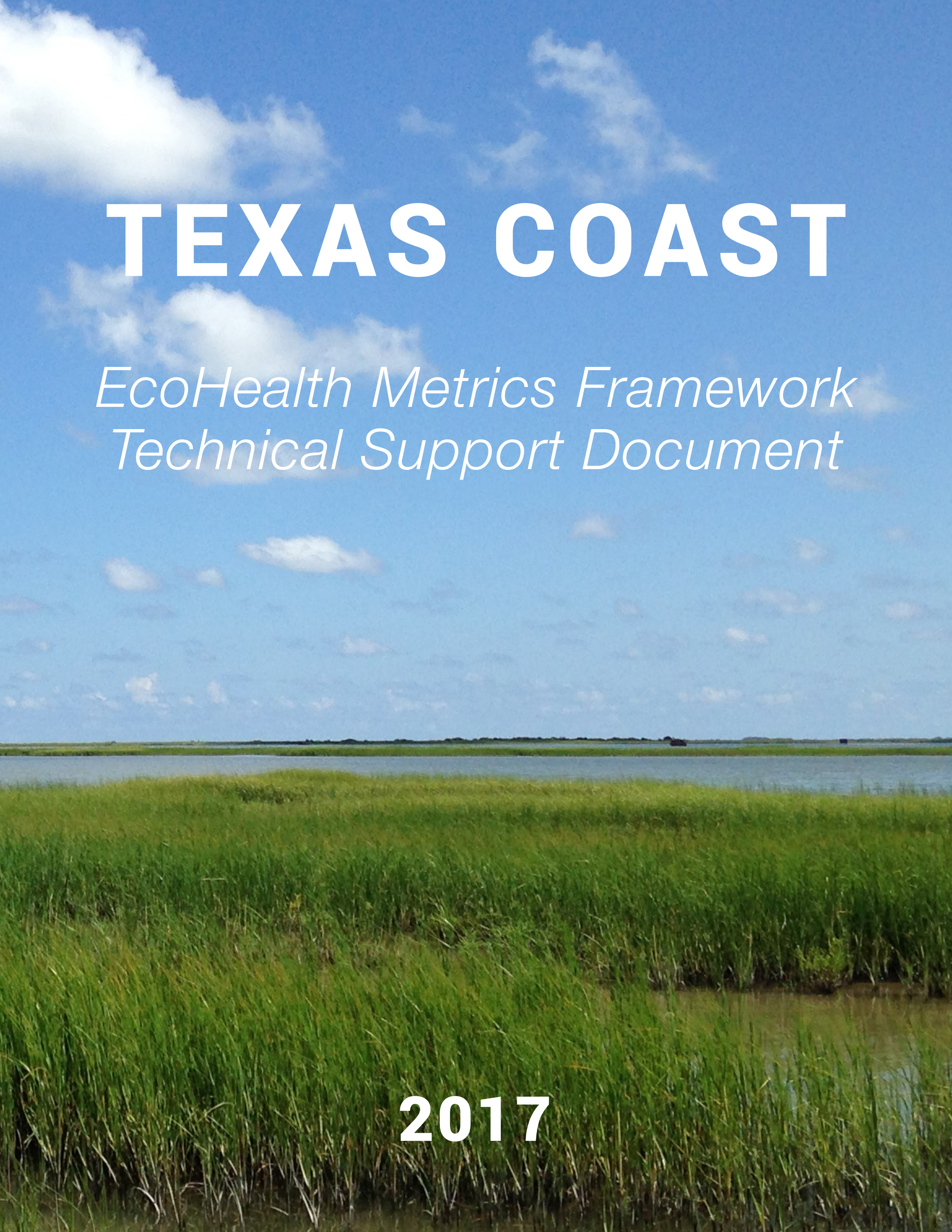

TEXAS COAST

EcoHealth Metrics Framework Technical Support Document

2017

EcoHealth Metrics Technical Support Document Table of Contents

I. Introduction — Vision for Gulf of Mexico EcoHealth Metrics

Abstract

The Harte Research Institute for Gulf of Mexico Studies has undertaken a multi-faceted project to develop and implement an integrated indicators and assessment framework. This framework, which we term the *Gulf EcoHealth Metrics*, is designed to characterize the health of the ecosystems of the Gulf of Mexico ecosystems, including their linkages to human communities, in support of management needs for restoring and sustaining a healthy Gulf of Mexico. Our vision is to develop a graphical representation of the environmental condition of the Gulf that will be scientifically based, widely accessible, and readily understandable by policy-makers, stakeholders, scientists, and, most importantly, the American public. A hierarchical structure, unified by a common conceptual framework, will provide the optimal 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. Additionally, the Gulf EcoHealth Metrics will be spatially explicit yet scalable, providing a way to compare the successful and not-so-successful outcomes across regions, habitats, and political boundaries. The Gulf EcoHealth Metrics will provide the scientific information and understanding necessary to evaluate the health of the Gulf, clearly demonstrate how well it is or is not progressing towards 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.

Introduction

The Gulf of Mexico is among the most ecologically diverse and valuable ecosystems in the world, comprising over 1.5 x 10^6 km^2 in area and consisting of offshore waters and coastal habitats of 11 US and Mexican states plus Cuba (Figure 1a). The Gulf's wetlands, beaches, coastal woodlands, and islands are major nurseries for breeding birds and provide foraging and stopover habitat for millions of birds that converge from some of the most important migratory flyways. Coastal marshes and near-shore 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 provided by a recent biotic survey that found over 15,400 species living in the Gulf of Mexico (Felder et al. 2009).

