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Conceptual Framework for Assessing Ecosystem Health

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ABSTRACT

Over the past century, the environment of the Gulf of Mexico has been significantly altered and impaired by extensive human activities. A national commitment to restore the Gulf was finally initiated in response to the unprecedented *Deepwater Horizon* oil spill in 2010. Consequently, there is a critical need for an assessment framework and associated set of indicators that can characterize the health and sustainability of an ecosystem having the scale and complexity of the Gulf. The assessment framework presented here was developed as an integration of previous ecological risk– and environmental management–based frameworks for assessing ecosystem health. It was designed to identify the natural and anthropogenic drivers, pressures, and stressors impinging on ecosystems and ecosystem services, and the ecological conditions that result, manifested as effects on valued ecosystem components. Four types of societal and ecological responses are identified: reduction of pressures and stressors, remediation of existing stressors, active ecosystem restoration, and natural ecological recovery. From this conceptual framework are derived the specific indicators to characterize ecological condition and progress toward achieving defined ecological health and sustainability goals. Additionally, the framework incorporates a hierarchical structure to communicate results to a diversity of audiences, from research scientists to environmental managers and decision makers, with the level of detail or aggregation appropriate for each targeted audience. Two proof-of-concept studies were conducted to test this integrated assessment and decision framework, a prototype Texas Coastal Ecosystems Report Card, and a pilot study on enhancing rookery islands in the Mission-Aransas Reserve, Texas, USA. This Drivers–Pressures–Stressors–Condition–Responses ($DPSCR_4$) conceptual framework is a comprehensive conceptual model of the coupled human–ecological system. Much like its predecessor, the ecological risk assessment framework, the $DPSCR_4$ conceptual framework can be tailored to different scales of complexity, different ecosystem types with different stress regimes, and different environmental settings. *Integr Environ Assess Manag* 2019;15:544–564. © 2019 The Authors. *Integrated Environmental Assessment and Management* published by Wiley Periodicals, Inc. on behalf of Society of Environmental Toxicology & Chemistry (SETAC)

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INTRODUCTION

We present here a conceptual framework with broad applicability for characterizing human–ecosystem interactions and for assessing ecosystem health. This initiative began with the objective of constructing a framework for assessment of the health of the Gulf of Mexico; our discussion, therefore, begins with that rationale. However, as the conceptual framework evolved, it became clear that its applicability is not limited to the Gulf of Mexico and its utility is not limited to a report card on progress toward desired conditions. Rather, we present this conceptual framework both as an organizing guide for assessing the health of an ecosystem, the forces that affect it, and potential management avenues to achieve defined goals, and as a generic conceptual model of the coupled human–ecological system, adaptable to virtually any ecosystem and any environmental problem set.

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The Gulf of Mexico is among the most ecologically diverse and valuable ecosystems in the world, comprising more than 1.5×10^6 km^2 in area and consisting of offshore waters and coastal habitats of 11 US and Mexican states plus Cuba. The Gulf's wetlands, beaches, coastal woodlands, and islands are major nurseries for breeding birds and provide foraging and stopover habitat for billions of birds that converge from some of the most important migratory flyways in the western hemisphere (Horton et al. 2019). Coastal marshes and nearshore habitats provide essential nursery habitat for ecologically, commercially, and recreationally important species of fish and invertebrates. Offshore habitats and species are biologically diverse and include deepwater corals, sponges, fish stocks, marine mammals, sea turtles, and other unique species and communities. These habitats are integral to the economic and cultural fabric of the Gulf, providing a range of ecosystem services, including fisheries, food and energy production, infrastructure protection, and recreational and wildlife-related activities. Testament to its impressive diversity is a recent biotic survey that found more than 15 400 species living in the Gulf of Mexico, including more than 2500 species of crustaceans, a similar number of mollusks, and 1975 species of vertebrates, comprising more than 1500 species of fish, 400 species of birds, and 30 species of mammals (Felder et al. 2009).

The Gulf's watershed covers more than half the continental USA (USEPA 2011), 40% from the Mississippi River Basin alone. This watershed is a source of a wide range of anthropogenic stressors: Nutrients (N and P) and other pollutants (e.g., hydrocarbons, pesticides, industrial wastes) contribute to degraded water quality in the Gulf, including more than 17 000 km^2 of annually occurring hypoxic conditions (USEPA 2011), peaking at 22 720 km^2 in 2017 (NOAA 2017). Oil and gas industry canals, pipelines, and other infrastructure crisscross the landscape, contributing to the loss of wetland habitat. Geologic land subsidence substantially exacerbates sea-level rise (Morton et al. 2005); for example, approximately 5000 km^2 of wetlands in Louisiana were lost in the last 7 decades (Couvillion et al. 2011). As a result of these and other natural and anthropogenic stressors, Gulf coastal ecosystems have become increasingly degraded for both human use and aquatic life. Scientific consensus has emerged for several continuing major threats to the health of the Gulf, including the following (Mabus 2010; USEPA 2011):

- loss of wetland habitats, coastal marshes, barrier islands, and shorelines;
- erosion of barrier islands and shorelines, undermining storm protection and reducing habitat for endangered or threatened species such as sea turtles and shorebirds;
- degradation of coastal estuaries, which provide essential nursery habitat for most of the Gulf fishery resources;
- overharvesting of commercially and recreationally important fisheries, exacerbated by the human health threats of methylmercury and other contaminants in finfish, harmful algal blooms (HABs), and human pathogens in shellfish;
- a large dead zone created by hypoxia offshore of the Mississippi River Delta; and
- global climate change with potentially increased frequency and intensity of storms, accelerated sea-level rise, and attendant economic risks and loss of coastal habitats and natural resources.

Superimposed on these threats was the April 2010 explosion on the *Deepwater Horizon* drilling platform operating in the Mississippi Canyon of the Gulf, resulting in the largest marine oil spill in US history, with an estimated 5×10^6 barrels released over 87 d (Mabus 2010; NAS 2012). The unprecedented combination of extreme depth of discharge (~1500 m) and massive use of dispersants (~3×10^6 L; Kujawinski et al. 2011) caused high uncertainty in predicting the transport and fate of oil and dispersant compounds and in understanding the severity and magnitude of ecological effects (Joye 2015).

In response to the oil spill, the Gulf Coast Ecosystem Restoration Task Force was established (Executive Order 13554, 5 October 2010) to develop a science-based Gulf of Mexico Regional Ecosystem Restoration Strategy to restore and conserve habitat, restore water quality, replenish and protect living coastal and marine resources, and enhance community resilience (USEPA 2011; https://www.restorethegulf.gov). This strategy requires an integrated, risk-based ecosystem assessment framework for informing decision making to achieve specific restoration goals. This framework in turn requires the identification of indicators and measures of success to evaluate the efficacy of the restoration program in meeting its goals. Indicators, along with measures of performance, must be quantifiable and understandable to the public, reflect the desired Gulf condition, and be sensitive to ecosystem changes (USEPA 2011; GCERC 2016).

We initiated a project to develop such an integrated assessment framework with associated set of indicators and metrics that could be used to characterize the health of the Gulf of Mexico ecosystems, including their linkages to human communities, termed the "Gulf EcoHealth Metrics Initiative." Our vision was to develop a comprehensive conceptual framework for the coupled human–ecological system from which an assessment of the environmental condition of the Gulf could be derived that is scientifically based, widely accessible, and readily understandable by policy makers, stakeholders, scientists, and the American public. A hierarchical communications structure, unified by a common conceptual framework, provides the basis for informing multiple audiences at the appropriate level of detail and aggregation, allowing one to dig deeper into the reasons for the various assigned metrics of ecosystem health.

The ultimate aim of the Gulf EcoHealth initiative is to provide the scientific information and understanding necessary to evaluate the health of the Gulf, clearly demonstrate how well it is or is not progressing toward desired long-term goals, and inform the decision-making process on the policies and resources needed to achieve sustainability of a healthy Gulf of Mexico. As the initiative proceeded, however, it became evident that although the assessment framework presented below (DPSCR$_4$ Framework: Need for a New Synthesis Framework) provides the conceptual foundation for achieving this goal, fully populating the elements of the framework may be more aspirational than feasible because of the insufficient availability of environmental data, both at present and in the plausible future. Nevertheless, this assessment framework can indicate what types of data would be most useful to have and can provide the rationale and priorities for designing an appropriate monitoring program. Its greater utility, however, is as a comprehensive conceptual framework for distinguishing those aspects of ecosystems and human–ecosystem interactions that matter from those that do not, thereby providing a roadmap for improved understanding of human interactions with ecosystems and a guide for environmental management decision making. Further, much like its predecessor, the ecological risk assessment (ERA) framework, this conceptual framework can be tailored to different scales of complexity, different ecosystem types with different stress regimes, and different environmental settings.

History of ecological health assessment frameworks

Environmental assessment indicators and report cards have become widespread as tools to characterize the status and trends of ecosystem health and to inform the allocation of resources for sustainability of healthy marine and coastal environments. The San Francisco Bay Index (The Bay Institute 2003), Gulf of Maine ecosystem indicators partnership (Mills 2006), Southeast Queensland healthy waterways report cards (Pantus and Dennison 2005), Chesapeake Bay Report Card (Williams et al. 2009, 2010; IAN 2013), Australia's Great Barrier Reef Report Card (Australian and Queensland Governments 2010), Florida Keys Ecosystem Report Card (NOAA 2011), scorecards for Marine Protected Areas (CEC 2011), US National Coastal Condition Report (USEPA 2012), Ocean Health Index (Halpern et al. 2012), the semiannual System-wide Ecological Indicators for Everglades Restoration reports (e.g., Brandt et al. 2016; www.evergladesrestoration.gov), and the America's Watershed Initiative (2015; americaswatershed.org) Mississippi River Watershed Report Card are examples of indicators and assessments being used to inform the public and decision makers about the health and sustainability of coastal ecosystems.

