Cumulative effects assessment of restoration programs: a framework to assess achievement of regional and programmatic goals

T.M. Davenport[1], D.A. Comba[1], P.S. Dalyander[2], N.M. Enwright[3], M.L. Palmsten[4], G.D. Steyer[5], and M.K. La Peyre[6,1]

[1] Louisiana State University Agricultural Center, School of Renewable Natural Resources, Baton Rouge, Louisiana, [2] The Water Institute of the Gulf, Applied Geosciences, 2021 Lakeshore Drive, Suite 310, New Orleans, Louisiana, [3] U.S. Geological Survey, Wetland and Aquatic Research Center, Lafayette, Louisiana; [4] U.S. Geological Survey, St. Petersburg Coastal and Marine Science Center, 600 4th St. S., St. Petersburg, FL St. Petersburg, Florida; [5] U.S. Geological Survey, Southeast Region, Baton Rouge, Louisiana [6] U.S. Geological Survey, Louisiana Cooperative Fish and Wildlife Research Unit, Baton Rouge, Louisiana

Cooperator Science Series # 162-2024

About the Cooperator Science Series:

The Cooperator Science Series was initiated in 2013. Its purpose is to facilitate the archiving and retrieval of research project reports resulting primarily from investigations supported by the U.S. Fish and Wildlife Service (FWS), particularly the Office of Conservation Investment. The online format was selected to provide immediate access to science reports for FWS, state and tribal management agencies, the conservation community, and the public at large.

All reports in this series have been subjected to a peer review process consistent with the agencies and entities conducting the research. For U.S. Geological Survey authors, the peer review process (http://www.usgs.gov/usgs-manual/500/502-3.html) also includes review by a bureau approving official prior to dissemination. Authors and/or agencies/institutions providing these reports are solely responsible for their content. The FWS does not provide editorial or technical review of these reports. Comments and other correspondence on reports in this series should be directed to the report authors or agencies/institutions. In most cases, reports published in this series are preliminary to publication, in the current or revised format, in peer reviewed scientific literature. Results and interpretation of data contained within reports may be revised following further peer review or availability of additional data and/or analyses prior to publication in the scientific literature.

The Cooperator Science Series is supported and maintained by the FWS, National Conservation Training Center at Shepherdstown, WV. The series is sequentially numbered with the publication year appended for reference and started with Report No. 101-2013. Various other numbering systems have been used by the FWS for similar, but now discontinued report series. Starting with No. 101 for the current series is intended to avoid any confusion with earlier report numbers.

The use of contracted research agencies and institutions, trade, product, industry or firm names or products or software or models, whether commercially available or not, is for informative purposes only and does not constitute an endorsement by the U.S. Government.

Contractual References:

This document (USGS IPDS # IP-167879) was prepared with critical contributions from the U.S. Fish and Wildlife Service, Gulf Restoration Office. Funding was provided from the Resources and Ecosystems Sustainability, Tourist Opportunities, and Revived Economies of the Gulf Coast States (RESTORE) Act through the 2017 Funded Priorities List: Comprehensive Plan Commitment and Planning Support grant, under agreement number IAACP18DI0065. In addition, the U.S. Geological Survey supported this work.

Recommended citation:

Davenport, T.M., D.A. Comba, P.S. Dalyander, N.M. Enwright, M.L. Palmsten, G.D. Steyer, and M.K. La Peyre. 2024. Cumulative effects assessment of restoration programs: a framework to assess achievement of regional and programmatic goals. U.S. Department of Interior, Fish and Wildlife Service, Cooperator Science Series FWS/CSS-162-2024, Washington, D.C.
https://doi.org/10.3996/css78994021

For additional copies or information, contact:

Megan La Peyre
U.S. Geological Survey
Louisiana Cooperative Fish and Wildlife Research Unit
E-mail: mlapeyre@usgs.gov

Cumulative effects assessment of restoration programs:

a framework to assess achievement of regional and programmatic goals

T.M. Davenport, D.A. Comba, P.S. Dalyander, N.M. Enwright, M.L. Palmsten, G.D. Steyer, M.K. La Peyre

Photos: M. La Peyre

Table of Contents

Abstract

Increasing global investments focused on conservation and restoration of natural resources aim to address challenges presented by climate change and biodiversity loss. Many restoration and conservation program assessments examine individual actions, assuming additive effects only, failing to acknowledge or capture potential synergistic or antagonistic effects across a region or program. Cumulative effects assessments (CEA) provide a more ecologically relevant framework to assess the outcome of large restoration efforts. These assessments are critical given the increasing frequency of projects and the potential for cross-project interaction, yet there are few efforts to document the presence and patterns of cumulative effects for large-scale restoration programs. Understanding both the individual and cumulative effects of projects within a large restoration program can also inform the conceptualization of future large-scale restoration efforts by enabling the full suite of outcomes to be evaluated and considered against no-action scenarios in future planning. Here, we describe the development of a conceptual framework for CEA from large-scale restoration efforts.

The framework identifies four key steps including establishing how the CEA will be used, a system assessment (check the best available scientific understanding of system dynamics, define the scope, and understand restoration effort), a data assessment (project data, regional or resource trend data) and a synthesis across this information to determine whether resource status and trajectories with and without restoration efforts can be evaluated, or identify where there are gaps. The conceptual framework is then applied to a study area within the north-central Gulf of Mexico (GOM) that is the subject of restoration funded by response to the *Deepwater Horizon* (DWH) oil spill, from which 9 billion U.S. dollars has been invested among 1,828 projects over the past 14 years. Barrier island and shorelines (BIS) within the north-central GOM were selected as a focal ecosystem given they are a priority for restoration and have a high density of restoration projects, and the framework was applied to assess the feasibility of CEA as a tool to assess progress toward achieving programmatic BIS restoration goals. We identified three critical gaps that limit CEA in this system. First, our understanding of the dynamic BIS system is missing connections from system dynamics to the restoration efforts funded by DWH and their intended and indirect effects. Without capacity to differentiate the intended effects of restoration effort from the dynamics of a changing system, CEA cannot attribute changes to restoration, and the effectiveness of adaptive management is also limited. Second, monitoring data are not available or require substantial effort to compile at appropriate spatial and temporal scales to document cumulative changes in target resources. A third gap that limits the capacity of CEA to assess progress toward a common programmatic goal is the lack of a clear definition and metrics to measure resilience, the identified goal for BIS. CEA planning and practice can provide a more robust, systematic, and efficient means to track progress and help meet regional management goals compared to assessing individual projects. With continued investment globally in restoration and conservation of natural resources and the services they provide, early efforts that incorporate CEA and potential cumulative effects into restoration planning can improve the understanding of programmatic effects and support adaptive management.

Glossary

Adaptive management: Adapting resource management strategies based on new data and/or understanding of management outcomes.

Cumulative effects assessment (CEA): The process of evaluating change in large ecosystems resulting from multiple sources (NASEM 2022). Here, we refer to CEA to assess multiple restoration projects, which may result in additive, synergistic, and/or antagonistic effects. An alternative definition of cumulative effects considers solely the combined sum of additive effects on a focal environmental aspect (Judd et al. 2015; Piet et al. 2021), though we consider additive, synergistic and antagonistic effects in our definition.

Cumulative impacts: The sum of additive, synergistic, and/or antagonistic effects (e.g., multiple stressors) on a focal environmental aspect (Goodsir et al. 2015). A synergistic interaction is a combined effect of multiple stressors that exceeds the sum of each individual stressor's effect, whereas an antagonistic interaction occurs when the combined effect of multiple stressors is less than that of their summed effect (Folt et al. 1999; Côté et al. 2016).

Conceptual model: An illustration of the linkages among system components, including variables and factors, that provides the basis for developing and testing causal hypotheses (Gentile et al. 2001). Conceptual models are also used to graphically represent interrelationships between drivers, pressures, stressors, restoration actions, and ecosystem response, based on one or a series of hypotheses (Gentile et al. 2001).

Conceptual framework: A network of linked concepts that together provide a comprehensive understanding of a phenomenon (or phenomena; Jabareen 2009).

Drivers: The fundamental forces, which may originate from natural or anthropogenic sources, that drive the system and are often large-scale or long-term forces that are not easily controlled, changed, or diverted (Harwell et al. 2019). Drivers may not cause a shift in resource availability by themselves but may do so when coupled with stressors (Harwell et al. 2019). We conceptualize drivers as the forces that drive the system dynamics that form background variation. They are likely to act at a larger spatial scale than the system and may be affected by global change.

Feedback: A change in one system component that is brought on by a change in a different system component along with a process that mechanistically links the two system components. With respect to restoration, projects with indirect relationships between restoration actions and the project's purpose or intended effect (e.g., restore a habitat to benefit a focal resources) typically rely on mechanistic processes to connect system components. When these restoration efforts occur in combination with cross-component mechanisms, feedbacks may result.

Function: The activity of an environmental system; what the system does (e.g., support wildlife and human activities).

Identity: The sum of characteristics differentiating an environmental system from others.

Restoration practice: The process of planning, designing, implementing, monitoring, managing, and studying restoration efforts.

Science-practice gap: A potential barrier to increasing the scope and effectiveness of restoration resulting from research or scientific understanding (ecological, geomorphological, or other relevant research) that is not effectively integrated with restoration practice (Bernhardt et al. 2007, Cabin et al. 2010).

Stressors: The physical, chemical, and/or biological factors that can directly cause a biological effect; what the system experiences (Harwell et al. 2019). One or more pressures, or a mix of pressures from natural and anthropogenic sources, may result in an environmental stressor (Harwell et al. 2019). We conceptualize stressors as the processes or phenomena that are the causative agents of acute change, and they are likely to have an anthropogenic origin or be exacerbated by anthropogenic activities.

Structure: The matter that makes up the physical parts of an environmental system, which may be geological, biological, chemical, geographical, and/or a combination (i.e., biogeographical) in nature.

System model: A conceptual model of an environmental system that depicts the relationships between its components of a system and their interactions.

System component: One of the parts of a system model. These include structures, functions, identity, and feedbacks.

Target resource: A resource that is altered intentionally by restoration. Resources may be non-living (e.g., water bodies, landforms like beaches or rocky outcroppings, infrastructure, recreational opportunities) or living (e.g., birds, sea turtles, forests).

Introduction

Globally, large investments in ecological conservation and restoration aim to address the dual crises of climate change and biodiversity loss. Some of these large-scale efforts include the U.N. Decade on Ecological Restoration (> 700 projects, totaling 7 billion U.S. dollars (7B USD) across 140 participating countries; UNEP 2024), the 30 by 30 movement (CBD 2020), the Bonn Challenge (Dave et al. 2019), and in the United States, the Infrastructure Investment and Jobs Act (Bipartisan Infrastructure Law, P.L. 117-58; IIJA 2021) and Inflation Reduction Act (P.L. 117-169; IRA 2022), which include climate, resilience, and habitat-related actions. These types of programs typically set area-based and economic restoration goals, which may be quantified as total area restored, lengths of stream reconnected, total dollars spent, total jobs created, and number of projects per year and/or over the lifetime of the program. Many of these metrics characterize investments made; while tracking restoration investments is important, this approach may not assess key project outcomes, which are important to evaluate efficacy and assess the need for adaptive management and/or changes to future ecosystem restoration planning. This additive tally approach also requires a simplifying assumption — that restoration outcomes are not affected by varying environmental conditions or by interactions with other projects. However, there is strong evidence to suggest that this assumption does not hold in all situations. Ecosystems operate through feedback loops, and drivers and stressors may have interacting impacts on restoration, conservation, and/or management actions, potentially leading to smaller, larger, or compounding effects on the target outcome (Côté et al. 2016; Hewitt et al. 2016; Carrier-Belleau et al. 2021; Pichon et al. 2024). Identifying cumulative effects from restoration provides valuable insight to improve restoration design and implementation of large-scale restoration activities and ensure they can meet regional and programmatic goals.

A more ecologically relevant framework to assess the outcome of large restoration efforts involves examining the potential for cumulative effects (i.e., synergistic or antagonistic) in addition to additive effects of restoration. Cumulative effects are defined as “the impact on the environment which results from the incremental impact of [an] action when added to other past, present, and reasonably foreseeable future actions…” (CEQ 1997). The concept of cumulative effects grew out of the cumulative impacts assessment, which originated as a method to track and understand environmental degradation resulting from multiple negative impacts (CEQ 1997). This concept recognizes that the impacts of multiple projects may be additive, synergistic, or antagonistic, that is, the total cumulative impact on environmental resources may be equal to, more than, or less than the sum of their component projects (Spaling 1994; Smit and Spaling 1995; CEQ 1997; Diefenderfer et al. 2011; Côté et al. 2016). Here, we refer to a cumulative effects assessment (CEA) as a process to evaluate change in large ecosystems and focus on changes resulting from conservation and restoration efforts (as in Diefenderfer et al. 2016; Gann et al. 2019; Greening et al. 2023).

Coastal ecosystems provide an array of important functions and services, including supporting habitats, species, and anthropogenic activities, and providing storm surge protection and wave attenuation (Barbier et al. 2011; Powers and Boyer 2014; Martin et al. 2016; Harris and Defeo 2022). Over 2 billion people live in the coastal zone globally (Reimann et al. 2023), and in the United States, approximately 40% of the population live in coastal counties as of

2020, despite coastal counties covering just 10% of land area (US Census Bureau 2020). This high coastal population density, combined with the importance of coastal systems (e.g., for culture and recreation, food security, biodiversity, storm sheltering and protection and more), ensures large scale conservation and restoration of coastal systems remains a priority to protect life and property (Waltham et al. 2020; Bridges et al. 2021; Kelso et al. 2024). For example, along the U.S. portion of the Gulf of Mexico coast, over 20B USD were identified for ecological restoration and economic recovery following the *Deepwater Horizon* (DWH) oil spill that occurred in 2010 (Ocean Conservancy 2015; DOJ 2015). According to the *Deepwater Horizon* Project Tracker summary, as of April 19, 2024, an estimated 10B USD (2024) has been invested in 1,828 projects (including all funding programs, states, project actions, project categories, and project resources), in the past 14 years in this region, with broad programmatic and regional goals of restoring the coastal and estuarine resources of the region (DU/GOMA/TPL 2024a).

With such large-scale investment in conservation and restoration efforts, understanding the individual and cumulative effects of these programs on natural resources and ecosystems helps ensure goals are being met. Diefenderfer et al. (2016) proposed a method to integrate evaluation techniques from evidence-based medicine and critical thinking into a CEA process for biological resources. Specifically, Diefenderfer et al. (2016) proposed a 4-step process that includes: 1) development of a conceptual model, identification of indicators for monitoring, and an associated hypothesis framework for target species; 2) assessment of monitored indicators; 3) synthesis of these results and assessment of their likelihood to have caused cumulative change using causal criteria; and 4) determination of the pattern and type of cumulative effects that are represented. Three patterns of accumulation of cumulative effects for large scale restoration programs were identified based on relationships among projects: 1) systemic; 2) spatial; and 3) temporal (Diefenderfer et al. 2021). Systemic cumulative effects of restoration include indirect relationships between projects and outcomes, such as restoring trophic structure in an estuary by reconnecting diked lands to a river system (Thom et al. 2018); spatial cumulative effects refer to changes in landscape patterns or crowding of many projects in space; and temporal cumulative effects could result from many projects occurring at the same time or altering the timing of stressors (Diefenderfer et al. 2021). CEAs can help identify strengths and/or weaknesses in programs resulting from accumulation patterns like these and help determine how the selection and placement of projects work collectively. Further, as the investment, footprint and diversity in conservation and restoration programs increase, so too does the importance of CEA to enable measurement of the true total net benefits of all projects toward broad programmatic goals.

Few examples of CEA of restoration in estuaries and coastal systems currently exist (Table S1; Greening et al. 2023). While discussion of cumulative impacts and effects in environmental systems and on natural resources has grown steadily since 1979 (Figure S1), less than 2% of prior work relates to restoration of estuarine and coastal systems (Table S1). The few examples that exist use long-term monitoring data, collate multiple data sources to create specialized indices, and/or assess multiple lines of evidence (Cretini et al. 2012; Stagg et al. 2013; Teichert et al. 2016; Beck et al. 2019). For example, Teichert et al. (2016) assessed the impacts of combined and individual stressors and restoration actions on fish ecological status across 90 European estuaries using data from long-term data collections mandated by the

European Water Framework Directive (https://environment.ec.europa.edu). Similarly, using data from multiple water quality datasets in the Tampa Bay, FL, USA region, Beck et al. (2019) investigated the impacts on changes in water quality for over 800 restoration projects within the area. The *in situ* data to support these types of evaluations are often limited, however, thus large-scale assessments of restoration programs often rely on other approaches such as change analyses using remote sensing data and the development of specialized indices that account for synergistic effects. Combining multiple assessments and data sources can form the basis of a multiple lines of evidence approach to estimate cumulative effects of restoration programs (Diefenderfer et al. 2016; Raposa et al. 2018; Beck et al. 2019). Recent guidance for large-scale restoration efforts recommends CEA, determining causal criteria when exploring effects of restoration on broad programmatic goals, and gathering multiple lines of evidence such as research on critical ecological uncertainties, evidence-based review of the literature, and physics-based ecosystem models (NASEM 2022; Greening et al. 2023). Operationalizing this approach has proven difficult in estuarine and coastal systems, including the northern Gulf of Mexico (Diefenderfer et al. 2021; Greening et al. 2023).

The recent initiation and increasing size of large-scale restoration programs highlight the need to understand how projects, individually and cumulatively, contribute to achieving regional and programmatic goals, yet few examples of CEA of restoration exist. Here, a conceptual framework is developed and applied for assessing the feasibility of CEA from restoration efforts. The framework includes documentation of the current scientific understanding of how restoration influences system components, the availability and relationships among projects, and the availability of monitoring and environmental trend data. The conceptual framework is then applied to a study area within the north-central Gulf of Mexico that is the subject of DWH-funded ecological restoration. Throughout the feasibility assessment process, common barriers to CEA are also identified that may serve as important focal areas for programs to promote the practice. Understanding the individual and cumulative effects of projects within large restoration programs, and the programs' progress toward programmatic goals, can then inform the design of future large-scale restoration efforts and enhance their efficiency and efficacy.

Conceptual framework to develop a CEA for a large-scale restoration program

The proposed conceptual framework highlights four critical requirements for enabling a CEA: 1) establishing the specific need and use for CEA within the large-scale restoration program, 2) a system assessment that demonstrates a clear understanding of system dynamics to ensure that potential interactions among the resources of interest with the surrounding environmental system are understood; 3) a project and data availability assessment to ensure that there is tracking of relevant restoration projects, including project and region-level data; and 4) a connection between system dynamics and the restoration effort and outcomes to determine where restoration has had cumulative effects on the resources of interest and environmental system components (Figure 1). This framework was developed to expand and operationalize previous discussions and methodologies suggested for CEAs of large-scale restoration programs, while outlining necessary information required to conduct a CEA. This framework provides guidance for future regional or large-scale restoration programs to include specific CEA goals, critical system understanding and data collection needs in the design and development of their programmatic goals and outcomes to enable CEA.

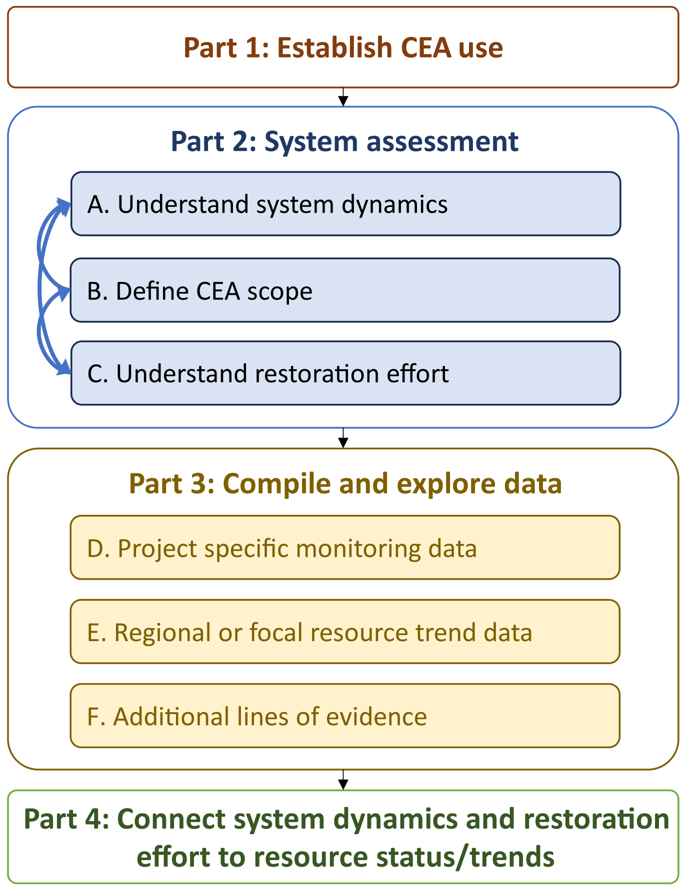

Figure 1. Conceptual framework to develop a Cumulative Effects Assessment (CEA) for a large-scale restoration program. Boxes and arrows depict a process flow chart in four parts: establishing how the CEA will be used, assessing the system in which CEA will take place, compiling and exploring data, and connecting system dynamics and restoration efforts to available data depicting resource status and trends.

Part 1: Use of the CEA

The first part of the CEA process is to clearly define what it will be used for and by whom, as a CEA could be designed to meet many different uses and its use helps inform the rest of the scoping decisions. For example, a CEA could be an exercise to measure trajectories of change and understand how a resource is evolving in relation to global change. An agency that has responsibility for managing trust species may be interested in understanding cumulative effects of any projects or impacts on that species, to better understand population trends for a threatened or endangered species. A locality may be interested in understanding if their community is more resilient to coastal hazards, like storms and sea-level rise, following investments in infrastructure and/or nature-based solutions. For a large-scale restoration program, the goal may be to assess the cumulative effects of individual restoration projects across multiple impacted resources and potentially the associated ecosystem services. The use of the CEA may be focused on assessing the status of a public trust resource of interest and comparing its status with and without intervention (e.g., a potential future condition or reference without restoration). This conceptual framework is focused on large-scale restoration programs. Further, identifying regulations, policies, mandates, or other management-related drivers of the CEA process and their required outcomes may further define the use of the CEA.

Part 2: System Assessment

Conducting a CEA for any defined use requires a clear understanding of the system dynamics, scope of the assessment, and distribution of restoration projects to be included (Figure 1; Part 2 Steps A, B, C). Revisiting the CEA's use and scope during each step can also help ensure decisions continue to be guided by the use of the CEA, ensure it will be useful, and avoid scope creep, particularly if its use and design have not been set ahead of planning restoration efforts.

A. Understand system dynamics: develop conceptual model and assess research effort

CEA of multiple restoration actions across a region requires an understanding of how the system and/or its component resources may change (i.e., Thom et al. 2012) with and without restoration actions. This understanding is articulated in a conceptual model of the target resource and its interactions with drivers and stressors, including direct and indirect drivers of changes, or system dynamics (Gentile et al. 2001; Diefenderfer et al. 2016).

Adapt a conceptual model: A conceptual model provides a means to describe the relationships among resources and the drivers and stressors that the restoration actions are expected to influence and vice versa (Gentile et al. 2001; Diefenderfer et al. 2016; Kombiadou et al. 2019). Here, a general system conceptual model is proposed to illustrate system components (i.e., identity, function(s), and structure(s)) and their potential interactions (i.e., feedbacks; Figure 2). Conceptual models are a helpful tool to clarify restoration project actions' intended indirect effects (i.e., where feedbacks among system components are assumed following restoration actions) and how adaptive management may be used to redirect projects as needed to ensure intended outcomes are met. The selection of model components and interactions was informed by a literature search for conceptual models used in examples of CEA from restoration and conservation (Davenport et al. 2024); system models from the broader resilience, complex adaptive systems, and panarchy literature (e.g., Holling 1973; Walker et al. 2004; Folke 2006*;* Folke et al. 2010); and applications of systems models to coastal environments (Kombiadou et al. 2019). While not pictured, each of these system components are made of interconnected cycles that influence one another (Holling and Gunderson 2002; Gunderson et al. 2012; Allen et al. 2014). From this general model, resource-specific conceptual models can be developed. This generalized conceptual model can be applied to a CEA by incorporating system-specific components and relationships. The model can include a system identity, geomorphological features and/or natural resources (i.e., structures) and their respective functions, system stressors and drivers, and potential direct or indirect effects (i.e., feedbacks) on target resources. Effects on the system can include changes to structures or functions from restoration, management, and/or conservation efforts. Known system components and their trends can often be found in the scientific literature. A literature search string to find system components could include descriptive terms in three groups: 1) the system of interest; 2) restoration, recovery and/or other relevant processes; and 3) system drivers, stressors and/or changes.

