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PERSPECTIVES

Assessing the Effectiveness of Large-Scale Environmental Restoration: Challenges and Opportunities

Holly S. Greening[1] · Kenneth L. Heck[2,3] · Larry D. McKinney[4] · Heida L. Diefenderfer[5,6] · Walter R. Boynton[7] · Barbara A. Kleiss[8] · Deepak R. Mishra[9] · Albert A. George II[10] · Bethany A. Carl Kraft[11] · Cathy A. Kling[12] · Laura A. Windecker[13]

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Abstract

A recent National Academies consensus report addresses monitoring and assessment of cumulative effects of large-scale and multiple restoration projects within the context of long-term environmental change. Fines and penalties from the *Deepwater Horizon* oil spill in the Gulf of Mexico (GoM) have supported hundreds of restoration projects at spatial scales not often possible in the past. Here, the report committee members and staff provide personal reflections from our time working on the study. We found that gaps in data collection, issues with data accessibility, and a lack of synthesis and analysis are hindering the ability to answer a basic question: What are the impacts of these many restoration efforts on improving ecosystem health and productivity in the GoM at the regional and Gulf wide scale? Restoration efforts are occurring in environments where many trends are changing and exhibiting higher variability than in the past, suggesting that previously successful restoration practices may no longer be adequate to compensate for the effects of environmental changes and variability. Our proposed approach to these challenges includes employing emerging monitoring technologies; using conceptual models; devising an adaptive management framework; rethinking restoration outcome goals; assessing cumulative effects; and undertaking rigorous synthesis and analysis of existing information on long-term environmental trends and restoration efforts. Restoration scientists and practitioners working in the GoM have an unprecedented opportunity to demonstrate large-scale environmental recovery if advances in monitoring, synthesis, assessment, and action are taken quickly. We are cautiously optimistic that, with mid-course adjustments, continued progress toward large-scale environmental recovery is possible.

Keywords Large-scale environmental restoration · Cumulative effects · Emerging monitoring techniques · Adaptive management · Synthesis · Coastal ecosystems · Gulf of Mexico

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✉ Holly S. Greening
hgreening@coastwisepartners.org

1 CoastWise Partners, Bradenton, FL 34211, USA

2 Dauphin Island Sea Lab, Dauphin Island, AL 36528, USA

3 School of Marine and Environmental Sciences, University of South Alabama, Mobile, AL 36688, USA

4 Harte Research Institute for Gulf of Mexico Studies, Texas A&M University, Corpus Christi, TX 78412, USA

5 Coastal Sciences Division, Pacific Northwest National Laboratory, Sequim, WA 98382, USA

6 School of Environmental and Forest Sciences, University of Washington, Seattle, WA 98195, USA

7 Chesapeake Biological Laboratory, University of Maryland Center for Environmental Science, Solomons, MD 20688, USA

8 Department of River–Coastal Science and Engineering, Tulane University, New Orleans, LA 70118, USA

9 Department of Geography, University of Georgia, Athens, GA 30602, USA

10 South Carolina Aquarium, Charleston, SC 29401, USA

11 National Audubon Society, Mobile, AL 36533, USA

12 Dyson School of Applied Economics and Management, Cornell University, Ithaca, NY 14850, USA

13 Meridian Institute, Washington, DC 20036, USA

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Table 1 Summary of recommendations from NASEM (2022). Full text available at https://doi.org/10.17226/26335