We reviewed the extensive literature on indicators of ecological condition and the literature on the conceptual frameworks for these and many other environmental assessments. Two approaches dominate, one derived from the perspective of stress ecology (e.g., Odum 1969, 1985; Holling 1973; Barrett et al. 1976; Rapport et al. 1985) and its derivatives, ERA and ecological indicators (e.g., Kelly and Harwell 1989, 1990; Gentile and Slimak 1990; USEPA 1992, 1998; Environment Canada 1994; Gentile et al. 1993; Harwell, Myers et al. 1999; Dale and Beyeler 2001; USEPA SAB 2002; Doren et al. 2009). In this approach, ecological condition or health is a result of causal stress–effect relationships, as manifested in specific indicators of selected components (both structural and functional) of ecosystems. Here stressors are defined as physical, chemical, or biological agents that can cause effects on ecological systems. Effects are manifested as changes in specific ecological attributes that are ecologically and/or societally important, often termed "assessment endpoints" (USEPA 1998) or "valued ecosystem components" (VECs) (CCME 1996; Harwell et al. 2011). This approach seeks to elucidate the causal mechanisms of ecological effects from human activities and natural processes; consequently, it is closely related to hypothesis-driven scientific studies on how ecosystems and their components respond to environmental stressors, whether natural or anthropogenic. However, a limitation of this approach, particularly at larger scales, is that there may be too many environmental stressors to be managed, exacerbated by too many interactions among stressors and too many pathways leading to effects.

The second approach is more environmental-management focused, based on the Pressure–State–Response (PSR) framework (OECD 1991, 1993) and its derivative, the Drivers–Pressures–State–Impacts–Response (DPSIR) framework (EEA 1999; Weber 2010). In the latter, drivers are the fundamental forces causing pressures that affect the state of the environment; impacts are how the state changes because of the pressures; responses are societal feedbacks through adaptation or curative action. The pressures in DPSIR originally excluded natural processes except for climate change, but more recent applications have relaxed that exclusion (e.g., Weber 2010). The DPSIR framework has been adopted by the United Nations, European Union, and some US agencies because it is more attuned to the needs of decision makers, stakeholders, and the public when addressing environmental issues on large scales. However, a significant deficiency of the PSR and DPSIR approaches is that pressures are typically defined at such a broad level (e.g., population growth, agricultural production) that their relationships to the state of the environment are by necessity correlative instead of causal. Hence, it may provide insufficient specificity of the relationships between human activities and ecological effects to identify what needs to be managed and what management actions would be required in order to achieve a healthy environment. The other serious deficiency of DPSIR is its distinction between impacts and state, implying that there exists some baseline or natural state for an ecosystem and that impacts constitute some deviation from that state; characterized this way, human interactions are conceived of only as adverse and no accommodation is provided for the positive contributions of ecosystem services (Kelble et al. 2013). In reality, ecosystems are dynamic, changing over time and space, and ecosystems became fundamentally altered by human presence long ago, so there is no default baseline against which impacts are measured.

Irrespective of the assessment framework used, the indicators to measure environmental condition have also been a topic of considerable research and discussion over the past few decades. The literature on the utility and purposes for ecological indicators and criteria for selecting them was developed early on (e.g., Kelly and Harwell 1989, 1990; Gentile and Slimak 1990; Hunsaker and Carpenter 1990; MacKenzie et al. 1990; Cairns et al. 1993). Some publications proposed specific indicators or indices that have been widely adopted, such as Karr's (1981) fish community-based index of biotic integrity to characterize the condition of freshwater streams, and the Landres et al. (1988) use of vertebrate indicator species to characterize wildlife habitat quality. Other ecological indicators have been suggested from the molecular (e.g., Goksøyr and Förlin 1992) to the landscape levels (e.g., Hunsaker et al. 1990). As the literature expanded, the journal *Ecological Indicators* was introduced in 2001, dedicated to the topic. Clearly, there is a plethora of indicators that could be used to characterize ecosystem health, so the issue is not whether indicators of ecosystem health exist but rather identifying the particular sets of indicators that are most efficacious for understanding ecological condition and informing environmental management. We suggest that the specific sets of indicators that should be used logically and directly emerge from the integrated assessment–decision framework, discussed next.

DPSCR$_4$ FRAMEWORK: NEED FOR A NEW SYNTHESIS FRAMEWORK

Developing a conceptual framework for assessing a system of the scale and complexity of the Gulf of Mexico, with the diversity of audiences that need to be informed, requires a synthesis of the risk-based and DPSIR approaches, building upon the strengths of each while avoiding their deficiencies. The resulting conceptual framework consists of Drivers–Pressures–Stressors–Condition–Responses elements (DPSCR$_4$; Figure 1). This framework includes terms that have been used elsewhere in similar contexts, but because there is often inconsistency across the literature in usage of many of these terms, we define each element here to provide the specific meaning of the words as they are used in the DPSCR$_4$ framework. A few examples of various components of the DPSCR$_4$ framework applied to the Gulf of Mexico illustrate the construct (Table 1). In actuality, an assessment framework capable of meeting those scale and complexity criteria becomes applicable to virtually any ecosystem and any stressor regime and thus not limited to the Gulf of Mexico.

Drivers

Drivers are the fundamental forces, natural or anthropogenic, that ultimately drive the system. Drivers tend to be large-scale, long-term forces that are not easily controlled or diverted. Examples include demographic drivers (e.g., global population growth or demographic age structure), social drivers (e.g., expansion of human populations into previously undeveloped sensitive habitats), economic drivers (e.g., industrial and energy development), and natural drivers (e.g., the unequal distribution of solar energy across latitudes).

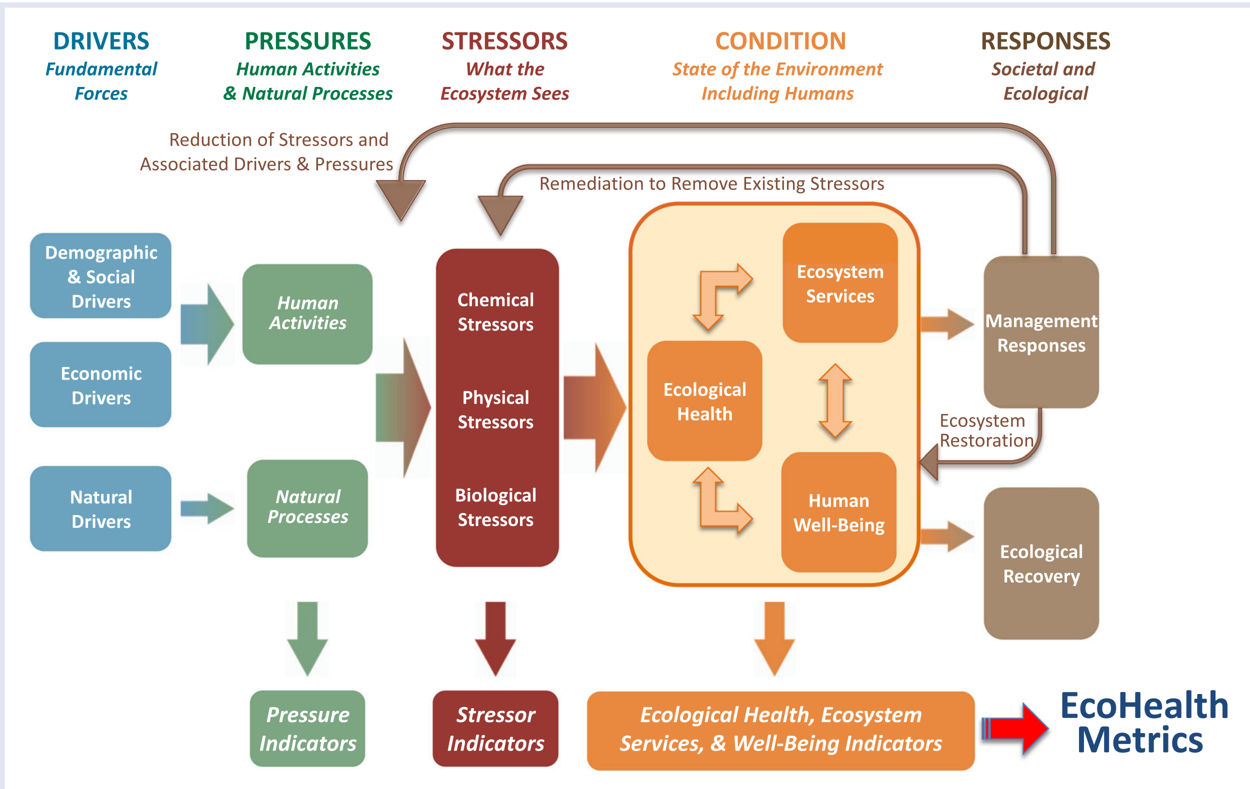

Figure 1. EcoHealth Conceptual Framework (DPSCR$_4$). DPSCR$_4$ = Drivers–Pressures–Stressors–Condition–Responses.

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Table 1. Examples of $DPSCR_4$ elements for the Gulf of Mexico

Drivers	Pressures	Stressors	Condition	Responses
Natural and anthropogenic	Human activities and natural processes	Natural and anthropogenic	Assessed on VECs	Societal and ecological
These are the fundamental forces	*These are what cause stressors*	*These are what the ecosystem sees*		*Reduction, remediation, restoration, and recovery*
Economic drivers	Human activities: Resource extraction	Biological stressors	Fish and wildlife VECs	Policies to reduce stressors
			Goal: Sustainable fish and wildlife	*Managing drivers and pressures*
• Industry	• Commercial fishing	• Invasive species	• Fisheries populations	• Environmental regulations
• Agriculture	• Recreational fishing	• Overfishing	• Avian populations	• Land-use management
• Development	• Oil and ga0s extraction	• Altered genetics	• Marine mammals	• Fisheries management
	• Groundwater usage	• Pathogens	• Sea Turtles	• Environmental education
		• Harmful algal blooms	• Endangered species	• Conserve special places
			• Economic species	
Demographic and social drivers	Human activities: Physical	Physical stressors	Habitats	Remediation
			Goal: Restore and sustain habitats	*Removing existing stressors*
• Population growth	• Coastal development	• Habitat alteration	• Wetlands	• Clean up oil spills
• Demographics	• Dredging	• Hydrological alteration	• Mangroves	• Clean up chemical spills
• Urbanization	• Shoreline structures	• Changes in salinity	• Oyster reefs	• Clean up toxic waste sites
• Social dynamics	• Transportation	• Changes in climate	• Seagrasses	
• Politics	• Channelization	• Suspended sediments	• Coral reefs	
	• Land-use changes	• Noise	• Barrier islands	
	• Dams	• Ocean acidification	• Freshwater and saltwater marshes	
		• Hypoxia		
Natural drivers	Natural processes	Chemical stressors	Ecological features	Restoration
			Goal: Restore ecosystem health	*Restoring ecosystems*
• Solar energy differences across latitudes	• Climate processes	• Nutrient inputs	• Connectivity of Gulf with coastal waters	• Plant seagrasses
• Earth's rotation	• Ocean dynamics	• Pesticides	• Landscape mosaic	• Restore freshwater flows
	• Sea-level dynamics	• Endocrine disruptors	• Biodiversity	• Increase wetland habitats
	• Biogeochemical dynamics	• Chemical or petroleum spills		• Remove invasive species
	• Trophic dynamics			Ecological recovery
				Ecological processes to return ecological health

$DPSCR_4$ = Drivers–Pressures–Stressors–Condition–Responses; VEC = valued ecosystem component.