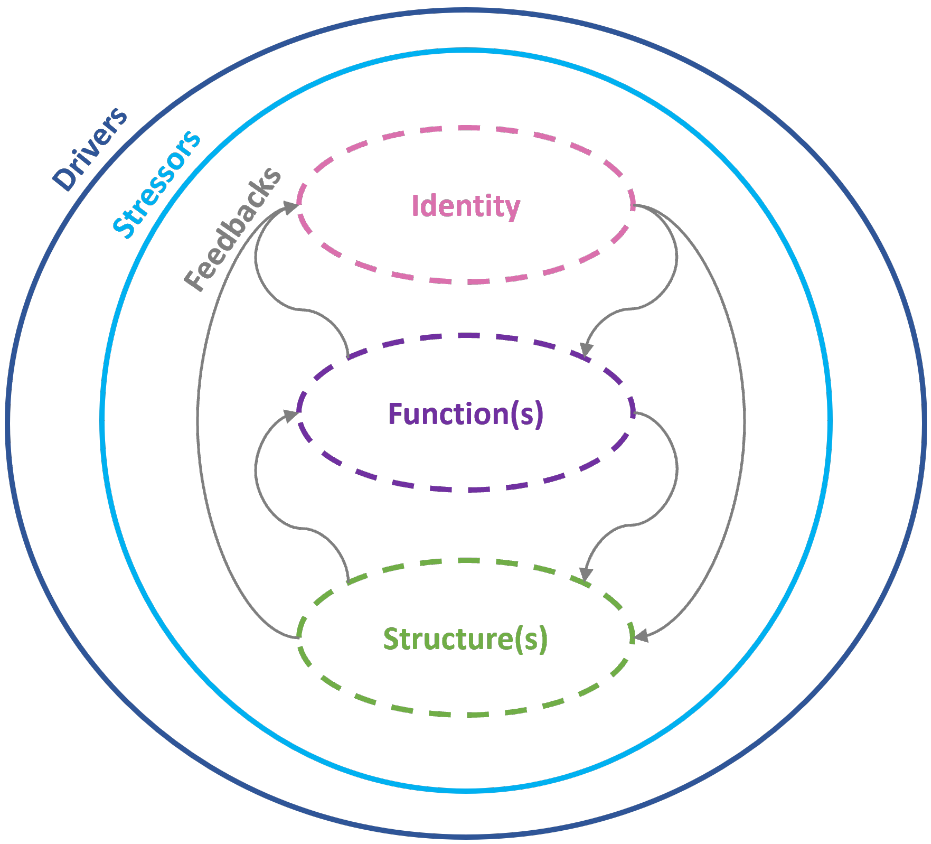

Figure 2. Conceptual model illustrating environmental system components, including identity, function, structure, and relationships (feedbacks) among these components. Drivers and stressors are also shown external to the system but may affect any component. Broadly, we define stressors as disturbances, and drivers as system characteristics, but refer to glossary for complete definitions of all terms. Adapted from Holling and Gunderson (2002).

Assess system understanding and research effort: Information from the literature searches can be used to adapt the generalized conceptual model to the system and visualize system components, including its resources, drivers, and stressors, and the dynamics that connect them. The conceptual model can illustrate how system drivers, stressors, and components (e.g., structures and functions) are connected, what processes may connect them, and how feedbacks may influence change in the system, including potential responses to restoration efforts. Literature from the search that is focused on different system components (structures, functions, and feedbacks) can be documented, known drivers and stressors across structure and function can be identified, and this information can be used to inform the conceptual model and help document how well system components and dynamics are understood. This process can also help identify potentially critical gaps in understanding the system or its drivers and stressors that need to be filled to identify the likelihood for individual or cumulative effects.

B. Define CEA scope: spatiotemporal extent, target resource(s), outcome indicators, and inclusion criteria

The scope of a CEA can vary from a narrow focus on a specific program and/or resource up to an assessment of broad programmatic goals that could include a suite of restoration actions and outcomes. Defining the scope of the CEA includes identifying the spatiotemporal extent of assessment, target resources, goals and outcome indicators, and inclusion criteria *a priori*. Scoping the CEA can also inform the development of a relevant conceptual causal model (Step A) and vice versa, so a revisit (and any necessary refinement) to Step A can be helpful during Step B. Ideally, a best practice would be to make these scoping decisions and plan the CEA before projects begin. When this is not possible, revisiting and connecting each step of the system assessment becomes especially helpful before moving on to parts 3 and 4 of the CEA.

Define spatiotemporal extent: A CEA may target a restoration program focused on a specific region and/or a specific resource or have some other spatiotemporal extent. Delineating the precise spatial and temporal extent of interest helps determine criteria for project inclusion and define outcome metrics for a CEA. In a best-case scenario, a set spatial and time frame may be clear from the intended use of the CEA. If a spatial and temporal frame are not set by the use of the CEA, they need to be clearly defined and may need to be revisited based on other developments of the scoping process. Spatial and temporal frames may have a strong influence on CEAs for coastal or estuarine resources, as the inclusion or exclusion of projects in the upper estuary or further inland may dramatically alter the conclusions just focused on projects in the lower estuary. For example, a CEA targeting an estuarine resource focused only on the estuary might assess restoration projects targeting direct habitat improvements (i.e., marsh restoration), and miss important benefits to the habitat of interest if it fails to incorporate restoration actions focused on upstream or watershed improvements (i.e., run-off mitigation impacting estuarine water quality). Similarly, defining the temporal scale of interest helps to also understand the scope of the CEA: short term pre- and post-restoration monitoring may provide information on immediate resource or region changes potentially attributable to restoration, but may fail to capture both positive or negative longer-term outcomes, or to fully account for background trends, independent of the restoration.

Define target resource(s): Target resources include any natural resources that are the focus of the CEA and may range from highly specific (e.g., a single bird species) to a whole system (e.g., Chesapeake Bay and its tidal tributaries). In a best-case scenario, where a CEA is planned concurrently with restoration efforts, target resources will also be clear from the CEA's intended use. If this is not the case, identifying target resources may help inform all other elements of the CEA scope. CEAs may focus on an individual resource or many, depending on their intended use, and incorporate projects that may have more target resources than the CEA. When restoration programs focus on improving environmental quality across a region, they may represent a wide variety of goals and targeted resources. Regional restoration programs, such as those focused on the Florida Everglades (LoSchiavo et al. 2013; NASEM 2023), Tampa Bay (Beck et al. 2019), the Lower Columbia River and Estuary (Diefenderfer et al. 2016; Ebberts et al. 2018; ERTG 2019), Puget Sound (PSP 2022), and others often include a portfolio of restoration actions; combined, these actions seek to restore overall functioning of a system. Regional restoration programs may have numerous targeted resources that are co-dependent, including living (e.g., birds, vegetation) or non-living (e.g., geomorphological forms like dunes, recreational opportunities, human infrastructure) resources. In contrast, some programs may target restoration of a specific resource, such as the Gulf of Mexico strategic oyster framework which has a primary goal to enhance overall oyster abundance (DWH Trustees 2016).

Identify restoration goals and outcome indicators: Restoration projects to be included in a CEA may be designed to have direct or indirect effects and be focused on many different resources. Thus, the restoration goals and effects to be measured (i.e., the outcome indicators) can take many forms, and restoration goals and outcome indicators need to be clearly defined to explore individual, additive or cumulative (i.e., synergistic or antagonistic) effects of restoration. Goals represent the desired outcomes, and indicators are something quantitative or qualitative that can be measured and assessed relative to the goals. In a best-case scenario, these goals and their respective outcome indicators are also laid out prior to planning and implementing restoration efforts. Where that is not possible, their definitions may help inform all other elements of the CEA scope and may need to be revisited after identification of available data. For natural resources restoration, these goals and their identified indicators can relate to structural aspects of a resource (e.g., acreage restored, abundance or density of plants) or can relate to functional aspects of the resource (e.g., storm surge abatement, reduced sediment movement, density of species using the structure, water quality indicators such as nutrient reduction). For individual projects, these indicators may be collected at project completion and, potentially, for some period after completion. In contrast, for a CEA, these indicators would need to be collected at the spatial and temporal scale(s) identified for the assessment.

Identify inclusion criteria: The development of inclusion criteria documents the decision-making behind inclusion or exclusion of restoration projects and their effects in the analysis. Some questions to consider while developing inclusion criteria are: 1) Will any project be included that has a potential impact on the resource of interest, no matter how indirect? For example, some restoration actions or projects are designed to have direct influences on living resources (e.g., seed restored oyster reefs with aquaculture derived spat to boost oyster abundance). However, other restoration projects could indirectly benefit a target resource without directly manipulating it (e.g., habitat improvements intended to enhance water quality). 2) Will projects with potential short-term negative impacts be included, and will those be considered in the evaluation? 3) Will only projects intended to have a positive impact on the resource(s) of interest be included? These decisions may drastically influence the scope of the effort. To answer these questions, it may be helpful to clearly define the mechanisms behind how projects may influence the focal resource (i.e., define direct and indirect impacts and positive, negative, or neutral impacts), so mechanisms can be applied consistently across projects (i.e., system assessment).

C. Understand restoration effort: project tracking, characteristics, and spatiotemporal distribution

Summarizing restoration projects' availability, characteristics, and spatiotemporal distribution in support of the identified CEA and its intended use and scope help to determine whether the restoration effort supports a CEA for its intended use.

Restoration project availability and tracking: Categorizing the effort and distribution of projects by their intended restoration targets can help determine if a CEA is likely to yield usable results for a given system or resource. In ideal cases, a program's overall restoration goals and restoration approaches are consistently laid out in clear and updated documentation, with funded restoration projects identified (e.g., DWH Trustees 2021) and their basic parameters maintained in an online project tracking database (e.g., NOAA 2024a). Ideally, such a project tracking database would include information to identify the project goals, desired outcomes, time scale of evaluation, specific actions, and location. Without access to such a database, one needs to be created with at least the listed information (project goals, desired outcomes, timing, actions, and location) to track projects and their relevance to the use of the CEA. Regardless of the existence of a prior database, extracting data and maintaining a separate database with CEA-relevant information may be beneficial. For instance, programs may fund projects that support or plan actions, such as research to resolve scientific uncertainties, provision of resources that facilitate further actions, and planning activities. These planning and support projects are typically not expected to contribute directly to cumulative effects, so categorizing them separately can identify input data sources for a CEA and/or ensure all relevant projects are included without double counting. This type of database is rarely developed or maintained. Monitoring may be incomplete or absent even in cases where it was mandated (e.g., Wortley et al. 2013; Blomberg et al. 2018). Therefore, critical data for a CEA may be inaccessible or difficult to discover.

Restoration project characteristics and alignment to the scope and conceptual model: The project database provides information to identify and link project characteristics to the system conceptual model. Specifically, using the conceptual model, characteristics of restoration project actions and outcomes matching conceptual model components, feedbacks, and drivers and stressors can be categorized to help assess potential restoration impacts on the system, or resource of interest. If a project database is not available or the required information is not included, the necessary information can be extracted or inferred where possible using available project information and desired outcomes. Restoration projects may directly or indirectly affect their targeted resources and system components. For example, if the project action and purpose are both to affect the same structure (e.g., replace lost sediment on a beach), then the relationship between action and outcome is direct, and completion of the project can be assumed to have the intended impact on the target resource in the short term if supported by post-restoration data collection. For CEA, this provides a straightforward assessment of restoration impacts by tracking structural extent or integrity through time. In contrast, and perhaps more common, are indirect relationships between restoration actions and focal resources and system components. For example, an indirect project action may alter structure by rebuilding damaged beach habitat but is intended to benefit function by providing nesting habitat for shorebirds. Ideally, project documentation will identify the expected outcomes on resources and the associated system dynamics, which can help support a CEA by facilitating project alignment to a conceptual system model (Diefenderfer et al. 2016). Aligning projects with a conceptual system model can identify which projects have indirect effects, wherein project success relies on feedbacks among system components (e.g., altering dune height to promote vegetation growth), and identify the quality of evidence demonstrating the existence, likelihood, and potential influence of shifting drivers or stressors on processes needed to induce feedbacks. Project alignment to a conceptual model can therefore be used to identify common assumptions and/or identify research gaps in the mechanistic proof or understanding underlying the intended feedbacks.

Assessing project spatiotemporal distribution: A CEA of restoration impacting a region or a resource on the spatial and temporal scales of interest requires understanding the spatiotemporal distribution of relevant projects. Recognized patterns of cumulative effects of large-scale restoration and management rely on spatial and/or temporal relationships and interactions among projects (e.g., space crowding and time crowding; Diefenderfer et al. 2021). Ideally, spatiotemporal data are available through project tracking, enabling the mapping of project footprints (e.g., maximum possible extent) or centroids, and understanding of the intended extent of project effects. If restoration program funding spans many years, binning the projects by their closure year may be beneficial to see spatiotemporal patterns. If multiple target resources are of interest, it may also help to generate separate maps for each resource. Examining these spatiotemporal outcomes is a critical first step to assess the feasibility of cumulative effects and may highlight limited numbers of projects completed (despite high investments), or a spatial distribution limiting a regional or even local CEA.

Summary: System assessment

Identifying gaps in system understanding and restoration effort can help identify specific research studies and/or data that would be highly valuable to improve (or enable) a CEA. Gaps in system understanding and restoration effort could be conceptual (e.g., what are feedback loops between marsh restoration, wave attenuation, sediment deposition, and long-term sustainability with sea-level rise?) or context-specific (e.g., insufficient data have been collected to evaluate the impacts of a specific project on the landscape). Gaps in restoration effort may be present where patterns of accumulation of ecological benefits among projects (e.g., Diefenderfer et al. 2022) are missing, such as limited spatiotemporal overlap among projects targeting similar resources. Several questions may help guide the identification of these gaps: 1) Are there areas lacking mechanistic understanding of drivers and stressors on the resource or system in question? 2) Are there resources for which restoration effort is lower than expected given their stated importance to system function evident in the literature? To identify science-practice gaps, questions may include: 3a) Does the research effort match the needs of the restoration projects? 3b) If feedbacks are necessary for success of many projects for the target resource, are the mechanisms behind these feedbacks known? 4) Does the availability of research on different system components meet the needs created by the frequency of restoration that depends on that information? 5) Will processes needed to connect indirect restoration projects to their intended outcomes be sustained given a changing climate or under other shifting stressors and drivers and how confident is the best available science supporting this conclusion? 6) Is there potential for restoration impacts at spatiotemporal scales larger than a single project? A CEA may be rendered unfeasible if there are substantial gaps in system understanding and/or restoration effort until steps are taken by restoration programs to plan and implement projects with CEA in mind. Targeted research efforts may be able to fill gaps and research questions identified with this process. Gaps that prevent CEA may be more pronounced in situations where CEA (or programmatic review) was not planned alongside restoration. In this case, restoration programs may need to take action to enable CEA, including investment in research that fills gaps in system understanding, or altering the project selection process to ensure spatiotemporal overlap.

Part 3: Compile and explore data

A CEA for a restoration program requires spatially and temporally relevant data to describe the dynamics of the system or resource of focus in relation to the restoration outcome indicators. These data are critical to: 1) assess how restoration efforts affected the target resource(s) (Figure 1 Part 3; Steps D, E, and F); 2) identify if and how restoration altered the trajectory of change and/or drivers and stressors on the system and its components, in the context of background trends in the resources (Figure 1; Steps E and F); and 3) understand how the restoration influenced the potential impact of extreme/discrete events impacting the system or resource of interest (Figure 1; Steps E and F).

D. Project specific monitoring data

Project specific monitoring data are the primary source of information to identify outcomes. Project monitoring data are also critical to assess the effectiveness of restoration actions at the project level and meet basic requirements for tabulating expenditures, actions, and sometimes outcomes. In a best-case scenario, project monitoring data will follow consistent guidelines to be interoperable across projects, measure common metrics (e.g., outcome indicators), and be collected at spatial and temporal scales large and long enough to identify overlaps with proximal projects. As noted above, many large restoration programs have some requirements and/or guidelines related to project accounting, including monitoring project progress and/or outcomes, which should track project outcomes in relation to their goals (i.e., OPA 1990, RESTORE Council 2019; PSEMP 2024; TBEP 2024). While project data availability has increased, including the development of publicly available online project databases (i.e., NOAA 2024a; GRIIDC 2024; CIMS 2024), the accessibility, completeness, and interoperability of data between projects remains challenging to reconcile as project monitoring and reporting requirements tend to be project specific, voluntary, and/or minimally funded (Palmer et al. 2007; Blomberg et al. 2018; Keating et al. 2020; La Peyre et al. 2022). In these cases, it may be necessary to determine the availability of compatible project specific monitoring data to be included in a CEA. Time lags in data availability can occur due to delays in project completion or data management and release protocols, potentially limiting opportunities to track or assess restoration efforts in real time.

E. Regional or focal resource trend data

Regional or resource information that enables tracking changes in resource trajectories beyond spatial and temporal boundaries of individual projects supports CEA. Data that can separate restoration impacts from broader system-wide and long-term background trends are critical to explore restoration effects on identified outcome metrics. Here, data exploration includes determining the availability, location, and spatiotemporal distribution of existing regional monitoring data and programs. Numerous programs exist, such as the U.S. Geological Survey National Water Information System which provides continuous water quality data (USGS 2024a), the Coastwide Reference Monitoring System (CRMS) in Louisiana (CPRA 2024), and the International Union for Conservation of Nature (IUCN) species biodiversity database (speciesmonitoring.org). Determining the spatial and temporal availability of data and aligning it with the defined scope (Step A) of the CEA provides critical data to support a CEA but may require significant effort to collate and assess the interoperability of the datasets, including their extrapolation across the region of interest. A CEA can also use widely available remote sensing data including satellite imagery, aerial imagery, and photogrammetry (e.g., Planet, Worldview-2, Landsat, Sentinel; for complied data see USGS 2024b). The spatial resolution of imagery may vary from sub-meter to tens of meters and have a temporal resolution of days or more (Phinn et al. 2010). Elevation data are typically collected using light detection and ranging (lidar) technology, with temporal resolution of years or more, although spatial resolution can be fine scale (e.g., 0.1 – 1 m; Phinn et al. 2010). Elevation data are often limited in spatial or temporal availability and can have variable quality based on technology and standards at the time of acquisition and/or data available for ground truthing and calibration (Thompson et al. 2017; ASPRS 2023). Thus, remote sensing data may not be available or suitable for CEA focused on temporal changes in structures, given that data may be unavailable on the time scales of interest and/or data collected at a single point in time may reflect short-time scale variability in dynamic coastal systems (e.g., post-storm erosion) rather than long-term trends or the influence of restoration projects. When available at appropriate spatial and temporal resolution, data analyses can be used to collectively assess changes to an area from a storm and assess effects of a restoration project (Thurman et al. 2023) and/or provide other information on how stressors and drivers are impacting an area (Bernier et al. 2021; Siranni et al. 2022).

F. Additional lines of evidence

Data availability from multiple sources is key to CEA to form multiple lines of evidence (Diefenderfer et al. 2016; NASEM 2022; Greening et al. 2023). The compilation and use of additional lines of evidence including but not limited to model results, meta-analyses, the use of machine learning, expert elicitation, and analyses on the target resources outside the assessment location can provide valuable information to inform both background trends in regional resources and identify potential impacts from restoration programs. These analyses can be used to evaluate the "future without action" for the region of interest (i.e., the trajectory if no restoration had occurred) and/or to provide an assessment of the impacts of individual projects to benchmark their cumulative effects. In habitat restoration, common effect scaling models that may be useful are Habitat Equivalency Analysis (HEA), Resource Equivalency Analysis (REA), and related updates (e.g., NOAA 1995; Baker et al. 2020). This type of assessment is particularly relevant to dynamic coastal systems, where the effects of restoration and/or their ecosystem service benefits may include a substantial effect of proactively mitigating the negative future effects of drivers such as sea-level rise (Khalil et al. 2013; Martin et al. 2021). These sources of evidence may be able to be used as is or modified to suit the analysis, but require significant investment, access to code, and understanding of the limitations of each data set or model.

Summary: Compile and Explore Data

Data gaps may be identifiable in the availability, operability, and spatiotemporal overlap of relevant project monitoring data; availability, spatiotemporal distribution, and resolution of larger- or regional-scale data on resource status and trends; and other lines of evidence that help support a CEA. Larger or regional data gaps could be filled by targeted monitoring and data collection efforts supported by restoration funding agencies to enable CEA. While individual researchers may be able to fill some gaps, the scale needed is likely too large to be filled without a coordinated effort. Project specific monitoring data that are inaccessible may be accessed on a case-by-case basis by reaching out to project managers, but this would be a laborious process and may have minimal success. Ultimately, development of project databases that contain accessible monitoring data may need to be intentionally created and maintained to enable a CEA.

Part 4: Connect system dynamics and restoration effort to resource status/trends

CEA of a large-scale restoration program relies on understanding environmental system dynamics to identify the expected impacts of restoration efforts and evaluate their realized effect(s) on the target resource(s) and/or system components. In a changing or dynamic system, these realized effect(s) of restoration also need to be understood in the context of that environmental change. The conceptual system model can be particularly useful to make connections among restoration effort, system components, and system change. Connecting restoration efforts to the model's environmental system components can help to identify expected outcomes of restoration actions, including effects on the structure of the resource (i.e., habitat creation), the function of the focal resource (i.e., habitat provision), and alteration to the drivers and stressors that may affect the resource structure and/or function (Figure 2). This connection process may also help identify where there are expected feedbacks among system components, and whether they may be influenced by drivers and/or stressors differently than separate system components or resources (Figure 2). Where CEA was planned alongside restoration efforts, the process of connecting system dynamics to restoration effort and resource status may be informed by available resources that outline the process (e.g., Diefenderfer et al. 2016). This framework approach, followed during restoration program development, would inform valuable research needs, and help support an integrated large or regional scale restoration program. In the case of planning a CEA after restoration has begun, connecting system dynamics to restoration efforts and resource status/trends can help determine if conducting a CEA is feasible, and/or identify where there are gaps that need to be filled to enable a CEA.

Where CEA is feasible, understanding the cumulative effects of restoration projects, particularly within dynamic systems, may benefit from examining trajectories of change with and without the cumulative influence of restoration programs. A method that may be particularly effective to evaluate resource changes and projected effects is the development of expected trajectories for areas with and without restoration efforts (e.g., Langhammer et al. 2024). Trajectories are often created during the restoration scaling process, and future scenarios with and without action developed during the environmental permitting process (i.e., National Environmental Policy Act, NEPA; Peterson et al. 2003; Baker et al. 2020; Baumann et al. 2020; Carle et al. 2020; CEQ 1997; EPA 1999). These with-and-without restoration trajectories may serve as starting places against which to track restoration progress. Identifying progress related to expected trajectories may include examining compounding effects, indirect effects, changes in landscape pattern, cross-boundary effects, and time lag effects (Diefenderfer et al. 2021), as well as a comparison of effect sizes from meta-analysis (Langhammer et al. 2024). The assessment of project characteristics is key to understanding expected resource trajectories, particularly as some projects may be indirectly related to intended outcomes, or alter structures when functions are the targeted resource (e.g., French McCay and Rowe 2003; French McCay et al. 2003). To fully capture restoration outcomes, all projects that alter a resource or system component, whether directly or indirectly, could be identified and included. Programmatic priorities may also suggest trajectories to examine. For example, if resilience is a programmatic goal for many of the projects targeting a certain resource, comparing an expected to realized trajectory may identify shifts in factors that maintain and/or predict the resilience of that resource in a changing environment (e.g., diversity, redundancy, interconnectedness; Biggs et al. 2012; Biggs et al. 2020; Capdevila et al. 2021).

System exploration, data analysis, and gap identification can help identify outstanding needs to determine trajectories of change and support CEA, including research questions to be answered, data to be collected, and/or needs for a monitoring database. Perhaps more important, filling these gaps may help to inform and improve future restoration efforts and support adaptive management.