Recommendation	Summary
A: Long-term monitoring	Enhanced, consistent, and sustained long-term monitoring, analysis, synthesis, and reporting of environmental trends and indicators are urgently needed. The DWH funding entities should immediately evaluate methods, identify funding mechanisms, and lead efforts to coordinate long-term priority monitoring; promote consistent data collection, analysis, reporting, and accessibility among programs; support periodic assessments of collected data and assess the use of advanced techniques
B: Data accessibility	Restoration funding entities should require that, as soon as available, all data, reports, and other project-specific information are deposited in freely accessible repositories that follow FAIR (Findable, Accessible, Interoperable, Reusable) principles. The DWH funding entities should allocate resources to ensure that these data repositories remain functional throughout the life of each program, and additional support (as needed) should be sought to maintain data access in the future
C: Programmatic scale guidance	The DWH funding entities should expedite the issuance of guidelines for adaptive management and cumulative effects assessment at the programmatic scale for DWH-funded large-scale and multiple restoration efforts. Guidance should include consistency in monitoring criteria that facilitate cumulative effects assessment
D: Synthesis	The DWH funding entities should immediately initiate a synthesis of available information from their funded projects to assess characteristics of successful and unsuccessful restoration efforts. Results should be utilized in designing and implementing future large-scale projects and/or adjusting restoration approaches with remaining DWH funds
E: Synergistic and antagonistic effects	DWH funding entities should evaluate mechanisms that support cross-state and Gulf-wide collaboration among researchers, resource managers, and practitioners, with an objective of designing restoration efforts that can assess antagonistic and synergistic effects
F: Cumulative effects assessment	To take advantage of the unprecedented opportunity to assess cumulative effects and inform restoration efforts ongoing and planned in the Gulf, DWH funding entities should evaluate and implement mechanisms for assessing cumulative effects. Mechanisms could include assigning responsibility to, and support for, an existing Gulf-wide entity; development of an independent, regional, multidisciplinary, multiagency team; or distributing effort between existing entities. One recommendation for accomplishing this is the "multiple lines of evidence" approach
G: Adaptive management	As additional monitoring data and scientific evidence become available, DWH program managers should collaboratively develop and implement an adaptive management strategy for the Gulf of Mexico restoration effort, including the development of ecosystem conceptual models. Priority issues should include a focus on progress in cumulative effects assessments and achievement of restoration objectives. Mechanisms to continue these efforts beyond the eventual sunset of DWH restoration programs should be identified and implemented

Introduction

On April 20, 2010, the *Deepwater Horizon* (DWH) drilling rig exploded in the Gulf of Mexico (GoM), resulting in the loss of eleven lives and the discharge of at least 3.19 million barrels of oil (Malakoff 2015). Oil reached more than 2100 km of Gulf coastline and impacted all five US GoM states (Nixon et al. 2016). The resulting civil and criminal litigation from the *Deepwater Horizon* oil spill led to approximately $16.7 billion in fines and penalties to be applied to economic recovery and environmental restoration-related activities in the GoM region (ELI 2020). Over the last decade, DWH fines and penalties have been used to fund more than 300 completed and ongoing environmental restoration projects (including habitat restoration and enhancement, species restoration, and water quality restoration and maintenance), plus over 100 planning and more than 60 monitoring and observation projects (https://dwhprojecttracker.org/; accessed July 6, 2022).

The recently released National Academies of Sciences, Engineering, and Medicine National Academies report entitled, "An Approach for Assessing U.S. Gulf Coast Ecosystem Restoration: A Gulf Research Program Environmental Monitoring Report" (NASEM 2022), addresses monitoring and assessment of the cumulative effects of GoM restoration projects beyond the project scale and within the context of long-term environmental change. This report, a consensus of 10 committee members, evaluates the current state of knowledge, examines tools and techniques for cumulative effects assessment, and recommends next steps to assess the effectiveness of large-scale and multiple restoration projects. A summary of recommendations appears in Table 1.

To encourage thought and discussion about how environmental management and restoration professionals may best make use of committee conclusions and recommendations, the authors here provide our personal assessment of the report's highlights. Although the report focused on challenges and opportunities for large-scale restoration in the GoM, perspectives presented here are in many ways globally applicable to large-scale environmental restoration.

Success of Large-Scale and Multiple Environmental Restoration Projects Requires Accounting for Changing Baselines, Including Long-Term Background Trends, Acute Events, and Increasing Environmental Variability

Long-term environmental trends (such as those associated with climate change) as well as acute events (such as hurricanes) can influence the success or failure of restoration efforts (NASEM 2022). Because environmental background trends currently exhibit higher variability than in the recent past (IPCC 2021), restoration practices that have previously been successful may no longer be effective. As an example, relative sea level rise (RSLR) in some locations in Louisiana and the state of Texas currently ranges from 6 to 9 mm/year, and there is evidence that in some instances, these rates may be underestimates (Veatch 2017). However, the Louisiana State Master Plan estimates that an annual RSLR rate of 7 mm or greater (White et al. 2019) would require that in addition to conventional wetland restoration efforts, sediment replenishment or augmentation would be needed for Louisiana wetlands to remain viable.