Pressures

Pressures are human activities or natural processes that generate environmental stressors. They also tend to be large scale and long term but often can be highly variable over space and time. Examples of anthropogenic pressures (i.e., human activities) include agriculture, aquaculture, geophysical resource harvesting (e.g., oil exploration and mining), biological resource harvesting (e.g., fishing and forestry), coastal development, marine transport, recreation and tourism, flood control, and the anthropogenic components of global climate change and sea-level rise. Natural processes include ocean dynamic processes (e.g., upwelling and currents), climate processes (e.g., jet stream dynamics, monsoons, and El Niño–Southern Oscillations [ENSO]), sediment dynamics (e.g., subsidence, sedimentation), episodic events (e.g., earthquakes, tsunamis, and hurricanes), and the natural processes components of global climate change and sea-level rise.

Stressors

Stressors are what the ecosystem directly experiences, that is, the physical, chemical, or biological factors that can directly cause an ecological effect. Stressors are the critical point of intersection between the drivers and pressures and the resultant effects on ecological systems; consequently, these are the central cause-and-effect relationships for scientific inquiry and hypothesis testing. Examples of physical stressors include habitat alteration and loss, altered sedimentation and light regimes, altered salinity regimes, drought, hypoxia, and hydrologic alterations. Examples of chemical stressors include oil and chemical spills, altered nutrient inputs, pesticides, and other xenobiotics. Examples of biological stressors include invasive and introduced exotic species, overfishing or overharvesting, pathogens and disease, HABs, and altered genetics. Stressors may secondarily generate other stressors; for example, hydrologic alterations can lead to hypoxia, invasive species, and altered regimes of flooding, sedimentation, turbidity, light, and salinity.

Stressors may involve natural attributes of a system (e.g., the salinity regime of an estuary), which only become stressors when there is a change in the attribute over time or space (e.g., reduced freshwater inflow causing hypersalinity in locations or at times where none previously existed), or they may involve something novel to the ecosystem, such as xenobiotic toxic chemicals or habitat alterations. An environmental stressor may result from one or more pressures or even a mix of natural and anthropogenic pressures. For example, water management that reduces freshwater flows (anthropogenic) and ENSO-induced alterations in precipitation patterns (natural) both can produce a similar stressor (changes in the salinity regime of an estuary). Finally, stressors are system specific, and what is a stressor to 1 ecosystem (e.g., fire in a mangrove forest) may not be a stressor to another ecosystem (e.g., fire in a grassland).

Ecological condition

The state of the ecosystem is its condition or "health." Because there is an almost unlimited number of specific aspects of an ecosystem that could be used to characterize an ecosystem, a subset of attributes must be identified that are important either ecologically and/or societally, that is, assessment endpoints (USEPA 1998) or VECs (CCME 1996; Harwell et al. 2011). It is advantageous to select a parsimonious set of VECs, with some VECs representative of other similar components of the ecosystem, thereby reducing the number of attributes and causal relationships that need to be characterized to a reasonable and practical set. The set of VECs selected to characterize ecosystem condition should not only focus on endangered or economic species, as is often the case, but also consider ecological scale and hierarchy, and both ecological structure and ecosystem processes. Examples of structural VECs include endangered species, economically important species (e.g., a valuable fisheries population), intertidal or benthic communities, and primary producers. Functional VECs are ecological processes, such as primary productivity, biogeochemical cycling, nutrient dynamics, and trophodynamics. The VECs may also broadly relate to environmental quality, such as water quality, habitat mosaic across the landscape, and biodiversity. Particularly useful for our integrated assessment framework is the subset of VECs that constitutes ecosystem services, including provisioning services (e.g., fish stocks), regulating services (e.g., C storage associated with habitat loss), and cultural services (e.g., bird-watching or other environmentally related recreation and tourism) (UNEP WCMP 2011; Egoh et al. 2012; Hattam et al. 2015).

Finally, in characterizing a VEC (e.g., brown pelican), it may be appropriate to measure the VEC directly (e.g., number of pelicans in a population), but often indicators need to be identified that indirectly reflect on the condition of the VEC. For instance, indicators could include the pelican population age structure, the frequency distribution of eggshell thicknesses, the areal extent and distribution of breeding colonies, or the body burden of PCBs in adult pelicans. Other examples of VECs and associated indicators for the Gulf include the following:

- indicators for VEC water quality: chlorophyll *a*, transparency, total suspended solids;
- indicators for VEC coral community health: coral cover, juvenile recruitment, algal cover, coral composition;
- indicators for VEC seagrass community health: areal extent, seagrass density, nutrient status, community composition; and
- indicators for VEC habitat mosaic: spatial frequency of habitat types and patch-size distributions.

In general, the metrics for each indicator should collectively represent the condition of the VEC at a particular point in time and space.

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It is the indicators that will form the foundation of the EcoHealth assessments, including not only indicators that characterize VECs, but also indicators that characterize stressors and pressures, thereby identifying risks to the environment or possible causes for observed effects, plus targets for responses to reduce stressors and improve environmental health. Additionally, the particular levels or trends characterized by the effects indicators can be compared with specific benchmarks, such as historical conditions, desired goals for the particular VEC, or benchmarks between impacted conditions and recovery (Harwell et al. 1996). This comparison allows assignment of qualitative categories of condition, such as degraded, fair, or healthy, or more quantitative ecological health metrics, such as grades, scores, or indices.

Responses

In the original environmental management–based PSR and DPSIR frameworks, response was meant to capture societal feedbacks in response to the ecological impacts, particularly environmental and economic policies and programs intended to prevent, reduce, or mitigate pressures and/or environmental damage (OECD 1993; EEA 1999). In the new framework, we expand responses to include not only such societal responses but also ecological responses, that is, changes in the ecological system. Four types of responses are identified: reduction of stressor sources, remediation of existing stressors, ecological restoration, and ecological recovery.

Reduction. Stressor source reduction consists of societal responses targeted at the management of the drivers and pressures in order to reduce stressors. Examples include policies to reduce greenhouse gas emissions or require more effective wastewater treatment systems. Stressor source-reduction responses may also entail activities such as enhanced environmental educational programs or providing consumers with clearer information on the source and safety of seafood in the markets, among many other examples.

Remediation. Remediation is the set of actions specifically aimed at reduction or elimination of a stressor that has been released into the environment, typically chemical stressors such as toxic wastes or an oil spill; thus, this component reflects the suite of cleanup (i.e., remedial) activities implemented under Natural Resources Damage Assessment (NRDA) regulations (derived from the Comprehensive Environment Response, Compensation and Liability Act [CERCLA 1980]) and the Oil Pollution Act of 1990 (OPA 90 1990) regulations (NOAA 1996a, 2010).

Restoration. Restoration occurs when intervention is made directly into the ecological system in order to undo ecological damage that has been done or to accelerate or enhance the process of ecological recovery, discussed next; it also a component of NRDA regulations (NOAA 1996b). Restoration may entail such actions as removal of invasive species, reconstruction of wetlands, planting of trees in riparian habitats, adding riffles and pools to a stream, or introduction of an endangered or extirpated species into its former habitat.

Recovery. Recovery, the final "R" in our framework, differs from the others in that it involves natural ecological processes of an ecosystem, once a stressor has been eliminated or reduced below adverse effects levels. Recovery reflects ecological resilience, that is, whether or not and how quickly an ecosystem returns to normal once it is no longer under stress (Holling 1973). Thus, recovery is an internal ecological feedback process, rather than a societal one. An ecosystem has recovered from an incident, such as a chemical or oil spill, once the stressors are gone and all VECs have returned to some baseline condition, given dynamical ecosystem changes and natural variability. Consequently, recovery occurs when there no longer are ecologically significant adverse effects (Gentile and Harwell 1998). The corollary is that recovery cannot fully proceed until the stressors are reduced to below an effects threshold. Where stressors are continuing or periodic, ecological feedbacks may entail permanent changes or even ecological phase shifts in place of recovery. More thorough discussions of ecological recovery are presented in Harwell et al. (2013) and Harwell and Gentile (2014).

Several advantages of the new $DPSCR_4$ construct underpin ecosystem health assessments: The full sequence of causal relationships is delineated from the ultimate source (fundamental societal or natural drivers) through its manifestation as pressures (human activities and natural processes) and the resulting environmental stressors that the system actually sees, to the effects on ecological condition and the responses that ensue, either through societal actions or natural ecological recovery processes. Second, by taking these relationships from the broad scale down to the specific cause–effect process, an EcoHealth assessment can characterize the system simultaneously from the big-picture policy level to the hypothesis-driven scientific level and back. When nested within a hierarchy of reporting levels, as discussed below (EcoHealth reporting structure), this framework can inform interested audiences at all levels. Similarly, this framework is ideal for aggregation and disaggregation, in which finer scale issues may be explored and illuminated, or in which broader relationships can be more readily perceived. Moreover, this framework can adapt and evolve as more information is gathered and the system becomes better understood, as things change over time or space, or as the scale of the environmental problem varies from small and local to very large scale and multidimensional. Thus, the EcoHealth assessment framework can become both responsive to new management needs or questions and useful in identifying uncertainties and new areas of research or monitoring.

The $DPSCR_4$ framework corrects the 2 serious flaws in the DPSIR framework (i.e., skipping over the critical stressors component and thus missing the causal part of cause-and-effects relationship, and the conflation of state and impacts).

