response relationships, and improve future seagrass and broader ecosystem restoration efforts.

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BIRD RESTORATION MONITORING

Why Restore Birds?

Birds are conspicuous organisms that often generate support for multi-scale restoration efforts. The seasonally and geographically diverse birdlife (see Box II.1) across the Gulf of Mexico is highly valued by the public, both for consumptive (e.g., hunting-related activities) and non-consumptive (e.g., wildlife viewing and photography activities) uses (NSRE, 2010). Wildlife-watchers in the five Gulf coast states, including birders, numbered over 16.4 million and spent over $22.5 billion on various activities in the region (U.S. Fish and Wildlife Service and U.S. Census Bureau, 2006). Furthermore, birds provide several other ecosystem services including several functions potentially relevant to the Gulf of Mexico ecosystem (Sekercioglu et al., 2004; Sekercioglu, 2006; Green and Elmberg, 2014). For example, many songbirds serve as important seed dispersers in the region, seabirds and wading birds could serve as nutrient depositors, and insectivorous and raptor species could limit insect and rodent damage, respectively, to Gulf coast habitats, crops, and homes. Petroleum oils threaten Gulf Coast birds (and the services they provide) primarily through coating of feathers, ingestion, and egg shell contamination (Leighton, 1993). As a result, "[the] quantified mortalities were estimated to range from 51,600 to 84,500 individual birds" (DWH NRDA, 2016, p 4-483) and when combined with the loss of productivity, estimate range as high as 56,100 – 102,400. However, other earlier estimates were significantly higher (Haney et al., 2014a; Haney et al., 2014b; Sackmann and Becker, 2015).

Box II.1

Gulf of Mexico Birdlife

Birdlife associated with the Gulf of Mexico is fantastically diverse and readily observed across the region. Over two-thirds of the landbirds east of the Mississippi River pass through the region twice a year, once in the spring heading north to breed and a second time heading south for the winter ([IP202a] Rappole and Ramos, 1994; Lincoln et al., 1998; Moore et al., 2005). Sand beaches with associated dune complexes are home to a wide variety of beach-nesting birds, while serving as critical winter habitat for the endangered piping plover (Plissner and Haig, 2000). North American waterfowl populations are highly dependent on bays, estuaries, and lagoons that ring the Gulf of Mexico [IP202b] as one of the most important areas for their winter survival – with an estimated 88 percent of the world's [IP202c] redhead duck population wintering in the Gulf region (Bellrose, 1980; Smith et al., 1989; Baldassarre and Bolen, 1994; Michot, 2000; Baldassarre, 2014). Long-legged wading birds [IP202d] such as herons, egrets, and [IP202e] roseate spoonbills are readily observed stalking the shallow waters of the Gulf, waiting patiently for an opportunity to snatch a small fish from just below the surface. As the rare reddish egret hunts, it dances crazily while pursuing small aquatic prey along shallow sandy beaches (Holderby et al., 2014). Approximately 62 percent of the North American tidal marshes are found fringing the Gulf of Mexico (Greenberg and Maldonado, 2006), which makes common marsh bird species such as clapper rail and seaside sparrow key metrics of healthy wetlands. Although infrequently seen among the emergent vegetation, these birds are widespread permanent resident species across the Gulf region, and monitoring efforts would benefit from their inclusion (Woodrey et al., 2012).

Restoration Objectives

The objective of restoring habitat upon which birds depend is widely considered useful and a frequently necessary element of effective bird restoration. Beyond this overarching objective, other (often related) restoration objectives can include reducing threats to birds, enhancing other supporting species, promoting ecosystem services, understanding cause-and-effect relationships that drive observed annual variation in bird populations, and understanding the impacts of management and restoration actions on birds. For example, a restoration project focused on creating emergent marsh habitat may not necessarily focus on marsh birds as a restoration objective, per se. Thus, one potential restoration target might be a desire to "produce [X] number of breeding clapper rails and [X] number of breeding seaside sparrows," an objective based on population status. For a project using multiple techniques to restore barrier island beach habitat, an objective might be "to provide wintering habitat for [X] number of wintering piping plovers." Alternatively, one might ask "how many nesting pairs of Wilson's plovers are produced using beach nourishment technique [Y] versus technique [Z]?" Many of these examples of potential objectives are being evaluated by and can be drawn from the Gulf of Mexico Avian Monitoring Network (GoMAMN).[108]

[108] The Gulf of Mexico Avian Monitoring Network (GoMAMN): https://globalchange.ncsu.edu/secsc/wp-content/uploads/GoMAMN-2-Pager-final.pdf.

Depending upon the chosen restoration objectives, it is generally good practice to consider issues such as the state of other habitats visited/used by target bird species, species-dependent responses of birds to restoration activities, the extent to which restoration is supplemented with management activities that may affect targeted populations, and the spatial scales (site-specific to regional) at which restoration objectives will be evaluated (George and Zack, 2001; Marzluff and Ewing, 2001; Smallwood, 2001; Morrison, 2002; Ausden, 2004; Sutherland and Green, 2004; Ortega-Alvarez and Lindig-Cisneros, 2012; Hutto et al., 2014). Given that many of the Gulf bird populations migrate across borders, monitoring would also benefit from including Mexican coastal sites as well and Caribbean Islands.

Why Monitor Bird Restoration?

Birds are perhaps the most studied and well-known wildlife worldwide. They have repeatedly been used as focal species because they can generally be surveyed at relatively low cost over large geographic areas, demographic parameters can be relatively easily assessed, and ecological requirements and habitat associations fairly well known for many species with diverse life history traits across a wide range of habitats (Gardali et al., 2006; Majer, 2009). Bird taxa often exhibit strong site fidelity and predictable diets (Novak et al. 2006; Rush et al. 2009); occupy high positions in trophic food webs, are important components of ecosystem energy flows, can move in response to ecological conditions (Ogden et al., in press); may provide an indication of habitat integrity (DeLuca et al. 2004, 2008; Novak et al. 2006); and often respond quickly to restoration efforts (Bergeon et al., 2014). Also, many species using the Gulf are transients, or migrate through the region, so have the potential to serve as short-term, localized indicator species (Henkel et al., 2014). Further, birds regularly engage the public in citizen science activities (Ortega-Alvarez and Lindig-Cisneros, 2012).

Decision-critical Uncertainties

Conceptual models are particularly useful early in a project (Ogden et al., 2005, 2014a, 2014b), when there is a need to focus on the important drivers, stressors, and attributes at the exclusion of a detailed ecological modeling approach (Gawlik, 2006). Although widely acknowledged as important, relatively few examples of bird-specific conceptual models are presented in the peer-reviewed literature (But see Figure II.4). Rather, birds are typically incorporated into multi-component ecosystem-based models. For example, Gentile et al. (2001; see Figure 7) used conceptual models to better understand the potential influence of ecosystem management on the sustainability of the Everglades and South Florida ecosystems.

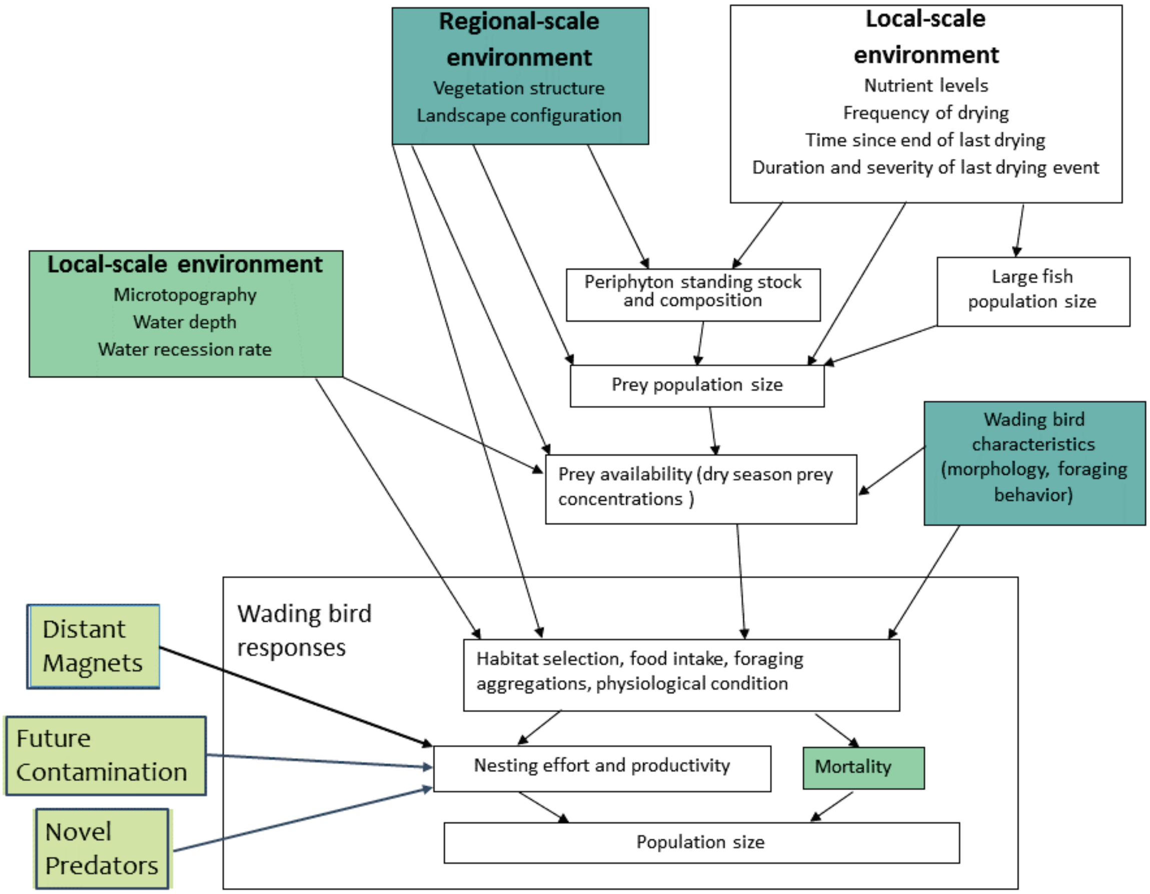

Figure II.4 Conceptual ecosystem model showing the relationship between multi-scale environmental factors and wading bird response in the Florida Everglades ecosystem. SOURCE: P. Frederick, D. Gawlik and J. Trexler, Unpublished.

Many uncertainties exist around bird response to various restoration techniques. For colonial waterbirds and solitary beach nesting shorebirds, the importance of sculpting or shaping the beach morphology of renourished islands to facilitate rapid colonization is poorly known and has been identified as a critical information gap (Guilfoyle et al., 2006; Grippo et al., 2007). Despite the use of a rigorous and robust before-after-control-impact paired study design (see Chapter 3), Grippo et al. (2007) found no significant changes in mean waterbird or shorebird abundance after replenishment, and consequently strongly recommend the use of multiple control sites and scheduling surveys to reduce potential sources of variability. The utility of dredged material as a management tool for colonial nesting habitat for terns and skimmers is a second important area of uncertainty in bird restoration. Although poorly understood outside the southeast Atlantic coast, guidance on how to create and manage dredged-materials islands as early successional bird habitat is available as a starting point for Gulf of Mexico projects (Golder et al., 2008).

There is also significant uncertainty around the response of marsh birds to various approaches to marsh restoration (such as those listed in the tidal wetland section of Part II) and many uncertainties are specific to individual species. Additional uncertainty is due to our lack of empirical data linking sea level rise to effects on marsh bird populations and reproductive success. In addition to sea level rise, climate-related drivers that could affect Gulf marsh birds include precipitation patterns, hydrologic and fire regimes, increased temperature, and hurricanes (Woodrey et al., 2012). One tidal marsh restoration technique that has promise is hydrologic, or tidal flow, restoration, although there is a high degree of uncertainty with regards to marsh bird response and thus a critical need to monitor in an adaptive management framework (Mitchell et al., 2006; Shriver and Greenberg, 2012). Regardless of the marsh restoration objective, the initial steps of creating an engineered, or sculpted, marsh involve careful attention to create the appropriate hydrology, elevation, and spoil characteristics (Palmer et al., 1997; Turner and Streever, 2002; Armitage et al., 2014). Fortunately, specific, testable hypotheses for estuarine systems can provide a framework for reducing uncertainties if used under an adaptive management framework (Conroy et al., 2010).

Long-legged wading birds such as herons, egrets, ibises, and storks are generally both highly mobile and responsive to landscape-scale changes in foraging and nesting habitat. These birds respond to prey availability, which is influenced by both prey density and water depth (Gawlik, 2002). Areas of concentrated prey resources are generally created in salt marshes by having shallow areas (at least at low tide) and pools that trap prey in the high marsh. Maintaining these features within a restored wetland complex would be key to maintaining these critical marsh bird resources. In addition, freshwater flow regime can strongly affect both vegetative structure of foraging habitat and prey density through changes in salinity (Bildstein et al., 1990; Battaglia et al., 2014; Lorenz, 2014). Therefore, a key uncertainty for bird response to restoration is whether restoration projects will retain critical freshwater flows, and what those regimes will be.

Another key uncertainty is whether long-legged wading birds will respond to positive changes that are intended to make habitats more suitable (e.g., increased food resources, appropriate hydrology) by being attracted to this habitat if it occurs. However, at a larger scale, these birds may simply concentrate at more suitable distant sites. The ability to say that wading birds definitely are not responding to restoration is highly dependent on making the argument that they are not somewhere else, which argues strongly for regional monitoring. This argument is clear in the Everglades, which is large enough to constitute a region (Frederick and Ogden, 2003). A third key uncertainty may have to do with nest predators. Although nesting is probably driven mostly by food availability (Frederick and Spalding, 1998; Beerens et al., in press), protection from mammalian nest predators is a pre-condition for any reproductive success. Therefore, in order to use wading bird nesting as a metric of foraging habitat suitability, the assumption of predator-free nesting space needs to be demonstrated. If predator-free, then birds will nest on almost any substrate, and will often nest in close proximity to human activity (Nell and Frederick, 2015; Nell et al., in press; Tsai et al., in press).

Project-level Monitoring and Assessment Plan Considerations

Information Needs Based on Monitoring Purpose and Project Objectives

As defined in Part I of this report, the three primary purposes of restoration monitoring include (1) assuring projects are built and are initially functioning as designed (*construction monitoring*); (2) assessing whether restoration goals and objectives have been or are being met (*performance* *monitoring*); and (3) informing restoration management, improving design of future restoration efforts, and increasing ecosystem understanding (*monitoring for adaptive management*). Bird-focused restoration projects, like all objective-driven restoration projects, will require various forms of monitoring (Hutto and Belote, 2013), with projects involving the placement and sculpting of sediment requiring a broader array of monitoring purposes.

Construction Monitoring. Although construction monitoring may seem tangential to bird-focused restoration projects, assessing the creation of habitat for colonial nesting waterbirds, solitary nesting shorebirds, and secretive marsh birds is critical. Stringent oversight during the construction phase is necessary (1) to ascertain specific quantitative recommendations available in the literature with regards to substrate composition, presence/absence of vegetation, vegetation species composition, vegetation height, elevation, slope, etc. (Golder et al., 2008); and (2) to ensure that physical construction requirements are met.