Applying the framework: Feasibility of a CEA for *Deepwater Horizon*-funded restoration on barrier islands and shorelines in the north central Gulf of Mexico

Here, the proposed conceptual framework (Figure 1) is applied to explore the potential for a CEA of post-DWH BIS system restoration across the north-central Gulf of Mexico. North-central Gulf of Mexico coastal areas support highly productive fisheries, extensive wetland systems, oil and gas production, and a valuable tourism industry (McKinney et al. 2021). Northern Gulf of Mexico ecosystems are also highly complex and dynamic, facing constantly changing drivers and considerable stressors from extractive industry, climate change, storms, and sea-level rise, among others (NASEM 2018; McKinney et al. 2021). In coastal systems, potential stressors may come from many sources (e.g., anthropogenic development, pollution, resource harvest, storms), act at a variety of spatial scales, result in a variety of outcomes (e.g., habitat loss, changes in water quality or quantity, and resource depletion), and be influenced by climate change and sea-level rise (Lange and Marshall 2017; Ostrowski et al. 2021; Carrier-Belleau et al. 2021; Glibert et al. 2022). Over the past two decades since the largest accidental oil spill in U.S. history — the DWH oil spill in 2010 — our understanding and investment in monitoring, data collection, and restoration efforts of Gulf of Mexico ecosystems have vastly increased (McKinney et al. 2021). Following DWH, a historic settlement and an Act of Congress directed billions of USD toward the restoration of living marine, recreational, and economic resources in the region (DOJ 2015; Ocean Conservancy 2015). This settlement allocated funds for restoration to several agencies, including the DWH Natural Resource Damage Assessment (NRDA, 8.8B USD), RESTORE Council (5.33B USD), and National Fish and Wildlife Foundation (2.54B USD; ELI 2020). Each of these entities has its own set of legislative mandates and/or priorities. Restoration activity from the Natural Resources Damage Assessment (NRDA), authorized by the Oil Pollution Act of 1990, is designed to recover lost or injured natural resources and their use (OPA 1990). The DWH NRDA Co-Trustees developed five broad goals to guide restoration projects of the northern Gulf of Mexico ecosystem. These goals include: 1) restoring and conserving habitat; 2) providing and enhancing recreational opportunities; 3) restoring water quality; 4) replenishing and protecting living coastal and marine resources; and 5) monitoring and adaptive management (DWH Trustees 2021). The northern Gulf of Mexico is an ideal test case for CEA application to inform large-scale restoration given that it is a highly productive region with multiple resources; has numerous, interactive environmental stressors; was significantly impacted by a recent environmental disaster; and is the focus of intense large-scale investments in restoration and recovery with clearly articulated resource and region-wide goals.

Restoration activities funded by the "Resources and Ecosystems Sustainability, Tourist Opportunities, and Revived Economies of the Gulf Coast States Act of 2012" (RESTORE Act of 2012; 31 C.F.R. Part 34) come from several funding components. States and the Gulf Coast Ecosystem Restoration Council (hereafter, "Council") make investment allocation decisions based on contributing to the overall economic and ecological recovery of the Gulf Coast (DOT 2012). Funds allocated directly to states must be led by a science-based planning effort that is approved by the Department of the Treasury or the Council (ELI, RESTORE). Funds are allocated to restore and protect natural resources or to benefit Gulf coastal economies through infrastructure projects, improvements to parks, promotion of tourism, or local seafood consumption (DOT 2012; DOT 2015). DWH restoration funding through the National Fish and Wildlife Foundation is allocated through the Gulf Environmental Benefit Fund (GEBF) for projects benefitting the natural resources of the Gulf Coast that were impacted by the DWH oil spill (GEBF 2024a). Specifically, GEBF funds are awarded to state and local organizations with available expertise to "conserve and enhance coastal habitats, restore beach and dune habitats, protect habitat important to coastal bird species, enhance commercial and recreational fisheries, and increase the capacity of networks to respond to mass stranding events benefiting marine mammals and sea turtles" (GEBF 2024a). Despite the importance of the region's natural resources and recent investments in restoration, CEA focused on understanding the impacts of the DWH funded restoration efforts has been limited (Greening et al. 2023).

Part 1: Use of the CEA

Given the presence of several large-scale restoration programs in the northern Gulf of Mexico, a CEA could be used to assess the trajectories of key resources of interest (identified as restoration priorities) with and without the cumulative effects of the restoration programs. Plans for CEA were not made in advance of DWH restoration planning and implementation, although the three major funding programs (DWH NRDA, RESTORE Council, and the NFWF Gulf Environmental Benefit Fund) do articulate programmatic priorities and restoration goals. These priorities include specific targets for resources (e.g., geomorphological structures, habitats, species, and recreational opportunities) affected by the DWH oil spill, including those found on barrier island and barrier shoreline systems (BIS), a key ecosystem supporting habitats, species and human activities within the region. Here, we explore CEA focused on BIS restoration activities and outcomes.

We selected BIS in the north-central Gulf of Mexico as this location contains over 270 environmental restoration projects that are in progress or were completed as of March 2022 (Davenport et al. 2024). The concentration of projects suggests the potential to result in cumulative spatial clustering effects (sensu Diefenderfer et al. 2021). In addition, this area has characteristics that are typical of large-scale restoration programs (articulated restoration priorities and associated project-specific monitoring; absence of planning specifically for CEA; focus across a broad range of trust resources including recreational access, migratory birds, and threatened and endangered species; etc.), making it a good case study for testing the practical applicability of the developed CEA framework.

Several restoration priorities articulated in the regional restoration planning and tracking documents are relevant to BIS in this area, including restoration of the beaches, dunes, and islands; coastal resilience; and fish and wildlife that use the coastal habitats (DWH Trustees 2016; RESTORE Council 2016; FWCC/FLDEP 2024; GEBF 2024b). We summarized programmatic goals (Table 1) into the following: 1) protect and maintain geomorphological structures on barrier islands, including beaches, dunes, wetlands and marshes and their functions including support of habitats (e.g., supratidal dune vegetation, backbarrier marshes) and species (e.g., coastal birds, sea turtles, beach mice); 2) protect and maintain estuarine resources within the lagoon systems created by a barrier island (e.g., fishes, oysters and reefs, submerged aquatic vegetation, water quality and quantity); 3) provide recreational opportunities, through the availability and function of recreational facilities; 4) provision and update of infrastructure that protects the integrity of healthy ecosystems; and 5) ensure ecosystem resilience to stressors. Although resilience is identified as a programmatic goal and project purpose associated with DWH-funded restoration in this area (DWH Trustees 2016; RESTORE Council 2016; FWCC/FLDEP 2024; GEBF 2024b), there is little agreement on how to define resilience or what constitutes a resilient system in practice. This lack of clarity makes project-specific definitions and interpretations critical to identifying metrics that measure progress toward resilience difficult. Without definitions of resilience or project-level interpretations available from the funders, we were unable to establish outcome indicators to match the broad resilience-related goals. Given our intent is to broadly assess feasibility of CEA, rather than focus on a single resource or system component, we included only the first four of these programmatic goals in our evaluation.

Table 1. Programmatic goals for a Cumulative Effects Assessment for a barrier island and shorelines (BIS) study area within the north-central Gulf of Mexico.

Goal	Description
1	Protect and maintain geomorphological structures on barrier islands, including beaches, dunes, wetlands and marshes and their functions including support of habitats (e.g., supratidal dune vegetation, backbarrier marshes) and species (e.g., coastal birds, sea turtles, beach mice)
2	Protect and maintain estuarine resources within the lagoon systems created by a barrier island (e.g., fishes, oysters and reefs, submerged aquatic vegetation, water quality and quantity)
3	Provide recreational opportunities, through the availability and function of recreational facilities
4	Provision and update of infrastructure that protects the integrity of healthy ecosystems
5	Promote ecosystem resilience to stressors.

Part 2: System assessment of barrier island and shoreline systems in the northern Gulf of Mexico

A. Understand system dynamics: develop conceptual model and assess research effort

BIS system components, including structures, functions, and the feedbacks among these components are well conceptualized in the literature (Kombiadou et al. 2019). BIS structures (Figure 3) are the geomorphological features of the system, including the mainland coast; the lagoon, bay and marsh separating the barrier island from the mainland; the subaerial barrier (i.e., dunes, beach, and supratidal vegetation); and the subaqueous nearshore platform, including the shoreface and tidal inlets (Davidson-Arnott 2009). The functions performed include supporting habitats, species, and anthropogenic activities, as well as providing storm wave and surge abatement (i.e., storm protection and sheltering; Moore and Murray 2018). The identity of a BIS is "a strip of sand and/or gravel, backed by a shallow coastal bay, separated wholly or partly from the mainland shore" (Davidson-Arnott 2009). BIS are highly dynamic and subject to changes from human development, storms, sea-level rise, sediment budgets, and climate change (Plant and Stockdon 2012; Stallins and Corenblit 2018; Passeri et al. 2020; Enwright et al. 2021). For example, both chronic and discrete drivers and stressors including coastal urbanization and climate change impact BIS geomorphology and system dynamics (Enwright et al. 2017). BIS within the northern Gulf of Mexico are also frequently shaped by discrete hurricane, tropical storm, extratropical storm, and pollution events (Grzegorzewski et al. 2011; Moore et al. 2014; Dalyander et al. 2020). A literature review focused on identifying BIS drivers and stressors identified 937 publications (Davenport et al. 2024). This research was explored to develop the conceptual model and assess system understanding (Figure 3).

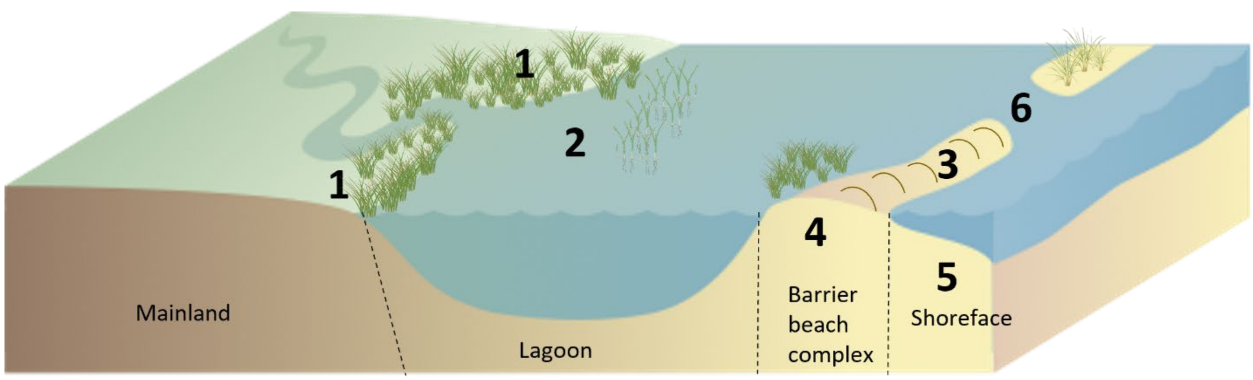

Figure 3. Conceptual diagram of barrier island system structures with the structural components labeled as follows: 1) mainland coast (including tidal creeks, rivers, tidal flats, and marshes), 2) lagoon, bay, and/or marsh separating the barrier islands from the mainland (may include emergent or submerged aquatic vegetation), 3) subaerial barrier (including dunes, beaches, and subaerial supratidal vegetation), 4) subaqueous sediment platform, 5) shoreface, and 6) tidal inlets and their associated deltas. Adapted from graphics provided by the Integration and Application Network at the University of Maryland Center for Environmental Science (https://ian.umces.edu/).

Adapt a conceptual model: We identified terms to adapt the conceptual model (Figure 2) to BIS systems (Table 2) using the literature review (Davenport et al. 2024). The literature review identified key functions as supporting habitats, species and anthropogenic activities and providing storm protection (Davenport et al. 2024). Over 30 different words were used to describe drivers and stressors on BIS, and included coastal physical and biological processes, climate and anthropogenic activity, storms/hurricanes, sea-level rise, pollutants, anthropogenic development, subsidence, sediment flux or transport, and human activities, including restoration activities (Table 1; Davenport et al. 2024).

Table 2. List of barrier island/barrier shoreline system components represented in the conceptual model, and the programmatic restoration goals (Table 1) linked to each component. Functions and structures as listed in Kombiadou et al. (2019).

Identity	Functions	Structures
A system composed of interacting structures (including a strip of sand and/or gravel, backed by a shallow coastal bay, separated wholly or partly from the mainland shore) that performs the listed key functions (Adapted from Stutz and Pilkey 2002). **Goals 1, 2, 3, 4**	Support habitats, species, and anthropogenic activities **Goals 1, 2, 3, 4**	Mainland coast **Goal 1**
	Storm protection and sheltering **Goals 1, 2, 3, 4**	Lagoon, bay and marsh separating the barrier island from the mainland **Goal 1**
		Subaerial barrier **Goal 1**
		Subaqueous sediment platform **Goal 1**
		Shoreface **Goal 1**
		Tidal inlets and deltas **Goal 1**

Assess system understanding and research effort. Research effort and scientific understanding were assessed by identifying the topics of study for the top third (313) most relevant records from the literature search on BIS drivers and stressors (Davenport et al. 2024). Research studies focused predominantly on sediment and its movement, including overwash and erosion processes (Table 3), with a significant focus on the relationship and feedbacks between storms and sediment movements (Figure 4a). Among both stressors/drivers and system components, the research output is heavily skewed toward studies of the impacts of stressors on barrier island and shoreline structures, especially the sub-aerial barrier, with significantly fewer studies exploring function (Figure 4b). Drivers and stressors other than storms, sea-level rise, and sediment movement were infrequently the topic of study, suggesting that either these drivers and stressors are overwhelmingly controlling BIS structure and function, or that there is a key information gap to connect drivers and stressors to function (Figure 4b). As a result, our system understanding is tilted towards management of BIS systems (i.e., structure) during storm events, with less information to drive restoration efforts targeting function.

Define spatiotemporal extent: We selected BIS along the north central Gulf of Mexico coast as it has been a focal system for initial and ongoing restoration over the past 13 years, with substantial investments made early in the DWH restoration process (DWH Trustees 2021; Figure 5). To delineate our case study site spatially, we selected USGS hydrologic unit code (HUC) level-10 watersheds (USGS 2024c) that were on or adjacent to BIS from Dauphin Island, AL to Bald Point State Park, FL.

Table 3. List of drivers and stressors identified as the topics of study in barrier island/barrier shoreline literature review, along with their frequency. Only terms used three or more times were retained.

Drivers	Frequency	Stressors	Frequency
Sediment (budget, flux, management)	17	Storms	111
Overwash	9	Sea-level rise	86
Species management	6	Erosion	19
Topography / Elevation	4	Anthropogenic activity / development	15
Land characteristics and/or loss	4	Restoration	10
Habitat type	4	Sediment limitation	8
Inlet width / migration	4	Overwash	6
Dune (height, loss)	3	Flooding	6
Migration (island, species)	3	Subsidence	5
Climate change	3	Climate change	5
		Habitat degradation	5
		Predation (e.g., of nests, native species)	5

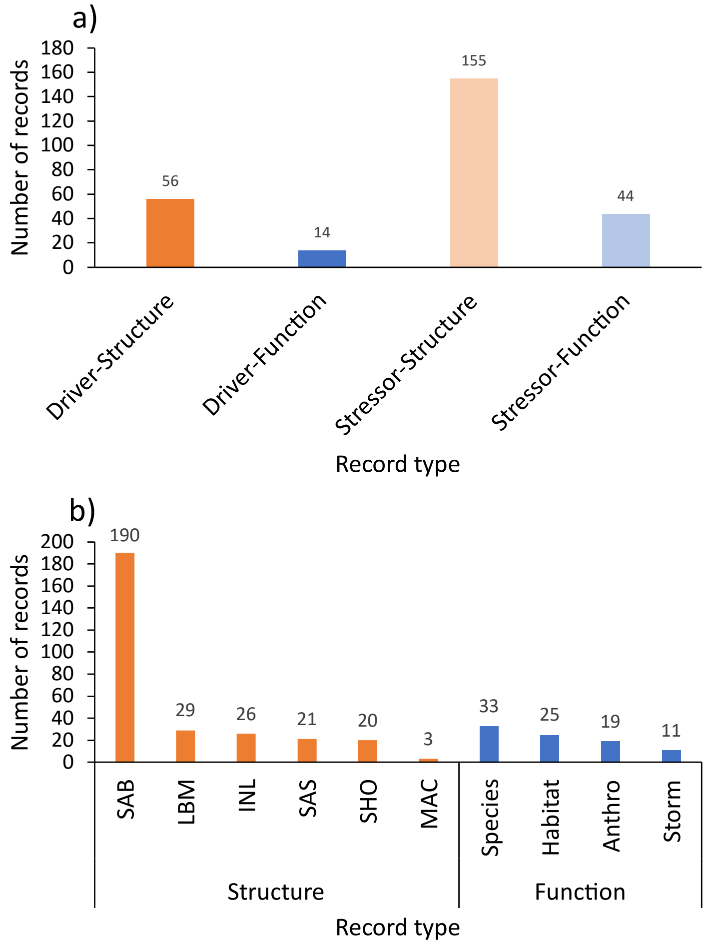

Figure 4. Number of records from the literature search for drivers and stressors on barrier island and shoreline systems within the 313 records screened (the top third of all 937 records sorted by relevance). a) Records grouped by their examination of each system component (function, structure, or both). b) Records grouped by their examination of specific types of structural aspects, including the six structural components of barrier island systems in orange ("SAB": subaerial barrier; "LBM": lagoon/bay/marsh; "INL" tidal inlets; "SAS": subaqueous sediments, "SHO": shoreface, and "MAC": mainland coast) and functional aspects, including support functions (i.e. support of species, habitats, and anthropogenic activities; "Species", "Habitat", and "Anthro") and storm protection and sheltering functions ("Storm"; system components as defined by Kombiadou et al. 2019).

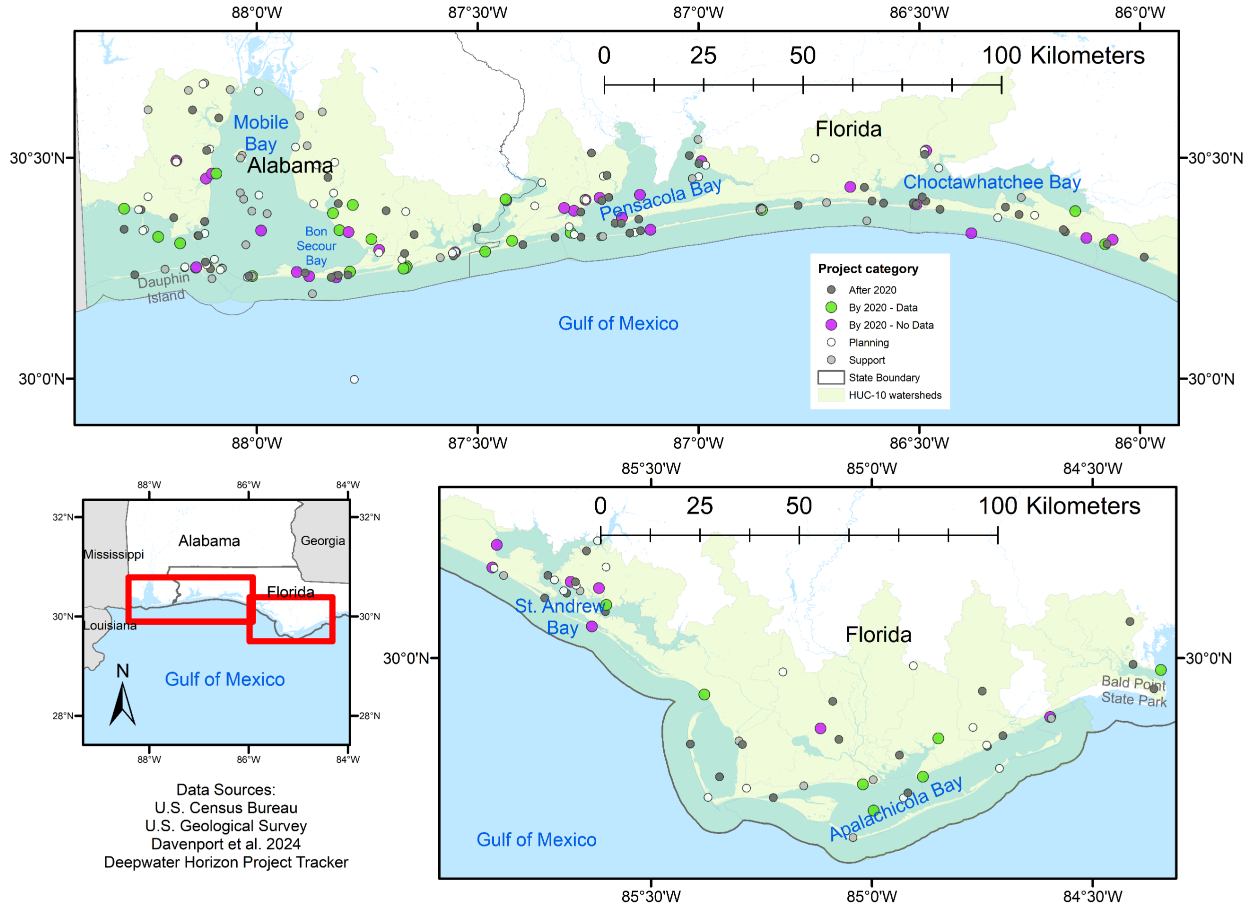

Figure 5. Map of project centroids identified as part of the *Deepwater Horizon* restoration program to address impacts from the 2010 *Deepwater Horizon* oil spill within selected HUC-10 watersheds that represent the study area boundary. Projects were extracted from the *Deepwater Horizon* Project Tracker (DU/GOMA/TPL 2024b) on March 23, 2022. Points represent all individual projects within the study site color-coded by whether restoration, conservation, and/or management projects will be completed after 2020 (black), or before 2020, and have available monitoring data (green) or not (purple). Projects in white and gray represent planning and support efforts, respectively; these are shown to capture the full extent of investment, but are not restoration, conservation and/or management actions. Red boxes show the extent of the larger maps. Data sources: *Deepwater Horizon* Project Tracker, U.S. Geological Survey and U.S. Census Bureau.

B. Define CEA scope: spatiotemporal extent, target resource(s), outcome indicators, and inclusion criteria

Define target resource(s): BIS systems provide ecosystem functions and services, and so their associated restoration projects include a variety of potential target resources. These resources include recreational opportunities, infrastructure, beaches and dunes (on barrier islands and shorelines or the mainland coast), wetlands and marshes (which may also be located on barrier islands and shorelines or the mainland coast), submerged aquatic vegetation, fish and wildlife species and their habitats (e.g., coastal birds, sea turtles, beach mice, fish, oysters), and water quality and quantity.

Identify restoration goals and outcome indicators: Potential outcome indicators for CEA by goal include the following. For goal 1, barrier island structures and functions: 1) metrics that capture the structure of the barrier islands, including potential change component analysis (i.e., net gain/loss of dune habitats) and barrier island migration (Enwright et al. 2021); 2) metrics that capture the storm protection and sheltering function of barrier islands, including flood risk mitigation using water level modeling (Passeri et al. 2020); 3) metrics that capture the supporting habitats, species, and anthropogenic activities function of barrier islands, including dune vegetation or backbarrier marsh percent cover, number of sea turtle nests and nesting success rate, beach mouse population size, population size of coastal wetland birds by species or guild, or recreational activity (see goal 3 for more detail). For goal 2, estuarine resources, outcome indicators may include the maintenance of fish and invertebrate biodiversity, recreational and/or commercial fish catch, structured habitats (e.g. oyster reefs), and more. For goal 3, recreational opportunities, outcome indicators may include recreational use and availability, economic growth opportunities, a shift in revealed preferences among activities, and more. For goal 4, provision of infrastructure to manage healthy ecosystems, outcome indicators may include water quality (environmental or drinking water), fish and wildlife community health, and more.

Identify inclusion criteria: Only projects with intended effects on the resource of interest (i.e., effects of restoration, management and/or conservation), both direct and indirect, were included in this case study application of the CEA workflow. Additionally, projects in phases prior to implementation (e.g. planning, engineering and design) were retained in the database for reference, but we excluded them from the case study.