Another example is changing riverine inputs to the GoM due to climate change and changing land and water management practices. Results from Rodgers et al. (2018, 2020) indicate reduced freshwater discharge from almost all rivers flowing into the GoM between 1950 and 2015 (the Mississippi River was not evaluated). Reductions in freshwater inflow could result in slower rates or reduced amounts of sediment accumulation, as well as changes in nutrient loading and salinity. These changes would directly impact expected restoration goals and would need to be accounted for in future project planning. Further, it is likely that future environmental change may not follow past trajectories and plans for better estimating future environmental trends need to be made now (NASEM 2022).

Currently, the significant spatial and temporal gaps in monitoring GoM environmental indicators hinder the ability to incorporate effects of changing environmental trends into restoration plans. Although examples of coordinated regional monitoring in the GoM exist (White et al. 2019; Beck et al. 2019; McKinney et al. 2019), long-term environmental trends are generally monitored by a patchwork of agencies, non-profits, and industries, with varying study designs, data collection methods, analyses, and data availability that are quite often not comparable. In addition, data and information from many restoration projects and programs are not readily accessible (NASEM 2022). Yet, the availability of high-quality environmental trends and project-specific data remain critical to both planning and assessing restoration effects.

Emerging Technologies Can Be Used to Complement Traditional Monitoring Methods and Help Assess Effectiveness of Multiple and Large-Scale Restoration Projects

Recent advancements in artificial intelligence (AI), machine learning, deep learning, and cloud computing are transforming many types of environmental monitoring[1]. In addition, traditional remote sensing, combined with the new technologies and AI, can generate high-quality monitoring and research data at spatiotemporal scales suitable for coastal systems analysis (Ridge et al. 2020). Field-based monitoring technologies have also improved greatly in the recent past, driven by advancements in AI, but also by crowdsourcing, low-cost sensors, uncrewed aerial and underwater systems, and small satellites[2]. Such advanced technologies have the potential to enhance data collection and analysis much less expensively than in the past, which will be more sustainable over the timeframes relevant to long-term environmental changes. These newer data-driven technologies are not expected to replace traditional monitoring methods but instead to complement and strengthen them, especially across the larger geographic areas needed for Gulf-wide assessments.

Advanced multi-platform sensing technologies, together with data analytics and visualization methods, can make post-restoration monitoring targeted, effective, relatively inexpensive, and hence, more sustainable. Although not comprehensive, the groundwork for a hybrid monitoring framework using emerging modeling techniques such as artificial intelligence (AI) driven, machine learning (ML), and deep learning (DL) exists but is being implemented in a limited number of ecosystem monitoring studies in the GoM (NOAA and USGS 2020). For example, NOAA's Council Monitoring and Assessment Program (CMAP) inventory assessment found only 7% of oyster restoration efforts used some newer techniques such as machine learning (NOAA and USGS 2020).

Although less widely understood and applied, yet an integral part of such a framework is the use of ML and DL-based data-centric environmental models. For large-scale synthesis across sites in the GoM, which are under constant as well

[1] https://www.microsoft.com/en-us/ai/ai-for-earth

[2] https://www.nsf.gov/cise/harnessingdata/.

as punctuated influences of natural and anthropogenic drivers, we suggest that ML/DL-based models capable of highlighting the complex non-linear cumulative effects relationships between restoration activities and ecosystem response need to be at the forefront. In a recent review, Ditria et al. (2022) summarized the current state of AI and automation techniques used in coastal and marine environments for improved monitoring in support of decision-making. To date, coastal environmental restoration has experienced minimal integration of ML/DL in modeling and data synthesis activities, due to challenges such as the requirement for large training data sets, data labeling, and computation needs (Lamba et al. 2019).

Conceptual Models Are Needed to Help Frame Large-Scale Science and Environmental Restoration Programs

In addressing large-scale and complicated environmental questions, conceptual models have been useful in building scientific consensus and reminding all investigators and stakeholders of the complexity of the issues. Agreement on the essential content of such models, and updates to them when new science emerges, prevents the "sweeping under the intellectual rug" of important issues that are not clear or generally agreed on. Conceptual models are not new in ecosystem restoration, including at the project-level in the Gulf (NASEM 2017), but because they have not been adequately embraced at larger spatial scales, we highlight them again here.