Performance Monitoring. Measuring restoration effectiveness on bird populations can be difficult for several reasons. Primarily, the population is responding at a scale much larger than the project and responding to factors outside the restoration project. Furthermore, detecting change in faunal populations is difficult, especially for relatively small marsh restoration projects. Vegetation changes over a project's lifetime can all contribute to increased variation in estimates of bird use for a given project. This increased variation can make statistical comparisons to evaluate restoration success problematic and any efforts to reduce this variation need to be employed. Shriver and Greenberg (2012) provide three recommendations to help reduce variance in bird use estimates: surveys need to (1) adhere to standardized protocols, including guild definitions, such as proposed by Konisky et al. (2006); (2) conduct post-restoration monitoring for longer time periods (up to 15 years); and (3) integrate newly developed analytical techniques such as occupancy modelling (MacKenzie et al., 2006).

Performance monitoring for bird-focused restoration projects need to collect information that is linked to the restoration project objectives. Monitoring efforts to assess progress towards these objectives focus on three broad categories of information needs: (1) abundance, (2) community composition, and/or (3) reproductive rates. For example, a project objective of restoring [X] acres of tidal marsh could measure the relative abundance (i.e., the number of individuals of a particular type as a percentage of the overall number in a given area) of breeding clapper rails and seaside sparrows (see Table II.4). If one is less interested in targets for specific species and more interested in ecological function, an appropriate objective might be "producing [X] acres of functioning sand beach habitat for wintering shorebirds." This objective links to metrics such as species richness, avian community diversity, and/or a community level integrity index, as compared to some appropriate reference data set (see Table II.4). Yet another project might focus on achieving a minimum viable population. Such projects may measure fledglings per nest in addition to population size for beach nesting Wilson's plovers. As the combination of specific metrics from and across these categories is potentially overwhelming, clearly worded objective(s) are critical to successful performance monitoring.

Monitoring for Adaptive Management. Management of natural resources is characterized by uncertainty, including in our ability to predict bird response to restoration or other management activities (Runge et al., 2011). Thus, framing site-level restoration projects or a group of similar restoration projects across a region within an adaptive management framework provides feedback for learning, or reducing uncertainty, about the system (Lyons et al., 2008). Nichols and Williams (2006) refer to this approach as 'targeted' (or focused) monitoring, which they associate with "integration into conservation practice, with monitoring design and implementation based on *a priori* hypotheses and associated models of system responses to management."

Understanding existing uncertainties (as well as which type(s) of uncertainty are being considered) and prioritizing reduction of uncertainty components is not an easy task (Williams, 2011). Although a few examples of relevant uncertainties are briefly outlined above, there are myriad possibilities and many approaches for making sense of these uncertainties (e.g.,Williams, 1997, 2001, 2011; Gregory and Keeney, 2002; Runge et al., 2011; Moore and Runge, 2012). Also, the GoMAMN group has initiated an effort to identify and prioritize critical avian-related uncertainties from both a management action and ecological processes perspective (Wilson, 2015). Thus, much of the bird-related background work is being done by a group of avian experts and is available to restoration practitioners along the Gulf of Mexico to help define restoration objectives and associated avian monitoring efforts to evaluate project success.

Choose Suitable Metrics

In the case of bird restoration monitoring, suitable metrics will include individual species or species groups. For the former, GoMAMN has compiled a list of priority birds useful for Northern Gulf of Mexico bird monitoring objectives and priorities. The list consists of approximately 100 species broadly grouped into guilds, including land birds, marsh birds, pelagic seabirds, raptors, seabirds, shorebirds, wading birds, and waterfowl (Wilson, 2015).[109] Although other species may be of interest at the project-level or local geography, it is good practice to include priority species from this list (at a minimum) as metrics for Gulf of Mexico restoration projects with bird-focused objectives and design (Sanderlin et al., 2014). A variety of metrics are available for evaluating avian response to restoration (see Table II.4). Practitioners might be tempted to choose the least rigorous of the approaches outlined below as a cost-saving measure, but to assess restoration performance, the metric(s) chosen should be directly linked to the objective(s) of the restoration project.

Abundance. Birds are often easily detectable because of their conspicuousness and their habit of singing. However, simple bird lists with counts of individuals by species are not always the most useful metric when monitoring bird response to restoration. Conversely, estimates of absolute abundance (i.e., the number of individuals of a given species per unit area), which account for imperfect detection, are not always a panacea. Highlighted below are several possible abundance metrics that need to be considered when measuring bird response to restoration efforts. Note these are generally arranged from the least expensive, least intensive, and easiest metrics to implement with low rigor to the more expensive and extensive metrics resulting in higher rigor (Elphick, 1996, Table 1; Wiens et al., 2008, Figure 8).

Birding checklists – The advent of eBird,[110] part of the growing field of human computation, is a web-based program that allows birders to enter their field observations into a

[109] This list is a compilation of a wide variety of priority bird conservation lists found in State Wildlife Actions Plans, Joint Venture plans, Landscape Conservation Cooperative documents, U.S. Fish and Wildlife Service Birds of Conservation Concern lists, the Audubon Watch List, the North American Wetlands Conservation Act, the International Union for Conservation of Nature, true Northern Gulf of Mexico pelagic birds, Gulf of Mexico endemic species, and the 10 most oiled bird species recovered during the Deepwater Horizon Oil spill.
[110] eBird information: http://ebird.org/content/ebird/.

web-platform database, and renders checklist-based observations more widely useful to enhance understanding of bird biology and conservation (Wood et al., 2011). The eBird database focus of analyses typically addresses bird distribution and abundance across broad spatial scales. Frequent, repeated site visits by bird-watchers, spread across seasons, provides basic species inventory data and a general sense of relative abundance. Diversity metrics corrected for effort indicate that eBird data can substitute for standardized surveys at the project-level (Callaghan and Gawlik, 2015).

Practitioners wishing to use eBirders to help assess the outcome of their restoration project(s) must consider a few critical issues relating to spatial scale and inference. First, the balance between data quality and quantity is critical for using citizen science data such as eBird (Sullivan et al., 2009), so surveyors must adhere to the broad guidelines set forth on the eBird website. Second, inferences can only be drawn for the site within areas of high frequency sampling, which eliminates bias based on a non-random selection of sampling locations (Dickinson et al., 2010). Third, based on the scant research to date, only projects using diversity as a metric can safely rely on eBird data. Projects where abundance is the metric of inference ought to follow more standardized survey methodologies conducted by trained individuals until eBird data can be rigorously evaluated with regards to using this as a measure of restoration success.

Indices of abundance – Indices, or relative abundance measures, have long been used in avian ecology, management, and conservation (Verner, 1985; Gregory et al., 2004; Johnson, 2008; Stephens et al., 2015). For this discussion, an index is defined to be a variable that correlates strongly with abundance or density of a species in an area (Caughley, 1977; Bart and Earnst, 2002; Bart et al., 2004; Johnson, 2008). Indices potentially suffer from bias due to imperfect detection in the field and novel quantitative methods have recently been developed to reduce this bias. Johnson (2008) argues that while these advances are valuable to understanding the detection process, "their practical application may well be limited, likely to intensive studies focusing on a small number of species." If the objective is to increase population size by a given number or proportional amount, monitoring with repeated measurements of a population index over a number of years would adequately address an objective focused on increasing population. Frequently, estimating a population index is much less resource-intensive than estimating population size, and a obtaining a reliable index value is often preferred over poorly estimating size(Gregory et al., 2004). Ultimately, abundance indices may be suitable to address most ecological or conservation objectives requiring population estimation (Caughley, 1977; Verner, 1985; Gregory et al., 2004; Johnson, 2008).

Occupancy – Oftentimes focusing on individual-level metrics can be costly, yet species-level metrics may often be more appropriate or feasible (e.g., MacKenzie and Nichols, 2005; Williams et al., 2002; Pacifici et al., 2012). For example, instead of spending the time and money necessary to estimate absolute abundance (i.e., the number of individuals per unit area; see Bart [2005]) of a species, one might choose to determine the presence or absence of a species at locations within the same area (Rhodes et al., 2006). This approach is generally referred to as species occurrence or occupancy (MacKenzie and Nichols, 2005; MacKenzie, 2012). In more technical terms, occupancy is defined as "the probability that a randomly selected site or sampling unit in an area of interest is occupied by a species" (i.e., the site contains at least one individual of the species) (MacKenzie et al., 2006). Estimating occupancy rates requires an estimate of detection probability, so efforts focused on this metric will require more effort to estimate than an index of abundance. However, traditional methods of distance sampling (Buckland and Anderson, 2003; Buckland and Rexstad, 2015) can be easily modified, thus reducing effort required, to allow for occupancy estimation (Shriver and Greenberg, 2012). Perhaps the simplest adaptation of traditional methods involves dividing a 20 minute fixed radius point count (recommended by Neckles et al. for monitoring marsh birds in New England marshes) into four separate 5 minute time intervals with all detected bird instances separated into discrete time blocks (Farnsworth et al., 2002; Rosenstock et al., 2002; Alldredge et al., 2007a,b). These data allow the application of occupancy modeling techniques that would not only estimate occupancy and abundance, but would simultaneously estimate detection probabilities (MacKenzie and Nichols, 2005; Shriver and Greenberg, 2012).

Absolute abundance – Recent and continuing criticisms of indices revolve around the issue of differential and/or imperfect detection of individuals (e.g., Thompson, 2002); reflecting only a proportion of individuals counted from a population (Johnson, 2008). Unfortunately, this proportion may not always be constant – birds farther from an observer are less likely to be detected or this proportion may vary across different habitats as a function of time and as a result of a differing habitat structure – yet many alternative approaches to address these issues have been developed . For example, distance sampling addresses the obvious differences in detectability the farther a bird is away from an observer (Buckland et al., 2001). Additional methods involving mark-recapture, multiple-observer methods, and time-of-detection techniques, among others, have been developed to address this issue (see Gregory et al., 2004 and Johnson, 2008 for technique-specific citations).

Community Composition. Community composition is an umbrella category for many specific community metrics. The premise behind this approach is that avian community diversity is a function of habitat diversity (Rafe et al., 1985). It is typical for created habitats to initially lack important microhabitats and microhabitat features required by some bird species or groups, resulting in less diverse bird assemblages. Melvin and Webb (1998) found species richness and diversity to be greater in natural salt marshes; yet created salt marshes did provide bird habitat, though not necessarily for the same species assemblage as natural marshes. For restoration objectives with a focus on community-based outcomes, a few primary metrics are repeatedly noted in the literature, including relative abundance by species (e.g., Lewis and Casagrande, 1997; Grippo et al., 2007), relative abundance by bird groups (e.g., Melvin and Webb, 1998), abundance/density (e.g., Weller, 1995; Shriver and Greenberg, 2012), species richness (e.g., Weller, 1995; Melvin and Webb, 1998, Grippo et al., 2007; Shriver and Greenberg, 2012), species diversity (e.g., Melvin and Webb, 1998; Shriver and Greenberg, 2012), species evenness (e.g., Shriver and Greenberg, 2012), species similarity (e.g., Shriver and Greenberg, 2012), foraging guilds (e.g., Weller, 1995; Lewis and Casagrande, 1997, Shriver and Greenberg, 2012), and occurrence of obligate species (i.e., those restricted to an area for part of their life cycle) (e.g., Lewis and Casagrande, 1997).

Like all project evaluation criteria, community-focused metrics require some consideration before selection and use for evaluating restoration outcome. For particular habitats, including tidal marsh, the direct relationships between marsh bird communities and site characteristics are generally poorly understood (Brawley, 1995). Thus, working with an ornithologist with specific habitat and avian community experience in the system of interest will provide considerable insight in project design and monitoring approaches. The development of robust target habitat-specific avian community criteria is problematic for some habitats, including salt marshes. Community profiles can be heavily biased by selection of control site(s). To address this potential bias, standard profiles of avian salt marsh communities have been suggested, and by logical extension, would be good practice to develop for any habitat across the Gulf of Mexico by sampling large number of marshes or 'pristine' locations of appropriate habitat across the region (Lewis and Casagrande, 1997).

In addition, Lewis and Casagrande (1997) also recommend further development of this method using relative foraging guild and species abundance data from habitats within biogeographic regions, in their case southern New England. Until these robust regional community profiles are developed, care should be taken that the chosen control site(s) represent a habitat that can be reasonably replicated by restoration. Despite these concerns, a community profile approach is appropriate for evaluating restoration of avian communities, because it captures a wide range of ecological functions quickly and inexpensively. Sole reliance on the presence of obligate species can be problematic, as well as conservative, for evaluating restoration success. Their presence can be highly variable in situations where a given species, such as secretive marshes birds, is difficult to detect (Conway, 2009, 2011; Johnson et al., 2009). The addition of facultative species for evaluation has been suggested given that many, particularly in wetlands, incur direct benefits from restoration (Lewis and Casagrande, 1997).

Birds are directly linked to ecosystem condition, such that changes in avian community composition needs to reflect changes in the ecological integrity of a site, and thus biological integrity indices ought to be a robust monitoring tool (e.g., Bryce et al., 2002; DeLuca et al., 2004; Shriver and Greenberg, 2012). Measurable avian restoration metrics (e.g., occupancy, abundance by species) can easily be integrated into a community-level integrity index to monitor tidal marsh condition (Deluca et al., 2004). This condition index approach, or similar ones that consider bird community assemblage, may allow more robust techniques to evaluate differences between tidal marsh restoration sites pre- and post-restoration or between reference and restored sites. A secondary benefit to using indices of marsh bird community integrity scores is that when combined with identification of land-use threshold(s), these indices are easy to interpret and may help communicate complex ecological data to natural resource managers and conservation planners (DeLuca et al., 2004; Frederick et al., 2009). Furthermore, given this approach has been used with tidal marshes, there is no reason to believe similar approaches could not be applied to avian assemblages across submerged aquatic vegetation, oyster, and/or sand beach habitats.

Reproductive Rates. Few avian restoration monitoring efforts include demographic parameters as outcome metrics, likely because associated demographic data can be difficult to collect and more expensive relative to other avian monitoring metrics (Larison et al. 2001; Smallwood, 2001; Williams et al., 2002; Fletcher et al., 2003, 2006; Thomson and Cooch, 2008; Lorenz et al., 2009). However, recent emphasis on the critical nature of these data for evaluating and understanding response to restoration efforts has been noted. Bjorndal et al. (2011) suggest that one of seven research plan elements be to "integrate demography with abundance trends for multiple life stages and determine environmental effects on those parameters." They stress that both demographic and abundance data are essential to determine causes of population declines. Shriver and Greenberg (2012) support this strong statement, noting that few demographic studies of tidal marsh bird populations, regardless of a focus on restoration, have been published while even fewer have focused on different marsh management approaches. Estimates of occupancy or abundance by themselves are not adequate to determine population persistence, a critical parameter for tidal marsh endemic populations (Shriver and Greenberg, 2012).