C. Understand restoration effort: project tracking, characteristics, and spatiotemporal distribution

Restoration project availability and tracking. We obtained all projects within our spatiotemporal extent from the DWH Project Tracker (DU/GOMA/TPL 2024b; accessed 3/23/2022) at any stage of development (e.g., planning, implementation, post-implementation monitoring, etc.). We extracted all projects in the tracker that were identified as within the case study area (277 projects) from 2010 through March 23, 2022. The DWH Project Tracker is an extensive and helpful resource that summarizes project information across all DWH-funded programs, including a unique project identifier, project name, location, what was done, restoration cost, funder, and links to publicly available documentation in a common location and format to the degree it is publicly available, in addition to providing links to additional project information from other sources (DU/GOMA/TPL 2024b*;* NOAA 2024a). Although several project databases for *Deepwater Horizon* projects provide publicly available project information and documentation, including the DWH Project Tracker and the National Oceanic and Atmospheric Administration (NOAA) DIVER database (DU/GOMA/TPL 2024b*;* NOAA 2024a), critical information to inform a CEA is often contained in text strings or across multiple documents. We therefore used the DWH Tracker and other data sources to create our own restoration project database including spatial footprint, closure year, stated actions, stated purpose, targeted resources, and system components affected (for a comprehensive list of all fields in the database, see Davenport et al. 2024). We were not able to locate conceptual models or underlying assumptions in the publicly available documentation for projects within our case study that included, for example, system and restoration feedbacks required for project success. We therefore used publicly available information and documentation for each project to identify project actions, goals, and target resources based on the activities outlined in the project description, then identified where actions and goals required feedbacks across system components to achieve success.

Several projects included multiple project actions, with unique actions, purposes, and target resources. We assigned each independent project action a separate line in the database along with an action type (i.e., restoration, conservation, management, support, planning, unfeasible, not applicable). Some projects not applicable to our CEA were included in the extraction from the DWH Project Tracker and were retained in the database (e.g., projects with economic benefits only, projects outside the area that may have been erroneously labeled, and projects deemed unfeasible; Davenport et al. 2024). There are 291 unique project actions among the 277 projects.

Restoration project characteristics and alignment to the programmatic goals: To understand the distribution of restoration effort relevant to our CEA, we assessed the distribution of the 291 unique restoration project actions across action type, and for implemented project actions (restoration, conservation, and/or management) we evaluated the system component and resources targeted by the actions (Figure 6). Just over half of the project actions (54%; 157) were implemented; 41% were in the planning stage or were supporting actions, and 5% were not applicable to our analyses (Figure 6). Over a dozen target resources were identified among projects in the case study area (Davenport et al. 2024). The 157 active restoration, conservation, and management projects were further categorized by programmatic goal and target resource, noting that many actions had intended effects on multiple goals and/or resources (Figure 7). The majority of actions (57%) targeted infrastructure (goal 4) followed by recreational resources (goal 3; 40%); all other resources were represented in 24% or less of project actions (Figure 7).

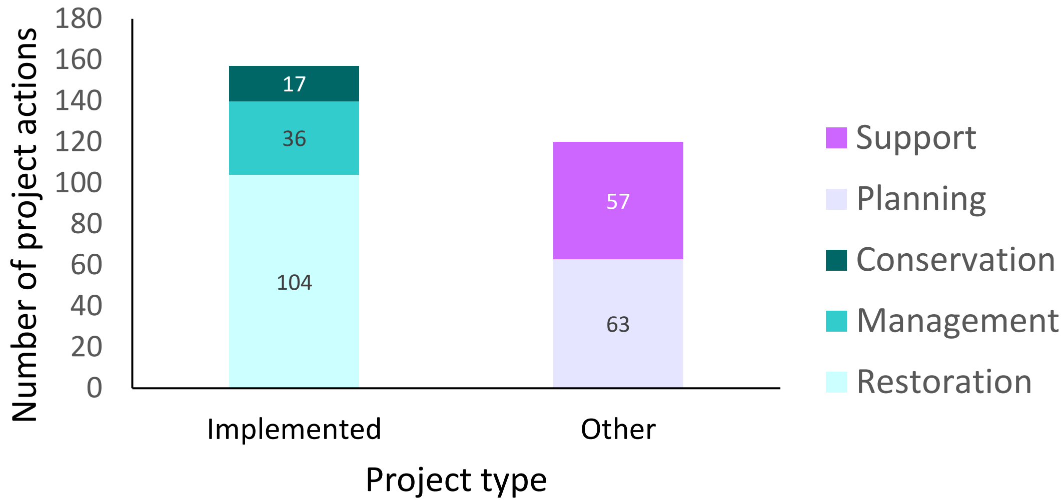

Figure 6. Distribution of restoration project actions associated with the *Deepwater Horizon* oil spill grouped by type, including implemented restoration, conservation, and/or management, and other actions. Out of the 277 identified projects there were 291 unique project actions of which 157 project actions that were implemented, with the remaining involving planning, support or other activities. Restoration actions fix, repair, or replace a damaged or loss resource. Conservation actions prevent the loss or further damage to a resource. Management actions change the way/rate at which a resource is managed or used (or sustains regular use or damage/pollution), change human behavior, and/or change access to a resource. Planning refers to the development of plans for future actions. Support refers to actions or data collection intended to support restoration, or adaptive management of other actions.

Assessing project spatiotemporal distribution: To assess the spatiotemporal distribution of project actions and explore potential clustering effects (sensu Diefenderfer et al. 2021), projects were mapped using the location information (X and Y coordinates) included in the DWH project tracker by their completion dates, and binned into five-year increments (ending in zero or five). Information on the expected extent of project impacts was not clear, so our mapping effort reflects points rather than polygons. We selected five-year bins because the annual distribution of projects demonstrated little spatial and temporal clustering, and we assumed projects were intended to function at least five years after their completion year. Projects were distributed in space and time across the study area (Figure 8). Based on completed projects (2020 or earlier), two areas showed a higher density of projects: Pensacola Bay, FL and Bon Secour Bay, AL regions (Figure 8). Based on planned projects, St. Andrew Bay, FL and Dauphin Island, AL will likely have clusters of projects in the future.

We also mapped projects in the five-year time bins to show their spatiotemporal distribution among the following programmatic goals and target resources: Goal 1 – Wetlands and marshes, Beaches and dunes, Birds and their habitat, Sea turtles and their habitat (Figures 8b-e); Goal 3 – Recreational resources (Figure 8f); Goal 4 – Infrastructure (Figure 8g). The distribution of projects grouped by their intended targeted resources is sparse; for projects completed by 2020, only wetland and marsh projects along the northern shoreline of Bon Secour Bay appear to have the potential for spatial clustering effects (Figure 8b). The distribution of projects completed by 2020 that were focused on other target resources within Goal 1 do not show the potential for spatial clustering effects or spatiotemporal overlap (Figures 8b-e). Future projects (completed by 2021 or after) targeting recreational resources are clustered at the mouths of Choctawhatchee and St. Andrew Bays (Figure 8f). Future projects (completed by 2021 or after) targeting infrastructure are clustered at the mouths of Pensacola and Choctawhatchee Bays (Figure 8g).

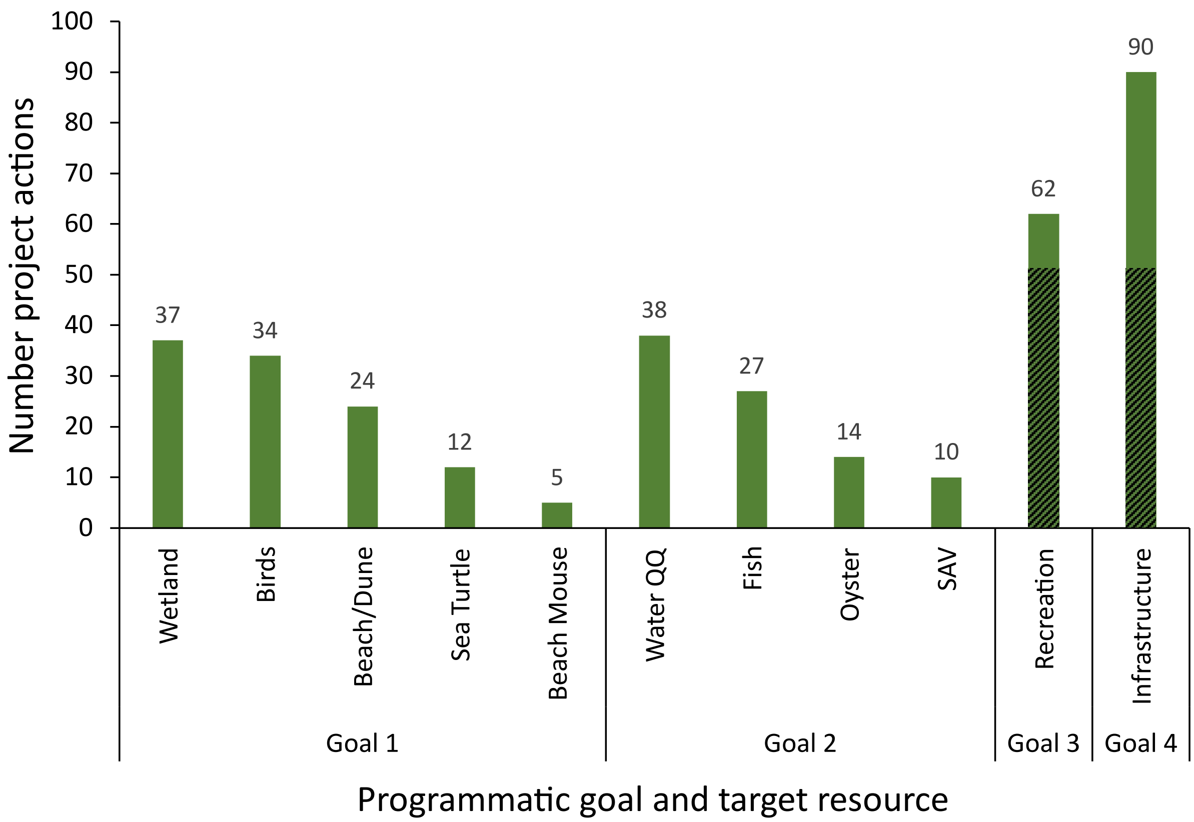

Figure 7. Distribution of the number of project actions associated with the *Deepwater Horizon* oil spill with intended effects among four programmatic goals and eleven commonly targeted resources. Cross-hatched areas for infrastructure and recreation represent project actions that target both these resources. Wetland = wetlands and marshes, Birds = coastal birds and/or their habitats, Water QQ = water quantity and/or quality, Fish = fishes and/or their habitats, Oyster = oysters and/or reefs, SAV = submerged aquatic vegetation. Goal refers to programmatic restoration goals (Table 1), in short: Goal 1 – barrier island structures and functions; Goal 2 – estuarine resources; Goal 3 – recreational opportunities; Goal 4 – Infrastructure. Note that some wetland and bird projects are also relevant to goal 2.

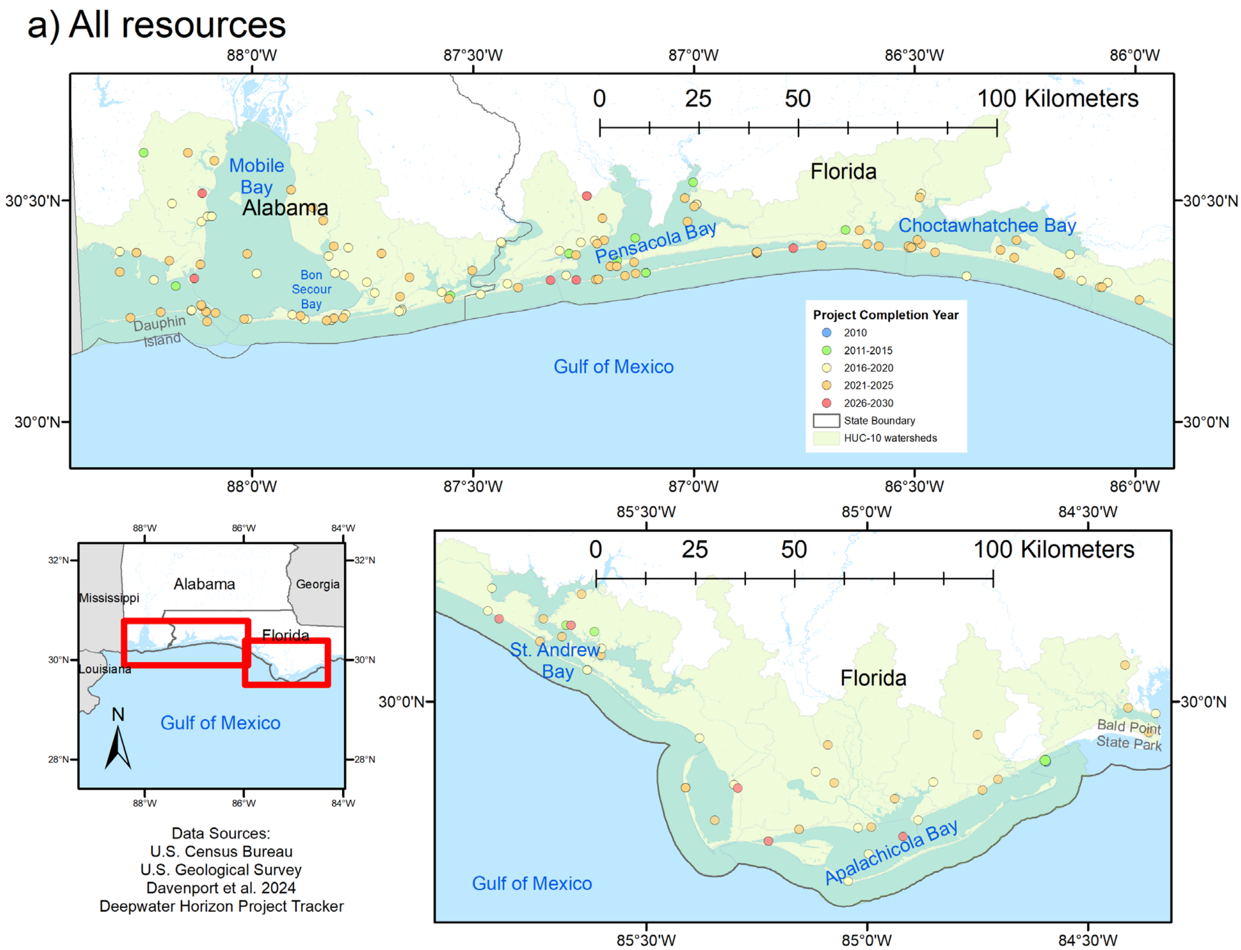

Figure 8. Map of restoration, conservation, and/or management project centroids identified as part of the *Deepwater Horizon* restoration program to address impacts from the 2010 *Deepwater Horizon* oil spill within selected U.S. Geological Survey hydrologic unit code (HUC)-10 watersheds that represent the study area boundary. Projects were extracted from the *Deepwater Horizon* Project Tracker (DU/GOMA/TPL 2024b) on March 23, 2022. Points represent individual projects within the study site color-coded by their reported or anticipated completion date within 5-year bins ending in -0 or -5. Red boxes show the extent of the larger maps. **Figure 8a:** Projects from all programmatic goals and target resources combined. **Figures 8b-g** are maps of projects categorized by programmatic goal (Figure 7) and/or target resource. b) Wetland and marsh habitats (goals 1 and 2). c) Beaches and dunes (goal 1). d) Birds and/or their habitat (goals 1 and 2). e) Sea turtles and/or their habitat. f) Recreational resources (goal 3). g) Infrastructure. Data sources: *Deepwater Horizon* Project Tracker, U.S. Geological Survey and U.S. Census Bureau, Davenport et al. (2024b).

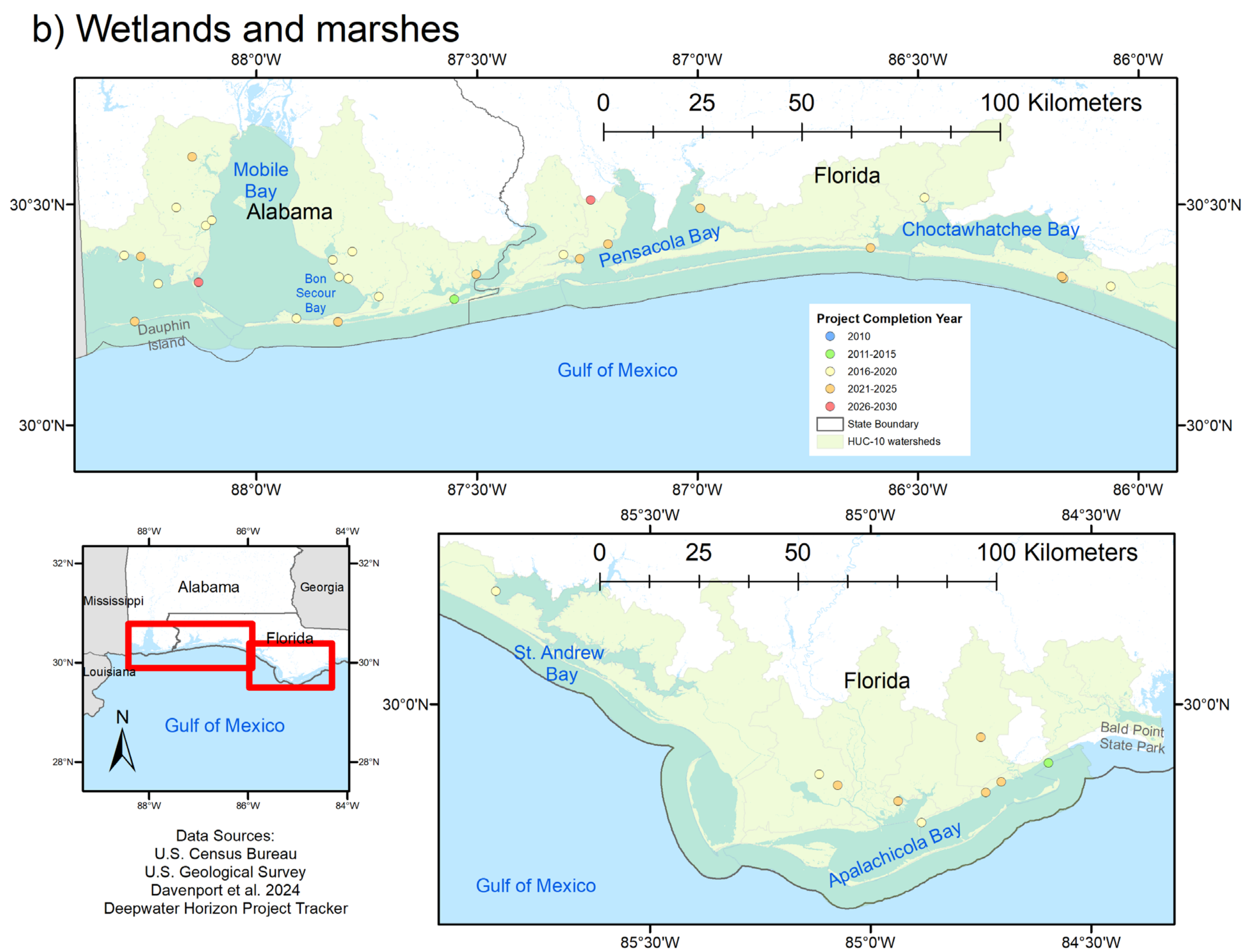

Figure 8. Map of restoration, conservation, and/or management project centroids identified as part of the *Deepwater Horizon* restoration program to address impacts from the 2010 *Deepwater Horizon* oil spill within selected U.S. Geological Survey hydrologic unit code (HUC)-10 watersheds that represent the study area boundary. Projects were extracted from the *Deepwater Horizon* Project Tracker (DU/GOMA/TPL 2024b) on March 23, 2022. Points represent individual projects within the study site color-coded by their reported or anticipated completion date within 5-year bins ending in -0 or -5. Red boxes show the extent of the larger maps. **Figure 8a:** Projects from all programmatic goals and target resources combined. **Figures 8b-g** are maps of projects categorized by programmatic goal (Figure 7) and/or target resource. b) Wetland and marsh habitats (goals 1 and 2). c) Beaches and dunes (goal 1). d) Birds and/or their habitat (goals 1 and 2). e) Sea turtles and/or their habitat. f) Recreational resources (goal 3). g) Infrastructure. Data sources: *Deepwater Horizon* Project Tracker, U.S. Geological Survey and U.S. Census Bureau, Davenport et al. (2024b).

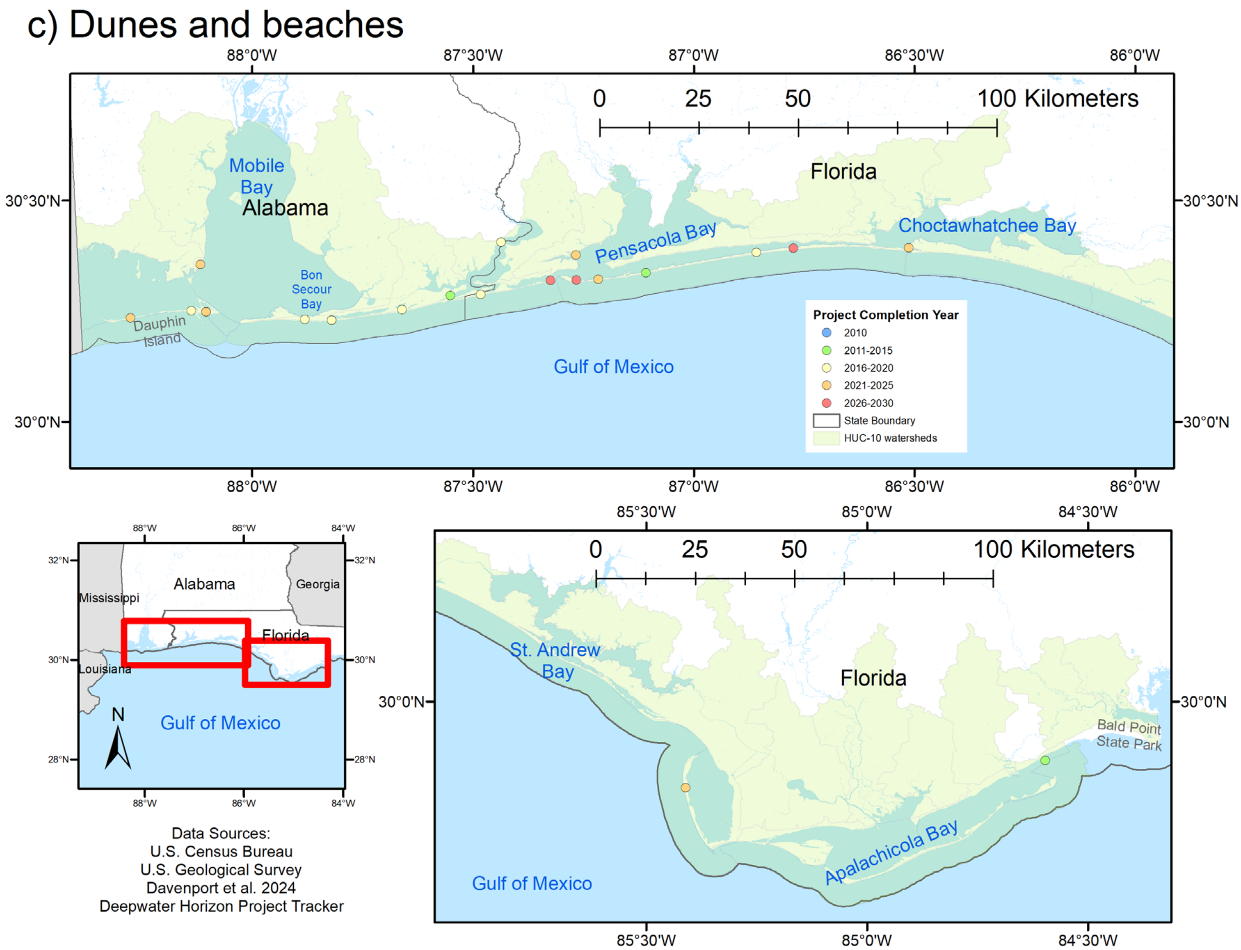

Figure 8. Map of restoration, conservation, and/or management project centroids identified as part of the *Deepwater Horizon* restoration program to address impacts from the 2010 *Deepwater Horizon* oil spill within selected U.S. Geological Survey hydrologic unit code (HUC)-10 watersheds that represent the study area boundary. Projects were extracted from the *Deepwater Horizon* Project Tracker (DU/GOMA/TPL 2024b) on March 23, 2022. Points represent individual projects within the study site color-coded by their reported or anticipated completion date within 5-year bins ending in -0 or -5. Red boxes show the extent of the larger maps. **Figure 8a**: Projects from all programmatic goals and target resources combined. **Figures 8b-g** are maps of projects categorized by programmatic goal (Figure 7) and/or target resource. b) Wetland and marsh habitats (goals 1 and 2). c) Beaches and dunes (goal 1). d) Birds and/or their habitat (goals 1 and 2). e) Sea turtles and/or their habitat. f) Recreational resources (goal 3). g) Infrastructure. Data sources: *Deepwater Horizon* Project Tracker, U.S. Geological Survey and U.S. Census Bureau, Davenport et al. (2024b).