Finally, the $DPSCR_4$ conceptual framework provides the basis and rationale for identifying the specific sets of indicators in EcoHealth assessments for pressures, stressors, and condition, the particular suite of attributes desired for each indicator and VEC, and insights into the management or societal actions that could be implemented to achieve ecological health goals; consequently, the $DPSCR_4$ framework provides guidance both for ecosystem health assessment and for environmental decision making. In essence, the $DPSCR_4$ framework functions as a systematic and comprehensive set of sieves, partitioning and filtering information about the coupled human–ecosystem of concern, from which emerges the specific set of indicators to comprise an ecosystem health report card or, as discussed next, the complete set of EcoHealth metrics (bottom of Figure 1).

EcoHealth reporting structure

The integrated ecosystem assessment framework is further structured to inform a diversity of audiences with differing concerns and levels of scientific understanding. This is accomplished by overlaying onto the $DPSCR_4$ framework a structural hierarchy that emphasizes tier-relevant components and indictors (Figure 2) appropriate to the differing types of audiences to be informed by an ecosystem health assessment. The top level is the target of the original PSR and DPSIR frameworks, focused on the overall condition of the environment, the broad pressures that influence it, and the societal responses that ensue. It requires very few indicators of health and thus constitutes the greatest degree of aggregation into the most simple-to-understand synthesis metrics and formats, that is, a report card.

The next lower level is the realm of people who make or influence environmental decisions and policy. This tier emphasizes impacts from pressures on the environment and specific societal responses to mitigate impacts by managing pressures. This level requires more information because the audience tends to be more engaged in the issues of concern. Below that is the level of hands-on environmental managers, for example, managing a park or conservation lands. These individuals need to understand a diversity of environmental issues relevant to their specific location or ecosystem types. Consequently, this tier focuses on specific stressors, their impacts on particular ecosystems of concern, and remediation and restoration activities that might be implemented to achieve management goals.

At the base of the hierarchy is the scientific community whose hypothesis-driven focus is on environmental stressors, their effects on ecological condition, and whether the effects constitute adverse health compared to baseline or benchmark conditions; remediation and restoration activities to improve the health of the environment; and the ecological processes underlying ecosystem recovery and determining when recovery has been attained. Indicators at this tier are numerous and aggregation is minimal, consistent with the many hypotheses concerning stress–effects relationships in ecosystems. These indicators are the ultimate foundation of the EcoHealth assessments, that is, specific qualitative or quantitative metrics that reflect the relevant characteristics of each VEC and of each pressure and stressor over time and space. The utility of each indicator depends on fidelity to condition, data availability, ability to interpret and explain results, and spatial and temporal applicability (Kelly and Harwell 1989, 1990; Dale and Beyeler 2001). Development of databases and monitoring for each indicator, including establishment of reference or benchmark conditions (Harwell et al. 1996; Harwell, Gentile et al. 1999; Harwell, Myers et al. 1999), can provide the foundation for understanding the dynamics of each VEC, its trajectory over time and space, and its health or recovery status.

The hierarchical reporting structure presents a dynamic framework for aggregating information into more integrative indicators at higher levels and for channeling specific information requests from higher tiers down to the appropriate level. As information is acquired by scientific investigations or through environmental monitoring, updated or new indicators can be provided to the tiers above. Concomitantly, information needs identified at higher levels can guide the scientific investigations performed, inform the allocation of resources to reduce important uncertainties, or encourage development of new integrative metrics. Thus, the $DPSCR_4$ hierarchy provides the template for this 2-way information exchange to occur and may lead to more efficacious acquisition and utilization of research and monitoring data. Similarly, it avoids the limitation of the strictly stress-effects–based assessment framework because its hierarchical structure and aggregation or disaggregation processes allow it to better accommodate multiple stressors.

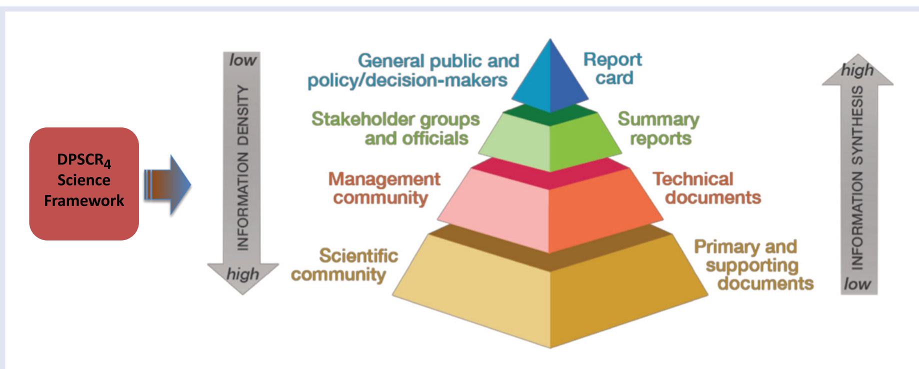

Figure 2. EcoHealth metrics hierarchical reporting structure.

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Constructing a Gulf EcoHealth report card

A long-term objective is to apply the $DPSCR_4$ framework to assess the ecosystem health of the Gulf of Mexico. The strategy is to disaggregate the Gulf into manageable regions, subregions, or other reporting units, and then sequentially follow the $DPSCR_4$ framework to develop the Gulf EcoHealth report card specific to that unit. The Gulf can be partitioned into several regional-scale subunits based on geographical, ecological, and/or political boundaries. Within each region are delineated specific habitat types of concern, such as seagrass or salt marsh communities, and within each habitat are identified specific sets of VECs and associated indicators. Moreover, crosscutting ecological components, such as migratory birds and marine mammals, are very relevant to ecosystem health and thus essential components of EcoHealth assessments. When completed, these component assessments would be reaggregated across spatial and ecological scales, essential for characterizing the health of such a large and complex ecosystem as the Gulf of Mexico.

We developed a stepwise process for constructing the EcoHealth report card for any particular area:

1) Develop the conceptual ecosystem model. This conceptual modeling process should involve scientists, managers, and stakeholders familiar with the systems of concern to ensure that ecosystem elements are adequately identified and long-term sustainability goals are appropriately defined. Typically, this is done in a workshop setting, in which the region or subregion is partitioned into its constituent ecological habitats, and the VECs of each habitat are identified, along with the drivers, pressures, and stressors impinging upon them. Next, a series of matrices are constructed linking the drivers or pressures and their resulting stressors with the VECs that would be affected, including assigning a relative strength of each stressor–effect relationship. An example of such a matrix is illustrated in the pilot study on coastal Texas rookery islands presented in the next section. By having knowledgeable workshop participants make such judgments on the interactions of every stressor and every VEC for each habitat in the ecosystem of concern, a substantial amount of information is captured about how the ecosystem responds to natural and anthropogenic stressors and the pressures and drivers that cause them. From these completed matrices a set of habitat-specific, risk-based graphical conceptual ecosystem models (CEMs) can be constructed; collectively, the CEMs for a region should reflect the connectivity among all the ecosystem components. In the format we use for these conceptual models (Supplemental Data Figure 1), the top tier (shown as rectangles) is pressures, in this case human activities that impinge on the Mission-Aransas Reserve, Texas, USA landscape. The next tier (ovals) is the environmental stressors that result from the pressures to which they are linked in the graphic, with thicker lines representing stronger linkages. At the bottom tier (hexagons) are the VECs, identified here for the landscape-level attributes of the Reserve, showing the weighted linkages between specific stressors and effects on specific VECs. For additional examples of this risk-based class of CEMs, see Cormier et al. (2000), Gentile et al. (2001), and Ogden, Davis, Barnes et al. (2005), and Ogden, Davis, Jacobs et al. (2005).
2) Select indicators. For each conceptual model derived from the $DPSCR_4$ framework, indicators are identified for spatially explicit reporting on each important pressure, stressor, and VEC. Selected indicators should be data driven, reliably measurable, and/or based on integrative techniques. Collectively, the goal is for a parsimonious set of indicators that captures the information needed to characterize and evaluate ecosystem health, reflecting current status and future trends for pressures or stressors and for ecological condition. Indicators should be chosen with consideration of their use within the EcoHealth assessments (Table 2) (Kelly and Harwell 1989, 1990).
3) Define goals, benchmarks, and thresholds for assessment. Goals are defined here as the desired condition for the particular ecosystem or ecosystem component, often identified in the context of ecological sustainability. Benchmarks are defined here as milestones along the way from the current condition toward the desired sustainable state (Harwell, Myers et al. 1999). Thresholds may be identified that mark particular levels of health, often useful for communicating ecosystem condition. A quantitative or qualitative metric that defines a desired condition or goal for each indicator should be established, allowing indicator metrics to be assessed and reported in the EcoHealth assessments. Goals and benchmarks can be set in several ways, including using established regulatory metrics (e.g., numerical ambient water quality criteria; Stephan et al. 1985), identifying biologically or ecologically relevant data values from the literature (e.g., defining hypoxia to be $\leq$2.0 mgL^{-1} dissolved O; Rabalais et al. 2002), comparisons to historical conditions prior to major impacts (e.g., assessing areal coverage of seagrass communities in the northern Gulf; Carter et al. 2011), or measurements of benchmarks that have been achieved in similar ecosystems elsewhere.
4) Characterize results. Indicator values are evaluated against specific goals, benchmarks, or thresholds. These may be standardized into assigned condition categories, and values for individual indicators may be integrated to produce an overall index or other metric for the VEC, pressure, or stressor. These may be spatially integrated to characterize a subregion or region of concern, and these in turn may be further integrated with other subregion or region results using an area-weighting approach.
5) Communicate results. The communication of results is the ultimate goal of the EcoHealth assessments; it should be multifaceted and transparent, structured hierarchically for different audiences (Figure 2). Each EcoHealth assessment document should be a graphics-rich, synthesis document that aggregates results to

Table 2. Purposes and criteria for selecting indicators

Purpose of indicators	Criteria for selecting indicators
Intrinsic importance—key: indicator is the endpoint • Examples: economically important species; endangered species Early-warning indicators—key: rapid indication of effects • Screening tool • Quick response time • Low signal-to-noise ratio, low discrimination • Accept false positives Diagnostic indicators—key: reliability in predicting effects • High stressor specificity • High signal-to-noise ratio • Minimize false positives Process or functional indicators—key: process in the indicator • Monitoring other than biota (e.g., decomposition rates)	Signal-to-noise ratio • Sensitivity to stressor • Intrinsic stochasticity Rapid response • Early exposure • Quick dynamics (e.g., short life span) Reliability or specificity of response Ease or economy of monitoring • Available field protocols • Preexisting database • Low-cost tools Relevance to the endpoint • Answers the "so what" question Feedback to managers

Modified from Kelly and Harwell (1990), with permission from Springer Nature. © 1990.

create an easily understandable message about the overall health of the ecosystem. Underlying information, source documents, and linkages to data sources are important to providing transparency of process and accessibility to information appropriate for managers, decision makers, program managers, and scientists. Assessment results may be communicated on an annual and/or multiyear cycle, similar to the series of Chesapeake Bay Report Cards and Everglades System Status reports (e.g., IAN 2007, 2013; ecoreportcard.org; evergladesrestoration.gov).