The collection of parameters such as fledgling success, fecundity, and age-specific survival could provide a valuable opportunity to assess the effects of restoration efforts on target taxa through development of complete life cycle models. Through this individual-based model structure, such as presented by Mattson and Cooper (2007), restoration practitioners and research ecologists alike will be able to predict effects of future environmental changes, such as sea level rise, on coastal restoration project outcomes (Woodrey et al., 2012). Projects that incorporate sampling pre- and post-restoration at multiple sites across a region will certainly provide the most informative results, but may likely be the most expensive and logistically challenging. It will depend on decision-makers and what management question these monitoring efforts aim to inform (see chapter 3 for a detailed discussion).

See Table II.4 for monitoring metrics that are generally accepted to measure ("standardized") for construction and performance monitoring of bird-related restoration activities, and monitoring metrics that are suggested by the Committee to assess bird restoration efforts at a program, region, or Gulf-wide scale (note that example metrics to support monitoring for adaptive management are not included because of their inherent project/program-specificity).

Monitoring Planning Considerations

Gregory et al. (2004) and Lambert et al. (2009) provide excellent guidance for how to plan a bird monitoring effort, in which key elements include the following: (1) determine monitoring objective(s), (2) determine need for absolute density metric or an index, (3) determine monitoring project boundaries, (4) determine if objectives require conducting a census or collecting a sample, (5) determine a monitoring objective-appropriate sampling strategy, (6) determine the size and shape of the sampling unit(s) in which surveys will take place, (7) determine the field method(s) to be used to adequately assess progress toward monitoring objective(s), and (8) consider and address issues of accuracy, precision, statistical power, and bias (see Chapter 3) when designing a survey. Carefully thinking through each of these steps will maximize the likelihood of achieving progress toward objectives, resulting in scientifically sound data for evaluating efficacy of restoration projects using avian monitoring metrics.

Appropriate baseline (pre-construction) data. Many restoration practitioners and natural resource managers associate the collection of baseline data within the project area as a means of measuring changes that are expected to occur to the parameters of interest (e.g., Reiger et al. 2014), possibly including birds, once a project has been implemented. However, best practice for a robust sampling scheme is to ensure that baseline data are also collected for multiple control/reference site(s) as well. In addition, because bird population numbers can vary due to their high mobility, it is important to have multiple years of baseline data against which to measure changes in abundance associated with a restoration project.

Appropriate control / reference sites. Selection of appropriate reference sites needs to include considerations of similarity in size, landscape context (i.e., habitat diversity, habitat fragmentation, and distance from human development), and vegetation community assemblages to restoration target(s), as well as locations with bird data available for calculating target metrics (Block et al., 2001; Morrison, 2009; Hutto et al., 2014). Restoration practitioners ought to choose multiple appropriate control and/or reference sites to reflect the desired endpoint(s) of a restoration project. In addition, appropriate control/reference site(s) need to be carefully selected to reflect the desired outcome of the restoration efforts. The avian monitoring survey design conducted at project site(s) should be repeated at the appropriate control/reference site(s) for the duration of the restoration project (Lewis and Casagrande, 1997). Finally, the ability to draw sound conclusions from a restoration projects is enhanced where multiple control sites are incorporated into the study design (Underwood, 1991).

Develop a rigorous and robust sampling design. Perhaps the most over-arching best practice for avian monitoring efforts is scientific rigor. It is one of three fundamental objectives identified and defined by GoMAMN as "Objective 2.0: Maximize Rigor of Monitoring Projects (increase emphasis on scientific rigor [study designs, sampling frameworks, power analysis, etc. – see Chapter 3] underpinning monitoring projects in the Gulf of Mexico)." The group further developed a set of performance metrics, or evaluation criteria, to determine required standards to reflect the rigor of a project design. In order to be considered a rigorous effort, a projects' monitoring plan needs to include (as discussed in Chapter 3) the following considerations:

1. Clearly state project objectives and/or hypotheses – emphasis placed on a monitoring design that clearly states objectives and/or hypotheses along with supporting details;
2. Maximize the monitoring design to achieve project objectives – emphasis placed on a survey[111] and sampling design that is clearly appropriate to measure progress toward achieving objectives;
3. Maximize appropriateness of target taxa – emphasis placed on a survey that uses the most appropriate target species for evaluating objectives and hypotheses;
4. Maximize appropriateness of response variable(s) – emphasis placed on a survey that uses the most appropriate and best suited response variable(s) to address project objectives/hypotheses;
5. Maximize appropriateness of the statistical analysis – emphasis placed on a survey that uses the most appropriate and best suited statistical technique(s) to address project objectives/hypotheses;
6. Conduct an appropriate formal power analysis – emphasis placed on a survey that explicitly states a desired effect sizes for meaningful ecological and management decisions;
7. Develop and articulate a data management plan – emphasis placed on a survey that includes a data management plan that addresses data acquisition, development, storage, and transfer;
8. Maximize the inference based on survey design – emphasis placed on a survey that provides broadly applicable data with a broad range of inference;
9. Maximize the budget – emphasis placed on a survey that has an appropriate, reasonable, and efficient budget to address objectives/hypotheses;
10. Maximize the timeline for the project – emphasis placed on a survey that has an appropriate and reasonable timeline to address objectives/hypotheses; and

[111] Here the term survey includes a number of different survey techniques, methodologies, and metrics.

11. Maximize the likelihood of meeting project objectives– emphasis placed on a survey in which aspects of the project are clearly aligned and the best way to achieve objectives/hypotheses (Wilson, 2015).

A focus on these criteria in the design of an avian monitoring effort will ensure both the scientific validity of the data collected, which is necessary to confidently support monitoring conclusions (see Table 3.1), as well contribute to progress towards meeting the project objectives.

Consider cost constraints. Cost constraints increase with the level of detail and specificity (e.g., going from simple checklists reflecting relative abundance to estimating multiple demographic parameters) determined to be appropriate for a given bird monitoring program. However, a few relatively novel technologies exist that could help reduce monitoring costs associated with a particular project. For example, autonomous recording units are a cost-effective class of tools for monitoring singing or calling birds (where individuals are rarely observed or hard to access on a regular basis (Acevedo and Villanueva-Rivera, 2006; Alquezar and Machado, 2015). Using autonomous recording units saves personnel costs by requiring fewer field technicians, but does involve human labor in data review, identification, and quality control. Regardless, these units could be particularly useful for monitoring bird species that vocalize frequently or for species such as breeding marsh birds, especially if occupancy is a monitoring metric of interest.

Recent technological advances with wildlife cameras have led to an explosion in the use of camera trapping to survey and monitor wildlife in recent years (O'Connell et al., 2011; Burton et al., 2015). The use of trail cameras likely reduces costs for field technicians to conduct repeated field surveys, both in terms of time and logistics. However, the use of this technology does not preclude consideration of several lessons learned regarding quantitative assessment of animal populations. For instance, issues such as imperfect detection, effective sampling area, occupancy modeling assumptions, and multi-species inference are topics that need to be addressed in a monitoring context (Burton et al., 2015). For example, in the Big Bend Region of Florida, Frederick et al. (2015) used trail cameras to estimate usage of restored oyster reefs by aquatic birds. They report cameras were not always reliable and detection of target wading birds was likely biased low due to dark conditions or occlusion by precipitation or fog. Ultimately, the cameras collected useable bird data, although many individuals could not be identified to species level (Frederick et al., 2015).

Other Technology Advances. Many new technologies are being developed to track wide-ranging organisms. For example, a very promising bird-tracking technology is the nano-tag (e.g., Taylor et al., 2011), where digitally encoded micro-transmitters are attached to individual organisms to track their movements. The main advantage of these micro-transmitters over conventional radio-transmitters is their smaller size and significantly longer battery life. In addition, these tags can be read by receiver towers that constantly and passively monitor the surrounding area (up to 25 km away) for nano-tag signals (Motus, 2011). The potential for understanding species movements across and around the Gulf cannot be overstated. The broad-scale implementation of this technology across the Gulf region would provide invaluable information regarding long distance movements as well as local-scale movements and site fidelity to restoration projects. Further, the development of a Gulf-wide network of automated radio telemetry towers, similar to the Motus Wildlife Tracking System (Motus, 2011) would facilitate monitoring from the project-scale to the Gulf-wide scale. When collaborative efforts, such as marking birds with nano-tag transmitters, are combined with a region-wide network of automated towers, this type of array could track birds across the widespread, diverse habitats of the Gulf of Mexico over thousands of kilometers (Motus, 2011).

Consider appropriate protocols / standard operating procedures. The utility of standard sampling frameworks and protocols cannot be overstated. In the case of secretive marsh birds in the northeastern United States, regional monitoring efforts exist that would not have been possible without an underlying unified sampling framework (Wiest et al., in press). In this case, partners throughout the region were willing to collect different portions of these data because sampling locations had been selected using a rigorously designed sampling framework (Johnson et al., 2009). This approach allows local and regional information needs to be addressed *simultaneously*. Most importantly for restoration practitioners, sampling effort (i.e., number of points observed) can be increased to make inferences at the restoration project scale while preserving the statistical design elements for inference at broader spatial scales. Further, this framework allows integration of restoration efforts into adaptive management schemes that address questions regarding the effectiveness of management activities for these species (Conroy et al., 2010). See Box II.2 for a case study of successful regional bird monitoring.

Box II.2

A Regional Monitoring Framework for Tidal Marsh Birds in the Northeast United States

Much of the tidal marshes and other wetland habitats across North America have been lost or severely affected by human activities (Batzer and Baldwin, 2012). As a result, many wetland-associated species have been designated as species of conservation concern at state, federal, or both levels. About 22 percent of the world's non-arctic tidal marsh is found in the Gulf of Mexico region; and in North America approximately 62 percent of tidal marsh habitat is found along the Gulf of Mexico coastline (Greenberg and Maldonado, 2006). Unfortunately, although distributions of marsh birds are very generally known, the conservation community lacks regional, state, and local level abundance and population size estimates, a situation that will limit the ability of restoration practitioners to evaluate the effectiveness of their efforts to restore coastal emergent wetlands and associated bird populations.

However, a recent effort in the northeastern United States has provided robust estimates of breeding marsh bird abundance across the region (Wiest et al., in press). Practitioners used two standardized monitoring components to generate rigorous and robust population and abundance estimates – a sampling design framework for monitoring breeding secretive marsh birds (Johnson et al., 2009) and a standardized North American marsh bird monitoring protocol (Conway, 2011). Briefly, Johnson et al. (2009) proposed a probabilistic sampling framework based on a two-stage design that uses hexagons defined by the US Environmental Protection Agency to define the sampling universe. The hexagons serve as primary sampling units while the actual sampling points serve as secondary sampling units. The flexibility and probabilistic design of such a framework easily allows integration with other regional wetland monitoring programs (e.g., Louisiana's Coastwide Reference Monitoring System) and inferences about marsh bird species to be made at multiple geographic scales (e.g., restoration project, state-wide, or regional scales) (Johnson et al., 2009, Wiest et al., in press). Once the actual sampling points are determined, field biologists follow the Standardized North American Marsh Bird Monitoring

Protocol to survey breeding marsh birds (see Conway [2011] for detailed guidelines explaining the field method instruction to ensure standardized efforts to monitor breeding marsh birds).

Program-level Monitoring and Assessment

Given the potential amount of tidal marsh restoration and geographic extent of emergent coastal wetland habitat across the Gulf of Mexico, the formation of a regional emergent marsh restoration team that includes restoration practitioners, monitoring experts, and wetland avian ecologists would be an extremely useful step in addressing protocols and standard procedures for the benefit for multiple projects and regional integration of their data (see Box II.2). Integrated and inter-disciplinary teams are especially valuable for their role in giving serious thought to the development of a regional marsh monitoring effort, including secretive marsh birds, that allows evaluation of restoration outcomes across the region, along with an understanding of the changes in marsh bird populations due to these directed efforts.

Building on the multitude of restoration efforts currently underway and proposed for the future across the Gulf of Mexico is critical to measuring avian response to Gulf NRDA, RESTORE, and NFWF activities (see Chapter 2). In order to generate robust and scientifically defensible measures of responses to restoration activities, taxa-specific regional sampling frameworks need to be designed and implemented. In addition, every attempt ought to be made to develop and implement standardized field sampling protocols that allow data compilation across various spatial scales. Although daunting to consider, this has been accomplished for secretive marsh birds in the Northeastern United States (Wiest et al., in press; See Box II.2).

Also, restoration projects have focused much recent attention on restoring marsh birds, and one major development is the testing, vetting, and agreement on a standardized monitoring protocol – the Standardized North American Marsh Bird Monitoring Protocol (Conway, 2011). The luxury of having a standard procedure for counting marsh birds allows for the quick and rigorous implementation of monitoring efforts across multiple scales. This methodology provides very explicit instructions for counting marsh birds to address a variety of fundamental objectives including (1) documenting presence or distribution of marsh birds; (2) comparing densities among management units, wetlands, or regions; (3) estimating population trends; (4) evaluating the effects of management efforts on marsh bird species; and (5) documenting habitat associations or wetland conditions that drive marsh bird abundance or occupancy. Regardless of the bird taxa of interest, these five objectives should likely serve as the basis for any bird-focused restoration project across the Gulf.

Several integration performance metrics highlight the need for standardization of mapping and survey data collection, as well as maximizing the accessibility, utility, and standardization of monitoring data. To address such concerns and support an integrated, explicit monitoring effort throughout the Gulf, avian ecologists, conservation biologists, and natural resource managers, among others, are working together as part of GoMAMN. Practitioners are using a structured decision making framework (Gregory and Keeney, 2002) to develop a systematic, rigorous, and comprehensive avian monitoring network (Wilson, 2015). The initial efforts of this group are focused on developing monitoring objectives to maximize the relevancy of bird monitoring data and ensure that projects are addressing current data needs irrespective of geographic scale.

Table II.4 Metrics considered good practice to monitor bird restoration activities for construction, performance toward project objectives, and program-level or large-scale assessments of (A) beach and dune, (B) emergent marsh, and (C) open water bird restoration.

NOTE: Since bird restoration efforts are usually more guild-specific than objectives-specific, symbols indicate metrics that are generally appropriate to sample for each guild for different purposes of monitoring.

[a] Bird guilds include land birds (LB), marsh birds (MB), pelagic seabirds (PS), raptors (RA), sea birds (SE), shore birds (SB), wading birds (WB), and waterfowl (WF).
[b] Seasons are defined as breeding (b; June-August), migration (m; March-May & September-November), and winter (w; December-February). Seasons are included for faunal monitoring attributes because birds show species-specific seasonal habitat use patterns along the Gulf of Mexico.
[1] Small and discrete vs large and extensive.
[2] Based on Coastal Change Analysis Program habitat descriptions.
[3] Natural or restored site.
[4] Defined here as flood, wild fire, prescribed fire, hurricane, tornado, straight-line winds or other major disturbance that occurred in the "target area."
[5] Defined here as prescribed fire, drawdown, flooding, disking, mowing, grazing, herbicide application, beach renourishment, marsh restoration, fisheries management, freshwater management, barrier island creation/restoration, vegetation planting.