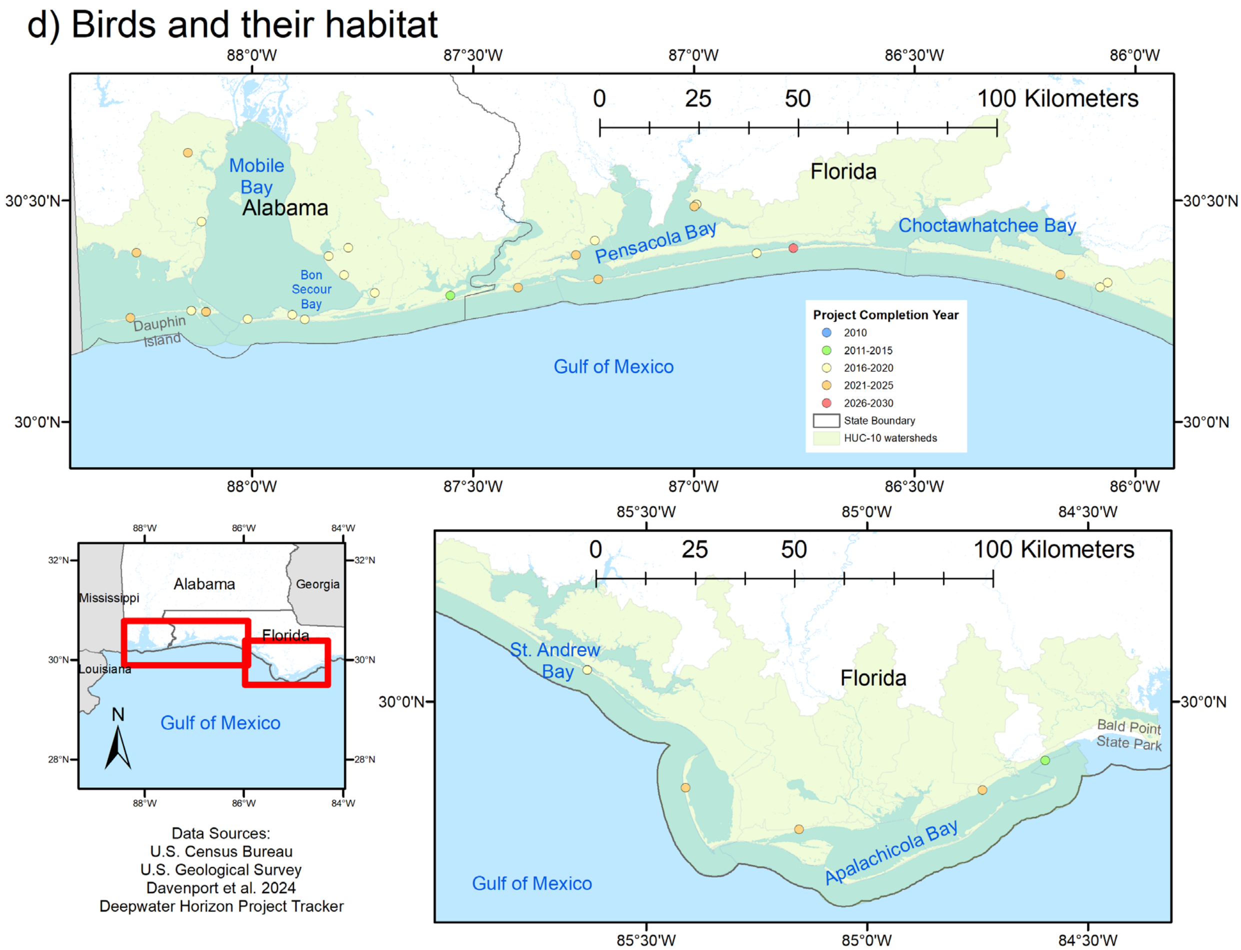

Figure 8. Map of restoration, conservation, and/or management project centroids identified as part of the *Deepwater Horizon* restoration program to address impacts from the 2010 *Deepwater Horizon* oil spill within selected U.S. Geological Survey hydrologic unit code (HUC)-10 watersheds that represent the study area boundary. Projects were extracted from the *Deepwater Horizon* Project Tracker (DU/GOMA/TPL 2024b) on March 23, 2022. Points represent individual projects within the study site color-coded by their reported or anticipated completion date within 5-year bins ending in -0 or -5. Red boxes show the extent of the larger maps. **Figure 8a:** Projects from all programmatic goals and target resources combined. **Figures 8b-g** are maps of projects categorized by programmatic goal (Figure 7) and/or target resource. b) Wetland and marsh habitats (goals 1 and 2). c) Beaches and dunes (goal 1). d) Birds and/or their habitat (goals 1 and 2). e) Sea turtles and/or their habitat. f) Recreational resources (goal 3). g) Infrastructure. Data sources: *Deepwater Horizon* Project Tracker, U.S. Geological Survey and U.S. Census Bureau, Davenport et al. (2024b).

e) Sea turtles and their habitat

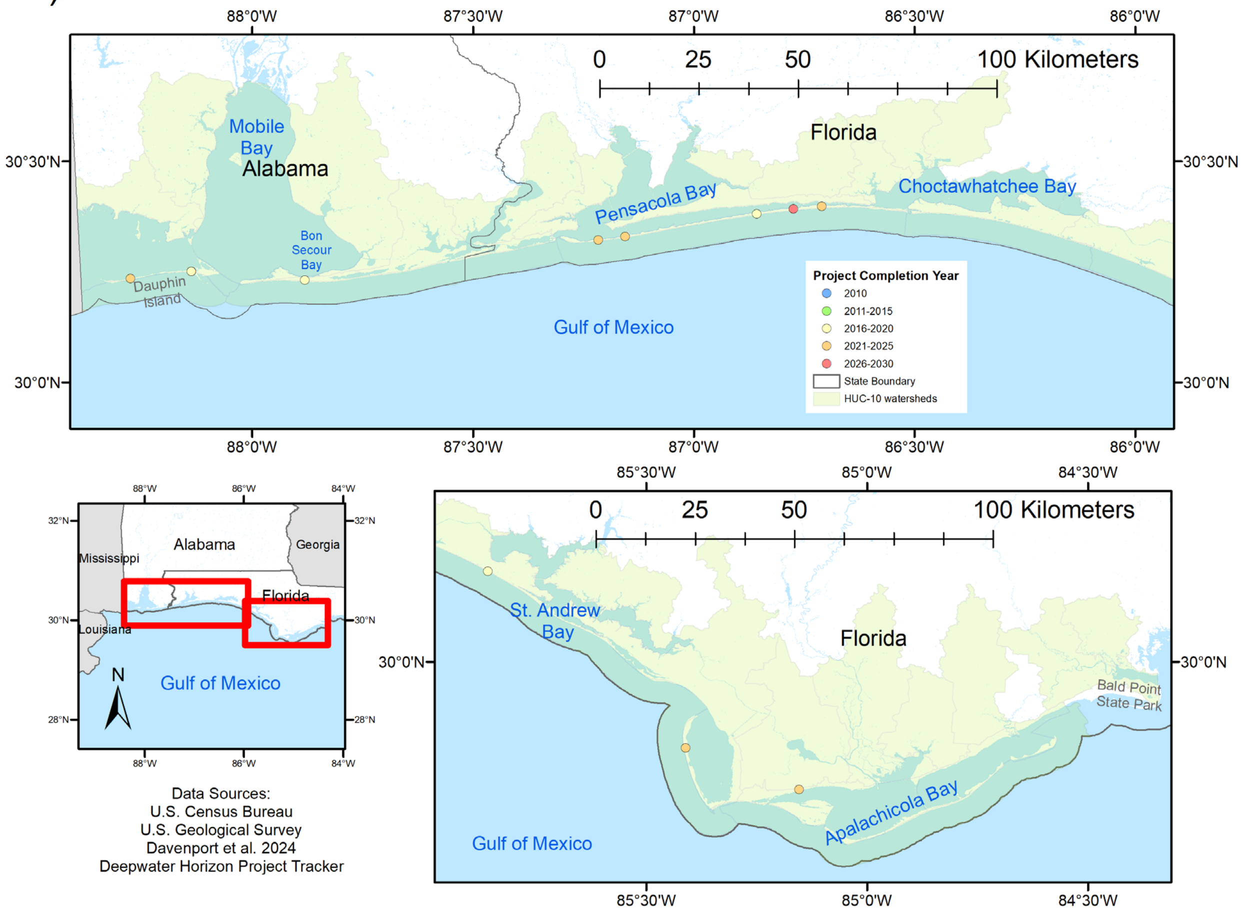

Figure 8. Map of restoration, conservation, and/or management project centroids identified as part of the *Deepwater Horizon* restoration program to address impacts from the 2010 *Deepwater Horizon* oil spill within selected U.S. Geological Survey hydrologic unit code (HUC)-10 watersheds that represent the study area boundary. Projects were extracted from the *Deepwater Horizon* Project Tracker (DU/GOMA/TPL 2024b) on March 23, 2022. Points represent individual projects within the study site color-coded by their reported or anticipated completion date within 5-year bins ending in -0 or -5. Red boxes show the extent of the larger maps. **Figure 8a:** Projects from all programmatic goals and target resources combined. **Figures 8b-g** are maps of projects categorized by programmatic goal (Figure 7) and/or target resource. b) Wetland and marsh habitats (goals 1 and 2). c) Beaches and dunes (goal 1). d) Birds and/or their habitat (goals 1 and 2). e) Sea turtles and/or their habitat. f) Recreational resources (goal 3). g) Infrastructure. Data sources: *Deepwater Horizon* Project Tracker, U.S. Geological Survey and U.S. Census Bureau, Davenport et al. (2024b).

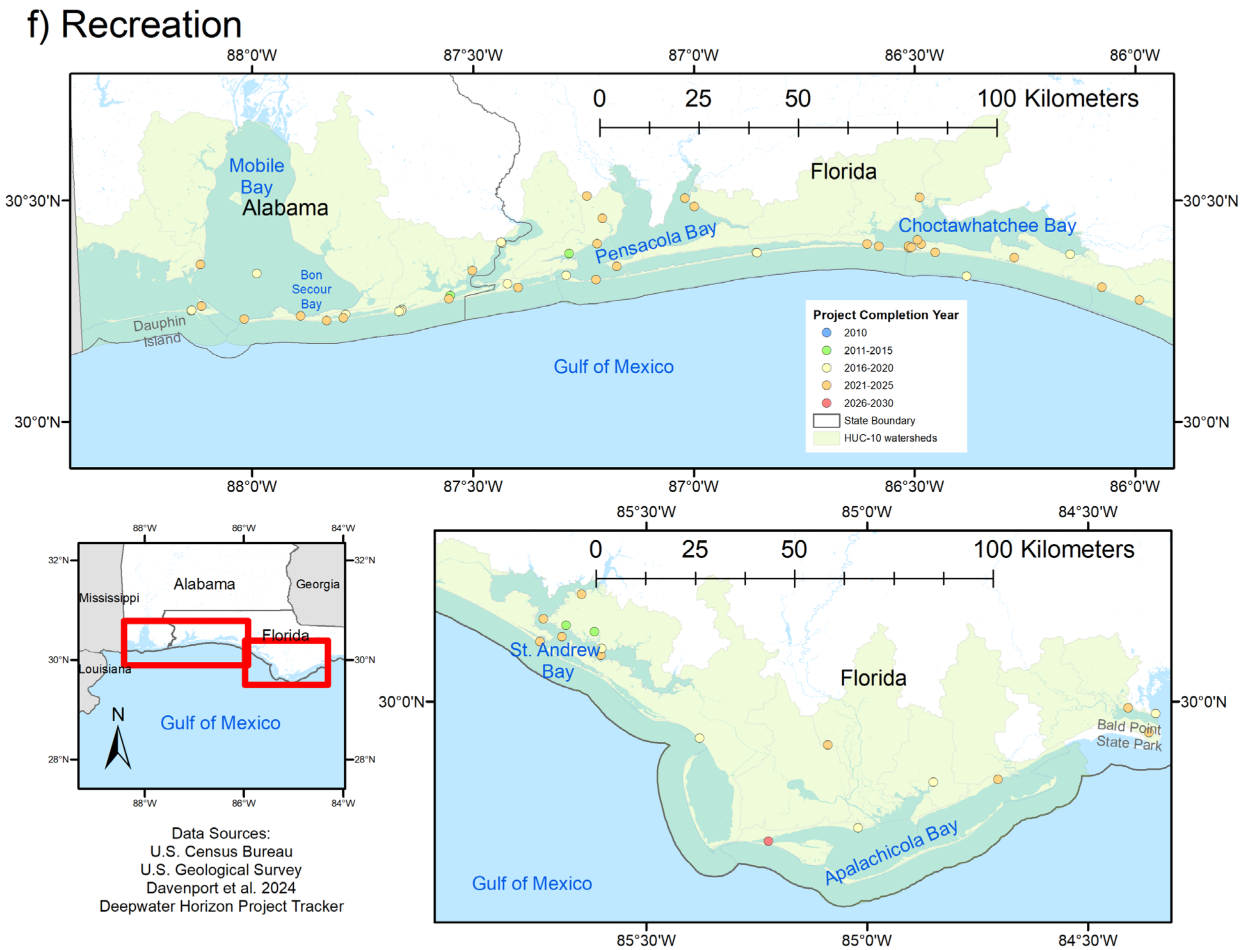

Figure 8. Map of restoration, conservation, and/or management project centroids identified as part of the *Deepwater Horizon* restoration program to address impacts from the 2010 *Deepwater Horizon* oil spill within selected U.S. Geological Survey hydrologic unit code (HUC)-10 watersheds that represent the study area boundary. Projects were extracted from the *Deepwater Horizon* Project Tracker (DU/GOMA/TPL 2024b) on March 23, 2022. Points represent individual projects within the study site color-coded by their reported or anticipated completion date within 5-year bins ending in -0 or -5. Red boxes show the extent of the larger maps. **Figure 8a**: Projects from all programmatic goals and target resources combined. **Figures 8b-g** are maps of projects categorized by programmatic goal (Figure 7) and/or target resource. b) Wetland and marsh habitats (goals 1 and 2). c) Beaches and dunes (goal 1). d) Birds and/or their habitat (goals 1 and 2). e) Sea turtles and/or their habitat. f) Recreational resources (goal 3). g) Infrastructure. Data sources: *Deepwater Horizon* Project Tracker, U.S. Geological Survey and U.S. Census Bureau, Davenport et al. (2024b).

g) Infrastructure

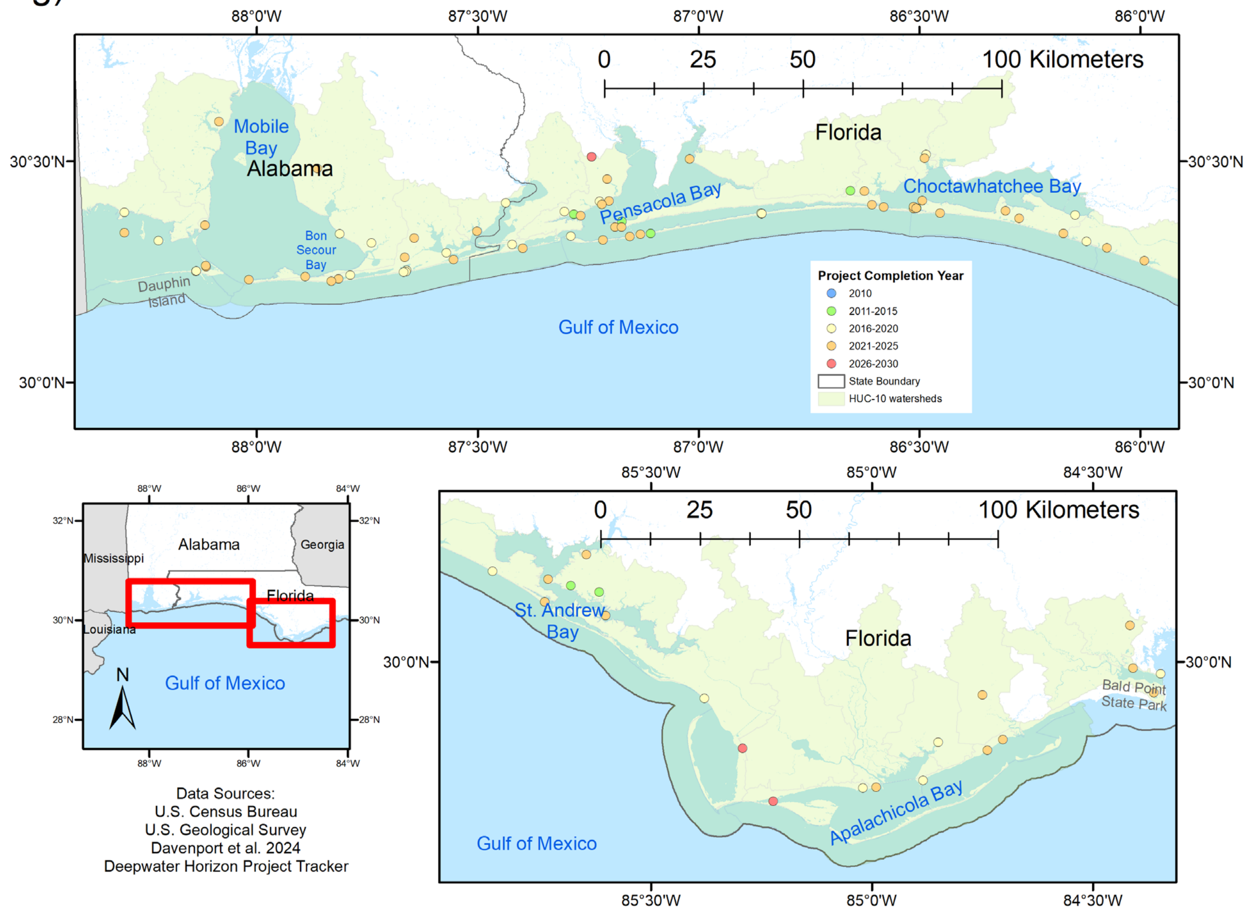

Figure 8. Maps of restoration, conservation, and/or management project centroids identified as part of the *Deepwater Horizon* restoration program to address impacts from the 2010 *Deepwater Horizon* oil spill within selected U.S. Geological Survey hydrologic unit code (HUC)-10 watersheds that represent the study area boundary. Projects were extracted from the *Deepwater Horizon* Project Tracker (DU/GOMA/TPL 2024b) on March 23, 2022. Points represent individual projects within the study site color-coded by their reported or anticipated completion date within 5-year bins ending in -0 or -5. Red boxes show the extent of the larger maps. **Figure 8a**: Projects from all programmatic goals and target resources combined. **Figures 8b-g** are maps of projects categorized by programmatic goal (Figure 7) and/or target resource. b) Wetland and marsh habitats (goals 1 and 2). c) Beaches and dunes (goal 1). d) Birds and/or their habitat (goals 1 and 2). e) Sea turtles and/or their habitat. f) Recreational resources (goal 3). g) Infrastructure. Data sources: *Deepwater Horizon* Project Tracker, U.S. Geological Survey and U.S. Census Bureau, Davenport et al. (2024b).

Summary: System assessment

Through system assessment, several key gaps were identified that may render CEA of progress toward several programmatic restoration goals, particularly 1 and 2, difficult. These gaps can be summarized as information to ensure indirect restoration actions are successful in a changing system, limited overlap among restoration projects, and no clear definition of resilience.

Gap 1 – Knowledge and understanding may be missing that is key to connect BIS system dynamics to restoration in support of goals 1 and 2, including to support adaptive management: A mismatch exists between the focus of research and literature on BIS structures and the focus of restoration projects on functions. Most of the scientific literature focused on BIS is centered on understanding the structural components of BIS, particularly the subaerial barrier, and how these structural components shift in response to stressors including storms, sea-level rise and climate change. In contrast, we found restoration practice in this case study to be predominantly focused on influencing the functions of BIS systems (Figure 9a) and functions are often restored using indirect intended effects (i.e., alter a structure to enhance a function). Half of the intended effects of restoration project actions in our case study rely on indirect effects, that is, a different system component is altered by restoration than the intended restoration effect. These projects are more frequently found in support of goals 1 and 2, particularly for project actions that target living resources (e.g., birds, fish, oysters, sea turtles, submerged aquatic vegetation [SAV], beach mice) or water quality (Figure 9b). Project actions with indirect intended effects also overwhelmingly focus on restoring habitats to recover their function (e.g., benefit the species that use them). In contrast, nearly all infrastructure projects (goal 4), and recreational projects (goal 3) have a direct pathway (Figure 9b). While a mismatch among research and restoration effort is not a problem on its own, we did not find clear information to articulate how these indirect project actions (i.e., the recovery of species by restoring habitat) might perform under the changing system conditions brought on by identified drivers and stressors. This gap is particularly critical if there are non-structural factors that can impact restoration success; for example, barrier island restoration for a target species may have little to no benefit on a species' population if predation and/or the lack of a sufficient adult population are dominant limiting factors in the region.

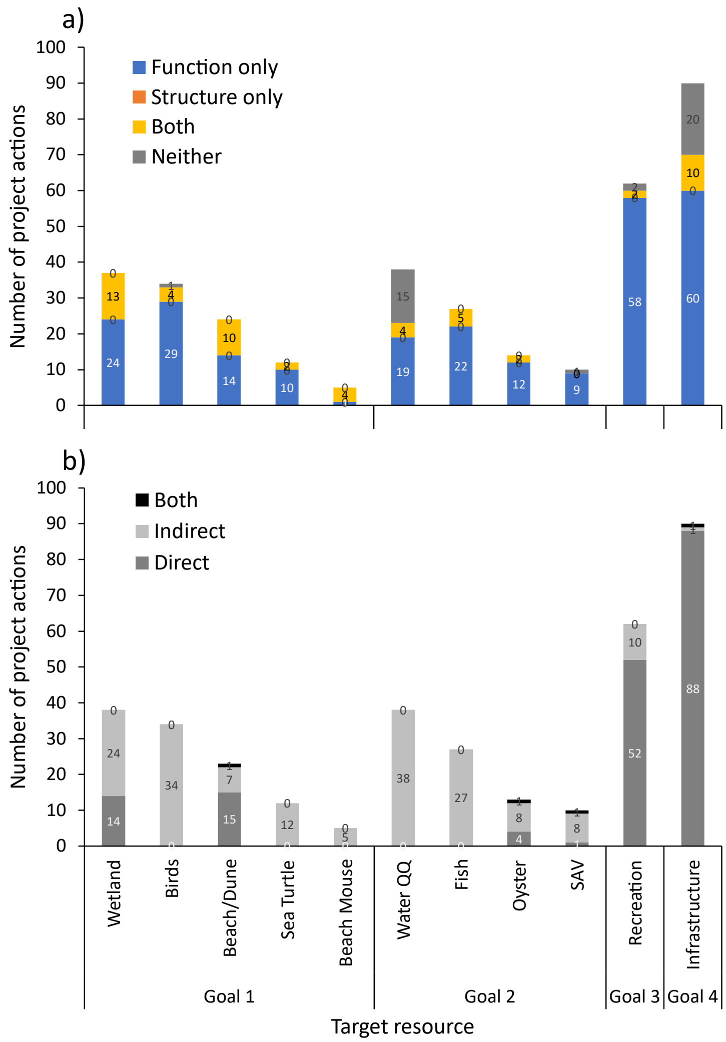

Figure 9. Distribution of project actions associated with the *Deepwater Horizon* oil spill among those targeting structure, function, or both, with direct and indirect pathways to affect each target resource. Programmatic and target resources as in Figure 7. a) Project actions color coded by their intended effect on target resources by system component: function only, structure only, both function and structure, or neither. In the case of neither, projects have intended impacts outside the barrier island and shoreline system. b) Project actions color coded by their intended pathway of effect: direct, indirect (e.g., alter a structure to have an intended effect on a function) or both. Wetland = wetlands and marshes, Birds = coastal birds and/or their habitats, Water QQ = water quantity and/or quality, Fish = fishes and/or their habitats, Oyster = oysters and/or reefs, SAV = submerged aquatic vegetation.