TESTING THE CONCEPTUAL FRAMEWORK: TEXAS COASTAL ECOSYSTEMS REPORT CARD AND MISSION-ARANSAS RESERVE ROOKERY ISLAND PILOT PROJECT

Because an EcoHealth Metrics for the Gulf of Mexico is so complex and diverse, we conducted a proof-of-concept evaluation of the $DPSCR_4$ conceptual framework and its implementation for assessments through constructing a prototype Texas coastal ecosystems report card. Coastal Texas and its watersheds provided an excellent pilot project for the entire Gulf because of the diversity and complexity of its ecosystems, human communities, and associated environmental pressures and stressors. In the present pilot study we followed the 5 steps listed in the preceding section, focusing on a manageable subset of Texas coastal ecosystems and crosscutting ecological components, specifically seagrass meadows, oyster reefs, recreational and commercial fisheries, and resident and migratory coastal birds. The resulting prototype Texas Coastal Ecosystems Report Card (McKinney et al. 2018a, 2018b) provides details on the pressures, stressors, VECs, ecosystem services, stress–effects matrices, CEMs, assessment data, scoring methodologies, and results for each system type evaluated; a summary of the fisheries and avian report cards are presented in the Supplemental Data.

This Texas pilot study demonstrated that the framework is ideal in providing a systematic and comprehensive methodology for understanding the coupled human–ecological systems and for identifying the elements of a comprehensive ecosystem health report card. Unfortunately, the available data for ecosystems assessment were limited to only a few selected attributes for some VECs of some systems, and other than water quality information, which has been collected at length by various state and local agencies, only minimal information exists on most pressure and stressor indicators for any ecosystem. As a result, we could not construct the Texas report card called for by the $DPSCR_4$ framework. From existing data we could derive the status and trends of the health of selected fish and avian species (Figures 3 and 4, respectively). However, the identical report card on these 2 ecosystem components could have resulted had we simply used existing protocols for report cards, such as the Chesapeake Bay and Mississippi River systems (e.g., IAN 2013; americaswatershed.org). Consequently, the $DPSCR_4$ conceptual framework provided no added value for conducting ecosystem health assessments when using existing data because of the paucity of data. On the other hand, the $DPSCR_4$ framework was very useful in identifying the elements of the environmental monitoring program that would be necessary for comprehensively assessing ecosystem health of the Gulf of Mexico and progress toward sustainability goals; that is, its essential utility is prospective, guiding future data acquisition and analyses. This is especially important given the extensive financial resources that are becoming available for Gulf of Mexico environmental research and monitoring resultant from the settlement of the Deepwater Horizon legal (e.g., Clean Water Act penalties) and legislative processes (e.g., the RESTORE Act 2012 and RESTORE Act 2015; see https://www.restorethegulf.gov/history/about-restore-act).

The second proof-of-concept pilot study was designed to examine the $DPSCR_4$ assessment and decision framework as applied to a specific management issue of the Mission-Aransas Reserve (https://missionaransas.org; Figure 5). Mission-Aransas is one of 29 National Estuarine Research Reserves around the country, each a federal and state partnership for conducting research, education, and stewardship programs. The Mission-Aransas Reserve, which is a partnership between National Oceanic and Atmospheric Administration (NOAA) and the University of Texas Marine Science Institute, has as its primary goals to improve knowledge of the ecosystem structure and function of Texas coastal ecosystems, promote understanding of the Texas coastal ecosystems by diverse audiences, and promote public appreciation and support for stewardship of coastal resources (Mission Aransas Reserve 2019).

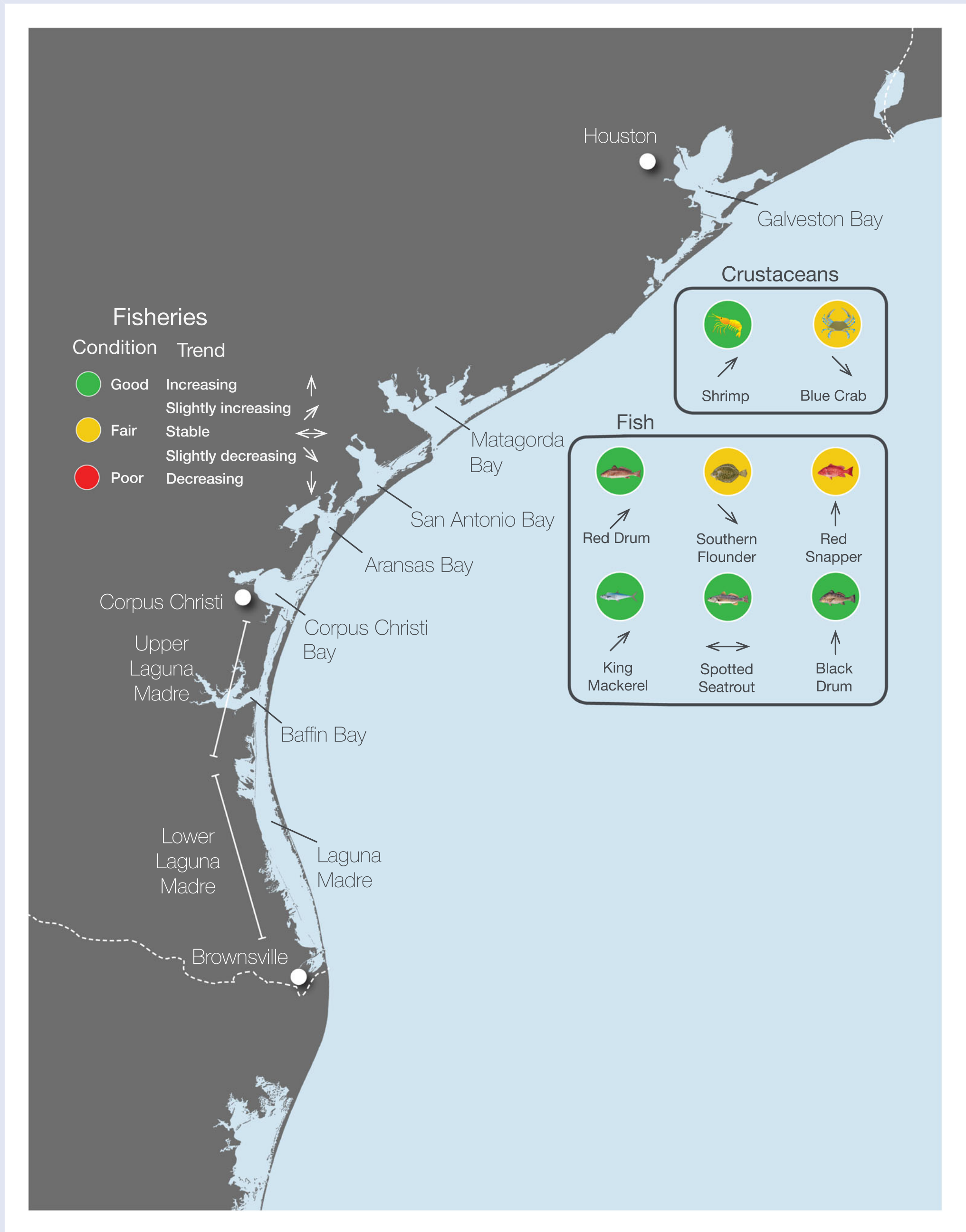

Figure 3. Status and trends for selected fish and invertebrate species.

The present pilot study was designed to use the components of the DPSCR$_4$ conceptual framework to characterize the critical linkages between the ecological and societal systems, identify specific key indicators for assessing ecological health and ecosystem services, identify management alternatives for assessment, and apply ecosystem-based management tools to analyze the options with respect to achieving management goals. We asked the managers and scientists from the Reserve to identify an important environmental management issue that might benefit from applying our integrated assessment framework for guidance. The management goal selected for the pilot study was to create or expand rookery islands in order to enhance nesting, breeding, and foraging habitat for both resident and migratory coastal birds. Colonial waterbirds function both as a critical ecosystem services component and as an important ecological functional component of the Mission-Aransas ecosystem.

The management focus on enhancement of rookery island habitat results from the risk to the long-term sustainability of resident and migratory coastal birds by the historical and ongoing degradation or loss of critical habitat in the coastal areas of the Mission-Aransas Reserve and the associated Coastal Bend Bays & Estuaries Program (CBBEP; http://www.cbbep.org). Analysis of data from 1973 to 2008 on 14 colonial waterbird species that