	A. BEACH AND DUNE		
	Monitoring Purpose		
	Construction	Performance	Program-level
Potential Monitoring Metrics	*Guilds* [a]	*Guilds*	*Guilds*
Project Characteristics			
Area	SE, SB, WB	SE, SB, WB	SE, SB, WB
General shape[1]			
Habitat			
Type[2]	SE, SB, WB	SE, SB, WB	SE, SB, WB
Interspersion/diversity			SE, SB, WB
Condition[3]	SE, SB, WB	SE, SB, WB	SE, SB, WB
Road Density			
Date and type of last natural disturbance[5]	SE, SB, WB	SE, SB, WB	SE, SB, WB
Date and type of last management action[6]		SE, SB, WB	SE, SB, WB
Geomorphology/Hydrology			
Time of the closest high tide		SE, SB, WB	SE, SB, WB
Tidal amplitude		SE, SB, WB	SE, SB, WB
Water level		SE, SB, WB	SE, SB, WB
Salinity			
Soils/sediments			
Substrate type		SB	SB
Substrate contaminant levels		SE, SB, WB	SE, SB, WB
Vegetation			
Percent cover of emergent vegetation	SE, SB, WB	SE, SB, WB	SE, SB, WB
Species composition of emergent veg			
Percent cover of submerged vegetation			
Species composition of submerged veg			
Percent cover of invasive plant species	SE, SB, WB	SE, SB, WB	SE, SB, WB
Species composition of invasive plant species			
Fauna			
Pre-construction birding checklist (in eBird)	SE (b,w)[b]; SB (b,m,w); WB (m,w)	SE (b,w); SB (b,m,w); WB (m,w)	
Index of abundance		SE (b,w); SB (b,m,w); WB (m,w)	
Occupancy			
Absolute abundance			SE (b); SB (b)
Species diversity		SE (b,w); SB (b,m,w); WB (m,w)	SE (b,w); SB (b,m,w); WB (m,w)
Avian community diversity		SE (b,w); SB (b,m,w); WB (m,w)	SE (b,w); SB (b,m,w); WB (m,w)
Community-level integrity index		SE (b,w); SB (b,m,w); WB (m,w)	SE (b,w); SB (b,m,w); WB (m,w)
Nest success		SE (b); SB (b)	SE (b); SB (b)
Fecundity		SE (b); SB (b)	SE (b); SB (b)
Age-specific annual survivorship		SE (b,w); SB (b,w); WB (w)	SE (b,w); SB (b,w); WB (w)
Ecosystem Services			
Birder travel cost			
Birder species preferences			
Birder satisfaction with birding experience (frequently during birding season)		SE, SB, WB	
Birder visitation rate to project site (daily during birding season)		SE, SB, WB	
Birder visitation rate to Gulf			SE, SB, WB
Hunter visitation rate to project site (daily during hunting season)		SE, SB, WB	
Fees from hunter permits sold for access to project site (seasonal)		SE, SB, WB	

	B. EMERGENT MARSH		
	Monitoring Purpose		
	Construction	Performance	Program-level
Potential Monitoring Metrics	*Guilds* [a]	*Guilds*	*Guilds*
Project Characteristics			
Area	LB, MB, SE, SB, WB, WF	LB, MB, SE, SB, WB, WF	LB, MB, SE, SB, WB, WF
General shape[1]			
Habitat			
Type[2]	LB, MB, SE, SB, WB, WF	LB, MB, SE, SB, WB, WF	LB, MB, SE, SB, WB, WF
Interspersion/diversity	LB, MB, SE, SB, WB, WF	LB, MB, SE, SB, WB, WF	LB, MB, SE, SB, WB, WF
Condition[3]	LB, MB, SE, SB, WB, WF	LB, MB, SE, SB, WB, WF	LB, MB, SE, SB, WB, WF
Road Density		LB, MB, WF	LB, MB, WF
Date and type of last natural disturbance[5]	LB, MB, SE, SB, WB, WF	LB, MB, SE, SB, WB, WF	LB, MB, SE, SB, WB, WF
Date and type of last management action[6]		LB, MB, SE, SB, WB, WF	LB, MB, SE, SB, WB, WF
Geomorphology/Hydrology			
Time of the closest high tide		LB, MB, SE, SB, WB	LB, MB, SE, SB, WB
Tidal amplitude		LB, MB, SE, SB, WB	LB, MB, SE, SB, WB
Water level		LB, MB, SE, SB, WB	LB, MB, SE, SB, WB
Salinity		LB, MB, SB, WF	LB, MB, SB, WF
Soils/sediments			
Substrate type			
Substrate contaminant levels		LB, MB, SE, SB, WB, WF	LB, MB, SE, SB, WB, WF
Vegetation			
Percent cover of emergent vegetation		LB, MB, SE, SB, WB, WF	LB, MB, SE, SB, WB, WF
Species composition of emergent veg		LB, MB	LB, MB
Percent cover of submerged vegetation			
Species composition of submerged veg			
Percent cover of invasive plant species		LB, MB	LB, MB
Species composition of invasive plant species		LB, MB	LB, MB
Fauna			
Pre-construction birding checklist (in eBird)	LB (b,m,w)[b]; MB (b,m,w); SE (b,w); SB (b,m,w); WB (b,m,w); WF (b,m,w)	LB (b,m,w); MB (b,m,w); SE (b,w); SB (b,m,w); WB (b,m,w); WF (b,m,w)	
Index of abundance		LB (b,m,w); MB (b,m,w); SE (b,w); SB (b,m,w); WB (b,m,w); WF (b,m,w)	
Occupancy			
Absolute abundance			LB (b,w); MB (b,w); SE (b,w); SB (b,w); WB (b,w); WF (b,w)
Species diversity		LB (b,m,w); MB (b,m,w); SE (b,w); SB (b,m,w); WB (b,m,w); WF (b,m,w)	LB (b,m,w); MB (b,m,w); SE (b,w); SB (b,m,w); WB (b,m,w); WF (b,m,w)
Avian community diversity		LB (b,m,w); MB (b,m,w); SE (b,w); SB (b,m,w); WB (b,m,w); WF (b,m,w)	LB (b,m,w); MB (b,m,w); SE (b,w); SB (b,m,w); WB (b,m,w); WF (b,m,w)
Community-level integrity index		LB (b,m,w); MB (b,m,w); SE (b,w); SB (b,m,w); WB (b,m,w); WF (b,m,w)	LB (b,m,w); MB (b,m,w); SE (b,w); SB (b,m,w); WB (b,m,w); WF (b,m,w)
Nest success		LB (b); MB (b); SE (b); SB (b); WB (b); WF (b)	LB (b); MB (b); SE (b); SB (b); WB (b); WF (b)
Fecundity		LB (b); MB (b); SE (b); SB (b); WB (b); WF (b)	LB (b); MB (b); SE (b); SB (b); WB (b); WF (b)
Age-specific annual survivorship		LB (b,w); MB (b,w); SE (b,w); SB (b,w); WB (b,w); WF (b,w)	LB (b,w); MB (b,w); SE (b,w); SB (b,w); WB (b,w); WF (b,w)

	B. EMERGENT MARSH		
	Monitoring Purpose		
	Construction	Performance	Program-level
Potential Monitoring Metrics	*Guilds* [a]	*Guilds*	*Guilds*
Ecosystem Services			
Birder travel cost			
Birder species preferences			
Birder satisfaction with birding experience (frequently during birding season)		LB, MB, SE, SB, WB, WF	
Birder visitation rate to project site (daily during birding season)		LB, MB, SE, SB, WB, WF	
Birder visitation rate to Gulf			LB, MB, SE, SB, WB, WF
Hunter visitation rate to project site (daily during hunting season)		LB, MB, SE, SB, WB, WF	
Fees from hunter permits sold for access to project site (seasonal)		LB, MB, SE, SB, WB, WF	

	C. OPEN WATER		
	Monitoring Purpose		
	Construction	Performance	Program-level
Potential Monitoring Metrics	*Guilds* [a]	*Guilds*	*Guilds*
Project Characteristics			
Area			
General shape[1]			
Habitat			
Type[2]	PS, SE, WF	PS, SE, WF	PS, SE, WF
Interspersion/diversity	PS, SE, WF	PS, SE, WF	PS, SE, WF
Condition[3]	PS, SE, WF	PS, SE, WF	PS, SE, WF
Road Density			
Date and type of last natural disturbance[5]	PS, SE, WF	PS, SE, WF	PS, SE, WF
Date and type of last management action[6]		PS, SE, WF	PS, SE, WF
Geomorphology/Hydrology			
Time of the closest high tide			
Tidal amplitude			
Water level			
Salinity	PS, SE, WF	PS, SE, WF	PS, SE, WF
Soils/sediments			
Substrate type			
Substrate contaminant levels	PS, SE, WF	PS, SE, WF	PS, SE, WF
Vegetation			
Percent cover of emergent vegetation			
Species composition of emergent veg			
Percent cover of submerged vegetation		WF	WF
Species composition of submerged veg		WF	WF
Percent cover of invasive plant species			
Species composition of invasive plant species			
Fauna			
Pre-construction birding checklist (in eBird)	PS (b,m,w)[b]; SE (m,w); WF (m,w)	PS (b,m,w); SE (m,w); WF (m,w)	
Index of abundance		PS (b,m,w); SE (m,w); WF (m,w)	
Occupancy			
Absolute abundance			PS (b,w); SE (w); WF (m,w)
Species diversity		PS (b,m,w); SE (m,w); WF (m,w)	PS (b,m,w); SE (m,w); WF (m,w)
Avian community diversity		PS (b,m,w); SE (m,w); WF (m,w)	PS (b,m,w); SE (m,w); WF (m,w)
Community-level integrity index		PS (b,m,w); SE (m,w); WF (m,w)	PS (b,m,w); SE (m,w); WF (m,w)
Nest success		PS (b)	PS (b)
Fecundity		PS (b)	PS (b)
Age-specific annual survivorship		PS (b,w); SE (w); WF (w)	PS (b,w); SE (w); WF (w)
Ecosystem Services			
Birder travel cost			
Birder species preferences			
Birder satisfaction with birding experience (frequently during birding season)		PS, SE, WF	
Birder visitation rate to project site (daily during birding season)		PS, SE, WF	
Birder visitation rate to Gulf			PS, SE, WF
Hunter visitation rate to project site (daily during hunting season)		PS, SE, WF	
Fees from hunter permits sold for access to project site (seasonal)		PS, SE, WF	

SOURCES: Johnson et al., 2009; Conway, 2011; Wilson, 2015; Wiest et al., 2016

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SEA TURTLE RESTORATION MONITORING

Why Restore Sea Turtles?

Sea turtles play numerous roles in marine ecosystems from mainland beaches to oceanic waters; for example their shells serve as mobile habitat or resting space for hundreds of species of invertebrates, fish, and birds, and they transport nutrients across ecosystems including from sea to land. As part of marine food chains, sea turtles affect many plants, animals, and habitat directly and indirectly through their foraging behavior, and as critical prey items for predators at multiple trophic levels (Heithaus, 2013). Sea turtles also play an important socio-economic role in the Gulf of Mexico. Ecotourism centered around sea turtle nesting beach programs where the public can watch a female lay her eggs on the beach is an important part of the economies of some coastal communities. Public hatchling releases also attract thousands of tourists every year and contribute to the economies of the areas where they are held annually. International case studies have estimated gross revenue for non-consumptive use of marine turtles to average over a million US dollars per site annually, and passive use value expenditures of $20 million per year on global marine turtle conservation (Troëng and Drews, 2004). However, in the Gulf the aesthetic and intrinsic nonuse values of sea turtles are unquantified.

All five species of sea turtle in the Gulf of Mexico (Kemp's ridley, loggerhead, green, hawksbill, and leatherback) are threatened or endangered, and are protected by the U.S. Endangered Species Act (ESA, 16 U.S.C. § 1531 et seq.). For example, the Kemp's ridley sea turtle (*Lepidochelys kempii*) species, which only nest on Gulf of Mexico beaches, declined in the 1960s-70s after decades of egg harvest and incidental capture in fisheries. By the mid-1980s only a few hundred female Kemp's ridleys came ashore to lay eggs in Mexico. Conservation practices implemented to reduce mortality and increase recruitment saved the species from extinction and led to exponential growth in the number of adult female Kemp's ridleys from only a couple of hundred turtles in 1985 to nearly 10,000 turtles in 2009. The dynamics of the genetically distinct Gulf loggerhead turtle are also important to understand for restoration and monitoring purposes, as well as the Florida green turtle population, which is recovering well enough from near-extinction to be moved from endangered to threatened status in 2016.

Restoration Objectives

The overarching goal of sea turtle restoration in the Gulf of Mexico following the Deepwater Horizon oil spill is to implement an integrated portfolio of restoration approaches to address all injured life stages (hatchling, juvenile, and adult) and all sea turtle species, as well as to restore the food sources and habitats that turtles require (DWH NRDA Trustees, 2016). This restoration portfolio currently includes reducing mortality of sea turtles by decreasing the primary threats in marine and terrestrial environments. These threats include incidental capture in commercial and recreational fisheries, acute environmental changes (when induced by human activity), loss or degradation of nesting beach habitat (e.g., beach armoring), and other natural and anthropogenic threats. Restoration approaches also include increasing recruitment of hatchling sea turtles by expanding efforts to locate and protect sea turtle nests on beaches to reduce the primary threats to nests, eggs, and hatchlings (e.g., predators, tidal inundation, artificial lighting) (DWH NRDA Trustees, 2016). The National Oceanic and Atmospheric

Administration (NOAA) Fisheries Service and the U.S. Fish and Wildlife Service (FWS) have shared jurisdiction for recovery and conservation of sea turtles listed under the ESA. NOAA leads the conservation and recovery of sea turtles in the marine environment, and FWS leads the conservation and recovery of sea turtles on nesting beaches.

Examples of common restoration objectives are provided in Table II.5, including enhancing hatching success by constructing corrals on sea turtle nesting beaches, reducing hatchling disorientation by controlling artificial lights on nesting beaches, enhancing survival by controlling predators on nesting beaches, restoring stranded turtles, and reducing adult mortality from fisheries bycatch. Most life history models indicate that population gains realized by improving conditions according to the first four objectives are often linked to reducing fishery bycatch. Table II.5 also lists a set of metrics (described below) that may help assess progress towards these objectives in many cases, and depending on the relevant monitoring purpose (note that example metrics to support monitoring for adaptive management are not included because of their inherent project/program-specificity).