During our discussions, we developed several conceptual models. One considered the effects of changing environmental trends associated with climate change and both acute and chronic pressures and stressors–including climate change interactions–on restoration efforts in the GoM (Fig. 1, which is Fig. 2.1 in NASEM 2022). A synopsis of what was included in this conceptual model provides a clear demonstration of the scope and complexity of assessing large-scale restoration. The climate change category indicates environmental trends that have longer time scales of influence. Terrestrial influence is shown by several large rivers in the background map that deliver freshwater, nutrients, and sediments to the coast, as well as by decadal-scale land-use changes that can result in increased or decreased pollutant loads to coastal waters. In addition to climate change more generally, both chronic (continuous) and acute (short-lived or episodic) system-scale influences are also shown. Four major restoration types are depicted: water quality restoration; the expansion and restoration of coastal and estuarine wetlands; submerged aquatic vegetation communities; and oyster reef communities. Pathways connecting the restoration types indicate possible synergistic or antagonistic interactions (or null effects of interactions) that need careful consideration. Potential environmental benefits resulting from the cumulative effects of restoration efforts are listed along with pathways indicating that chronic and acute pressures and stressors, most of which are also related to climate change influences, can have negative effects on restored communities.

Importantly, Fig. 1 did not simply appear in finished form. Hand-drawn conceptual models such as the Baltic Sea example (Fig. 2) that depicted ecosystem elements, interactions, and forcing influences sparked committee discussion of ecosystem-level stressors and effects in the GoM. Working drafts of Fig. 1 kept us focused on the appropriate spatial, temporal, and complex-system scales and reflected input from our individual diverse scientific backgrounds.

Adaptive Management and Synthesis Beyond the Project Scale Are Critical for Successful Restoration Efforts in the Future

Implementation of an adaptive management framework at the project scale facilitates the implementation of restoration activities in the face of uncertainty (NASEM 2017). Further, the completion of the adaptive management cycle at the project scale enables results to be leveraged to conduct a similar cycle of "plan-implement-evaluate-adjust" at the program level of management and the multi-project geographic scale (NASEM 2022). Establishing an adaptive management approach beyond the project scale requires not just the collection and synthesis of project-level data but may also require additional investment in monitoring and data collection to determine what, if any, ecosystem changes occur as a result of project implementation.

Additionally, it requires close collaboration among multiple restoration entities to develop quantitative goals for restoration projects, and a framework for assessing progress toward those goals, and adjustment of those goals or project approaches, if warranted.

In support of an adaptive management approach, synthesis is critical to determine the magnitude and extent to which local restoration efforts, collectively, have affected coastal ecosystems. Importantly, the types of data synthesized provide a basis and, ultimately, mechanisms for adjusting practices to produce better restoration outcomes. Synthesis at