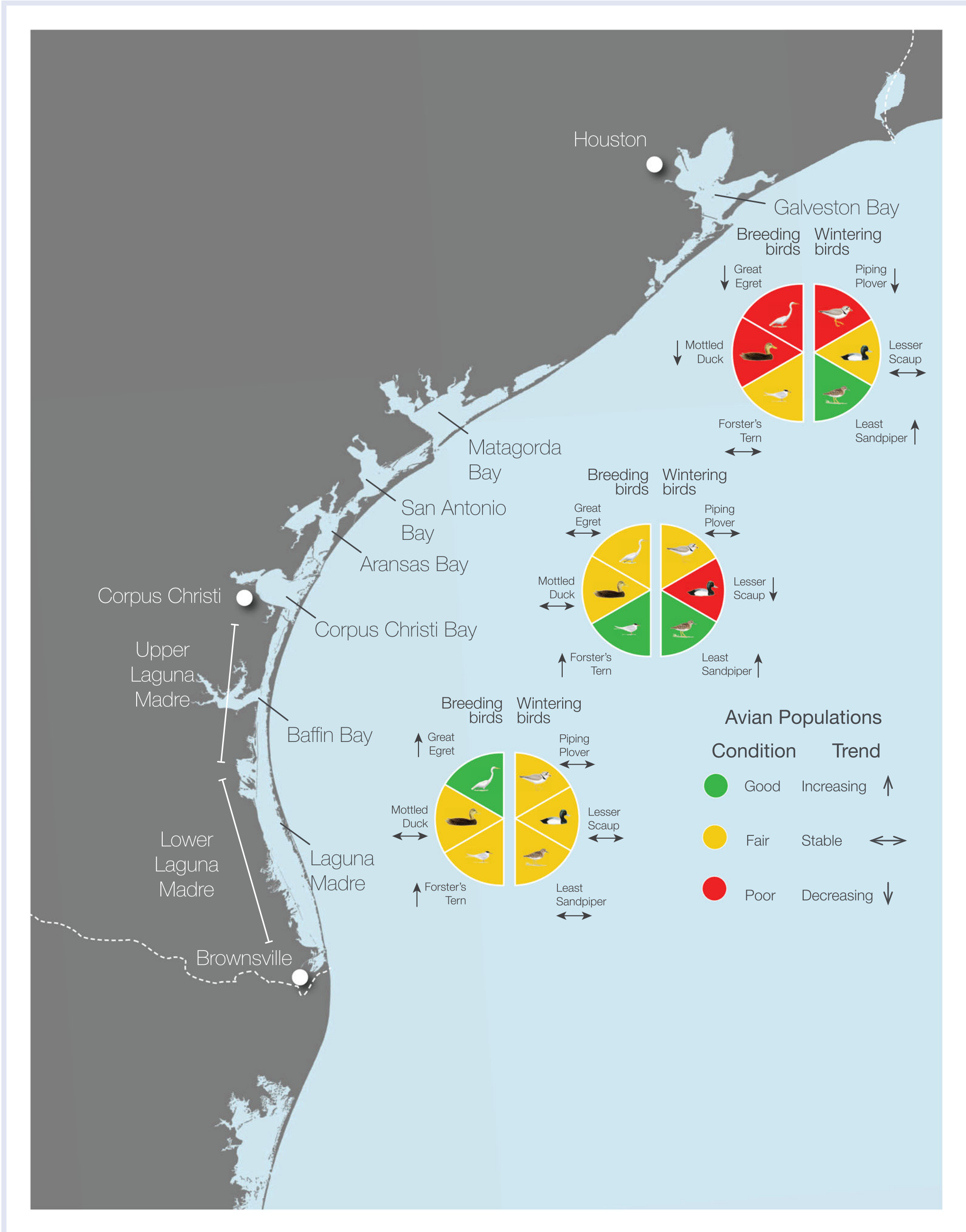

Figure 4. Status and trends for selected breeding and wintering bird species.

use the Texas Coastal Bend area shows that the populations of several species are decreasing, driven primarily by a decrease in available waterbird island nesting habitat, resulting from sea-level rise and storm-surge erosion, subsidence, increasing human pressure and habitat loss adjacent to both nesting and feeding areas, and a scarcity of adequate nesting substrate. Consequently, Reserve and CBBEP managers and scientists identified suitable nesting habitat to be the major limiting factor in the long-term sustainability of waterbird species in the Coastal Bend area (CBBEP 2010). Colonial-nesting waterbirds require islands for breeding that provide suitable nesting habitat (e.g., shrubs for wading birds, bare ground for terns) free from predators and disturbance sources and relatively close to feeding areas. Unlike barrier islands in the region, the rookery islands are typically smaller and consequently less affected by predators (CBBEP 2010), and thus became the focus of the pilot study.

The pilot study approach was to apply a structured decision-support system to the $DPSCR_4$ framework and use geospatial ecosystem-based management tools and scenario–consequence analyses to assess the management options. We systematically characterized each of the $DPSCR_4$ components for rookery islands (Table 3), which suggested stressors to be minimized and attributes to be optimized in rookery island site identification and selection.

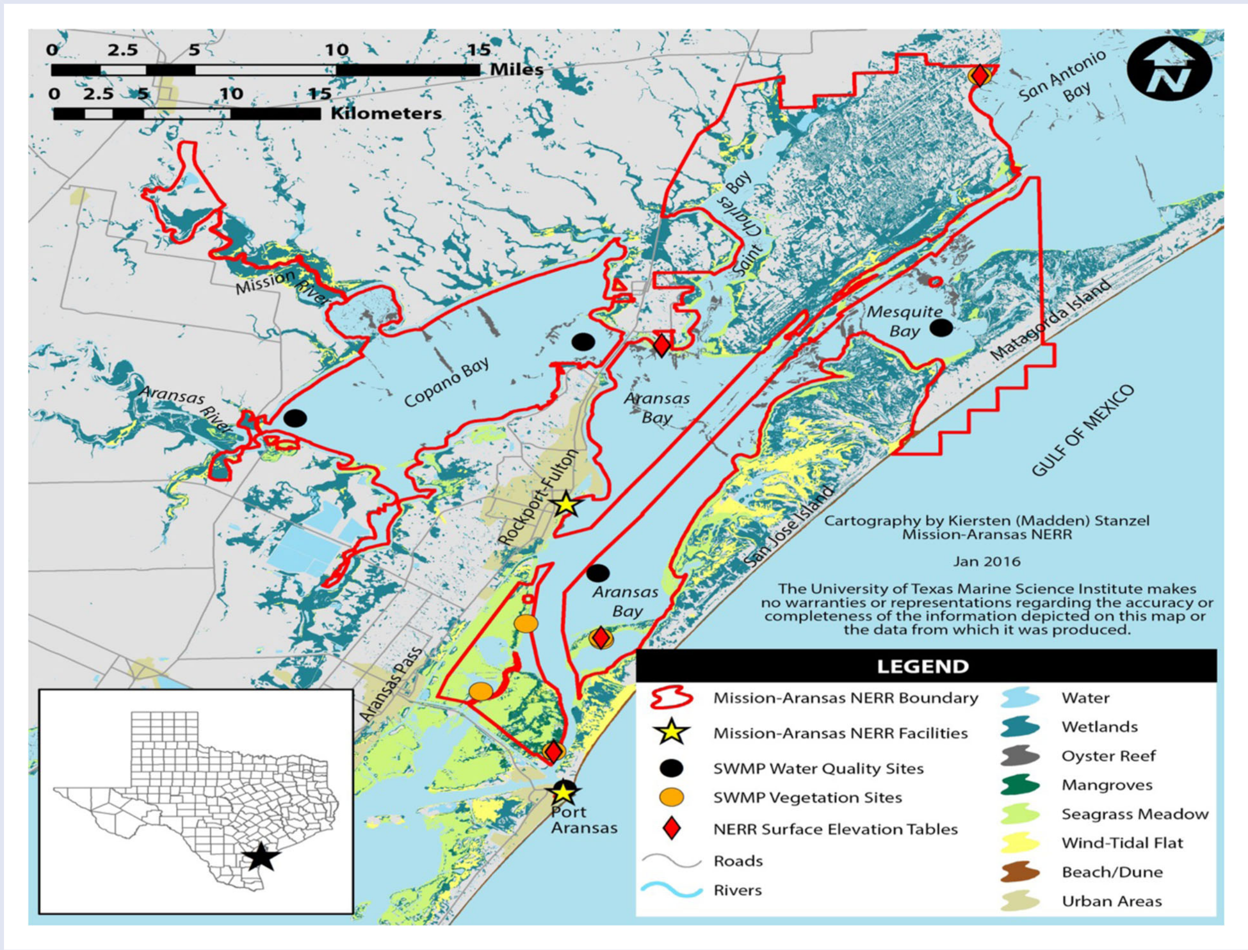

Figure 5. Map of the Mission-Aransas National Estuarine Research Reserve. NERR = National Estuarine Research Reserve; SWMP = System-Wide Monitoring Program.

We began with the development of conceptual ecosystem models for the rookery islands by examining the stressor–effects relationships as shown in the causal matrices for physical, chemical, biological, and climate-change stressors (Table 4). Each entry in the matrix reflects how large an effect, if any, on each VEC would occur by the presence of each stressor at current or plausibly anticipated levels of intensity, duration, and extent. For example, the stressor changes in the hydrological regime was expected to have a high effect on rookery island areal extent and/or location, structural complexity, successional patterns, and habitats for resident and migratory birds, whereas the stressor marine debris was not expected to have any effects on areal extent and only low-level effects on the other structural attributes. By systematically capturing the consensus expert opinion on the strength of stressor–effects relationships for all stressors and all VECs of a system, the risk regime of that system is essentially characterized. The complete rookery island CEMs are shown in Supplemental Data Figure 2.

The key factors in rookery island habitat emerge from the application of the $DPSCR_4$ framework to the Mission-Aransas environmental issues and the development of the details of Table 4, including 1) the Reserve management's emphasis on ecosystem services and well-being highlighted the particular value of rookery islands to support bird-watching and associated activities in the Texas Coastal Bend region; 2) the structural attributes of rookery islands directly affect their functional attributes; 3) a number of important stressors can adversely affect the spatial extent and habitat quality of rookery islands, which are critical to sustainability of the coastal bird populations; 4) specific site characteristics affect the potential of rookery islands to achieve desired attributes (e.g., distance from major land mass in order to preclude invasion by predators that often seriously inhibit or prohibit nesting birds); and 5) the rookery island site-selection process was guided by the $DPSCR_4$ framework toward reducing those specific stressors and optimizing those desired structural and functional attributes.

Two management scenarios were explored in the Mission-Aransas pilot study: 1) enhancing existing rookery islands in order to improve the availability of habitats for nesting and/or migratory birds and 2) identifying the optimal location and configuration for new artificial rookery islands for single- or multipurpose use (e.g., adding oyster reefs or recreational fishing habitat). The spatially explicit Texas Colonial Waterbird Society data for 1970 to 2015 were acquired for specific locations of islands or island

Table 3. The $DPSCR_4$ framework populated for Mission-Aransas rookery islands

Stressors	Condition attributes	Ecosystem services	Well-being attributes
Physical stressors	Structural attributes	Bird watching	Recreation
Changes in salinity regime	Areal extent	Recreation	Economic
Changes in precipitation	Habitat diversity	Navigation	Cultural
Erosion	Structural complexity	Habitat value	Health
Sea-level rise	Successional patterns	Biodiversity	
Inundation	Breeding resident birds		
Storms	Winter-migratory birds		
Noise	Functional attributes		
Chemical stressors	Colonial waterbird breeding habitat		
Nutrients			
Petroleum releases	Waterbird nonbreeding habitat		
Pesticides and herbicides	Whooping crane habitat		
Biological stressors	Marsh habitat		
Food availability	Seagrass habitat		
Predation	Fish habitat		
Harmful algal blooms	Invertebrate habitat		
Human presence	Oyster habitat		
	Erosion protection		

$DPSCR_4$ = Drivers–Pressures–Stressors–Condition–Responses.

clusters within the Reserve and surrounding area (TCWS 2019). Additional geospatial data were acquired for important landscape variables (e.g., distance and direction from land masses and sources of predators), hydrological attributes (e.g., bathymetry), and biological attributes (e.g., benthic cover, presence of existing rookery site) that could be used to identify candidate sites for rookery island creation or enhancement.