Decision-critical Uncertainties

Sea turtles are long-lived vertebrates that have delayed maturity, complex life cycles that span multiple habitats from mainland beaches to oceanic waters, and wide-ranging migrations. Interspecific and intraspecific variation exist in the ecology and life histories of the five sea turtle species that occur in the Gulf of Mexico, however general patterns exist and these form the basis of our understanding of sea turtle distribution. Post-hatchling sea turtles are epipelagic, migrate far from land, and gather in surface circulation features such as convergence zones where seagrass, algae, and other material gather, providing food and shelter for this critical juvenile life stage. After a few years, juvenile turtles of most species migrate back towards inshore and nearshore habitats where they feed primarily on benthic organisms. Juveniles mature sexually after many years (decades for some species) and migrate to breeding areas, often located in nearshore waters adjacent to the nesting beach of their natal origin, to mate and later nest. After the breeding season adult males and females migrate to feeding areas where they may reside until their next reproductive cycle (2-5 years). Sea turtles typically disperse widely after nesting and undertake long migrations nearshore for some species and far offshore for others, crossing through the waters and territories of multiple states and nations.

A conceptual model of sea turtle life history is useful to understand the complexities of monitoring sea turtles. This qualitative model (Figure II.5), highlighted in a recent National Research Council (NRC) study undertaken to improve assessment of sea turtle status and trends (NRC, 2010), is a causal loop diagram of the Pacific loggerhead sea turtle (*Caretta caretta*). This model is a simple illustration of a typical sea turtle life cycle that characterizes the relationship between sea turtle demography and some of the known anthropogenic and natural stressors in a complex biological system. Coupling this conceptual model with the established practices widely used to assess sea turtle status and trends reveals deficiencies of current assessment methods. Furthermore, monitoring vital rates, such as the example metrics listed in Table II.5, can improve the capacity of models to assess sea turtle population recovery. Improving the quality and quantity of information gathered from mark-recapture and stranded animal tissue analysis should help make this link possible, and facilitate assessment of future catastrophic event impacts on vulnerable populations. Also, critical habitats for sea turtle life stages, including rafts of algae

(*Sargassum* spp.), seagrass beds, and nearshore continental shelf habitats, have been identified but not yet well mapped.

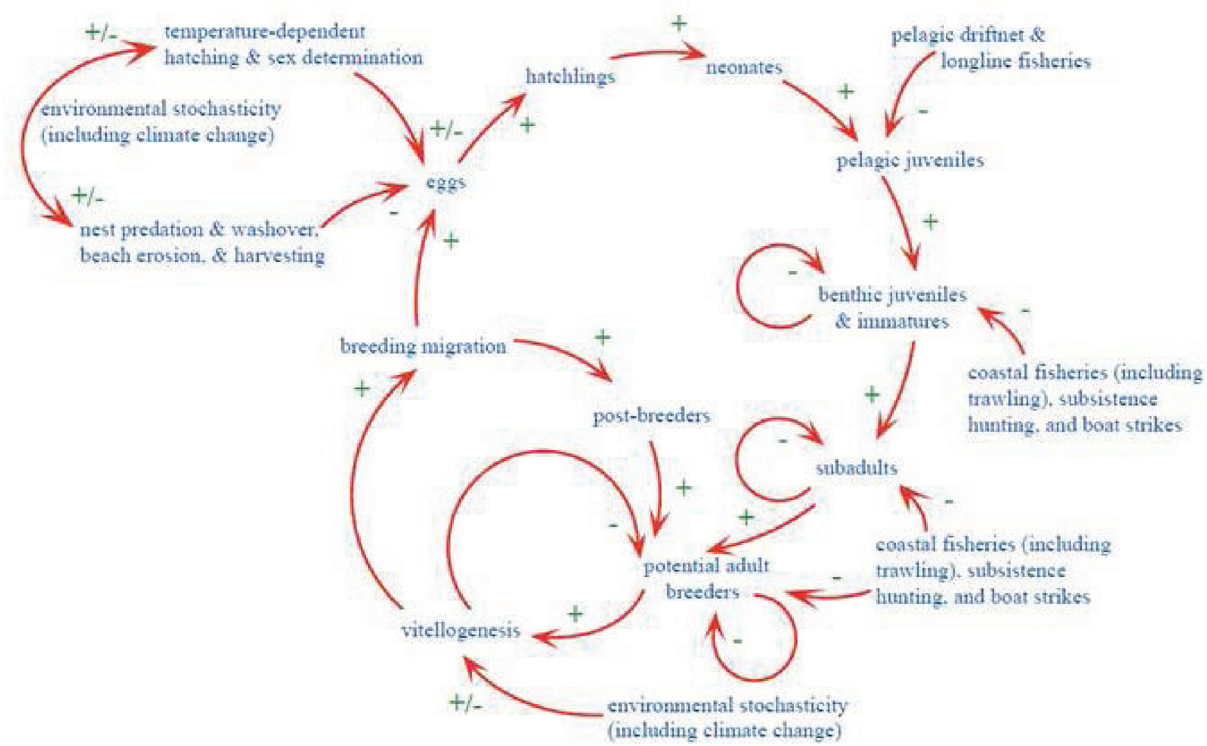

Figure II.5 A conceptual model to illustrate age-class structure and demographic processes of the Pacific loggerhead sea turtle. Plus signs indicate two components moving in the same direction; minus signs indicate components moving in opposite directions. SOURCE: NRC, 2010.

Much of the good practice that is presented here on assessment of sea turtle status and trends is provided in greater depth in the recent NRC (2010) report; readers are advised to use this resource for details and comprehensive source information beyond the following overview. Examples of techniques discussed in this report include mark-recapture studies to estimate frequency of reproduction, annual survival, and growth of turtles on beaches and in water. Current approaches to assess sea turtle status and trends rely heavily on data collected from long-term monitoring projects that estimate the abundance of adult females nesting at beaches (NRC, 2010; Bjorndal et al., 2011). These data alone are insufficient for a number of reasons. First, using abundance data based on a single life-stage is not representative of the entire population. Data collected at nesting beaches provides estimates of only reproductively active adult females, a small fragment of any sea turtle population. Juveniles, subadults, males and non-breeding adult females are excluded from abundance estimates, therefore, we know very little about both abundance and mortality rates of these life stages. Second, because sea turtles take a long time to attain sexual maturity (decades for some species) and most adult females do not reproduce annually, decades of monitoring are needed to observe population changes and it does not enable diagnosis of the cause(s) of population increase or decrease. Finally, most fundamental vital rates necessary for population assessments cannot be collected at nesting beaches. Demographic information such as age-specific and sex-specific survival, age at sexual maturity, and other vital rates are necessary to interpret population changes, identify threats in marine habitats and their relative impacts, predict risk, evaluate the impacts of management activities, and competently assess sea turtle populations (Heppell et al., 2003; Bjorndal et al., 2011). Therefore, many key uncertainties remain regarding the above conceptual model, including abundance of various life stages in the water, reproductive and early survival rates, demographic information across the Gulf, and confidence in existing quantitative assessment of threats (NRC, 2010).

Develop a Project-level Monitoring and Assessment Plan

Information Needs based on Monitoring Purpose and Project Objectives

Sea turtles are difficult to monitor, and practices used to assess status and trends have focused on the life stages that are most easily accessible on land. As defined in Part I of this report, the three primary purposes of restoration monitoring include (1) assuring projects are built and are initially functioning as designed (*construction monitoring*); (2) assessing whether restoration goals and objectives have been or are being met (*performance monitoring*); and (3) informing restoration management, improving design of future restoration efforts, and increasing ecosystem understanding (*monitoring for adaptive management*). For these purposes, baseline monitoring of sea turtles occurs world-wide at nesting beaches using established methods that yield important information about increasing and decreasing trends of populations and species (Eckert et al., 1999). The data collected have been used extensively for many years by state and federal agencies responsible for sea turtle recovery to assess the status and trends of sea turtle populations and species, and the success of various management strategies. There are many different types of sea turtle restoration projects currently planned. These range from projects designed to protect eggs at nesting beaches to projects that will facilitate rapid response to episodic mass stranding events (see Table 4.1 and NRC [2010] for more details on the value of monitoring strandings). The types of monitoring and evaluation plans used to assess the impacts of individual projects will vary according to their objectives. As post-DWH restoration activities increasingly (but often independently) occur across the Gulf of Mexico to improve turtle-dependent habitats and food sources, it would be beneficial to coordinate such efforts (see Table 4.1 for examples of related restoration activities) to improve the likelihood of effective sea turtle recovery. Table II.5 describes the relationship between objectives of restoration projects and the metrics that are monitored to assess progress towards those objectives.

Table II.5 Metrics considered good practice to monitor sea turtle restoration activities for construction, performance toward project objectives, and program-level or large-scale assessments.

NOTES: Examples are provided to illustrate linkages between restoration situations/objectives and appropriate metrics. Example #1 (linkages shown in the table by “#1”) is to construct corrals on sea turtle nesting beaches; Example #2 is to reduce artificial lights on sea turtle nesting beaches; Example #3 is to control predators on sea turtle nesting beaches; Example #4 is to restore stranded turtles; and Example #5 is to reduce fisheries bycatch. The “X” symbol indicates metrics that are suggested by the Committee as appropriate to sample across multiple projects at a program, region, or Gulf-wide scale.

	Monitoring Purpose		
	Construction	Performance	Program-level
Potential Monitoring Metrics	*Examples*	*Examples*	*Suggested*
Habitat			
Nesting beach location	#1, #2, #3	#1, #2, #3	X
Beaches where stranding data are recorded	#4	#4	X
Feeding ground location	#5	#5	X
Migratory corridor location	#5	#5	X
Date and location of possibly interacting management activities			X
Nesting Beach Variables			
Number of nests laid		#1, #2	X
Number of nests incubated *in situ*		#1, #3	
Number of nests relocated to corrals		#1	
Number of nests relocated to incubation facility			
Location of nests relative to artificial lights		#2	
Number of eggs$*$turtle^{-1}$*$clutch^{-1}			X
Number of eggs$*$turtle^{-1}$*$year^{-1}			X
Number of clutches$*$turtle^{-1}$*$year^{-1}			X
Number of tracks on nesting beach		#2	X
Number of nesting females observed		#2	X
Number of hatchlings produced in corrals		#1	X
Number of hatchlings produced *in situ*		#3	X
Number of hatchlings produced in incubation			X
Hatching success of nests incubated *in situ*		#1, #3	X
Hatching success of nests relocated to corrals		#1	X
Hatching success of nests relocated to			X
Hatchling orientation		#2	
Hatchling sex ratio		#1	
Number of remigrants nesting			X
Remigration interval (years)			X
Number of first time breeders nesting			X
Number of nests predated		#3	X
Number of predators removed	#3	#3	
Number of functioning corrals	#1		
Beach light levels	#2	#2	

	Monitoring Purpose		
	Construction	**Performance**	**Program-level**
Potential Monitoring Metrics	*Examples*	*Examples*	*Suggested*
In-water Variables			
Ageclass- and sex-specific foraging-ground abundance			X
Ageclass- and sex-specific survival probabilities			
Ageclass- and sex-specific dispersal			
Growth rate			
Age at sexual maturity			
Adult sex ratio			
Number of turtles counted at the surface		#5	X
Number of turtles counted underwater		#5	X
Number of turtles captured per unit effort		#5	X
Number of turtles killed per unit effort		#5	
Number of turtles stranded alive		#4	X
Number of turtles stranded alive, rehabilitated and not returned to the wild		#4	
Number of turtles stranded alive, rehabilitated and returned to the wild		#4	
Number of turtles stranded dead		#4	
Number of mortalities due to known causes			
Number of mortalities due to commercial and recreational fisheries			
Number of mortalities due to unknown causes			
Number of fishing vessels per fishery	#5		
Number of fishing vessels per fishery using bycatch reduction tools and/or methods			
Number of fishing vessels per fishery not using bycatch reduction tools and/or methods			
Ecosystem Services			
Existence value			
Wildlife watching			

SOURCES: Eckert et al., 1999; Ehrhart and Ogren, 1999; Schroeder and Murphy, 1999; Heppell et al., 2003; NRC, 2010; Bjorndal et al., 2011; DWH NRDA Trustees, 2016; Committee.

Monitoring Planning Considerations

Project planning prior to implementation is critical and involves defining project goals and specific measurable objectives as well as considering location, scope, timing, feasibility, data collection methods, and evaluation. Good practice is for projects to be located in areas where sea turtles occur and if possible, where long-term data are available to provide estimates of their abundance prior to project implementation. On land, documented nesting beaches with long-term projects already established provide the best opportunity for monitoring nesting females, eggs, and hatchlings. In the water, long-term monitoring and research projects already established provide the best opportunity for monitoring sea turtles at sea, however few exist. New in-water monitoring projects are designed to determine if restoration efforts on land and at sea (e.g., to reduce bycatch) are effectively enhancing the in-water life stages of sea turtles. These projects would benefit from initiation and location in documented sea turtle feeding grounds (e.g., seagrass patches or beds for juvenile turtles) and/or migratory corridors, and in areas where turtles are regularly captured in recreational fisheries (e.g., hook and line fishing). Good practice is for projects that will monitor incidental capture of sea turtles in commercial fisheries to be located on relevant vessels, and at a sufficient level of observer effort, in the fisheries that are known to interact with sea turtles. Coordinated data collection among all projects on land and in water is critical to ensure the relevant data are collected and that data collection methods are standardized among sites.

Construction Monitoring. Monitoring to determine if project activities are being implemented according to initial direction, requirements, and standards is fairly straight-forward and considered good practice for all types of planned sea turtle restoration projects. The type of monitoring, parameters measured, and timeframe for construction monitoring will vary according to the project activity and objectives. For example, if corrals will be constructed to protect sea turtle eggs, then construction monitoring might entail measuring the post-construction amount of beach protected, the location of the corral relative to the high tide line, and the density of vegetation in the corral. For projects that will facilitate rapid response to episodic mass stranding events (potentially in coordination with marine mammal stranding response) and rely on the use of mobile and temporary shelter for sea turtles, Construction Monitoring will require design and construction of such units customized to the field environments in which they will be deployed.

Performance Monitoring. For sea turtle restoration, performance monitoring to determine the effectiveness of restoration to meet objectives requires measuring changes over time, and is a little more difficult and costly to undertake than construction monitoring. Project objectives may range from increasing hatchling recruitment by relocating eggs to a protected area to reducing disorientation of turtles by minimizing artificial lights on nesting beaches. These projects require a variety of measurements over relevant time and spatial scales and will vary according to the project type and objectives. There are numerous metrics routinely used on sea turtle nesting beaches and in the water to estimate sea turtle abundance. These range from visual counts of eggs, nests, hatchlings, turtle tracks, and individual nesting females on land to the capture of turtles in the water using nets (Eckert et al., 1999). A rigorous and robust sampling design requires repeated measurements over a sufficient time period that is scaled to the objectives of each specific project (see Chapter 3). Single project performance monitoring time-scales of multiple years can evaluate the impacts of restoration activities. Determining the effectiveness of restoration activities applied over multiple sea turtle restoration projects will take decades if current practices are used to assess sea turtle population status and trends, and it will not be possible to determine the relative contributions of individual projects to observed changes. It is possible, however, to identify population improvements by analyzing changes in age or size structure, as well as other population indices as recommended in the NRC (2010) report. Further metrics of sea turtle status and trends are described in Table II.5.