Restoration projects in our study area often mention adaptive management as an option when projects are faced with unexpected events or known stressors like storms, sea-level rise, climate change, and anthropogenic disturbance (project purpose details found in Davenport et al. 2024). The knowledge gaps connecting indirect restoration effects and system drivers and stressors limits CEA, but also means we lack information needed to adjust and/or plan restoration projects for future conditions or inform the adaptive management process for targeting function. Conceptual models can connect restoration to both CEA and adaptive management options, but we could not identify conceptual models associated with project information, although an exhaustive search for this information was beyond the scope of our study. If conceptual frameworks are constructed but not easily discoverable, this communication gap could be resolved by clearly reporting the conceptual frameworks used during restoration decision making along with project documentation. For example, the DWH NRDA Co-Trustees provided guidance for establishing a conceptual setting for a monitoring and adaptive management (MAM) Plan (DWH Trustees 2021), although the guidance is non-binding and only applies to projects funded by NRDA. Alternatively, restoration decision-making that relies on intended indirect effects (i.e., feedbacks), with a limited scientific understanding of the processes that connect system components under changing system conditions, represents a science-practice gap. In this case, further research or changes in restoration practice may be needed to reflect system understanding. Applying the conceptual models developed for CEA to restoration programs and projects can help the scientific community identify the intended feedbacks and where to focus needed mechanistic studies, which may further help improve communication among practitioners and scientists, and develop corrective actions and trigger points for adaptive management that are more effective by taking into account system inputs on projects (Palmer et al. 2007; Suding 2011; Ebberts et al. 2018; Ladouceur et al. 2022).

Gap 2 – Restoration effort seldom overlaps: Projects in our case study have limited potential for spatial and temporal overlap when assessed by target resource, whereas many pathways for cumulative effects involve spatial and/or time crowding (Diefenderfer et al. 2022). Given this outcome, projects seem to have been planned independently rather than with a possible cumulative benefit (or effect) in mind. The lack of clustering may also reflect implicit or explicit priorities by managers, or programmatic and/or legislative mandates, to spatially distribute restoration funding and effort, specifically for potential benefits to be accrued across all states impacted by DWH. To achieve cumulative effects that are greater than projects can have alone, focusing effort on priority resources or within priority watersheds may be beneficial, rather than distributing projects evenly among resources and political subdivisions. Additionally, to inform CEA and programmatic and/or region-wide planning, the expected extent of project impacts is needed.

Gap 3 – Resilience lacks a clear definition: Despite being a programmatic (and sometimes project-specific) goal for DWH restoration, we were unable to develop outcome indicators for resilience, and therefore CEA of restoration progress toward resilience remains a challenge. A major impediment is a lack of a shared definition of resilience (programmatic goal 5) and its metrics, which is needed to identify the outcome indicators with which to create trajectories of change. Project planners may have hypothetical resilience goals and metrics, but until these goals and metrics of interest are made explicit, measuring progress toward resilience is not possible. Without specifying how project designs are intended to influence resilience or making available adaptive management plans that indicate metrics of resilience, we are unable to suggest outcome indicators of resilience for CEA. To thoroughly explore the feasibility of CEA, we continue through the conceptual framework (Figure 1) to address all programmatic goals except goal 5 (Table 1), given outcome indicators could not be identified for this goal.

Part 3: Explore data and information

With 157 project actions implemented within this region and a few areas of spatiotemporal clustering evident, CEA of trajectories toward programmatic goals 1-4 (Table 1) could potentially provide valuable information to inform the single and cumulative impacts of restoration activities and their impacts on BIS. Since CEA feasibility depends on project specific and regional data, along with potential additional lines of evidence, we explored their availability here.

D. Project-specific monitoring data

Project monitoring data were examined to summarize where project and/or cumulative effects toward each programmatic goal could be differentiated from background system changes. Overall, 46% of the implemented project actions closed out on or before 2020 had associated monitoring data available (33 of 72; Figure 10). However, monitoring data availability varied by programmatic goal (and target resource): projects for goal 3, recreation (63%) and goal 4, infrastructure (58%) were more likely than not to have monitoring data (Figure 10). However, much of their monitoring data were indications of whether a project met engineering and design specifications at initial completion, not measures of their function, and are therefore not likely to support our CEA of trajectories of change. For goal 1, beach and dune projects most frequently have associated project monitoring data (6 projects; 55%), while 31% of wetland, 26% of bird and bird habitat, 20% of sea turtle, 0% of SAV, and one of the two beach mouse project actions have available monitoring data (Figure 10). Available project monitoring data are sparse in time and inconsistent across projects, therefore they fail to support a CEA of programmatic restoration goal 1 even if they provide information relevant to project-specific outcome indicators. For example, available annual reports for five dune planting projects do not all contain quantitative data; the frequency and timing of monitoring varies and does not exceed a year post-construction; quantification methods of vegetative survival differ; community composition is only included in one case; and one project did not monitor vegetation at all (Davenport et al. 2024). Project monitoring is therefore not adequate for CEA, despite it being a requirement for many funding sources. For goal 2, only 6 of 39 projects across all target resources have monitoring data available, suggesting these data are inadequate to conduct CEA for goal 2, whether they are interoperable or not (Figure 10).

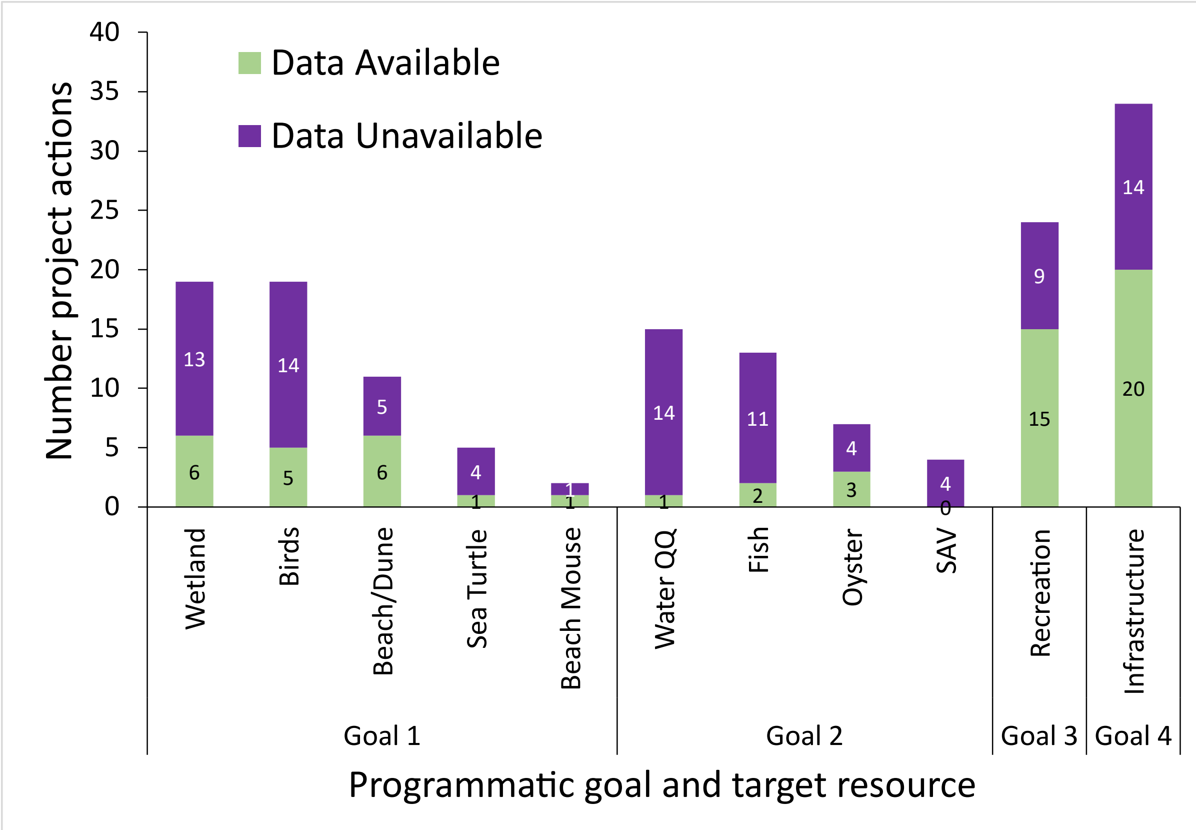

Figure 10. Distribution of project actions associated with the *Deepwater Horizon* oil spill completed before 2020 by the availability of their project monitoring data, grouped by programmatic goal and target resource. Green bars show the number of project actions with data available, and purple bars show the number of project actions for which project monitoring data are unavailable.

E. Regional or focal resource trend data

System-wide data are similarly sparse and/or inadequate for CEA. In particular, few long-term or large-scale monitoring efforts are available that can track changes in habitat function (goals 1 and 2).

Data to examine barrier island structure (goal 1) exist but may have limitations on their support of CEA. Land cover classifications are widely available through the national land cover products like the USGS National Land Cover Dataset (Homer et al. 2015) and the National Oceanic and Atmospheric Administration's Coastal Change Analysis Program (Dobson et al. 1995), but the spatial, temporal, and thematic resolution of these data are often too coarse to track small-scale or linearly distributed habitat changes, such as those from dune restoration (Enwright et al. 2019). For projects targeting geomorphology of beaches and dunes, the total barrier island width, marsh width, dune height, and proximity of the back barrier to the mainland are all critical metrics for BIS resilience (Kombiadou et al. 2019) and are typically monitored using lidar methods. However, in our study system, lidar data tends to be collected after storms have already altered barrier islands, leading to patchy and incomplete availability by year, and preventing the identification of background trends against which to judge change due to restoration, or to assess resilience and recovery from a storm (Figure S2). Additionally, some lidar datasets are focused on shoreline surveys and provide incomplete spatial coverage. Other data types (e.g., in situ observations) exist that have been used to document or research spatial changes in habitat distribution and migration; barrier island evolution in response to sea level and storminess scenarios; erosion; and dune growth at Dauphin Island, AL (Enwright et al. 2017, 2021; Passeri et al. 2020; Dalyander et al. 2020). These data can support habitat restoration and island geomorphology assessment at specific locations, but the spatial extent is too limited for a CEA, and developing the associated models and analyses on a regional scale is prohibitively time and resource intensive. These input sources could support a CEA if collected or generated on a set schedule over the targeted region of interest.

To assess goals 1 and 2, monitoring programs and assessments in the Gulf of Mexico are grouped by focus area (habitat monitoring, mapping, and water quality) and are compiled and available in the Gulf Coastal Monitoring and Assessment Portal (CMAP), a project of the RESTORE Council that links to 818 data sources across the Gulf states (RESTORE Council 2024). A search of this database for habitat monitoring on Alabama or Florida barrier islands identified nine potential data sources. Of these sources, five are monitoring programs, focused on: sharks, shoreline change, barrier island evolution, sediment movement, and natural resource conditions (changes in area, land cover and use, erosion, and conservation practices). The remaining four are site-specific assessments. While there may be limited opportunities to use these data for CEA, most data sources are focused on documenting structural change and/or are unavailable over the needed spatial or temporal scales, and biological data are too patchy for tracking long term changes in habitat function across our study site. An exception to regional data limitation may be coastal birds, given recent efforts to enhance the interoperability and availability of avian monitoring data. The Gulf of Mexico Avian Monitoring Network (GoMAMN) is an example of a non-binding effort by over 30 organizations to help organize avian monitoring interoperability. However, GoMAMN is an agreement among data collectors, not a platform for data storage and dissemination. A recent Avian Data Monitoring Portal, released January 2024, was funded by the Louisiana *Deepwater Horizon* Trustee Implementation Group and DWH Regionwide Trustee Implementation Group and may help boost data availability for colonial waterbirds (CPRA/RWTIG 2024). For goal 4, provision and update of infrastructure that protects the integrity of healthy ecosystems, the same data from goals 1 and 2 would be needed and carefully associated with infrastructure projects; thus, sparse and/or non-interoperable data that limit goals 1 and 2 also limits goal 4.

For goal 3, sources of regional data to assess change in recreational opportunities include visitation and use by state and national parks; the purchase of fishing, hiking, and recreational use licenses; and recreational fishing (e.g., creel) surveys. Visitor use data from the National Park Service is publicly available in aggregate or by building a custom query on the Visitor Use Statistics Dashboard (NPS 2024). The U.S. Census Bureau hosts population and housing data on with the American Community Survey at one-year intervals, which may be useful to assess changes in the accessibility of restoration opportunities by local communities (USCB 2024). To document recreational catch, effort, and target species, recreational fishing data for coastal areas is available through the NOAA Fisheries Marine Recreational Fishing Program database (NOAA 2024b), and inland waters through CreelCat (Sievert et al. 2023). Data from state and local parks or other agencies would need to be identified and gathered by contacting park managers and agencies, which was beyond the scope of our study.

F. Additional lines of evidence

The literature search showed that research in this system is largely focused on describing structural changes and shifts in response to drivers and stressors, such as sea level, flooding, and storm impacts (Davenport et al. 2024). Yet, connecting these shifts to restoration efforts, particularly those related to BIS functions, remains an open area for investigation. In lieu of studies specific to this need, information from several other sources may help inform our CEA. Ongoing efforts to document BIS system drivers, dynamics, and geomorphological changes in this study area include the Atlantic Hurricane Database (HURDAT) database, which compiles information about tropical cyclones including intensity and track (Landsea and Franklin 2013). In addition, the USGS Coastal Change Hazards Portal includes short- and long-term shoreline change data, historical shoreline positions (Shoreline Change theme), storm assessment information, as well as the National Unvegetated to Vegetated Marsh Ratio (UVVR; in the Sea Level Rise theme), which provides high-resolution imagery of coastal wetlands to identify those most vulnerable to stressors such as storms and sea-level rise (USGS 2024d). An updated tool for predicting total water levels, including tides, surge and wave run-up is also operational for the U.S. Atlantic and Gulf of Mexico sandy coastlines (Stockdon et al. 2023; USGS/NOAA 2024). While not yet available in the Gulf of Mexico, the Coastal Change Likelihood assessment combines over 20 sources of coastal data that describe the coastal landscape and hazards (e.g., sea level rise, storms, waves and erosion) to determine the likelihood of change on the coast over a ten-year period (USGS 2024e).

Additional evaluations of geomorphological change, including land cover change and inundation probability over time in this study system may provide critical information to inform CEA. Tracking geomorphic change can provide information on restoration efforts aimed at bolstering habitat availability and resilience to storms, particularly by documenting changes in habitat composition or configuration and the risk of exposure to stressors such as high tide flooding. Specific geomorphic change metrics might include habitat heterogeneity, total edge density, dune crest elevation, and subaerial land cover. Information from change analysis could provide lines of evidence (sensu Diefenderfer et al. 2016) for a CEA, especially if it is conducted at a scale relevant to capture interactions among restoration projects. This information could fill some critical gaps around long-term trends in geomorphology that could also be related to functional changes.

Research and documentation of habitat use by species that depend on BIS was found in our literature search on the influence of drivers and stressors, especially for nesting shorebirds (e.g., terns and plovers), and to a lesser extent for sea turtles (Davenport et al. 2024). For example, on barrier islands of the northern Gulf of Mexico in Louisiana, several studies have examined the breeding parameters of terns on northern Gulf of Mexico barrier islands, and found strong relationships between flooding and nesting failure, trophic interactions between breeding terns and fisheries discards, common foraging at marsh habitats, and reduced site breeding fidelity at unstable habitats (Liechty et al. 2016, 2017; Windhoffer et al. 2017; Rolland et al. 2020). While these findings may relate to terns and/or other species using BIS, targeted studies would be needed for confirmation. In the Florida panhandle, Snowy Plovers' (*Charadrius nivosus* (Cassin, 1958)) flight response to anthropogenic disturbances, particularly dogs, suggests strong reasons to protect brood-rearing areas in addition to nesting habitat, and prohibit dogs on nesting beaches given the long distances at which responses were observed (Durkin and Cohen 2021). Waddle et al. (2023) conducted a study to see how restoration impacted site occupancy for a suite of focal shorebird species for two sites in coastal Louisiana. Information like this, when confirmed by multiple sources, could provide evidence for the effectiveness of such management and restoration actions to separate anthropogenic disturbances and nesting birds (e.g., Project IDs 27, 268, 691, 750, 1213, 1215 and 1377 in project database; Davenport et al. 2024), in the presence of data confirming increased nesting success of key species after project implementation. For sea turtles, we identified several studies on sea turtle use of barrier island habitats in our literature search (Davenport et al. 2024), such as preferences among habitat characteristics, impacts of artificial lighting, and influences of nest temperatures and predation on population dynamics (through sex ratios and hatchling survival). However, since none of these studies took place in our study area, further effort is needed to determine the relevance of these findings to restoration outcomes in our study site.

Summary: Compile and Explore Data

Available regional or focal resource data are sparse and often are not interoperable. While we were able to collate detailed project information (i.e., metadata), limited project-specific monitoring data were available to examine outcomes or support a CEA. This is further exacerbated by a lack of systematic, regional or system-wide monitoring data related to BIS systems and their functions. In addition, available information about drivers and stressors generally does not align with the intended effects of restoration efforts, preventing assessment of cumulative restoration effects on ameliorating drivers and stressors. This is particularly true for goals 2 and 4 (Table 1); limited data may exist to support CEA for goal 1, particularly for geomorphological structures and coastal birds. Recreational resources (goal 3) could theoretically be supported by project monitoring and regional data. The development of regional databases to track region-wide trends in specific focal resources (i.e., BIS, wetlands, sea turtles), potential drivers (i.e., urbanization, barrier island evolution) and potential stressors of BIS (i.e., storm events, sea-level rise) would be valuable in developing a framework for future CEA.

Part 4: Connect system dynamics and restoration effort to resource status/trends

The goal of a CEA is to determine if the trajectory of change of the focal system or resource (in this instance BIS) is altered and if this change can be attributed to restoration activities. By working through the CEA framework, we assessed the feasibility for CEA of four programmatic restoration goals for BIS in the northern Gulf of Mexico and found limited options to attribute change in the outcome indicators to cumulative restoration activities. This limitation comes from common gaps we found across multiple goals (Table 4) including scientific understanding needed to connect the restoration effort to a changing system (and its resilience), the restoration effort itself, and the available data. Ideally, CEA would have been integrated into restoration planning, project selections and data collection. However, significant on-going regional-scale restoration activities necessitate identifying cumulative effects. Filling these gaps in research and/or scientific understanding would also be helpful to inform future restoration efforts, ensure programmatic goals are met, and facilitate future CEA.

The following are potential areas in which a CEA could be explored. Assuming regional data are available upon request, a CEA of changes in recreation opportunities (goal 3) may be possible. While socioeconomic effects were outside the scope of this report, projects focused on recreational resources are clustered in several estuaries in FL, which may support economic valuation(s) of ecosystem services from these projects and comparisons to timeframes prior to such investment. For goal 1, approaches to document land cover change and habitat distribution along barrier islands could help support CEA of upcoming restoration projects focused on the subaerial barrier, including beaches, dunes, and backbarrier marshes, particularly where more projects are planned along AL barrier islands. For living resources on barrier islands (goal 1), targeted assessment of existing data may identify cumulative effects of clustered restoration projects focused on wetlands and marshes, and birds and their habitat in AL. While these limited opportunities for CEA may be valuable as academic exercises, they fall short of assessing trajectories of change to target resources and progress toward programmatic restoration goals.

Discussion

Given the global focus on restoration and conservation of natural systems, developing restoration programs that capitalize on synergistic benefits (and avoid antagonistic impacts) would help achieve regional and programmatic restoration goals more effectively. Here, we developed a conceptual framework to initiate cumulative effects assessment(s) at appropriate scale(s) for a regional restoration program, with the goal of highlighting critical information required to facilitate CEA. Ideally, this framework can be used in designing and selecting restoration projects that are hypothesized to work synergistically towards identified programmatic and restoration goals, then as part of monitoring and adaptive management of those projects within a holistic approach to restoration.

Over the last decade, several frameworks and discussions regarding CEA have been promoted (Diefenderfer et al. 2016; Gann et al. 2019; NASEM 2022), however, a clear limitation in implementing these frameworks is data availability and background trend information. Thus, we developed a process to initiate a CEA and identify its feasibility by systematically documenting and synthesizing information about the system and restoration effort. With this framework, we intend to help identify potential regional or programmatic restoration efforts that may support a CEA, and to ensure that future regional or large-scale restoration can effectively enable CEA. Our proposed system assessment helps identify where a mechanistic understanding of the system dynamics and changes in relation to restoration practice is strong and where it is limited, and how these relationships may limit both CEA and restoration practice. We suspect there are key differences among restoration programs for which CEA has occurred, and those for which it is uncommon, likely aligning with the knowledge, effort, and data gaps we uncovered during our synthesis of the system and restoration assessments. Programs and regions with decades of investment toward understanding and/or influencing a focused resource and monitoring its

Table 4. Science and/or practice gaps identified through Cumulative Effects Assessment (CEA) feasibility assessment. NASEM 2022 references indicates where these gaps or similar language are referenced in the NASEM 2022 report ("An Approach for Assessing U.S. Gulf Coast Ecosystem Restoration: A Gulf Research Program Environmental Monitoring Report"). Additional examples lists where these gaps are referenced by other studies of assessment across restoration programs.

Science and/or practice gaps	NASEM 2022 references	Additional examples
System understanding: Need to connect restoration of structures to functional project goals in the context of changing system drivers and stressors. This involves the identification of intended feedbacks (e.g., restore structures to benefit functions) and whether they are influenced by drivers and stressors.	Recommendation G (page 9)	Palmer et al. 2007, Suding 2011, Ebberts et al. 2018, Ladouceur et al. 2022, Pichon et al. 2024
Monitoring data (at project and regional-scale) need to be: - publicly available and queryable (i.e., in a publicly accessible tracking database) - interoperable (i.e., collecting common metrics) - collected at appropriate spatial and temporal scales to document likely changes in target resources among projects in space and over time	Recommendations A, B, C (pages 7 and 8)	Palmer et al. 2007, Beck et al. 2019, Blomberg et al. 2018, Keating et al. 2020, La Peyre et al. 2022, Ladouceur et al. 2022, Greening et al. 2023
Monitoring data (project and among-project) needs to allow for assessment of relative project effectiveness to inform future planning (i.e., to support adaptive management)	Recommendations C, G (pages 8 and 9)	Beck et al. 2019, La Peyre et al. 2022
Restoration projects need to be distributed in space and/or time with sufficient overlap to identify patterns of accumulation of ecological benefits	Not found	Diefenderfer et al. 2021 and examples therein
Resilience needs to be defined beyond its use as a metaphor to be measured as a response to restoration and allow for development of specific goals, outcome indicators and metrics to demonstrate a change in resilience. That is, define: - "to what": the context of specific desired outcomes (i.e., what are the resources and disturbances/hazards to which resilience is needed) - "of what": what is the desired state of these resources [how should the resources change or stay the same] in the context of disturbances/hazard - at both the restoration project and programmatic levels	Not found	Suding 2011

changes, (e.g., salmonids in Pacific Northwest estuaries; Diefenderfer et al. 2011, 2016) have advanced the practice of CEA for restoration. These programs can serve as case study examples to develop and plan effective CEA methods for other programs and regions. By using this framework to identify gaps, researchers, restoration programs and resource managers may be able to course correct to better align with the needs of CEA to evaluate restoration outcomes and inform future restoration planning.

While applying this framework to a case study (BIS in the north central Gulf of Mexico), we identified several critical gaps in the scientific understanding of the system, restoration effort, and data availability and interoperability that represent critical information to link restoration effects to system trends and facilitate future CEA (Table 4). These findings closely align with the series of recommendations from a recent National Academies of Science Report (NASEM 2022), including a need for "…long-term monitoring, analysis, synthesis, and reporting of environmental trends and indicators" (recommendation A), data, reports, and other project-specific information that are in organized and freely accessible repositories (recommendation B), and consistent monitoring criteria to facilitate the interoperability of monitoring data (recommendation C; NASEM 2022). Our findings are also consistent with those of CEAs on restoration of water quality and oyster populations within the north Gulf of Mexico. A lack of project monitoring information limits the application of the lessons learned to the design of future restoration efforts, and without comparable project data and regional trends, assessments are limited to individual projects (Beck et al. 2019; La Peyre et al. 2022). The north central Gulf of Mexico provides a case study for a system that is highly dynamic, and hosts hundreds of restoration projects implemented by multiple funding entities, each with individual mandates, regional goals, and approaches, and representing over a dozen different target resources. Significant funding (B USD) is being invested in restoration of the coastal northern Gulf of Mexico; the development of a framework that supports CEA in the future, would be beneficial, and help ensure efficient and effective restoration programming.