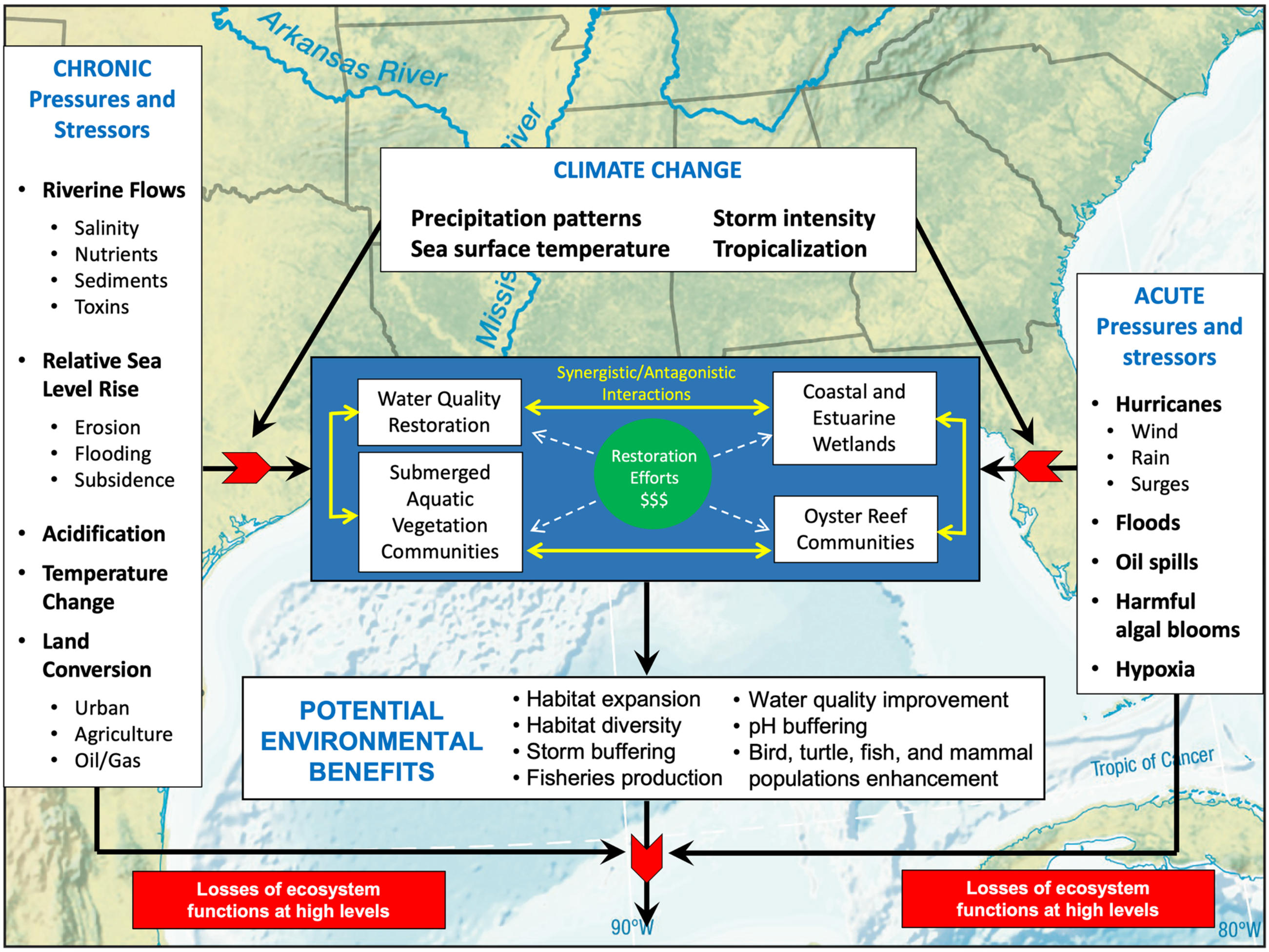

Fig. 1 Conceptual model depicting factors and interactions affecting large-scale restoration in the Gulf of Mexico. Source: National Academies of Sciences, Engineering, and Medicine. 2022. An Approach for Assessing U.S. Gulf Coast Ecosystem Restoration: A Gulf Research Program Environmental Monitoring Report. https://doi.org/10.17226/26335. Reproduced with permission from the National Academy of Sciences, Courtesy of the National Academies Press, Washington, D.C

ecosystem and larger scales is also needed because of the strong and concerning trends in both chronic and acute stressors and their effect on the success of restoration projects.

Conducting synthesis and adaptive management across multiple projects and large spatial scales is not without challenges. Critical elements for success include the availability of adequate and relevant data, the development of ecosystem conceptual models, and the trust among partners that facilitates sharing information and lessons learned. Perhaps the most important are commitments among partners to continually evolve the adaptive management framework to account for uncertainties and complicated interactions among social, political, and ecological components of a restoration program. Without periodic synthesis and evaluation, wise and well-informed course corrections cannot be made.

Restoration and Related Outcome Expectations May Need to be Adapted to Reflect Changing Environmental Conditions

Given that changes in long-term environmental trends such as sea level rise and warming water temperatures are likely to continue for the foreseeable future (IPCC 2021), it is increasingly unlikely that restoration efforts will return ecosystems to an undisturbed or reference state. Moreover, it may even be undesirable to attempt to achieve such conditions because a resilient ecosystem in a particular location today may look and function differently than an ecosystem of years or decades ago (e.g., Coleman et al. 2020; Harris et al. 2006). Thus, it is increasingly prudent for restoration practitioners and natural resource managers