Much of the project-level baseline data are already available for sea turtle populations in the Gulf. For projects on land, long-term programs to monitor adult female Kemp's ridleys (*Lepidochelys kempii*), loggerhead (*Caretta caretta*), and green turtles (*Chelonia mydas*) at nesting beaches provide baseline information including direct counts of nesting females, or counts of their tracks and nests. There are also several in-water sea turtle projects in the Gulf of Mexico that can provide useful baseline data to assess sea turtle population trends. Consistency and standardization of methods used to collect data prior to project implementation enables comparison with data collected after implementation.

Monitoring for Adaptive Management. Monitoring for adaptive management may be achievable for certain types of individual projects. The feedback obtained from project monitoring can inform whether activities are achieving the intended project-specific goals and objectives. For example, projects to reduce hatchling disorientation on nesting beaches will monitor hatchling dispersal after artificial lights have been modified, and ideally compare this metric with baseline information to assess any change. If hatchling disorientation continues, additional management measures to further reduce artificial lights can be implemented and evaluated. Similarly, projects aimed at increasing hatchling recruitment by relocating eggs to corrals or controlling predators will monitor metrics such as hatchling abundance, production, and survival before and after restoration and/or compared to wild, unmanipulated nests to estimate the extent of change due to restoration at a population level, beyond individual nests. If hatchling production does not increase to meet stated objectives, then additional management measures to increase hatching success can be implemented if the causes for egg and/or hatchling mortality are understood.

Monitoring for Adaptive Management across multiple projects to determine if activities are restoring sea turtles in the Gulf of Mexico is possible despite the decision-critical uncertainties noted earlier, and the high uncertainty of key parameter values that limit the ability to fully interpret the changes in sea turtle population abundance. This will require significant planning, resources, and cooperation and communication among the multiple agencies with oversight for restoration.

In particular, more effective approaches for monitoring and assessing Gulf of Mexico sea turtle restoration activities will have to be used to overcome some of the key uncertainties in the system conceptual model and the limitations of current monitoring practices used to assess sea turtle status and trends. These approaches include

- monitoring sea turtles on nesting beaches (Schroeder and Murphy, 1999) and in the water (Ehrhart and Ogren, 1999);
- collecting more comprehensive data about reproduction and early survival, which have large effects on the variability in sea turtle abundance (Heppell et al., 2003);
- integrating demographic information with abundance estimates (NRC, 2010; Bjorndal et al., 2011);
- quantifying known threats (NRC, 2010); and
- using quantitative population models (NRC, 2010; Bjorndal et al., 2011).

To evaluate sea turtle trends in abundance and determine causes of population change and the relative effects of various restoration projects, further integration of quantitative population models with demographic information is needed (NRC, 2010; Bjorndal et al., 2011). Researchers already gather data from multiple sources and analyze them with the aim of finding correlations. This work would be enhanced by implementing the data management, stewardship, and sharing recommendations provided in Chapter 5, as well as further consideration of the interconnectedness and cause/effect relationships between various restoration and management actions and outcomes, as described in Chapter 6. Without these steps, it will be difficult to diagnose potential causes of population trends and determine the relative impacts of various restoration projects and approaches.

New Observing Technologies

New approaches to monitor sea turtle movement, habitat use, and behavior have been developed, are in limited use, and promise to overcome many of the key limitations of conventional methods used to track the distribution and abundance of highly mobile marine animals with life stages that are difficult to access. Conventional tracking methods rely on satellite or radio telemetry. Both methods are very expensive relative to the value of their outcomes, and rely on sea turtles spending time at the surface of the water in order to receive a signal, process it, and calculate an accurate location. Sea turtles spend very little time at the surface and as a result these conventional tracking methods do not provide robust information; location accuracy is estimated and error rates can be quite high (Plotkin, 1998). Underwater acoustic telemetry has been used to track sea turtles for more than two decades, but has never been in wide use because the cost of following turtles with mobile acoustic receivers in boats made this endeavor expensive and impractical.

New underwater acoustic technology using fixed acoustic arrays and buoys or mobile gliders provides a low cost alternative and is changing the way we study the oceans and manage marine resources. Acoustic transmitters are now available at a fraction of the cost they once were, are smaller, can be coded to identify individuals, have a long battery life (years), and there is no location error – a signal is either received or not received at a fixed location. This emerging technology can provide information on sea turtle movements and density (Blumenthal et al., 2009) and can also be used to measure vital rates important to sea turtle assessments (e.g., survivorship of juvenile life stages) that traditional monitoring methods are currently unable to estimate. The Gulf of Mexico Coastal Ocean Observing System[112] has a coordinated network of acoustic observing systems, infrastructure, and platforms that can be used to track sea turtles in the Gulf of Mexico and provides a viable opportunity to reduce cost constraints. Because the sample sizes possible from satellite and acoustic tagging are generally not large enough to determine vital rates, a potential option to estimate survival is introducing inexpensive mortality tags to mark and recapture sea turtles.

Example of How Monitoring Can Aid Sea Turtle Restoration

Monitoring and assessment of Kemp's ridley sea turtle (*Lepidochelys kempii*) abundance, based on the number of nests counted, illustrates the limitations of relying on just nesting beach monitoring to interpret population change. Kemp's ridley is a critically endangered species that breeds only in the Gulf of Mexico and spends the majority of its life cycle there. After the population dropped to a few hundred in 1985, restoration through protection of nesting beaches

[112] The Gulf of Mexico Coastal Ocean Observing System (GCOOS): http://gcoos.org/.

and new fishing technology and restrictions led to an increase in the number of Kemp's ridleys in Mexico and Texas, an expansion of their nesting range in the Gulf of Mexico, and exponential growth through 2009 to nearly 10,000 turtles (Heppell et al., 2007; Crowder and Heppell, 2011). However, because many of the key demographic parameters for Kemp's ridley are unknown, the relative contribution of each conservation action toward the species' increase in abundance is currently beyond our reach.

By 2010, a significant decline in the number of Kemp's ridley nests was detected at nesting beaches (Caillouet, 2014; Plotkin and Bernardo, 2014) and the number of nests has fluctuated since then. Demographic model predictions had forecast population growth at an estimated rate of 19 percent per year during 2010-2020, assuming survival rates within each life stage remained constant and egg-to-hatchling survival rate remained high (NMFS et al., 2011). Instead, the population's pre-2010 exponential growth was interrupted (Caillouet, 2010, 2011, 2014; Crowder and Heppell, 2011; Gallaway et al., in press). Monitoring nesting Kemp's ridleys for more than 30 years was critical to obtain abundance estimates for the species and detect the increase from the 1990s to 2010, largely due to beach protection and increased survivorship to maturity, likely through gear improvements that have reduced bycatch. However, the absence of basic demographic information has prevented analysis of the specific actions that led to the root cause of the fluctuation in nest numbers since 2010 (i.e., reproductive output of nesting females).

MARINE MAMMAL RESTORATION MONITORING

Why Restore Marine Mammals?

Marine mammals in the Gulf of Mexico are highly valued by the public, and have been adversely affected by the cumulative impacts of human activities over the past 50 years, with large die-offs receiving considerable public attention (Vollmer and Rosel, 2013). Mortality, reduced reproductive rates, and poor health of individuals have been observed over this timeframe (Litz et al., 2014). The DWH oil spill resulted in further mortality, organ damage, immunosuppression, and decreased reproduction for a number of species of marine mammals (Schwacke et al., 2014; Lane et al., 2015). The disaster also damaged habitat for prey, thus limiting food availability and exacerbating the physical and toxic effects of oil and dispersants. As marine mammals are long-lived, slow to reproduce, and are apex predators, impacts of the spill are likely to continue even as restoration activities are started. Due to the ecological diversity of the marine mammal species and stocks in the Gulf of Mexico, impacts of the spill on these stocks are varied, with the most severe injuries documented in stocks with ranges overlapping the DWH oil spill footprint and accessible to study, especially coastal bottlenose dolphin stocks from Barataria Bay and Mississippi Sound (Schwacke et al., 2014). Offshore large whales have been harder to study, but estimates of mortality reached 17 percent of the Bryde's whale population and 6 percent of the sperm whale population (DWH MMIQT, 2015).

Restoration Objectives

Considering the variation in range and behavior of the many species of whales, dolphins, and manatees living in the Gulf of Mexico, restoration activities will differentially affect different marine mammal stocks. This consideration increases the logistical challenge of documenting effects of restoration for many offshore species, with the notable exception of coastal bottlenose dolphins. Restoration projects in the Gulf of Mexico will aim to recover marine mammal populations by enhancing habitat, by reducing stressors known to cause morbidity (reduced fitness and illness) and mortality, and by addressing direct human-caused threats. These projects will address the following objectives under two overarching goals:

A. Restore healthy populations of marine mammals through habitat improvement and mitigation of key stressors by

- enhancing habitat for prey,
- reducing pollution of coastal waters,
- decreasing anoxic zones and harmful algal blooms,
- decreasing and/or mitigating interactions with commercial and recreational fishing,
- reducing illegal feeding and harassment,
- reducing noise impacts, and
- reducing vessel collisions; and

B. Improve the understanding of impacts to marine mammal populations by external stressors to inform adaptive management by

- enhancing stranding network capabilities,
- enhancing stock assessments, and
- ensuring restoration activities aimed at enhancing recreational and economic resources, or restoring coastal habitat through sediment and hydrologic diversions do not adversely impact marine mammals.

Examples of common restoration objectives are provided in Table II.6, including rehabilitating healthy populations by reducing illegal feeding of dolphins, improving coastal habitat (which may affect coastal dolphins), and reducing noise from dredging activities. Table II.6 also lists a set of metrics (described below) that may help assess progress towards these objectives in many cases, and depending on the relevant monitoring purpose (note that example metrics to support monitoring for adaptive management are not included because of their inherent project/program-specificity).

Decision-critical Uncertainties

Marine mammal species in the Gulf of Mexico vary ecologically, from coastal residents that feed on local prey, to offshore pelagic and migratory species that may feed on prey from outside the Gulf. Marine mammals are long-lived and slow to reach reproductive maturity, and as the effects of oil on health may be exerted on second generation individuals, effects of oil exposure during the DWH spill may still be occurring at the same time as effects of restoration activities a decade later. Although the release of oil during the DWH spill was mostly offshore in deep water, most restoration activities are coastal. Impacts of restoration activities thus may act on marine mammals at different temporal and spatial scales from the activity itself. In addition, many restoration activities could have cumulative impacts on marine mammals by affecting different stressors that act synergistically on marine mammal health. Understanding the effects of restoration activities relative to the continuing impacts of an oil spill requires carefully designed monitoring that may be best addressed in the context of an adaptive management program.

For some marine mammal species and stocks in the Gulf of Mexico, baseline (pre-spill) data on population size, reproductive rates, and seasonal distribution of animals are poorly known (Waring et al., 2015). For other stocks, especially coastal bottlenose dolphins, these data are available, as well as more detailed information on health and causes of death and morbidity. Unusual mortality events involving hundreds of dead marine mammals washing ashore have occurred over the last 20 years, with multiple factors including fresh water inflow, viral epidemics, harmful algal blooms (HABs), and the DWH oil spill contributing to death of these animals (Schwacke et al., 2010; Carmichael et al., 2012, Litz et al., 2014; Venn-Watson et al., 2015). The relative importance of each factor in some years is unclear, as these factors can be synergistic. HABs can cause immunosuppression, increasing susceptibility to infectious disease. Some infectious diseases predispose animals to other diseases, and changes in prey distribution and/or water temperature can alter marine mammal distribution, and thus exposure to HABS. Many of these factors can increase the likelihood to strand. Understanding the complexity of these interactions (see Figure II.6) will require extensive evaluation of health and stranding data throughout restoration activities, concurrent with the evaluation of stressors, to enable adaptive management and effective restoration of marine mammal populations.

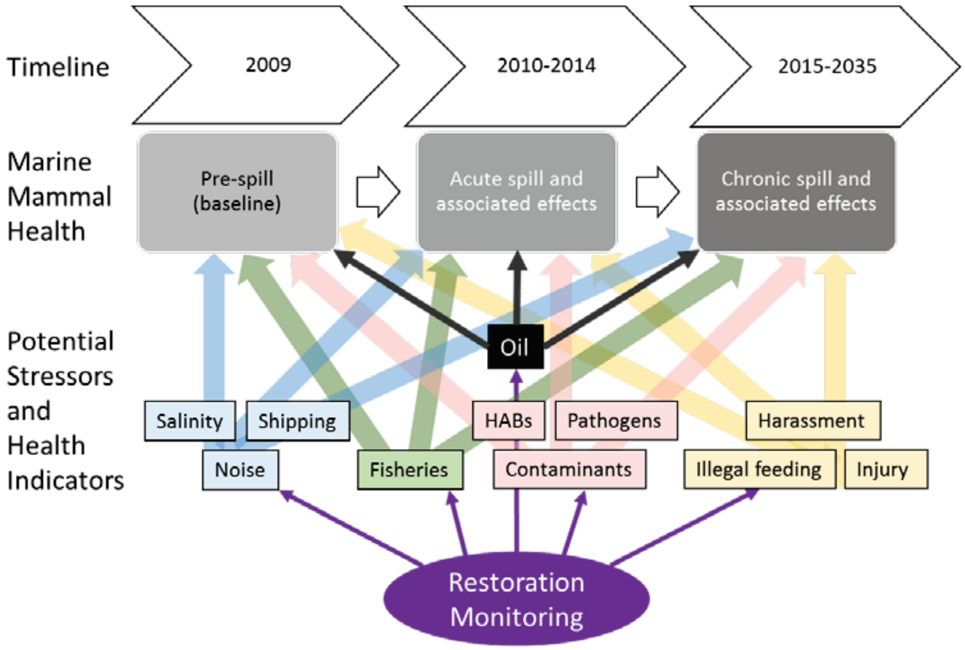

Figure II.6 Schematic model of baseline, acute, and chronic influences on marine mammal health from an oil spill. Note that this diagram is missing speculative elements that would benefit from future research, including the effects of dispersants on marine mammals. Also note that the baseline conditions shown here usually do not account for microbial ecology, which is an important area of future research. SOURCE: Committee.

Project-level Monitoring and Assessment Plan Considerations

Information Needs Based on Monitoring Purpose and Project Objectives

As defined in Part I of this report, the three primary purposes of restoration monitoring include (1) assuring projects are built and are initially functioning as designed (*construction monitoring*); (2) assessing whether restoration goals and objectives have been or are being met (*performance monitoring*); and (3) informing restoration management, improving design of future restoration efforts, and increasing ecosystem understanding (*monitoring for adaptive management*). Restoration activities specifically designed to restore marine mammal populations will be monitored using a combination of construction and performance monitoring (see Table II.6). In addition, monitoring for adaptive management is needed to help reduce uncertainties and guide management decisions, given the limited experience implementing restoration for marine mammals. Furthermore, although many restoration activities that are executed with entirely different objectives will not aim to restore marine mammals, they may influence ecosystem parameters or stressors that in turn affect these species (see Box II.3).