Conclusion: With continued investment globally in restoration and conservation of natural resources and the services they provide, early planning efforts to account for potential cumulative effects, and development of frameworks to support CEA of regional and large-scale restoration efforts would be valuable. When only additive, rather than cumulative, effects are documented, the possibility for interactive relationships among projects (i.e., synergisms and antagonisms) is lost, along with the capacity to assess the effectiveness of programs toward their programmatic goals. In this effort, an operational framework for conducting a CEA was developed, and a regional restoration program was used as a case study. Despite the heavy emphasis on articulation of goals, inclusion of monitoring, and consideration of cumulative effects that underpinned the program, multiple gaps in the planning, data collection, and system understanding limited our ability to conduct the CEA. If a CEA is not feasible in a case study that has been the focus of project investments greater than many international efforts (i.e., UN Decade of Restoration), then without addressing the gaps and needs identified here, it is unlikely to be feasible for other programs, let alone large-scale international programs that are under development. This suggests that greater focus is needed early in restoration program development on explicitly considering potential cumulative effects, system resilience, data collection, adaptive management, and future CEA. This consideration can also guide the distribution of restoration efforts and related research activities. While monitoring and adaptive management of individual projects has dominated restoration planning and practice over the last couple decades, CEA planning and practice would provide a more robust, systematic, and efficient means to help meet programmatic or regional management goals. The conceptual framework presented here provides a means to initiate a CEA and identify its feasibility, identify critical gaps, and note whether system understanding is capable of differentiating effects from restoration effort from the dynamics of a changing system. Applying this process will further facilitate CEA and improve restoration outcomes. As the practice of CEA for restoration programs matures, it will be possible to better understand the impacts of restoration programs, and ensure the services promised to the public are realized.

Acknowledgements

Funding from the Resources and Ecosystems Sustainability, Tourist Opportunities, and Revived Economies of the Gulf Coast States (RESTORE) Act through the 2017 Funded Priorities List: Comprehensive Plan Commitment and Planning Support grant, under agreement number IAACP18DI0065 and the U.S. Geological Survey supported this work. Several staff from the USFWS Gulf Restoration Office provided critical contributions to this work; Sophie Williams found project footprints and catalogued spatial data and Dr. Jon Hemming and Dr. Jonny Kleinman shared their vision for the project and an early project database. Conversations with Dr. Jerrod Penn helped shape outcome indicators for recreational opportunities. We thank Genesis Mize for her assistance with the literature screening. We thank our reviewers, Dr. Elise Irwin, and Dr. Melissa Carle for their constructive comments. Any use of trade, firm or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Referenced datasets for this project are available: Davenport, T.M., Comba, D.A., La Peyre, M.K., Enwright, N.M., Dalyander, P.S., Palmsten, M.L., Han, M., Williams, S.C., Kleinman, J.S., Steyer, G.D., and Hemming, J.M., 2024, Information supporting a cumulative effects assessment of restoration in barrier island and shoreline systems of the north central Gulf of Mexico: U.S. Geological Survey data release, https://doi.org/10.5066/P9JQ07OH.

References

Allen, C. R., D. G. Angeler, A. S. Garmestani, L. H. Gunderson, and C. S. Holling. 2014. Panarchy: Theory and Application. Ecosystems 17:578–589.

ASPRS. American Society for Photogrammetry and Remote Sensing (ASPRS), 2023. ASPRS Positional Accuracy Standards for Digital Geospatial Data (EDITION 2, VERSION 1.0 - AUGUST 2023), https://publicdocuments.asprs.org/PositionalAccuracyStd-Ed2-V1.

Baker, M., A. Domanski, T. Hollweg, J. Murray, D. Lane, K. Skrabis, R. Taylor, T. Moore, and L. DiPinto. 2020. Restoration Scaling Approaches to Addressing Ecological Injury: The Habitat-Based Resource Equivalency Method. Environmental Management 65:161–177.

Barbier, E. B., S. D. Hacker, C. Kennedy, E. W. Koch, A. C. Stier, and B. R. Silliman. 2011. The value of estuarine and coastal ecosystem services. Ecological Monographs 81:169–193.

Baumann, M. S., G. F. Fricano, K. Fedeli, C. E. Schlemme, M. C. Christman, and M. V. Carle. 2020. Recovery of Salt Marsh Invertebrates Following Habitat Restoration: Implications for Marsh Restoration in the Northern Gulf of Mexico. Estuaries and Coasts 43:1711–1721.

Beck, M. W., E. T. Sherwood, J. R. Henkel, K. Dorans, K. Ireland, and P. Varela. 2019. Assessment of the Cumulative Effects of Restoration Activities on Water Quality in Tampa Bay, Florida. Estuaries and Coasts 42:1774–1791.

Bernhardt, E. S., E. G. Sudduth, M. A. Palmer, J. D. Allan, J. L. Meyer, G. Alexander, et al. 2007. Restoring rivers one reach at a time: results from a survey of U.S. river protection practitioners. Restoration Ecology 15:482-494

Bernier, J. C., J. L. Miselis, and N. G. Plant. 2021. Satellite-Derived Barrier Response and

Recovery Following Natural and Anthropogenic Perturbations, Northern Chandeleur Islands, Louisiana. *Remote Sensing*, 13(8), 3779. https://doi.org/10.3390/rs13183779.

Biggs, C. R., L. A. Yeager, D. G. Bolser, C. Bonsell, A. M. Dichiera, Z. Hou, S. R. Keyser, A. J. Khursigara, K. Lu, A. F. Muth, B. Negrete Jr., and B. E. Erisman. 2020. Does functional redundancy affect ecological stability and resilience? A review and meta-analysis. Ecosphere 11:e03184.

Biggs, R., M. Schlüter, D. Biggs, E. L. Bohensky, S. BurnSilver, G. Cundill, V. Dakos, T. M. Daw, L. S. Evans, K. Kotschy, A. M. Leitch, C. Meek, A. Quinlan, C. Raudsepp-Hearne, M. D. Robards, M. L. Schoon, L. Schultz, and P. C. West. 2012. Toward Principles for Enhancing the Resilience of Ecosystem Services. Annual Review of Environment and Resources 37:421–448.

Blomberg, B. N., J. B. Pollack, P. A. Montagna, and D. W. Yoskowitz. 2018. Evaluating the U.S. Estuary Restoration Act to inform restoration policy implementation: A case study focusing on oyster reef projects. Marine Policy 91:161–166.

Bridges, T. S., E. M. Bourne, B. C. Suedel, E. B. Moynihan, And J. K. King. 2021. Engineering With Nature: An Atlas, Volume 2. ERDC SR-21-2. Vicksburg, MS: U.S. Army Engineer Research And Development Center. http://dx.doi.org/10.21079/11681/40124.

Cabin, R. J., A. Clewell, M. Ingram, T. McDonald, and V. Temperton. 2010.Briding restoration science and practice: Results and analysis of a survey from the 2009 Society for Ecological Restoration International Meeting. Restoration Ecology 18:783-788.

Capdevila, P., I. Stott, I. Oliveras Menor, D. B. Stouffer, R. L. G. Raimundo, H. White, M. Barbour, and R. Salguero-Gómez. 2021. Reconciling resilience across ecological systems, species and subdisciplines. Journal of Ecology 109:3102–3113.

Carle, M. V., K. G. Benson, and J. F. Reinhardt. 2020. Quantifying the Benefits of Estuarine Habitat Restoration in the Gulf of Mexico: an Introduction to the Theme Section. Estuaries and Coasts 43:1680–1691.

Carrier-Belleau, C., D. Drolet, C. W. McKindsey, and P. Archambault. 2021. Environmental stressors, complex interactions and marine benthic communities' responses. Scientific Reports 11:4194.

CBD. Center for Biological Diversity (CBD) 2020. Global Biodiversity Outlook 5. Convention on Biological Diversity, Montreal.

CIMS. Coastal Information Management System (CIMS) 2024. Louisiana Coastal Protection and Restoration Authority's Coastal Information Management System (CIMS). https://cims.coastal.la.gov/. Accessed 9 May 2024.

CPRA/RWTIG. Coastal Protection and Restoration Authority and the *Deepwater Horizon* Regionwide Trustee Implementation Group (CPRA/RWTIG) 2024. Avian Data Monitoring Portal. https://experience.arcgis.com/experience/010503b4c64b4ff6a7f3570220a53647. Accessed 9 May 2024

CPRA. Coastal Protection and Restoration Authority of Louisiana (CPRA) 2024. Coastwide Reference Monitoring System-Wetlands Monitoring Data. Retrieved from Coastal Information Management System (CIMS) database. http://cims.coastal.louisiana.gov. Accessed 10 May 2024.

Côté, I. M., E. S. Darling, and C. J. Brown. 2016. Interactions among ecosystem stressors and their importance in conservation. Proceedings of the Royal Society B: Biological Sciences 283:20152592.

CEQ. Council for Environmental Quality (CEQ) 1997. Considering Cumulative Effects Under the National Environmental Policy Act. Council on Environmental Quality, Executive Office of the President, Washington, DC. January. Accessed 11 March 2024: https://ceq.doe.gov/publications/cumulative_effects.html.

Cretini, K. F., J. M. Visser, K. W. Krauss, and G. D. Steyer. 2012. Development and use of a floristic quality index for coastal Louisiana marshes. Environmental Monitoring and Assessment 184:2389–2403.

Dalyander, P. S., R. C. Mickey, D. L. Passeri, and N. G. Plant. 2020. Development and Application of an Empirical Dune Growth Model for Evaluating Barrier Island Recovery from Storms. Journal of Marine Science and Engineering 8:977.

Dave, R., Saint-Laurent, C., Murray, L., Antunes Daldegan, G., Brouwer, R., de Mattos Scaramuzza, C.A., Raes, L., Simonit, S., Catapan, M., García Contreras, G., Ndoli, A., Karangwa, C., Perera, N., Hingorani, S. and Pearson, T. (2019). Second Bonn Challenge progress report. Application of the Barometer in 2018. Gland, Switzerland: IUCN. xii + 80pp.

Davenport, T.M., Comba, D.A., La Peyre, M.K., Enwright, N.M., Dalyander, P.S., Palmsten, M.L., Han, M., Williams, S.C., Kleinman, J.S., Steyer, G.D., and Hemming, J.M., 2024, Information supporting a cumulative effects assessment of restoration in barrier island and shoreline systems of the north central Gulf of Mexico: U.S. Geological Survey data release, https://doi.org/10.5066/P9JQ07OH.

Davidson-Arnott, R., B. Bauer, and C. Houser. 2019. Introduction to Coastal Processes and Geomorphology. Cambridge University Press, UK.

DWH Trustees. *Deepwater Horizon* Natural Resource Damage Assessment Trustees (DWH Trustees). 2016. *Deepwater Horizon* oil spill: final programmatic damage assessment and restoration plan and final programmatic environmental impact statement. https://www.gulfspillrestoration.noaa.gov/restoration-planning/gulf-plan. Accessed 9 May 2024.

DWH Trustees. *Deepwater Horizon* Natural Resource Damage Assessment (DWH Trustees). 2021. *Deepwater Horizon* Natural Resource Damage Assessment Programmatic Review. November. Available: https://www.gulfspillrestoration.noaa.gov/media/document/2021-11deepwaterhorizontcfinal2021programmaticreviewpdf.

Diefenderfer, H.L., L. D. McKinney, W. R. Boynton, K. L. Heck Jr., B. A. Kleiss, D. R. Mishra, H. Greening, A. A. George, B. A. Carl Kraft, and C. L. Kling. 2022. Ten years of Gulf Coast ecosystem restoration projects since the Deepwater Horizon oil spill. Proceedings of the National Academy of Sciences 119:pe2213639119. https://doi.org/10.1073/pnas.221363911.

Diefenderfer, H. L., G. D. Steyer, M. C. Harwell, A. J. LoSchiavo, H. A. Neckles, D. M. Burdick, G. E. Johnson, K.E. Buenau, E. Trujillo, J. C. Callaway, R. M. Thom, N. K. Ganju, and R. R. Twilley. 2021. Applying cumulative effects to strategically advance large-scale ecosystem restoration. Frontiers in Ecology and Environment 19:108-117. Doi:10.1002/fee.2274.

Diefenderfer, H. L., G. E. Johnson, R. M. Thom, K. E. Buenau, L. A. Weitkamp, C. M. Woodley, A. B. Borde, and R. K. Kropp. 2016. Evidence-based evaluation of the cumulative effects of ecosystem restoration. Ecosphere 7:e01242.

Diefenderfer, H. L., R. M. Thom, G. E. Johnson, J. R. Skalski, K. A. Vogt, B. D. Ebberts, G. C. Roegner, and E. M. Dawley. 2011. A Levels-of-Evidence Approach for Assessing Cumulative Ecosystem Response to Estuary and River Restoration Programs. Ecological Restoration 29:111–132.

Dobson, J. E., E. A. Bright, R. L. Ferguson, D. W. Field, L. L. Wood, K. D. Haddad, H. Iredale III., J. R. Jensen, V. V. Klemis, R. J. Orth, and J. P. Thomas. 1995. NOAA Coastal Change Analysis Program (C-CAP): Guidance for Regional Implementation.

DOJ. Department of Justice (DOJ) 2015. US and five Gulf states reach historic settlement. United States Department of Justice Office of Public Affairs Press Releases. https://www.justice.gov/opa/pr/us-and-five-gulf-states-reach-historic-settlement-bp-resolve-civil-lawsuit-over-deepwater. Accessed 9 May 2024.

DOT. Department of Transportation (DOT) 2012. Resources and Ecosystems Sustainability, Tourist Opportunities, and Revived Economies of the Gulf Coast States Act of 2012. Subtitle F-Gulf Coast Restoration. U.S. Department of the Treasury. https://home.treasury.gov/system/files/216/Final-Restore-Act.pdf. Accessed 8 May 2024.

DOT. Department of Transportation (DOT) 2015. Department of the Treasury regulations for the Gulf Coast Restoration Trust Fund. Final Rule. U.S. Department of the Treasury. https://home.treasury.gov/system/files/216/Final-Rule-Federal-Register-2015-31431.pdf. Accessed 8 May 2024.

Ducks Unlimited /Gulf of Mexico Alliance /Trust for Public Land (DU/GOMA/TPL) 2024a. *Deepwater Horizon* Project Tracker. Ducks Unlimited, Gulf of Mexico Alliance, The Trust for Public Land. May 2024. https://dwhprojecttracker.org/summaries/. Last accessed 19 April 2024.

Ducks Unlimited /Gulf of Mexico Alliance /Trust for Public Land (DU/GOMA/TPL) 2024b. *Deepwater Horizon* Project Tracker. Ducks Unlimited, Gulf of Mexico Alliance, The Trust for Public Land. May 2024. https://dwhprojecttracker.org/download-project-information. Last accessed 9 May 2024.

Durkin, M. M., and J. B. Cohen. 2021. Responses of Imperiled Snowy Plovers (Charadrius nivosus) to Anthropogenic and Natural Disturbance in the Florida Panhandle. Waterbirds 44.

Ebberts, B. D., B. D. Zelinsky, J. P. Karnezis, C. A. Studebaker, S. Lopez-Johnston, A. M. Creason, L. Krasnow, G. E. Johnson, and R. M. Thom. 2018. Estuary ecosystem restoration: implementing and institutionalizing adaptive management. Restoration Ecology 26:360–369.

ELI. Environmental Law Institute (ELI) 2020. Gulf Coast Recovery & Restoration: 10-Year Review. Environmental Law Institute. http://eli-ocean.org/wp-content/blogs.dir/2/files/Gulf-Restoration-Recovery-10-Year-Review.pdf. Accessed 8 May 2024.

Enwright, N. M., L. Wang, P. S. Dalyander, H. Wang, M. J. Osland, R. C. Mickey, R. L. Jenkins, and E. S. Godsey. 2021. Assessing Habitat Change and Migration of Barrier Islands. Estuaries and Coasts 44:2073–2086.

Enwright, N. M., L. Wang, S. M. Borchert, R. H. Day, L. C. Feher, and M. J. Osland. 2019. Advancing barrier island habitat mapping using landscape position information. Progress in Physical Geography: Earth and Environment 43:425–450.

Enwright, N., L. Wang, S. Borchert, R. Day, L. Feher, and M. Osland. 2017. The Impact of Lidar Elevation Uncertainty on Mapping Intertidal Habitats on Barrier Islands. Remote Sensing 10:5.

EPA. Environmental Protection Agency (EPA) 1999. Consideration Of Cumulative Impacts In EPA Review of NEPA Documents U.S. Environmental Protection Agency, Office of Federal Activities (2252A) EPA 315-R-99-002/May 1999, https://www.epa.gov/sites/default/files/2014-08/documents/cumulative.pdf Accessed 3 May 2024.

ERTG. Expert Regional Technical Group (ERTG) 2019. Landscape principles for CEERP restoration strategy. Portland, OR: Bonneville Power Administration, US Army Corps of Engineers, and National Oceanic and Atmospheric Administration Fisheries. ERTG 2017-02 Landscape Principles_ FINAL.pdf (estuarypartnership.org). Accessed 24 April 2024.

Folke, C. 2006. Resilience: the emergence of a perspective for socio-ecological systems analyses. Global Environmental Change 16:253-267. Doi:10.1016/j.gloenvcha.2006.04.002.

Folke C., S. Carpenter, B. Walker, M. Scheffer, T. Chapin, and J. Rockstrom. 2010. Resilience thinking: integrating resilience, adaptability and transformability. Ecology and Society. 15: 20-32. http://www.ecologyandsoceity.org/vol15/iss4/art20/

Folt, C. L., C. Y. Chen, M. V. Moore, and J. Burnaford. 1999. Synergism and antagonism among multiple stressors. Limnology and Oceanography 44:864-877. https://doi.org/10.4319/lo.1999.44.3_part2.0864.

French McCay, D., C. Peterson, J. DeAlteris, and J. Catena. 2003. Restoration that targets function as opposed to structure: replacing lost bivalve production and filtration. Marine Ecology Progress Series 264:197–212.

French McCay, D., and J. Rowe. 2003. Habitat restoration as mitigation for lost production at multiple trophic levels. Marine Ecology Progress Series 264:233–247.

FWCC/FLDEP. Florida Fish and Wildlife Conservation Commission / Florida Department of Environmental Protection (FWCC/FLDEP) 2024. Florida Gulf Environmental Benefit Fund Restoration Strategy. Florida Fish and Wildlife Conservation Commission and Florida Department of Environmental Protection. https://floridadep.gov/sites/default/files/Gulf%20Environmental%20Benefit%20Fund%20Restoration%20Strategy%20Report%20FINAL%20%283%29.pdf. Accessed 8 May 2024.

Gann, G. D., T. McDonald, B. Walder, J. Aronson, C. R. Nelson, J. Jonson, J. G. Hallett, C. Eisenberg, M. R. Guariguata, J. Liu, F. Hua, C. Echeverria, E. Gonzales, N. Shaw, K. Decleer, and K. W. Dixon. 2019. International principles and standards for the practice of ecological restoration. Second edition. Restoration Ecology 27:S1-S46. Doi:10.1111/rec.13035.

GEBF. Gulf Environmental Benefit Fund (GEBF) 2024a. Gulf Environmental Benefit Fund. National Fish and Wildlife Foundation. https://www.nfwf.org/gulf-environmental-benefit-fund. Accessed 9 May 2024.

GEBF. Gulf Environmental Benefit Fund (GEBF) 2024b. Gulf Environmental Benefit Fund in Alabama. National Fish and Wildlife Foundation. https://storymaps.arcgis.com/stories/81af65a09b15488495855b7b1d2025af. Accessed 9 May 2024.

Gentile, J. H., M. A. Harwell, W. Cropper Jr, C. C. Harwell, D. DeAngelis, S. Davis, J. C. Ogden, and D. Lirman. 2001. Ecological conceptual models: a framework and case study on ecosystem management for South Florida sustainability. Science of The Total Environment 274:231–253.

Glibert, P. M., W.-J. Cai, E. R. Hall, M. Li, K. L. Main, K. A. Rose, J. M. Testa, and N. K. Vidyarathna. 2022. Stressing over the Complexities of Multiple Stressors in Marine and Estuarine Systems. Ocean-Land-Atmosphere Research 2022.

Goodsir, F., H. J. Bloomfield, A. D. Judd, F. Kral, L. A. Robinson, and A. M. Knights. 2015. A spatially resolved pressure-based approach to evaluate combined effects of human activities and management in marine ecosystems. ICES Journal of Marine Science 72, 2245-2256. https://doi.org/10.1093/icesjms/fsv080.

Greening, H. S., K. L. Heck, L. D. McKinney, H. L. Diefenderfer, W. R. Boynton, B. A. Kleiss, D. R. Mishra, A. A. George, B. A. C. Kraft, C. A. Kling, and L. A. Windecker. 2023. Assessing the Effectiveness of Large-Scale Environmental Restoration: Challenges and Opportunities. Estuaries and Coasts 46:293–301.

Grzegorzewski, A. S., M. A. Cialone, and T. V. Wamsley. 2011. Interaction of Barrier Islands and Storms: Implications for Flood Risk Reduction in Louisiana and Mississippi. Journal of Coastal Research 59:156–164.

GRIIDC. Gulf of Mexico Research Initiative Information and Data Cooperative (GRIIDC) 2024. GRIIDC Gulf Science Data repository. Gulf of Mexico Research Initiative. https://www.griidc.org/. Accessed 9 May 2024.

Gunderson, L. H., C. R. Allen, and C. S. Holling. 2012. Foundations of ecological resilience. Island Press.

Harris, L. R., and O. Defeo. 2022. Sandy shore ecosystem services, ecological infrastructure, and bundles: New insights and perspectives. Ecosystem Services 57:101477.

Harwell, M. A., J. H. Gentile, L. Mckinney, J. W. Tunnell, W. Dennison, H. Kelsey, K. M. Stanzel, G. W. Stunz, K. Withers, J. Tunnell. 2019. Conceptual framework for assessing ecosystem health. Integrated Environmental Assessment and Management 15:544-564. Doi:10.1002/ieam.4152.

Hewitt, J. E., J. I. Ellis, and S. F. Thrush. 2016. Multiple stressors, nonlinear effects and the implications of climate change impacts on marine coastal ecosystems. Global Change Biology 22:2665–2675.

Holling, C. S. 1973. Resilience and the stability of ecological systems. Annual Review of Ecology, Evolution and Systematics 4: 1-23. https://doi.org/10.1146/annurev.es.04.110173.000245.

Holling, C. S., and L. H. Gunderson. 2002. Resilience and adaptive cycles. In: Panarchy: Understanding Transformations in Human and Natural Systems, 25-62.

Homer, C., J. Dewitz, L. Yang, S. Jin, P. Danielson, J. Coulston, N. Herold, J. Wickham, and K. Megown. 2015. Completion of the 2011 National Land Cover Database for the Conterminous United States – Representing a Decade of Land Cover Change Information. Photogrammetric Engineering and Remote Sensing.

IIJA. Infrastructure Investment and Jobs Act of 2021, Pub. L. No. 117-58, 135 Stat. 429 (2021). https://www.govinfo.gov/content/pkg/PLAW-117publ58/pdf/PLAW-117publ58.pdf. Accessed 9 May 2024.

IRA. Inflation Reduction Act of 2021, Pub. L. No. 117-58, 136 Stat. 1818 (2022). https://www.govinfo.gov/content/pkg/PLAW-117publ169/pdf/PLAW-117publ169.pdf. Accessed 9 May 2024.

Jabareen, Y. 2009. Building a conceptual framework: Philosophy, definitions, and procedure. International Journal of Qualitative Methods. 8:49-62. https://10.1177/1609406900800406.

Judd, A. D., T. Backhaus, and F. Goodsir. 2015. An effective set of principles for practical implementation of marine cumulative effects assessment. Environmental Science & Policy 54:254–262.

Keating, K.S., M. Gloekler, N. Kinner, S. Mesick, M. Peccini, B. Shorr, L. Showalter, and J. Henkel. 2020. Coordination of long-term data management in the Gulf of Mexico, Shore & Beach 88(1), 17-22. http://doi.org/10.34237/1008812. Accessed 24 May 2024.

Kelso, M. A., A. E. Stovall, B. G. Reguero, G. Franco, and M. W. Beck. 2024. Nature-based Solutions & Risk Management: Recommendations for Integrating Nature into Risk Science & Insurance. UCSC and USACE, Washington, D.C.