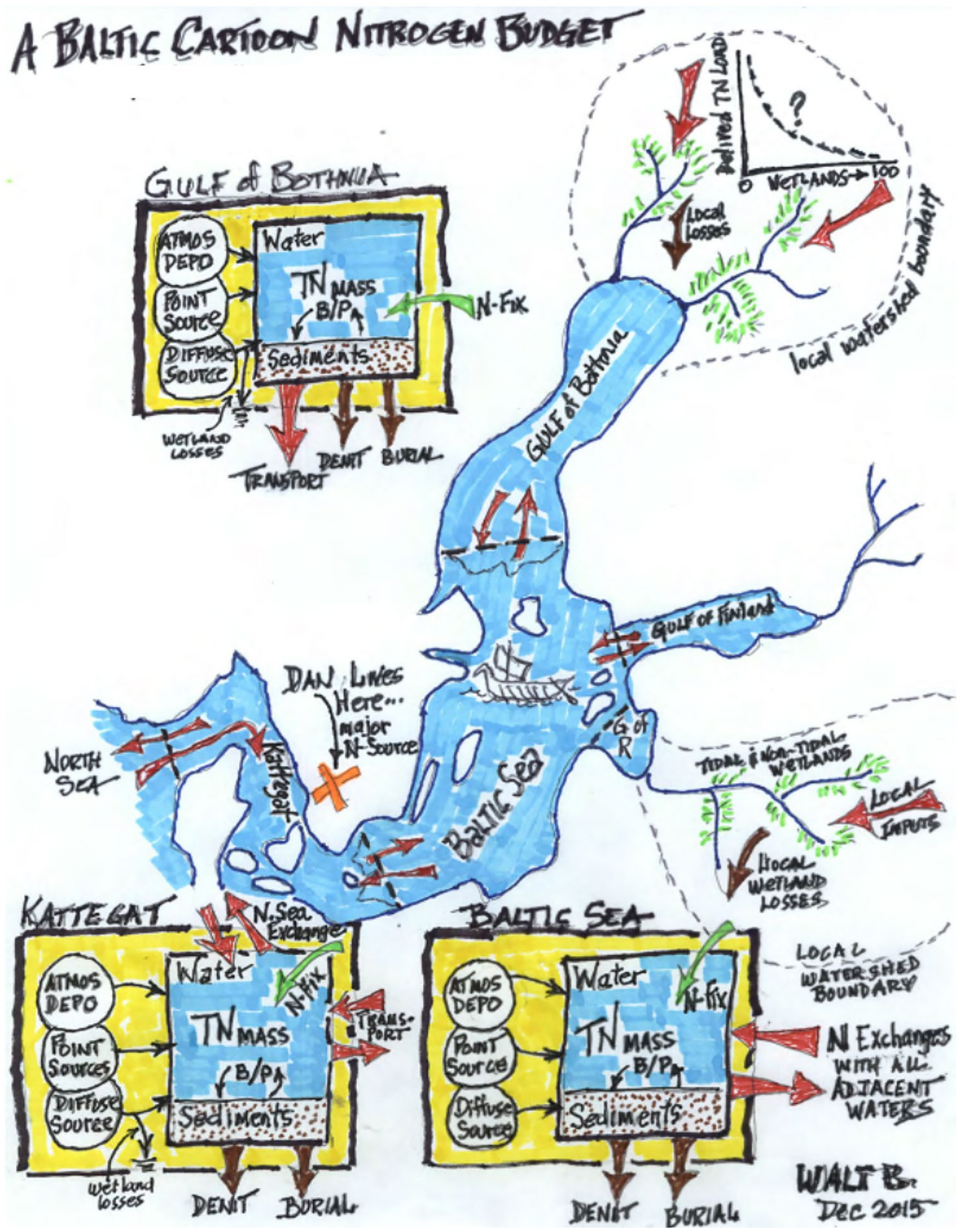

Fig. 2 An example of the type of hand-drawn “cartoon” conceptual diagram that helped spark discussion of ecosystem effects and visualize the complex factors impacting large-scale restoration efforts. Source: W. Boynton

to consider an expanded range of desirable possible outcomes when developing restoration goals, including:

- *Slowing the Decline*. Given increasing environmental pressures and stressors on ecosystems and limited resources, it is worth acknowledging that it may not be possible or desirable to fully restore or maintain the present state of an ecosystem. However, there may be value in taking interim actions to slow ecosystem decline for a specified period of time. For example, the 2017 Louisiana Master Plan includes a 50/50 split between restoration and protection projects and assumes a 50-year timeframe.[3] The goal of these protection projects is to effectively slow the decline of wetland extent and function.
- *Improvement for a Period.* Similar to the above, instead of assuming that a restoration action will be permanent or semi-permanent, it might be helpful in some instances to restore an ecosystem with the expectation that these improvements will be successful for a shorter time (e.g., a few years to a few decades). This approach is particularly relevant in the con-

[3] https://coastal.la.gov/our-plan/2017-coastal-master-plan/

Table 2 Seven lines of evidence organize typical methods used in ecosystem restoration including statistical and non-statistical analyses and various types of modeling (adapted from NASEM 2022)

Line of evidence	Typical analytical methods in ecosystem restoration
Research on critical ecological uncertainties	Summarize advances in understanding cause-effect associations; iterative improvement of conceptual models
Evidence-based review of the literature	Systematic global literature search, including relevant unpublished local reports; filtering, review, and scoring based on formal criteria; meta-analysis when multiple quantitative reports of effect size warrant it
Physics-based and ecosystem models	Hydrodynamic modeling of inundation and sedimentation patterns; models of the spatiotemporal dynamics of biotic assemblies
Meta-analysis of restoration action effectiveness	Qualitative or quantitative assessment of studies of action-effectiveness in the restoration program; analysis of data from previously restored sites
Analysis of data and modeling of target species	Collection and analysis of necessary data and population modeling; trends in migratory species populations and habitats
Modeling of cumulative net ecosystem improvement	Additive modeling of change in function, restored area, and probability of success
Change analysis on the landscape setting	Remote-sensing data analysis; land cover and other change trajectories in watersheds and estuaries; environmental trends

text of the socio-economic, cultural, and ecological heritage of human populations along the GoM coast during a period of rapid change with direct effects on that heritage.

In addition, and somewhat contrary to the accepted ecological restoration aiming "to move a degraded ecosystem to a trajectory of recovery that allows adaptation to local and global changes…" (Gann et al. 2019), a third restoration outcome to pursue may be:

- *Maintenance.* For an ecosystem that is generally healthy but under increasing pressures and stressors, there may be value in undertaking preemptive management and restoration actions that help maintain that ecosystem (e.g., to a specific areal extent or to specific ecosystem structures, processes, and functions) for a specified period of time within a range of uncertainty.

For systems that are degraded or experiencing some loss of function, each of these three outcomes could be considered possibilities in a decision-making context. For currently healthy ecosystems, the first and third outcomes would be possible options.

Rigorously Assessing the Cumulative Effects of Multiple and Large-Scale Environmental Restoration Projects Is Both Needed and Possible

Synergistic and antagonistic interactions can be either positive or negative, which seems counter-intuitive (Côté et al. 2016). As examples, oyster reef restoration can induce the establishment of seagrass, a benefit, unless it displaces another critical habitat. Nitrogen reduction is usually deemed positive, unless it reduces algal production so much that fisheries that depend on algae for food are also reduced.

We reviewed different approaches to assess cumulative effects of restoration projects, including several described by Diefenderfer et al. (2021). The use of "multiple lines of evidence" was determined to be an especially relevant approach for assessing cumulative effects from multiple and large restoration projects. In essence, it is a search for converging consensus regarding the status of ecosystem recovery from multiple data and information sources. It is an evidence-based methodology (Table 2) using causal criteria to compensate for experimental designs without control or reference sites and those cases with a paucity of pre-and post-restoration data.

We identified specific lines of evidence that might be useful in the GoM, as well as causal criteria and tools for gathering evidence that facilitate the general use of this approach, and we identified examples and case studies to better illustrate the approach. Although the concept of using multiple lines of evidence to assess ecosystem restoration has been published under that name relatively recently (Diefenderfer et al. 2016), long-term science and management programs in the GoM and other coastal regions have for decades used the concepts of multiple lines of evidence in developing watershed management strategies and continue to use them in locations including Galveston, Tampa, and Chesapeake Bays (NASEM 2022).