Box II.3

Interactions Among Restoration Activities

Some restoration activities have the potential to benefit marine mammals through habitat and water quality enhancements and the restoration of submerged aquatic vegetation, thus replenishing prey. However, activities guided by other objectives may adversely affect marine mammals, such as hydrologic diversions that intend to reduce salinity in coastal areas, but inadvertently affect skin health and electrolyte balance of dolphins (Wilson et al., 1999) or affect the distribution of dolphin prey (Barros and Odell, 1990). Dredging to remove contaminated sediments can temporarily re-suspend pollutants into the water column, where they may be ingested by marine mammal prey (Martins et al., 2012), and re-suspended nutrients can exacerbate or contribute to the development of harmful algal blooms (Van Dolah, 2000). Disturbance from construction activities and associated vessel traffic can increase sound levels and disrupt marine mammal foraging, habitat use, daily or migratory movements, and behavior (Nowacek et al., 2001). Dredging has been shown to displace bottlenose dolphins (Pirotta et al., 2013), and increased vessel traffic increases the risk of vessel strikes (Laist et al., 2001; Bechdel et al., 2009). See Table 4.1 for other examples of unintended potential consequences of unrelated restoration activities.

An integrated and coordinated approach to monitoring marine mammals in the Gulf is needed to determine how they are affected by restoration activities operating under a variety of objectives, rather than only those activities targeting marine mammals specifically, in an ecosystem that is impacted continually by multiple stressors. This effort will depend upon a synthetic data management system that integrates monitoring data from different sources and projects (see Chapter 4). Collaborative, consistent, comparable, and standardized data collection and analysis is important, due to the long time-scale of the data series and the multiple collectors. Investment in marine mammal data management beyond existing levels will enable these considerations, so that synthesis of the effects of restoration projects on marine mammals can be effective (see Chapter 5), and performance of projects can be refined to ensure enhancement of marine mammal populations (see Chapter 6).

Construction Monitoring. Construction monitoring is needed to determine whether a particular project was implemented as designed, such as monitoring enforcement, fisheries bycatch observer effort, and compliance with state and federal laws protecting marine mammals. Ready access to data on the status of other restoration projects not aimed specifically at marine mammal restoration, but likely to affect marine mammals (e.g., through salinity changes, dredging activity, noise), is also needed.

Performance Monitoring. Performance of restoration activities for marine mammals will be monitored by quantifying parameters such as abundance, distribution, and health, as well as the key stressors that impact these factors (e.g., salinity, prey abundance, shipping activity, noise, HABs, direct human actions such as illegal feeding, sport killing, and fisheries bycatch) (Vollmer and Rosel, 2013). The extent to which each of these factors can be measured will vary among marine mammal stocks, due to differences in accessibility and logistical challenges. It is good practice to determine impacts on population abundance for all species and stocks broadly using coordinated ship-based and aerial surveys and passive acoustic monitoring. Ideally, each stock abundance would be determined at least every two years, and opportunities to coordinate with sea turtle surveys would be investigated.

Monitoring for Adaptive Management. Data obtained from the marine mammal stranding network on marine mammal health and causes of morbidity and mortality can be synthesized to aid adaptive management (see Table 4.1). For example, if changes in dolphin skin health resembling those typically caused by changes in salinity were detected in association with restoration projects that are known to affect the salinity of dolphin habitat, a likely link could be determined. NOAA Fisheries Service's Marine Mammal Health and Stranding Response Program manages responses to stranded cetaceans and evaluates their health and health trends; correlates health and trend data with biological, physical, and chemical environmental parameters; and coordinates responses to unusual mortality events. The Manatee Salvage and Necropsy Program at the Florida Fish and Wildlife Research Institute supports efforts to salvage and necropsy Florida manatees throughout their range, including animals that strand outside the state of Florida, and monitors trends in manatee mortality. The U.S. Fish and Wildlife Service also responds to calls about injured and distressed manatees throughout the southeastern United States. Archiving these diverse data in an integrated database will allow sharing and synthesis from multiple sources so that data can be synthesized to produce population abundance, distribution, and health estimates. Such a database will require considerable investment and management, yet would ensure maximal benefit to marine mammal population restoration from executed projects.

Choose Suitable Metrics

Abundance. Abundance of marine mammal stocks (21 species and 56 stocks of marine mammals occur within the Gulf of Mexico) is mostly determined through ship-based and aerial surveys, which in the Gulf are performed and coordinated by NOAA Fisheries Service through the Stock Assessment Reports[113] (Waring et al., 2015). The Fisheries Service has validated different survey techniques (aerial and ship-based line transects, mark-recapture techniques using photographs and biopsies, passive acoustic monitoring) and modeling methodologies, as the lead agency in coordinating abundance estimates of marine mammals in the Gulf (Fulling et al., 2003; Hubard et al., 2004). However, current federal resources to support abundance estimates are inconsistent and would benefit from augmentation to ensure more extensive and consistent spatial and temporal coverage of abundance estimates. As small-scale restoration projects will not likely have the ability to perform marine mammal abundance surveys, a program to which small projects or project coordinating agencies can contribute resources, would be beneficial. Data from federal, state, private, and academic institutions that can augment abundance estimates (e.g., photo-identification data, acoustic monitoring, movements) would benefit from integration by NOAA Fisheries Service with investments in data management and synthesis. Good practice is to continue monitoring abundance for at least two marine mammal generation times, which for some large whales is 70 years (Thomas et al., 2015).

In addition to abundance, data to inform stock structure are needed (e.g., genetics, movements) to improve characterization of stocks beyond current knowledge of coastal bottlenose dolphin stock structure (Sellas et al., 2005). These can be obtained through biopsy,

[113] NOAA Stock Assessment Reports: http://www.nmfs.noaa.gov/pr/sars/species.htm.

photo-identification, tagging, and passive acoustic monitoring (Wells and Scott 1990). A unique lineage of Bryde's whale, for example, was only recently characterized (Rosel and Wilcox, 2014). As mortality of this population following DWH was estimated at 17 percent, and these animals are affected by human activities such as noise, ship strikes, and fisheries interactions, their designation as a discrete stock can affect these activities if mortality exceeds permissible unintentional human-induced mortality for the stock.[114]

Distribution. Distribution data informs spatial planning tools, such as habitat use mapping, so spatial adaptive management approaches can be used during restoration activities. Data on marine mammal distribution can be obtained through direct observation from vessels and airplanes; acoustic monitoring of produced sounds by acoustic buoys, bottom-mounted acoustic units, towed arrays, and glider mounted devices; and tagging of animals with radio and satellite-linked telemetry devices (Hansen et al,. 1996; Garrison et al., 2002; MMC, 2011; Hildebrand et al., 2015). Different approaches are needed for different species, due to variations in accessibility, movement, and availability of baseline data. Frequency of monitoring will depend upon the monitoring tool(s) used, and the species to be assessed, but need to obtain data on species distribution at least biennially (see Chapter 3 for general good practices on monitoring scale and frequency). Tagging of representative offshore species, such as sperm whales at sites with differing degrees of anthropogenic activity, would be a useful approach to monitoring as some baseline data exist for this species (Jochens et al., 2008; McConnell et al., 2010). Passive acoustic monitoring is useful for gathering data on recovery of deep diving offshore species (Hildebrand et al., 2015). Integrating data into a Gulf-wide database including other environmental parameters and stressors that influence marine mammal distribution, such as the Gulf of Mexico Coastal Ocean Observing System (GCOOS), would be beneficial. Data on distribution can be combined with habitat use and stressor information to generate fine scale habitat use models that can guide management and restoration activities.

Health. Monitoring health of marine mammals focuses on monitoring representative populations at index sites for which baseline data exist and logistically feasible techniques have been developed. Animals that are most likely to be affected by perturbations resulting from restoration activities, as well as other stressors, are logical subjects for health monitoring. Coastal bottlenose dolphins, especially the Barataria Bay and Mississippi Sound populations, meet these criteria and were used by NOAA to assess the damage to natural resources from the DWH spill. Representative populations' health is monitored through photography, remote biopsy, and live capture-sampling-release programs that include clinical evaluations, life history assessments, and sample collection. Samples can be evaluated for specific health parameters and measures of organ function, and individual animals given health scores using predetermined suites of parameters (Schwacke et al., 2014). Good practice is to monitor dolphins that include a coastal population at a restoration site (e.g., Barataria Bay, Mississippi Sound) and a population at a site within the Gulf unaffected by the spill or restoration projects (e.g., Sarasota Bay). Sampling for health monitoring ought to be performed annually at reference sites.

Changes in health may also be detected through surveillance of stranded animals. The stranding network is also vital to monitoring efficacy of restoration projects to reduce marine mammal bycatch and interaction rates with fishing gear (Byrd et al., 2008, 2014). Enhancing the

[114] See NOAA Fisheries Stock Assessment reports and Potential Biological Removal process: http://www.nmfs.noaa.gov/pr/sars/.

stranding network throughout the Gulf of Mexico (potentially in coordination with sea turtle stranding response operations) would result in standardized detection, monitoring, sampling, and reporting systems, as well as data integration through GCOOS with information such as water quality and harmful algal blooms. This would allow data on marine mammal health and abundance to inform managers of effects of restoration activities (positive or negative) on marine mammal populations, and thus guide future restoration project planning to optimize marine mammal restoration (see Table II.6). Data collection by the stranding network ought to be continual, with real time reporting to managers.

Table II.6 Metrics considered good practice to monitor marine mammal restoration activities for construction, performance toward project objectives, and program-level or large-scale assessments.

NOTES: Examples are provided to illustrate linkages between restoration situations/objectives and appropriate metrics. Example #1 (linkages shown in the table by “#1”) is to reduce illegal feeding of dolphins; Example #2 is to improve coastal habitat; and Example #3 is to control noise from dredging. The “X” symbol indicates metrics that are suggested by the Committee as appropriate to sample across multiple projects at a program, region, or Gulf-wide scale.

	Monitoring Purpose		
	Construction	Performance	Program-level
Potential Monitoring Metrics	*Examples*	*Examples*	*Suggested*
Habitat			
Map of animal distributions (transect observations, biologging tag coordinates, GPS photo identification, passive acoustic monitoring, stranded animal location)	#1, #2, #3	#1, #2, #3	X
Location and timing of extractive activities			X
Location and timing of recreational activities	#1	#1	X
Location and timing of construction activities	#3	#3	X
Date and location of possibly interacting management activities		#2, #3	X
Oceanographic Conditions			
Salinity	#2	#2	X
Calibrated noise measurements with GPS coordinates of recorders and times	#3	#3	
Weather (fog, glare, visibility)			
Sea state			
Tidal state			
Water depth			
Biotoxin concentration			
Number of boats illegally feeding animals	#1	#1	
Fauna			
Abundance and distribution (counted or estimated)		#2	X
Photographs of coastal dolphins		#2	
Species composition			
Group size			
Age/size/gender categories			
Biopsies of coastal dolphins		#2	
Health assessment of live-capture-released coastal dolphins or manatees	#2	#2	X
Number of stranded dolphins with fresh water skin lesions	#2	#2	
Number of injured dolphins, whales, or manatees (photo-IDs)		#1	
Number of stranded dolphins, whales, or manatees	#2	#1	X
Number of harassed individuals			
Number of individuals taken/killed			
Behavior patterns (possibly extrapolated from distribution information)			
Ecosystem Services			
Existence value			
Wildlife watching			

SOURCES: Wells and Scott, 1990; Hansen et al., 1996; Garrison et al., 2002; Mullin and Fullin, 2004; Wells et al., 2004; Torres et al., 2005; ION, 2012; Navy, 2012.

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APPENDIX A

COMMITTEE AND STAFF BIOGRAPHIES

Committee

Frank W. Davis (*Chair*) is Director of the National Center for Ecological Analysis and Synthesis and Professor of Landscape Ecology and Conservation Planning at the Bren School of Environmental Science and Management, University of California, Santa Barbara. He brings conservation science and geographical analysis to bear in land use planning and the conservation of wild species. Dr. Davis heads the Biogeography Lab at the Bren School, and his research focuses on the landscape ecology of California plant communities, the design of protected-area networks, rangeland and farmland conservation, and the biological implications of regional climate change. He has received several honors and awards including the Aldo Leopold Leadership Fellow and Fellow of the American Association for the Advancement of Science. Dr. Davis has previously chaired the National Research Council (NRC) Committee on Independent Scientific Review of Everglades Restoration Progress and served as a member on numerous NRC committees. He received a PhD in Geography and Environmental Engineering from The Johns Hopkins University, and a BA in Biology from Williams College.

David M. Burdick is the Interim Director of the Jackson Estuarine Laboratory and Research Associate Professor of Coastal Ecology and Restoration in the Department of Natural Resources and the Environment, University of New Hampshire. His research focuses on ecology and management of coastal wetlands, and design, implementation, and assessment of habitat restoration. Dr. Burdick places emphasis on understanding how tidal wetlands play invaluable roles in supporting marine ecosystems and coastal populations. He is interested in the functions of tidal habitats, how plants respond to stresses (flooding, salinity, pollution, disease, invasive species, and human alterations), and how plants interact with physical processes to maintain these habitats. Dr. Burdick received his PhD in Marine Sciences from Louisiana State University and a BS in Chemistry from Hobart College.

Loren Coen is an Affiliate Research Professor and Scientist in the Department of Biological Sciences and Harbor Branch Oceanographic Institute, at Florida Atlantic University. Dr. Coen has worked for over 30 years on the eastern seaboard of the US, in the Gulf of Mexico, and in the Caribbean Sea on marine and estuarine ecosystems and their associated habitats (marshes, submerged aquatic vegetation, mangroves, and oyster reefs). He is a marine ecologist with a broad range of expertise in marine ecology (especially on bivalves) and related restoration. His recent research includes studies on oyster reef ecology, related habitat mapping, and restoration. Past research includes seagrass-bivalve interactions in the Gulf of Mexico, coral reef ecology in Belize focusing on plant-animal interactions, restoration ecology including sampling of oyster reef habitats, work on the ecological value of estuarine habitats as nurseries for various species including parallels of shellfish aquaculture with natural systems, assessing non-native species 'introductions' in U.S. waters, and large-scale habitat mapping efforts directing teams with diverse backgrounds. In 2011, he served on an IUCN (International Union for Conservation of Nature) workshop to assess the conservation status of the world's habitat-forming bivalves for inclusion on the IUCN Red List of Threatened Species. Its primary goal was to bring together regional and international scientific experts to assess the global extinction risk of individual species of the *Ostreidae* and *Mytilidae* families. This work marked the initial appearance of these important marine species on the Red List. He also organized one of the first restoration workshops (and a dedicated website) as part of the effort to develop standardized methods and related goals and success criteria for restoration efforts with a focus on ecosystem services, and has been involved on the steering committee with nearly all of the ICSR (International Conference on Shellfish Restoration) conferences since its inception in 1996. He coauthored recent studies on the status of shellfish habitats across the US and globally and a handbook related to assessing oyster habitat restoration. He is currently a member of the National Shellfisheries Association and the Coastal and Estuarine Research Federation.