Khalil, S. M., C. W. Finkl, and R. C. Raynie. 2013. Development of new restoration strategies for Louisiana barrier island systems, northern Gulf of Mexico, USA. Journal of Coastal Research:1467–1472.

Kombiadou, K., S. Costas, A. R. Carrasco, T. A. Plomaritis, Ó. Ferreira, and A. Matias. 2019. Bridging the gap between resilience and geomorphology of complex coastal systems. Earth-Science Reviews 198:102934.

La Peyre, M. K., D. A. Marshall, S. C. L. Buie, A. Hijuelos, and G. D. Steyer. 2022. Are We Falling Short on Restoring Oysters at a Regional Scale? Environmental Management 70:581–592.

Ladouceur, E., N. Shackelford, K. Bouazza, L. Brudvig, A. Bucharova, T. Conradi, T. E. Erickson, M. Garbowski, K. Garvy, W. S. Harpole, H. P. Jones, T. Knight, M. M. Nsikani, G. Paterno, K. Suding, V. M. Temperton, P. Török, D. E. Winkler, and J. M. Chase. 2022. Knowledge sharing for shared success in the decade on ecosystem restoration. Ecological Solutions and Evidence 3:e12117.

Landsea, C. W. and J. L. Franklin, 2013: Atlantic Hurricane Database Uncertainty and Presentation of a New Database Format. Mon. Wea. Rev., 141, 3576-3592.

Lange, R., and D. Marshall. 2017. Ecologically relevant levels of multiple, common marine stressors suggest antagonistic effects. Scientific Reports 7:6281.

Langhammer, P. F., J. W. Bull, J. E. Bicknell, J. L. Oakley, M. H. Brown, M. W. Bruford, S. H. M. Butchart, J. A. Carr, D. Church, R. Cooney, S. Cutajar, W. Foden, M. N. Foster, C. Gascon, J. Geldmann, P. Genovesi, M. Hoffmann, J. Howard-McCombe, T. Lewis, N. B. W. Macfarlane, Z. E. Melvin, R. S. Merizalde, M. G. Morehouse, S. Pagad, B. Polidoro, W. Sechrest, G. Segelbacher, K. G. Smith, J. Steadman, K. Strongin, J. Williams, S. Woodley, and T. M. Brooks. 2024. The positive impact of conservation action. Science 384:453–458.

Liechty, J. S., Q. C. Fontenot, and A. R. Pierce. 2016. Diet Composition of Royal Tern (*Thalasseus maximus*) and Sandwich Tern (*Thalasseus sandvicensis*) at Isles Dernieres Barrier Island Refuge, Louisiana, USA. Waterbirds 39:58–68.

Liechty, J. S., A. K. Minor, M. Nepshinsky, and A. R. Pierce. 2017. Apparent Survival of Royal Tern Thalasseus Maximus and Sandwich Tern T Sandvicensis at Isles Dernieres Barrier Islands Refuge, Louisiana, Usa.

LoSchiavo, A. J., R. G. Best, R. E. Burns, S. Gray, M. C. Harwell, E. B. Hines, A. R. McLean, T. St. Clair, S. Traxler, and J. W. Vearil. 2013. Lessons Learned from the First Decade of Adaptive Management in Comprehensive Everglades Restoration. Ecology and Society 18:art70.

Martin, C. L., S. Momtaz, T. Gaston, and N. A. Moltschaniwskyj. 2016. A systematic quantitative review of coastal and marine cultural ecosystem services: current status and future research. Marine Policy 74:25–32.

Martin, S., E. L. Sparks, A. J. Constantin, J. Cebrian, and J. A. Cherry. 2021. Restoring Fringing Tidal Marshes for Ecological Function and Ecosystem Resilience to Moderate Sea-level Rise in the Northern Gulf of Mexico. Environmental Management 67:384–397.

McKinney, L. D., J. G. Shepherd, C. A. Wilson, W. T. Hogarth, J. Chanton, S. A. Murawski, P. A. Sandifer, T. Sutton, D. Yoskowitz, K. Wowk, T. M. Özgökmen, S. B. Joye, and R. Caffey. 2021. The Gulf of Mexico AN OVERVIEW.

Moore, L.J., Murray, A.B. (Eds.), 2018. Barrier Dynamics and Response to Changing Climate. Springer.

Moore, L. J., K. Patsch, J. H. List, and S. J. Williams. 2014. The potential for sea-level-rise-induced barrier island loss: Insights from the Chandeleur Islands, Louisiana, USA. Marine Geology 355:244–259.

NASEM. National Academies of Sciences, Engineering, and Medicine (NASEM) 2018. Understanding the Long-Term Evolution of the Coupled Natural-Human Coastal System: The Future of the U.S. Gulf Coast. The National Academies Press, Washington, DC.

NASEM. National Academies of Sciences, Engineering, and Medicine (NASEM) 2022. Committee on Long-Term Environmental Trends in the Gulf of Mexico, Gulf Research Program. An

Approach for Assessing U.S. Gulf Coast Ecosystem Restoration: A Gulf Research Program Environmental Monitoring Report. Page 26335. National Academies Press, Washington, D.C.

NASEM. National Academies of Sciences, Engineering, and Medicine (NASEM) 2023. Progress Toward Restoring the Everglades: The Ninth Biennial Review - 2022. Washington, DC: The National Academies Press. https://doi.org/10.17226/26706.

NOAA. National Oceanic and Atmospheric Administration (NOAA) 2024a. Data Integration, Visualization, Exploration and Reporting (DIVER) platform hosted by the National Oceanic and Atmospheric Administration's Office of Response and Restoration https://www.diver.orr.noaa.gov/. Accessed 8 May 2024.

NOAA. National Oceanic and Atmospheric Administration (NOAA) 2024b. Data and Tools; Recreational Fisheries Statistics Queries. https://www.fisheries.noaa.gov/topic/recreational-fishing-data. Accessed 8 July 2024.

NOAA. National Oceanic and Atmospheric Administration (NOAA) 1995. Habitat equivalency analysis: An overview. March 21, 1995. Revised October 4, 2000 and May 23, 2006. NOAA Damage Assessment and Restoration Program. Policy and Technical Paper Series, Number 95–1. 24 pp.

NPS. National Park Service (NPS) 2024a. Social Science Visitor Use Statistics Dashboard. https://home.nps.gov/subjects/socialscience/visitor-use-statistics-dashboard.htm. Accessed 8 July 2024.

Ocean Conservancy 2015. Full Details of $20.8 Billion BP *Deepwater Horizon* Settlement Released for Public Comment. Ocean Conservancy Newsroom. https://oceanconservancy.org/news/full-details-20-8-billion-bp-deepwater-horizon-settlement-released-public-comment/ Accessed 9 May 2024

OPA. Oil Pollution Act (OPA) 1990. Text - H.R.1465 - 101st Congress (1989-1990): Oil Pollution Act of 1990. Library of Congress. https://www.congress.gov/bill/101st-congress/house-bill/1465/text. Accessed 9 May 2024.

Ostrowski, A., R. M. Connolly, and M. Sievers. 2021. Evaluating multiple stressor research in coastal wetlands: A systematic review. Marine Environmental Research 164:105239.

Palmer, M., J. D. Allan, J. Meyer, and E. S. Bernhardt. 2007. River Restoration in the Twenty-First Century: Data and Experiential Knowledge to Inform Future Efforts. Restoration Ecology 15:472–481.

Passeri, D. L., P. S. Dalyander, J. W. Long, R. C. Mickey, R. L. Jenkins, D. M. Thompson, N. G. Plant, E. S. Godsey, and V. M. Gonzalez. 2020. The Roles of Storminess and Sea Level Rise in Decadal Barrier Island Evolution. Geophysical Research Letters 47.

Peterson, C., R. Kneib, and C. Manen. 2003. Scaling restoration actions in the marine environment to meet quantitative targets of enhanced ecosystem services. Marine Ecology Progress Series 264:173–175.

Phinn, S., C. Roelfsema, and R. P. Stumpf. (2010). Remote sensing: Discerning the promise from the reality. In: Integrating and applying science: A handbook for effective coastal ecosystem assessment. Edited by B.J. Longstaff, T.J.B. Carruthers, W.C. Dennison, T.R. Lookingbill, J.M. Hawkey,, J.E. Thomas, E.C. Wicks,, and J. Woerner. Cambridge, MA, U.S.A: IAN Press.201-222.

Pichon, B., S. Kéfi, N. Loeuille, I. Lajaaiti, and I. Gounand. 2024. Integrating ecological feedbacks across scales and levels of organization. Ecography:e07167.

Piet, G. J., J. E. Tamis, J. Volwater, P. De Vries, J. T. Van Der Wal, and R. H. Jongbloed. 2021. A roadmap towards quantitative cumulative impact assessments: Every step of the way. Science of The Total Environment 784:146847.

Plant, N. G., and H. F. Stockdon. 2012. Probabilistic prediction of barrier-island response to hurricanes. Journal of Geophysical Research: Earth Surface 117.

Powers, S. P., and K. E. Boyer. 2014. Marine restoration ecology. Marine community ecology and conservation. Sinauer Publishing, Sunderland:495–516.

PSP. Puget Sound Partnership (PSP) 2022. Action Agenda. Accessible at https://www.psp.wa.gov/2022AAupdate.php. Accessed 24 April 2024.

PSEMP. Puget Sound Ecosystem Monitoring Program (PSEMP) 2024. Puget Sound Ecosystem Monitoring Program (PSEMP) Overview. Puget Sound Partnership. https://www.psp.wa.gov/PSEMP-overview.php. Accessed 9 May 2024.

Raposa, K. B., S. Lerberg, C. Cornu, J. Fear, N. Garfield, C. Peter, R. L. J. Weber, G. Moore, D. Burdick, and M. Dionne. 2018. Evaluating Tidal Wetland Restoration Performance Using National Estuarine Research Reserve System Reference Sites and the Restoration Performance Index (RPI). Estuaries and Coasts 41:36–51.

Reimann, L., A. T. Vafeidis, and L. E. Honsel. 2023. Population development as a driver of coastal risk: Current trends and future pathways. Cambridge Prisms: Coastal Futures 1:e14.

RESTORE Council. Gulf Coast Ecosystem Restoration Council (RESTORE Council) 2016. Comprehensive Plan Update 2016: Restoring the Gulf Coast's Ecosystem and Economy. Gulf Coast Ecosystem Restoration Council. https://www.restorethegulf.gov/sites/default/files/CO-PL_20161208_CompPlanUpdate_English.pdf. Accessed 9 May 2024.

RESTORE Council. Gulf Coast Ecosystem Restoration Council (RESTORE Council) 2019. RESTORE Council Monitoring and Adaptive Management Guidelines December 2019. Gulf Coast Ecosystem Restoration Council. https://restorethegulf.gov/sites/default/files/Final_Council_MAM%20Guidelines_20191211_508.pdf. Accessed 9 May 2024.

RESTORE Council. Gulf Coast Ecosystem Restoration Council (RESTORE Council) 2024. Gulf Coastal Monitoring and Assessment Portal (CMAP). Gulf Coast Ecosystem Restoration Council. https://restorethegulf.gov/cmap/. Accessed 8 May 2024.

Rolland, V., M. Nepshinsky, E. D. Windhoffer, J. S. Liechty, A. K. Minor, and A. R. Pierce. 2020. Foraging areas and movements of royal term *Thalasseus maximus* breeding at the Isle Dernieres Islands Refuge, Louisiana. Marine Ornithology 48:163-168.

Sievert, N. A., A. J. Lynch, H. S. Embke, A. Robertson, M. Lang, A. L. Kaz, M. D. Robertson, S. R. Midway, L. Wszola, and C. P. Paukert. 2023. CreelCat, a Catalog of United States Inland Creel and Angler Survey Data. Scientific Data 10:762.

Siranni, H., M. J. Sirianni, D. J. Mallinson, N. L. Lindquist, L. M. Valdes-Weaver, M. Moody, B.

Henry, C. Colli, B. Rubino, M. M. Peñalver, and C. Henne. 2022. Quantifying Recent Storm-Induced Change on a Small Fetch-Limited Barrier Island along North Carolina's Crystal Coast Using Aerial Imagery and LiDAR. Coasts, 2, 302-322. https://doi.org/10.3390/coasts2040015.

Smit, B., and H. Spaling. 1995. Methods for cumulative effects assessment. Environmental Impact Assessment Review 15:81–106.

Spaling, H. 1994. Cumulative effects assessment: concepts and principles. Impact Assessment 12:231–251.

Stagg, C., L. A. Sharp, T. McGinnis, and G. Snedden. 2013. Submergence Vulnerability Index development and application to Coastwide Reference Monitoring System Sites and Coastal Wetlands Planning, Protection and Restoration Act projects. Open-File Report.

Stallins, J. A., and D. Corenblit. 2018. Interdependence of geomorphic and ecologic resilience properties in a geographic context. Geomorphology 305:76–93.

Stockdon, H. F., J. W. Long, M. L. Palmsten, A. Van Der Westhuysen, K. S. Doran, and R. J. Snell. 2023. Operational forecasts of wave-driven water levels and coastal hazards for US Gulf and Atlantic coasts. Communications Earth & Environment 4:169.

Stutz, M. L., and O. H. Pilkey. 2002. Global Distribution and Morphology of Deltaic Barrier Island Systems. Journal of Coastal Research 36:694–707.

Suding, K. N. 2011. Toward an Era of Restoration in Ecology: Successes, Failures, and Opportunities Ahead. Annual Review of Ecology, Evolution, and Systematics 42:465–487.

TBEP. Tampa Bay Estuary Program (TBEP). 2024. Our Work Data Visualization. https://tbep.org/our-work/data-visualization/. Accessed 9 May 2024.

Teichert, N., A. Borja, G. Chust, A. Uriarte, and M. Lepage. 2016. Restoring fish ecological quality in estuaries: Implication of interactive and cumulative effects among anthropogenic stressors. Science of The Total Environment 542:383–393.

Thom, R. M., S. A. Breithaupt, H. L. Diefenderfer, A. B. Borde, G. C. Roegner, G. E. Johnson, and D. L. Woodruff. 2018. Storm-driven particulate organic matter flux connects a tidal tributary floodplain wetland, mainstem river, and estuary. Ecological Applications 28:1420–1434.

Thompson, D. M., P. S. Dalyander, J. W. Long, and N. G. Plant. 2017. Correction of elevation offsets in multiple co-located lidar datasets: U.S. Geological Survey Open-File Report 2017–1031, 10 p., https://doi.org/10.3133/ofr20171031.

Thurman, H. R., N. M. Enwright, W. C. Cheney, J. Dugas, D. M. Lee, D.M., and W. Jones. 2023.

Mapping habitats and shorelines pre-, during, and post-restoration on Caminada Headland and Whiskey Island, Louisiana, 2012–2020. *In*: Barataria-Terrebonne National Estuary Program, U.S. Geological Survey, and University of Louisiana-Lafayette (eds.), *Evaluation of Restoration for Avian Species at Caminada Headland and Whiskey Island in Louisiana*.

UNEP. United Nations Environment Programme (UNEP) 2024. Welcome to UN Environment Open Data. https://open.unep.org/. Accessed 16 January 2024.

USCB. U.S. Census Bureau (USCB) 2024. Surveys and Programs: American Community Survey (ACS). https://www.census.gov/programs-surveys/acs/. Accessed 8 July 2024.

USGS. U.S. Geological Survey (USGS) 2024a. National Water Information System: Web Interface. U.S. Geological Survey. https://waterdata.usgs.gov/nwis?. Accessed 9 May 2024.

USGS. U.S. Geological Survey (USGS) 2024b. Earth Explorer. U.S. Geological Survey. https://earthexplorer.usgs.gov. Accessed 24 May 2024.

USGS. U.S. Geological Survey (USGS) 2024c. Access National Hydrography Products. U.S. Geological Survey. https://www.usgs.gov/national-hydrography/access-national-hydrography-products. Accessed 24 April 2024.

USGS. U.S. Geological Survey (USGS) 2024d. Coastal Change Hazards Portal. U.S. Geological Survey. https://marine.usgs.gov/coastalchangehazardsportal/. Accessed 30 May 2024.

USGS. U.S. Geological Survey (USGS) 2024e. Coastal Change Likelihood: A synthesis of factors that determine future coastal change. United States Geological Survey. https://geonarrative.usgs.gov/ccl/. Accessed 30 May 2024.

USGS/NOAA. U.S. Geological Survey / National Oceanic and Atmospheric Administration (USGS/NOAA) 2024. Total Water Level and Coastal Change Forecast Viewer. United States Geological Survey and National Oceanic and Atmospheric Administration. https://coastal.er.usgs.gov/hurricanes/research/twlviewer/. Accessed 30 May 2024.

Waddle, H., W. Barrow, C. Jeske, J. Schultz, R. Dobbs, D. LeBlanc, A. Anderson, B. Geary, T.J. Zenzal, N. Enwright, H. Thurman and D. Lee. 2023. Chapter 3: Site Occupancy of Focal Shorebird Species at Whiskey Island and Caminada Headland, Louisiana 2012–2020, In: Evaluation of Restoration for Avian Species at Caminada Headland and Whiskey Island in Louisiana, Louisiana Coastal Protection and Restoration Authority, Baton Rouge, LA, https://cims.coastal.la.gov/RecordDetail.aspx?Root=0&sid=26011.

Walker B., C. S. Holling, S. R. Carpenter, A. P. Kinzig. 2003. Resilience, Adaptability and Transformability in Social-Ecological Systems. Ecology and Society 9: 5-15. Doi:10.5751/ES-00650-090205

Waltham, N. J., M. Elliott, S. Y. Lee, C. Lovelock, C. M. Duarte, C. Buelow, C. Simenstad, I. Nagelkerken, L. Claassens, C. K.-C. Wen, M. Barletta, R. M. Connolly, C. Gillies, W. J. Mitsch, M. B. Ogburn, J. Purandare, H. Possingham, and M. Sheaves. 2020. UN Decade on Ecosystem Restoration 2021–2030—What Chance for Success in Restoring Coastal Ecosystems? Frontiers in Marine Science 7:71.

Windhoffer, E. D., T. M. Owen, J. S. Liechty, A. K. Minor, D. K. Curtiss, M. Nepshinsky, and A. R. Pierce. 2017. Variability in Gull-Billed Tern (*Gelochelidon nilotica*) Breeding Parameters at the Isles Dernieres Barrier Islands Refuge, Louisiana, USA. Waterbirds 40:390–395.

Wortley, L., J.-M. Hero, and M. Howes. 2013. Evaluating Ecological Restoration Success: A Review of the Literature. Restoration Ecology 21:537–543.

Supplementary Figures and Tables

Table S1. Changes in the availability of literature focused on cumulative effects when adding the following focus areas: assessments, coastal and estuarine systems, and conservation and/or restoration. Number of records is based on entering “Search terms” (from Davenport et al. 2024) on Web of Science, core collection, from 1975-present. Accessed on 24 April 2024. CIA/CEA = Cumulative Impact Assessment/Cumulative Effects Assessment; NA = not applicable

Search name and description	Search terms (Web of Science 1975 to present, core collection, Accessed Feb 16, 2024)	Number records	% difference
A) Mentions of cumulative environmental impacts/effects	ALL=(“cumulative effect*” OR "cumulative impact*") AND ALL=("ecolog*“ OR "habitat*" OR "ecosystem*" OR “system*" OR)	5,605	NA
B) Specify possible assessments (likely overestimate)	All terms in A AND ALL=("assessed" OR “assessment*")	1,500	~27% of CIA/CEA related records (A) mention assessment (1,500/ 5,605)
C) Specify study site	All terms in B AND ALL =("estuar*" OR "coast*“ OR "shore*" OR "island*")	254	~17% of potential assessments (B) also mention our study site (254/ 1,500)
D) Assess restoration or conservation in study site	All terms in C AND ALL =("restor*“ OR “conserv*”)	102	< 7% potential assessments (B) are both in our study site and mention conservation or restoration. (102/1,500)
E) Assess restoration in study site	All terms in C AND ALL =("restor*")	28	< 2% potential assessments (B) are both in our study site and mention restoration. (28/1,500)

Figure S1. Number of publications (bars) and citations (line) over time (1975 to present), from a Web of Science Core Collection search performed on 22 April 2024 focused on identifying cumulative effects assessments. Search contains the following terms: ALL=("cumulative effect*" OR "cumulative impact*") AND ALL=("ecolog*" OR "habitat*" OR "ecosystem*" OR "system*" OR); 5,605 total records on 24 April 2024.
One record was identified from 1977, but was a poor fit to this search, so was excluded.

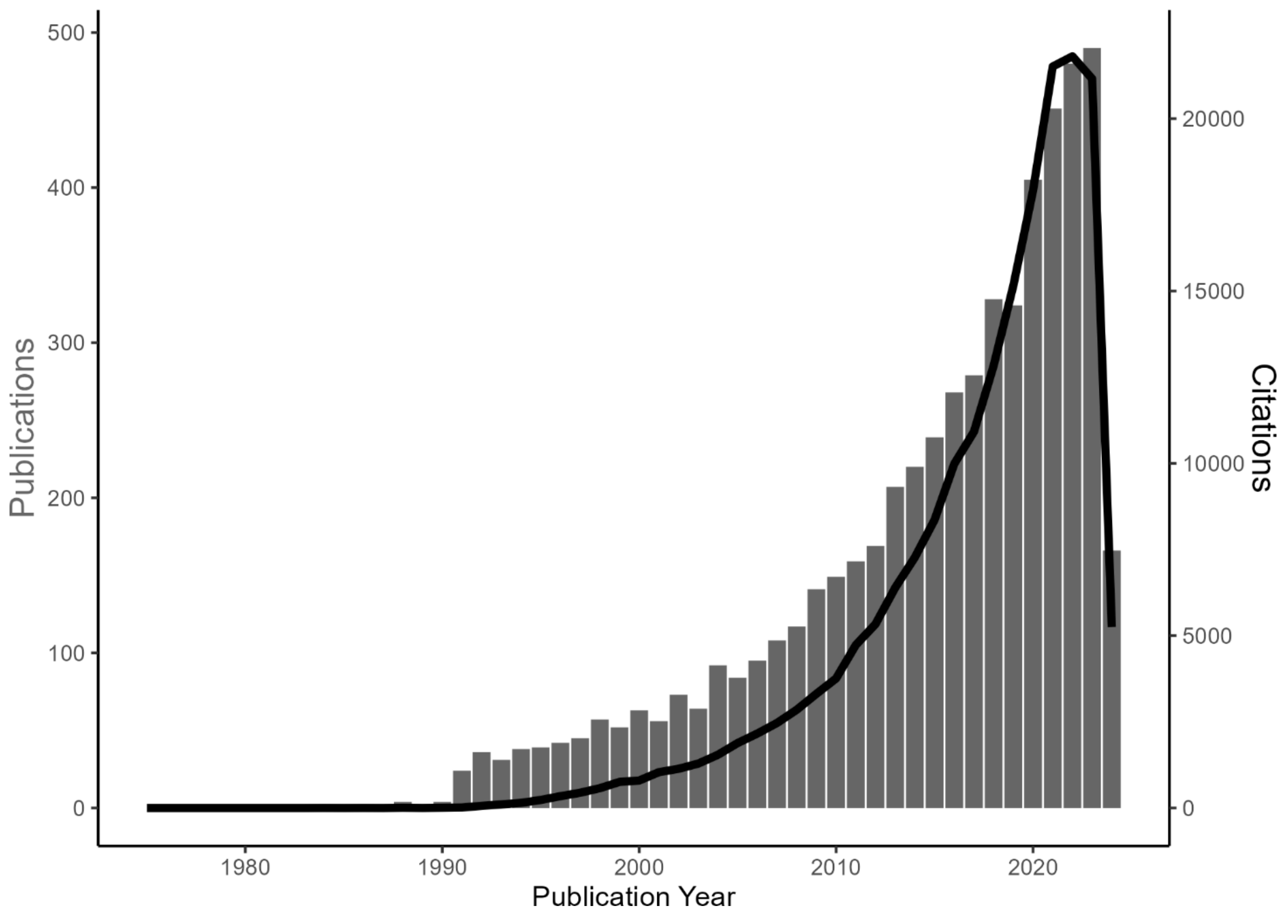

Figure S2. Spatiotemporal distribution of lidar datasets, colored by frequency of data collection from 2010-2020, and sourced from the U.S. Interagency Elevation Inventory (https://coast.noaa.gov/inventory).