These geospatial data were layered into the geographical information system (GIS) software extension package, NatureServe Vista (NatureServe 2019), to develop an index that characterizes the Mission-Aransas Estuary system and adjacent estuary systems vis-à-vis their suitability for rookery island development. Suitability factors related to rookery island creation and/or enhancement (e.g., water depth, distance from shoreline, benthic habitat cover) were determined with input from local experts and were characterized spatially across the landscape on the basis of their assigned suitability characteristics (Table 5). The suitability index was calculated from the weighted values of each relevant suitability factor. NatureServe Vista was then used to determine where the most suitability factors for rookery island creation or enhancement were found together (for details, see Stanzel 2017).

Suitability scores were calculated for the entire study area. The highest priority sites (i.e., specific areas where the most suitability factors overlapped) were identified using the Site Explorer tool within NatureServe Vista. If the high-suitability grid cells were located adjacent to another high-suitability grid cell with the same score, multiple cells were aggregated, resulting in 30 high-suitability candidate sites. To allow for better visualization to distinguish existing rookery island sites that are suitable for enhancement versus high-priority sites for creation of a new multipurpose rookery island, each of the high-suitability candidate sites was identified using a single point in the grid.

Each of the 30 high-suitability sites were further characterized using the following information: 1) suitability score, 2) size (number of acres), 3) location (latitude/longitude), 4) average water depth, 5) benthic habitat type, 6) average distance from shoreline, 7) average direction from shoreline, 8) water with depth of 4 feet located within 800 feet of site, and 9) presence of an existing rookery. These characteristics proved to be helpful to managers as they prioritized within the list to determine which sites should be further explored for their potential for restoration or enhancement. For example, "water with depth of 4 feet within 800 feet" suggests which sites may be more accessible by barges carrying material for island creation or restoration, and characterization of the nearby habitat can help determine the likelihood that mitigation for damage to seagrass or oysters caused by island construction would be required.

In a final workshop, scientists and managers from the Harte Research Institute, the Mission-Aransas Reserve, CBBEP, and other state and federal agencies used the index results and the suitability criteria to select priority sites for additional investigation (Figure 6). For enhancing existing rookery island sites, Deadman's Reef and Third Chain of Islands were assigned highest priority, and Redfish Bay and Big Bayou Spoil were identified as worthy of further exploration. For creating a new rookery island, top priority was assigned to Seadrift in San Antonio Bay, and the sites deemed worthy of further exploration were Falcon Point, Second Chain of Islands, and Cape Carlos.

Unfortunately, shortly after these analyses were completed in August 2017, Hurricane Harvey passed directly over the study area. A post hurricane reconnaissance survey of rookery islands in the area by staff from CBBEP found widespread destruction, including near-complete loss of several islands, severe habitat degradation on nearly all the islands, and loss of almost all protective signage, along with

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Table 4. Stressor–effects matrix for Mission-Aransas rookery islands: Physical, chemical, biological, and climate-change stressors

Table 4. (*Continued*)

	Stressors																																								
	Physical																		Chemical										Biological									Climate			
Rookery islands VECs	Hydrological changes	Salinity regime	Precipitation regime	Sedimentation	Erosion	Habitat alteration	Fire regime	Sea-level rise	Inundation	Hurricanes or storms	Resource harvesting	Marine debris	Solid waste disposal	Temperature changes	Turbidity	Noise	Subsidence	SAV damage	Nutrient loading	Organic loading	Toxic metals	Petroleum releases	Petroleum spills	Other chemical spills	Pesticides/herbicides	Hypoxia	Atmospheric deposition	Pharmaceuticals	Altered food availability	Predation	Pathogens	Invasive species	Resource harvesting	Harmful microalgal blooms	Harmful macroalgal blooms	Marsh management	Human presence	Precipitation regime	Temperature changes	Hurricanes or storms	Sea-level rise
Structural attributes																																									
Areal extent or location	H	—	—	H	H	H	—	H	H	H	H	—	—	—	—	—	M	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	H	H
Diversity of habitats on/around islands	M	M	M	M	M	H	M	H	M	M	M	L	L	L	M	—	H	M	H	M	L	H	H	H	H	M	L	L	L	L	L	M	M	M	M	M	L	M	L	M	H
Structural complexity of island	H	M	M	L	H	H	M	H	M	M	L	L	L	L	L	—	H	M	H	M	L	M	M	M	M	M	L	L	L	L	L	H	L	L	L	L	L	M	L	M	H
Successional patterns	H	M	M	L	H	H	M	M	M	M	L	L	L	L	L	—	M	L	L	M	L	M	M	M	M	M	L	L	L	L	L	H	L	L	L	L	L	M	L	M	M
Breeding-residents: Terns, skimmers, herons, egrets	H	H	H	L	L	L	L	H	H	H	L	L	L	L	L	H	L	L	H	L	L	H	H	H	H	L	L	L	H	H	L	L	L	H	H	L	H	H	L	H	H
Wintering-migratory: Plovers, sandpipers, knots	H	L	M	L	L	L	L	H	H	H	L	L	L	M	L	M	L	L	L	L	L	MH	MH	MH	L	L	L	L	H	M	L	L	L	M	L	H	H	M	M	H	H
Functional attributes																																									
Wave and erosion protection	H	—	—	M	H	H	—	H	H	H	M	—	—	—	—	—	M	—	L	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	H	H
Colonial waterbird breeding habitat	H	—	—	M	H	H	—	H	H	H	M	H	L	—	—	L-H	L	—	—	—	L	H	L	L	—	—	—	—	—	—	?	L	—	—	—	—	H	—	—	H	H
Waterbird nonbreeding habitat	H	—	H	M	H	H	—	H	H	H	M	L	L	L	—	—	M	—	L	—	L	H	L	L	—	—	—	—	—	—	?	L	—	—	—	—	L	H	L	H	H
Whooping crane habitat	H	—	H	M	H	H	—	H	H	H	M	H	L	L	—	L-H	M	—	L	—	L	H	L	L	—	—	—	—	—	—	?	L	—	—	—	—	H	H	L	H	H
Fish habitat	L	L	L	L	L	L	L	—	L	L	L	L	L	L	L	L	L	M	L	L	L	H	H	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
Invertebrate habitat/community	MH	M	M	MH	L	M	L	—	L	L	L	L	L	L	L	L	L	M	L	L	L	H	H	L	L	L	L	L	L	L	L	L	L	L	L	L	L	M	L	L	L
Seagrass habitat	M	M	L	M	M	H	-	M	L	L	L	L	L	L	H	-	M	H	H	H	H	H	H	H	H	H	L	L	L	L	L	L	L	H	H	H	L	L	L	M	M
Oysters habitat	M	H	M	MH	M	H	-	M	L	M	H	L	L	M	H	-	M	L	H	H	H	H	H	H	H	H	L	M	L	L	H	L	H	H	H	H	L	M	M	M	H
Marshes habitat	H	H	M	M	M	H	L	M	M	M	L	L	L	L	L	-	M	L	L	L	L	H	H	H	H	M	L	L	L	L	L	M	L	L	L	L	L	M	M	H	H

— = no effects; ? = high uncertainty or unknown effects; H = high effects; L = low effects; L-H = low or high effects, depending on nesting season; M = medium effects; MH = medium-high effects; VEC = valued ecosystem component; SAV = submerged aquatic vegetation.

Table 5. Summary of conservation elements and suitability criteria used in the rookery Island pilot study

Conservation element	Rationale	Suitability	Weighting
Water depth	Water depth affects the cost or feasibility of rookery island creation: As the water gets deeper, it becomes cost prohibitive to create above-water habitat.	Water depth ≤ 2 ft = 1.0	1.0
		Water depth 2–4 ft = 0.7	
		Water depth 4–6 ft = 0.2	
		Water depth ≥ 6 ft = 0.0	
Distance from shoreline	Distance of the rookery from mainland shorelines affects the ability of predators to reach the island: The farther an island is from other shorelines, the less likely it is to be invaded by predators.	Distance of rookery from shoreline < 0.5 mi = 0.0	1.0
		Distance of rookery from shoreline ≥ 0.5 mi = 1.0	
Direction from shoreline	Because of locally prevailing southeasterly winds, the direction from mainline shorelines affects the ability of predators to sense a rookery.	Southeast = 1.0	0.5
		East = 0.8	
		South = 0.5	
		All other directions = 0.0	
Habitat	The presence of seagrass and oysters will result in the need for habitat mitigation, which increases project costs. Locating islands in areas where mitigation potential is lower is a desired attribute.	Seagrass present = 0.0	1.0
		Oyster present = 0.0	
		Unconsolidated bottom = 1.0	
		Unknown = 0.8	
Location of known rookery islands	Location of active and inactive rookeries could increase the potential for restoration and /or enhancement.	Active rookery = 1.0	1.0
		Inactive rookery = 0.5	

deposition of large debris across former nesting habitats (Newstead and Fitzsimmons 2017). The specific sites that we had identified as priority sites were in the hardest-hit areas and were severely damaged or destroyed. The scientists implemented a rapid response to do as much habitat restoration as possible during the subsequent several months before the nesting season was to begin the following spring. This storm not only illustrated the high vulnerability of those sites but also redoubled the need for rookery island restoration as a critical component in recovery and sustainability of Texas colonial waterbirds. Fortuitously, our pilot study results were immediately available to assist in the restoration process for recovery from the hurricane, and the tool is ready for longer-term application to implement rookery island nesting habitat restoration.

NEXT STEPS: EXPANSION TO THE GULF OF MEXICO AND BEYOND

The next steps regarding this effort to develop a continuing ecosystem health reporting system for the Gulf of Mexico is expected to be in 2 parts. The initial Texas prototype report card, as summarized here, will be updated with more detailed data and analyses and extended to include an independent section on water quality, which was identified as an important stressor in each of the prototype assessments. This will be issued as a Texas coastal ecosystems report card intended for broad public consumption and continuing thereafter as a sustainable, ongoing report of ecosystem health for the Texas coast.