Peter Doering is currently a Section Administrator in the Applied Sciences Bureau at the South Florida Water Management District where he leads a team of estuarine scientists and modelers. The goal of their work is to quantify the responses of estuarine ecosystems to changes in the quality and quantity of freshwater inflow. The results support comprehensive water resources management and are specifically applied to the development of Minimum Flows and Levels, Water Reservations, Total Maximum Daily Loads, Lake Regulation Schedules, and the design and evaluation of Everglades restoration projects. Prior to this appointment he served as the district-wide expert on estuarine ecology. Dr. Doering has published extensively in the areas of water quality and water management as it impacts estuarine restoration efforts. He received a PhD in Biological Oceanography from the University of Rhode Island.

Frances Gulland is the Senior Scientist at The Marine Mammal Center. She has provided medical care for thousands of seals and sea lions, has published over 100 peer-reviewed articles, and is coeditor of the CRC Handbook of Marine Mammal Medicine. She chaired the Working Group on Marine Mammal Unusual Mortality Events for six years, has a lead role on recovery teams for the Hawaiian monk seal and southern sea otter, and is a member of the committee of scientific advisors to the Marine Mammal Commission. Dr. Gulland was sworn in as one of three Commissioners, U.S. Marine Mammal Commission, to serve the federal government with a focus on the protection and conservation of marine mammals. She served as a committee member on the NRC study entitled Alaska Groundfish Fishery and Stellar Sea Lions. She holds a DVM and PhD from the University of Cambridge.

Kenneth L. Heck, Jr. is a Senior Marine Scientist and Professor at the University of South Alabama and Chief Marine Scientist and Chair of University Programs at the Dauphin Island Sea Laboratory. His research efforts focus on ecological studies of seagrasses and seagrass-associated macrofauna, especially shrimps, crabs, and fishes. Dr. Heck's current studies include assessments of seagrass nursery value, investigations of herbivory, and the direct and indirect effects of nutrients and predator removal as they influence seagrass meadows. Furthermore, his work includes seagrass restoration projects and the evaluation of restoration efforts. He carries out both laboratory and field studies of seagrass-dominated ecosystems at the population and community levels, and employs a team approach to problem solving. Goals are to better understand the relative importance of physical-chemical and biological factors as they influence the health of seagrass meadows, as well as an increased understanding of how such high levels of plant and animal productivity are sustained in seagrass ecosystems. Dr. Heck received a PhD from Florida State University.

Matthew K. Howard is a Research Scientist in the Department of Oceanography at Texas A&M University in College Station, TX. He is a physical oceanographer with 40 years of experience and training. His interests include data management, informatics, and interoperability. He has been involved with the U.S. Integrated Ocean Observing System (IOOS) since 1998 as well as its precursors, and served on their Data Management and Communication Steering and Quality Assurance of Real-Time Oceanographic Data Program Advisory Teams. He is a member of the Marine Metadata Interoperability Executive Team. He is currently the Data Manager for the Gulf of Mexico Coastal Ocean Observing System and a Principal Investigator in the Gulf of Mexico Research Initiative Information and Data Cooperative. He has been the principal data manager for some of the largest field experiments conducted in the Gulf of Mexico including LATEX, NEGOM, and the MCH Hypoxia surveys. Recently he has become active in Gulf of Mexico glider deployments in support of hypoxia studies. He holds a PhD in Physical Oceanography from Texas A&M University.

Michael S. Kearney is Professor in the Department of Environmental Science and Technology at the University of Maryland. His areas of specialization include coastal marsh processes and rates of marsh loss, sea level rise, barrier island dynamics, and applications of remote sensing to the study of coastal processes and land use change. He has published extensively on impacts of sea level rise, climate, and land use change as they relate to both the Atlantic and Gulf of Mexico coastal processes. Dr. Kearney received an MA in Quaternary Studies/Geomorphology from Western Illinois University and a PhD in Paleoclimatology/Environmental Reconstruction from The University of Western Ontario.

Paul Montagna is Endowed Chair for Ecosystem Studies and Modeling at the Harte Research Institute for Gulf of Mexico Studies, Texas A&M University Corpus Christi. He received an MS from Northeastern University and a PhD from the University of South Carolina. His research is on how organisms control and regulate marine ecosystems and coastal environments. For the past 30 years, he has performed monitoring studies on bottom-living organisms and various attributes of water and sediment quality in Gulf of Mexico estuaries, continental shelves, and the deep-sea. This work is critical in guiding resource management decisions through his studies of environmental flows, nutrients, hypoxia, acidification, and oil and gas activities.

Pamela Plotkin is Director for Sea Grant Texas at Texas A&M University. She is a broadly trained marine scientist who has spent most of her career conducting science to inform and influence domestic and international policies and conservation practices. She has a deep understanding of policies related to sea turtle conservation and restoration in the Gulf of Mexico and in the Pacific. She also has led administrative teams at three different institutions of higher education in research administration, development, and support. Her early research career focused on the feeding ecology of loggerhead sea turtles in the Gulf of Mexico, which led to the discovery of their feeding grounds and a previously undescribed benthic community located in nearshore waters of the South Texas coast. During this time, she also worked at the University of Texas Marine Science Institute, where she studied marine pollution and its impact on marine organisms, and worked as a research assistant in the physical oceanography program during research cruises in the Gulf of Mexico. She holds a BS in Wildlife Science from Pennsylvania State University and an MS and PhD in Zoology from Texas A&M University.

Kenneth A. Rose is the Associate Dean of Research in the School of the Coast and Environment and Professor, Department of Oceanography and Coastal Sciences at Louisiana State University. His current research is focused on modeling population dynamics of fish and aquatic food webs, and how they respond to a variety of types of stressors including changes in water flows and quality, lethal and sub-lethal effects of contaminants, hypoxia, alteration of physical habitat, and climate change. Dr. Rose has wide experience using a variety of types of monitoring data for evaluating restoration actions, their use in adaptive management, and as part of developing and testing ecological models. He recently published a model of the population dynamics of the delta smelt, which is a listed species in the California Delta that is the center of controversy about how much water can be pumped out of the system for irrigation and water supply. He has also published on lower trophic level (algae and micro and macro zooplankton) food web dynamics. Dr. Rose was a member of review teams for several biological opinions involving delta smelt and salmon. He has served on two NRC committees, including the Committee on Sustainable Water and Environmental Management in the California Bay-Delta that evaluated the mitigation and conservation actions of biological opinions and the science underlying the short-term and long-term environmental and water usage decision-making of the system. He received a BS from State University of New York, Albany and an MS and PhD in Fisheries Science from the University of Washington.

Eric P. Smith is a Professor and Department Head in the Department of Statistics at the Virginia Polytechnic Institute and State University. His research interests include: multivariate analysis and graphics, biological sampling and modeling, ecotoxicology, data analytics, and visualization. Dr. Smith previously served as a member of the National Research Council Committee to Review and Evaluate the Department of Interior's Biomonitoring of Environmental Status and Trends Program. He has received many awards and honors, namely being elected as a member of the International Statistics Institute and as a fellow of the American Statistical Association. Dr. Smith received his MS and PhD in biomathematics from the University of Washington.

Heather M. Tallis is Lead Scientist at The Nature Conservancy. She founded and directs the organization's Human Dimensions Program (HDP), an initiative to bring human well-being considerations into conservation practice from the planning stage forward. HDP advances the use of ecological, social and economic sciences in conservation and natural resource decision-making. Heather's current scientific inquiries focus on understanding hidden connections between nature and people, with specific focus on how classroom views affect learning, how individuals can have the greatest impact on water consumption, and how natural resource management affects time use and poverty. Heather has led the development of open source software tools used broadly by governments and non-government groups to account for nature's benefits in environmental impact assessment, national accounting, land use planning, payment for ecosystem service design, and monitoring. She received an MS in Chemical Oceanography from the University of California, Santa Cruz, an MS in Marine Ecology from the University of Otago in New Zealand, and a PhD in Zoology from the University of Washington.

Ronald Thom is Staff Scientist at the Pacific Northwest National Laboratory. Additionally, he is an Affiliate Associate Professor in the School of Aquatic and Fisheries Sciences at the University of Washington. His research includes coastal ecosystem restoration, adaptive management of restored systems, effects of pollution, benthic primary production, climate change, and ecology of fisheries resources. He has worked on programs in systems in California, Washington, Oregon, Alaska, Massachusetts, New York, Nebraska, Alabama, and the Gulf of Mexico. Over his 43-year professional career, Ron has directed approximately 200 multidisciplinary ecological studies. He has published five book chapters, over 60 peer reviewed journal articles, hundreds of reports, made hundreds of professional presentations, and served on numerous professional committees. From 1985-1989 he chaired the Technical Advisory Committee of the Puget Sound Estuary Program. In 2009, Ron was appointed to serve on the Science Team that will guide research conducted by the Northwest Straits Commission, and in 2014 he was appointed to the Commission. Because of the growing international reputation of Ron and his group, he was invited to present a keynote address on Coastal Ecosystem Restoration in South Korea in June 2009. Based on this presentation and discussions with Korean scientists and federal agency officials, he was invited to formulate a research collaboration agreement with Inha University and Chungnam University, South Korea to focus on an ecosystem restoration program for that county. In 2010, he led the development and signed a Memorandum of Cooperation for joint research in coastal restoration between PNNL and East China Normal University, State Key Laboratory of Estuarine & Coastal Research in Shanghai, China. Ron was elected to the Washington State Academy of Sciences in 2010, and presently serves as a member of the Board of Directors of the Academy. He was selected to Chair the upcoming 2015 Coastal and Estuarine Research Federation (CERF) Conference. He received a BS in Biological Sciences from California State College, an MS in Marine Algal Ecology from California State University, and a PhD in Fisheries from the University of Washington.

Mark S. Woodrey is a Coastal Ecologist at the Mississippi State University Coastal Research and Extension Center. He also serves as the Research Coordinator at the NOAA/Mississippi Department of Marine Resources Grand Bay National Estuarine Research Reserve in Moss Point, Mississippi, where he manages a monitoring program to assess restoration efforts in the estuarine reserve. Mark has extensive background developing monitoring programs and conducting avian conservation biology research. In addition to his recent focus on marsh bird research, he has studied a variety of bird groups including intercontinental landbird migrants, winter forest birds, colonial beach-nesting birds, grassland birds, and breeding birds of bottomland hardwood forests. He now coordinates the Grand Bay NERR's System-wide Monitoring Program, a national standardized water quality and meteorological monitoring effort, and is involved in collaborative research projects focused on the ecology of estuarine fishes, effects of prescribed fire and sea-level rise on coastal plant and animal communities, levels of mercury contamination in estuaries, and the nesting ecology of diamondback terrapins. The main goal of his research is to better understand the ecological relationships between coastal flora and fauna to facilitate the informed and effective management and conservation of coastal ecosystems along the northern Gulf of Mexico. He received his PhD in Biology from the University of Southern Mississippi.

Staff

Claudia Mengelt is a senior program officer with the Ocean Studies Board. She joined the full-time staff of the National Academies of Science, Engineering, and Medicine in 2005. While with the Academies, she has led several climate change studies including the Analysis of Global Change Assessments (2007) and Adapting to the Impacts of Climate Change (2010). She has also conducted several programmatic reviews such as Strategic Guidance for the NSF's Support of Atmospheric Sciences (2007); Earth Observations from Space: The First 50 Years of Scientific Achievements (2007); Tsunami Warning and Preparedness (2010); and the review of the new National Ocean Acidification Research Plan (2012). Dr. Mengelt has also published a range of science policy articles related to climate change adaptation. She obtained her MS in Biological Oceanography from the College of Oceanic and Atmospheric Sciences at Oregon State University and her PhD in Marine Sciences from the University of California, Santa Barbara.

Stephanie E. Johnson is a senior program officer with the Water Science and Technology Board. Since joining the National Research Council in 2002, she has worked on a wide range of water-related studies, on topics such as desalination, wastewater reuse, contaminant source remediation, coal and uranium mining, coastal risk reduction, and ecosystem restoration. She has served as study director for over 15 committees, including the series of committees assessing Everglades restoration progress. Dr. Johnson received her BA in Chemistry and Geology from Vanderbilt University, and her MS and PhD in Environmental Sciences from the University of Virginia.

Heather Coleman is a Postdoctoral Fellow with the Ocean Studies Board and Board on Atmospheric Sciences and Climate. She graduated from UC Santa Barbara with a PhD in Environmental Science & Management after studying ecological and demographic effects of natural oil seeps on marine invertebrate populations. For her MA in Economics, she studied the history, politics, social dynamics, ecological effects, costs, and benefits of restoring the Golden Horn estuary in Istanbul. She has also researched the ecological effects of marine debris, oceanic biogeochemical cycling, invasive plant ecology, and coral reef community dynamics. Before joining the Academies, Heather aided marine conservation and resource use planning efforts with the Pacific Marine Analysis and Research Association (PacMARA). As PacMARA's Science and Policy Advisor, she led a program to inform marine planning and management in Canada and internationally by training government agencies, researchers, NGOs, industry groups, and stakeholders on technical and political aspects of marine spatial planning.

Payton Kulina joined the Ocean Studies Board in June 2013 as a Senior Program Assistant. He graduated from Dickinson College in 2010 receiving a BA in Policy Management. He is currently pursuing a MS degree in Finance through the Kogod School of Business at American University. Prior to this position, Payton worked as a coordinator with BP Alternative Energy, also in Washington, DC.

APPENDIX B

GLOSSARY

***Baseline**:* Information collected before or at the start of a given project that provides a basis for planning and/or evaluating subsequent progress and related impacts.

***Control**:* A site (or other entity) that is similar to the conditions of site/entity to be restored, before any restoration activities take place; similarity should be judged by parameters that are relevant to project objectives.

***Goal**:* High-level, strategic contribution of a program or endeavor.

***Example**:* A restoration *goal* may be to improve habitat in an area. An underlying *objective* could be to improve and maintain oxygenation levels adequate to sustain aquatic life within the next year. An appropriate *metric* could be measuring dissolved oxygen (DO) before restoration (*baseline*) and at *control*/*reference* site(s) every month at the restoration site. A reasonable *target* may be DO levels exceeding the chronic criterion for growth of 4.8 mg/L (EPA, 2000).

***Metric**:* Attributes used to measure the degree to which restoration action(s) meets a given target; performance metrics may be quantitative or qualitative.

***Objective**:* Concrete statement of the condition/state one expects restoration to achieve; the specific means of measuring progress towards a goal, along with clear timelines.

***Reference**:* A site (or other entity) that is similar to the desired future state of the site/entity to be restored, after restoration activities take place; similarity should be judged by parameters that are relevant to project objectives.

***Target**:* Expected value/level of a metric at a specified future point in time to evaluate progress; the standard against which actual results are compared and assessed.

Uncertainty: The term uncertainty as used in this report is comprised of different sources of uncertainty including a) "limited knowledge about underlying biological relationships [or processes] (structural uncertainty), sampling variation […] (partial observability), and uncontrolled variation [in the environment] (partial controllability)" (Williams et al., 1996)