Significant Improvements in Data Collection, Analysis, Synthesis, and Reporting Are Needed to Enable Adaptive Management to Support Effective Large-Scale Environmental Restoration

There are needs for transformational changes in capturing, recording, transmitting, synthesizing, archiving, and extracting meaningful data and information (physical, chemical, geological, and biological/ecological) about restoration projects across the GoM, arising from multiple sources, users, and scales. Ecosystem restoration and monitoring communities will collectively benefit from using hybrid methods that combine the traditional approaches with the new tools and techniques described above. Such changes would apply to data collection, modeling, synthesizing, and disseminating information. To be successful in implementing such a framework across restoration localities, there must be a willingness to adhere to the *Open Data* concept, which means that data must be accessible and freely available to be repeatedly used and distributed.

Funding for monitoring, especially long-term monitoring programs, is difficult to obtain, even though monitoring data are key to understanding what type of restoration has and has not worked. Without the analysis of high-quality monitoring data, coastal scientists and managers will unlikely ever be able to quantify whether, and to what degree, habitats and ecosystems have been improved by restoration efforts.

To address the challenges of obtaining the long-term and accessible environmental trend data needed for both restoration planning and the assessment of multiple restoration projects, we find it critically important that the parties responsible for managing large-scale restoration funds designate and fund an entity that is empowered to lead efforts to achieve four key objectives: (1) enhancing long-term priority monitoring efforts by promoting consistent data collection, analysis, synthesis, and reporting among programs; (2) supporting periodic assessments of collected data; (3) assessing the use of advanced techniques and how they can be implemented; and (4) ensuring data availability through the establishment of accessible data repositories.

There Is an Unprecedented Near-Term Opportunity to Evaluate Large-Scale Environmental Recovery in the GoM and to Course-Correct Management Actions Where Needed

The *Deepwater Horizon* oil spill reset many priorities in the Gulf of Mexico, and restoration projects at scales, complexity, and scopes rarely attempted became possible. What has been the impact of these restoration efforts to date on improving ecosystem health and productivity? What have we learned that we can apply to future efforts to maximize ecosystem benefits, and do so in the most cost-effective ways, which are beneficial for the communities involved?

Answering these questions has broad implications for future restoration efforts that include large-scale or multiple projects, especially those with diverse ecosystem improvement goals such as those at estuarine or watershed scales or even larger regions. Globally, as documented by the U.N. Decade on Ecosystem Restoration[4], such large-scale efforts will become more important as long-term environmental trends continue to interact with anthropogenic drivers. In the GoM, there is an unprecedented opportunity to demonstrate to restoration scientists and practitioners throughout the world that these challenges can be met effectively–but only if the intellectual and fiscal investment is made and made quickly.

Leading government, academic and private sectors restoration scientists have laid the foundation for accomplishing this goal and assuring that future restoration builds on both successes and failures of what has occurred to date. The tools and expertise are in place to take advantage of what we are learning from the collective restoration experience and use this knowledge to enhance the effectiveness and sustainability of future restoration efforts. This can best be done by moving from simple output metrics such as acres of wetlands or miles of shoreline restored to outcome metrics that better reflect ecosystem health and productivity.

Throughout our 18 plus months of deliberations and reviewing information, we developed an increasing sense of concern that the basic questions about the effectiveness of the massive restoration efforts cannot currently be answered. For this to happen, there is a critical need to synthesize data and information already collected but unavailable and to use findings from evaluating these data to inform future DWH settlement-funded restoration efforts. Existing information on background trends Gulf-wide are sparse, and to date synthesis activities and application of adaptive management have not been utilized to the extent needed.

Nevertheless, we are cautiously optimistic that, with a mid-course assessment and corrective actions, quantifiable progress toward large-scale environmental recovery in the GoM can, and will, be made. Although committed and expended DWH settlement funds are approaching half of the total amount available, there are adequate funds to address the challenges identified by our study. To do so, rapid, coordinated decisions by the DWH funding entities can ensure the effectiveness of future restoration efforts and the smart use of the remaining restoration funds.

If we are to effectively make the case that funding restoration generates a worthwhile return that encourages future investment, we need to demonstrate that value, in terms that decision-makers can appreciate and apply. Since at least the beginnings of the industrial age, it has been recognized that environmental restoration is needed, and the rapidly changing climate is adding new complications that are yet to be understood by restoration practitioners. The ability to adequately inform future restoration decisions remains a challenge, but, if implemented properly, the tools and means are available to meet this challenge.

[4] https://www.decadeonrestoration.org

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Declarations

Competing Interests The authors declare no competing interests.

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