Secondly, a goal of the authors is to develop a sustainable report card for the whole Gulf of Mexico. The Texas prototype and its successor report card will be the model for a broader Gulf of Mexico Report Card. The means and methods to do so were an important outcome of the Texas exercise and "proof of concept" that will lay the foundation for that effort. The initial exercise of expanding to the Gulf of Mexico will require an expert workshop to partition the Gulf into units that have both ecosystem and resource management meaning. A follow-up task will be to agree on appropriate indicators that match the scale of the Gulf as a large marine ecosystem but that also have resource management meaning. Again, the prototype provides guidance in accomplishing this task and the subsequent analytical process to develop assessments that can be sustained. An important challenge will be to develop a reporting format and style that are appropriate to the expected and diverse users in the Gulf of Mexico.

In addition to expansion of the EcoHealth assessment framework, we also envision adoption of the $DPSCR_4$ framework in a much broader context as a generalized conceptual model of the coupled human–ecological system, with applicability across a full suite of ecological systems, natural and anthropogenic pressures and stressors, and management issues. Much as the US Environmental Protection Agency ERA framework and guidelines (USEPA 1992, 1998) have been

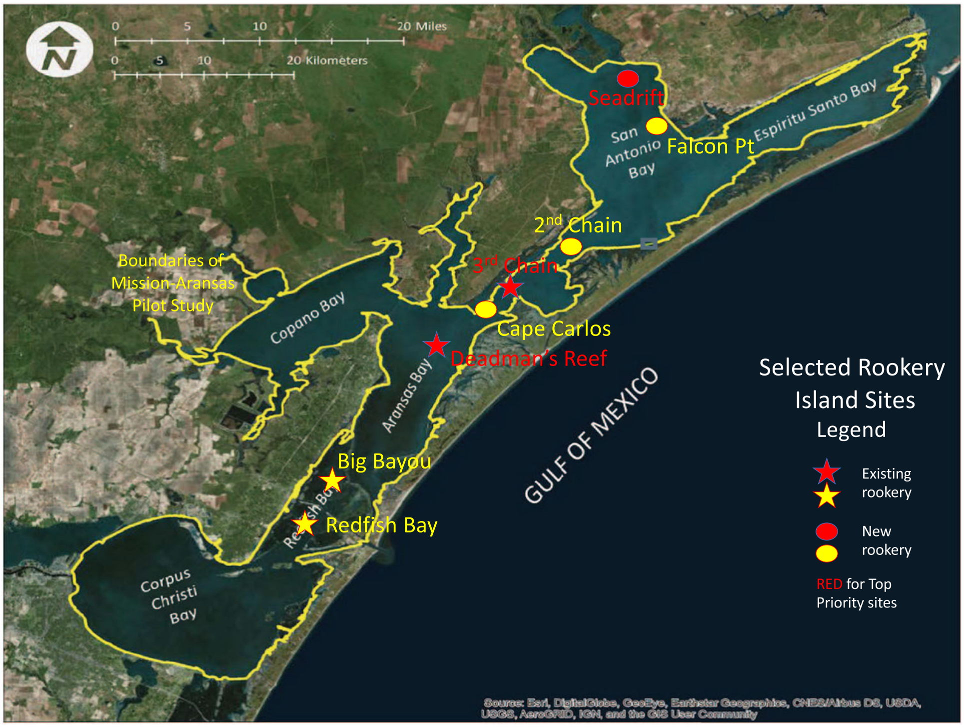

Figure 6. Priority sites selected for creating or enhancing rookery islands.

applied to a wide diversity of ecological systems and risk management problems (e.g., OSTP 1999; Suter 2007), we assert that the $DPSCR_4$ framework provides a systematic and comprehensive guidance to understanding environmental issues and managing for desired outcomes.

As one example of the applicability of the $DPSCR_4$ conceptual framework, the risk assessment guidelines emphasize the importance of making informed judgments regarding the purpose, scope, and technical approaches early when planning a risk assessment. During the initial planning of an ERA, the manager and risk assessor collaborate to determine who or what is at risk; what are the environmental hazards and stressors of concern, what are the sources of the hazards and stressors, and what are the potential routes of exposure and valued ecological components that are potentially at risk and the focus of the assessment. Thus, the $DPSCR_4$ conceptual framework provides a systematic and comprehensive construct for the problem formulation phase of the risk assessment, identifying the full spectrum of human and natural pressures, the hazards and stressors that the pressures create, the VECs that potentially are exposed and at risk, and the ecosystem and societal services they provide, including their links to human well-being. This process unfolds as the risk assessor gathers the information to populate the $DPSCR_4$ (e.g., Table 3).

The populated $DPSCR_4$ conceptual framework is valuable as an organizing framework for the problem formulation phase of an ERA, thereby providing a comprehensive and systematic picture of the risk landscape for a particular problem. It is also an invaluable tool for conducting a relative-risk ranking of the potential risks, that is, a process for identifying the most important risk hypotheses needing further examination in the analysis phase of an ERA process. As potentially high-priority risks are identified, the risk assessor can prepare a series of conceptual ecological models to illustrate the exposure pathways linking the pressure to stressors to the structural and functional ecological and ecosystem services endpoints. By identifying the high-priority risks, the $DPSCR_4$ conceptual framework can facilitate reducing the dimensionality of the risk landscape, allowing the decision makers and risk assessors to focus on the parsimonious set of risk hypotheses that will then become the subject of detailed examination as part of the ERA's analysis phase, which seeks to understand causal relationships and reduce associated uncertainties (USEPA 1992, 1998).

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We thank the participants (listed in the Supplemental Data) of the 4 workshops convened at the Harte Research Institute for Gulf of Mexico Studies (HRI) in support of this study, including the initial report card conceptual workshop in 2011; the 2 workshops in 2016 to develop and refine the integrated assessment/decision framework, initiate the prototype report card, and initiate the Mission-Aransas pilot study; and the final NOAA RESTORE workshop in which the suitability index-defined candidate rookery island sites were analyzed and selected. We greatly appreciate the contributions of all the workshop participants; a list is provided in the Supplemental Data.

We particularly thank Chris Onuf (retired), who led the prototype report card development for seagrass communities, Jennifer Pollack (Department of Life Sciences, Texas A&M University–Corpus Christi), who led the prototype report card development for oysters, and Beau Hardegree (USFWS), Owen Fitzsimmons (CBBEP), and David Newstead (CBBEP), who provided essential avian and geospatial physical data and expert analyses for the rookery island site suitability/site selection process.

Disclaimer—The authors declare no conflicts of interest.

Data Accessibility—The only newly created data in this study were the stress–effects relationships for the stressors and VECs of the rookery islands of Mission-Aransas Reserve, which were based on expert judgment and are fully reported in Table 4.

The data used in the prototype Texas coastal fisheries report card were derived from publicly available status reports on fish stocks, as detailed in Stunz et al. (2018). Co-author GW Stunz is the contact person for readers requesting additional information (Greg.Stunz@tamucc.edu). The data used in the prototype Texas coastal birds report card were derived from publicly available bird count data, including the Audubon Christmas Bird Count and the North American Breeding Bird Survey Data (https://www.pwrc.usgs.gov/bbs/); details are provided in Withers (2018). Co-author K Withers is the contact person for readers requesting additional information (Kim.Withers@tamucc.edu). The complete prototype Texas Report Card and supporting technical support documents are available online at https://www.harteresearchinstitute.org/project/gulf-mexico-report-card-prototype-texas; the technical support documents provide the details on the pressures, stressors, VECs, ecosystem services, stress-effects matrices, CEMs, assessment data, scoring methodologies, and results for each system type evaluated.

The Mission-Aransas rookery island site-selection suitability factors were derived from publicly available geospatial data based on the Texas Colonial Waterbird Society data for 1970 to 2015 on 14 colonial waterbird species for the Texas Coastal Bend area; additional existing publicly available geospatial data were used for important landscape variables (e.g., distance and direction from land masses), hydrological attributes (e.g., bathymetry), and biological attributes (e.g., benthic cover) for the study area. These data were entered and the analyses were conducted by co-author KM Stanzel using the NatureServe Vista GIS software package; details of the data sources and suitability factors calculations are presented in the text and in Stanzel (2017). Stanzel is the contact person for readers requesting additional information (kstanzel@cbbep.org).

The conceptual ecosystem model for human activities affecting the Mission-Aransas landscape-level ecosystem, cited in the text as Supplemental Data Figure 1, is available through figshare; the complete set of conceptual ecosystem models for the rookery island ecosystems, cited in the text as Supplemental Data Figure 2, is available through figshare.

SUPPLEMENTAL DATA

Supplemental Data Coastal Texas Report Card is a summary description of the prototype Texas coastal report card for the fisheries and avian components. This is the section that was removed from the initial manuscript in response to a review comment, both to shorten the manuscript and to reflect the absence of adequate data to fully create the Texas report card.

Supplemental Data Figure 1 presents an example conceptual ecosystem model for the Mission-Aransas National Estuarine Research Reserve to illustrate the types of conceptual ecosystem models described in the manuscript.

Supplemental Data Figure 2 is the complete set of conceptual ecosystem models for the rookery islands of the Mission-Aransas Reserve and Texas Coastal Bend regions.

Supplement Data Workshop Participants provides the full list of participants for all workshops.

We thank the participants of the four workshops convened at the Harte Research Institute for Gulf of Mexico Studies (HRI) in support of this study, including the initial report card conceptual workshop in 2011; the 2 workshops in 2016 to develop and refine the integrated assessment/decision framework, initiate the prototype report card, and initiate the Mission-Aransas pilot study; and the final NOAA RESTORE workshop in which the suitability index-defined candidate rookery island sites were analyzed and selected.

Collectively, these workshop participants included: Becky Allee (NOAA RESTORE Program Office); Ray Allen (Coastal Bend Bays & Estuaries Program, CBBEP); Porfirio Alvarez (Consortium of Marine Research Institutions of the Gulf of Mexico); Patrick Biber (Gulf Coast Research Laboratory, University of Southern Mississippi); Wylie Barrow (USGS); Melissa Brewer (TAMUCC-HRI); Joanna Burger (Department of

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