The Gulf's watershed covers 56% of the continental US (USEPA 2011), 40% from the Mississippi River Basin alone (Figure 1b). 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 an average of over 17,000 km^2 of annually occurring hypoxic conditions (USEPA 2011). 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); e.g., ~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 pressures, the Gulf's estuaries have become increasingly degraded for both human use and aquatic life. Several major threats to the health of the Gulf have been identified (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 methyl-mercury in finfish, harmful algal blooms (HABs), and human pathogens in shellfish;
- hypoxia offshore of the Mississippi River Delta;
- 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 20 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 days (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). This strategy calls for an adaptive management framework using an integrated risk-based ecosystem assessment approach for informing decision-making to achieve specific restoration goals. This 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; NOAA 2015).

The purpose of the Gulf of Mexico EcoHealth Metrics project, which has been undertaken by the Harte Research Institute for Gulf of Mexico Studies, is to develop such an integrated set of indicators and associated metrics that can be used to characterize the health of the Gulf of Mexico ecosystems, including their linkages to human communities.

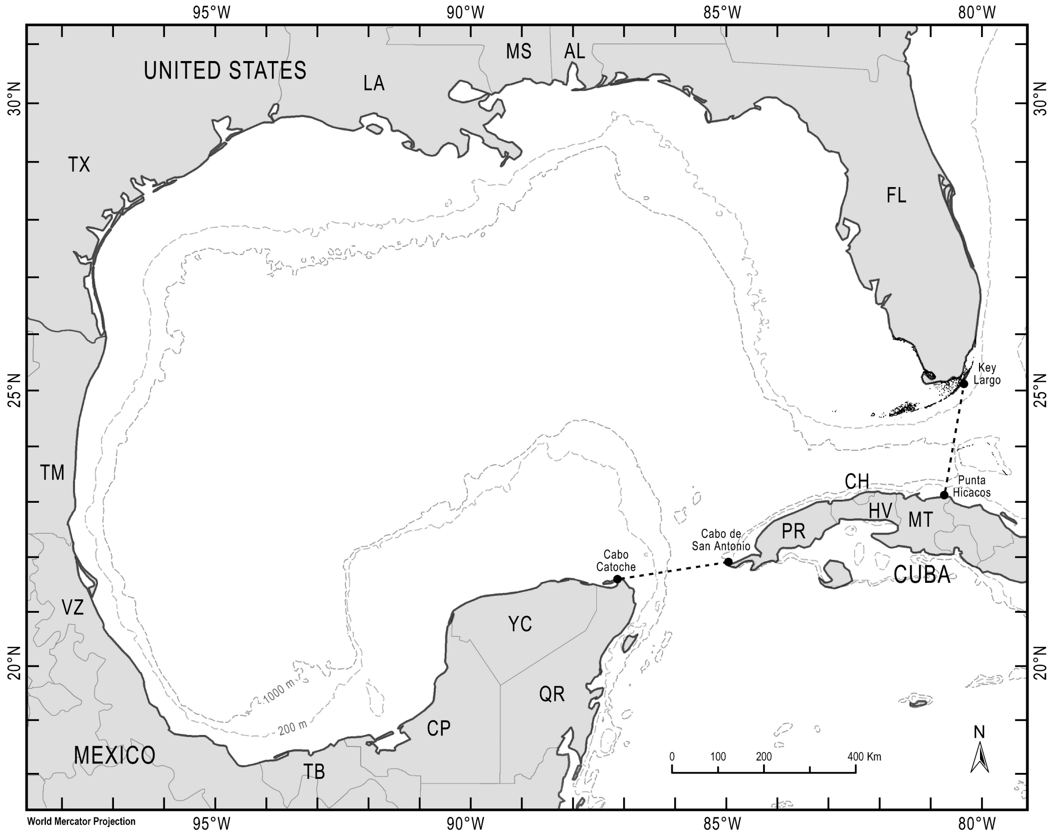

Figure 1a. The Gulf of Mexico, delimiting the geographic boundaries considered in the Gulf EcoHealth Metrics. Abbreviations for the states (counterclockwise) from Florida: FL = Florida, AL = Alabama, MS = Mississippi, LA = Louisiana, TX = Texas, TM = Tamaulipas, VZ = Veracruz, TB = Tabasco, CP = Campeche, YC = Yucatán, QR = Quintana Roo, PR = Pinar del Rio, CH = Ciudad de la Habana, HV = La Habana, MT = Matanzas. (Map prepared by Fabio Moretzsohn, Harte Research Institute for Gulf of Mexico Studies.)

Figure 1b. Map of the Gulf of Mexico watershed

Process for Developing the Gulf EcoHealth Metrics

Because the Gulf of Mexico is so complex and diverse, a systematic process for developing and implementing the EcoHealth Metrics is required. We envision a modular approach following these series of steps:

1. **Partitioning the Gulf of Mexico into discrete units —** The intent of partitioning was to reduce the scale of the problem to manageable levels by segmenting the Gulf by regions, by ecosystem/habitat types (e.g., mangrove, seagrass, and marsh communities), and by cross-cutting components (e.g., migratory birds, fish communities). The regional-EcoHealth Metrics we envision are: a) Western Gulf Coast (Texas); b) Eastern Gulf Coast (Florida); c) Northern Gulf Coast (Louisiana, Mississippi, Alabama); d) Mexican Gulf Coast; e) Cuban Gulf Coast. The Texas Coast has now been used as a proof-of-concept region for developing and testing the concepts and methodology for the Gulf EcoHealth Metrics.

2. **Develop Integrated Assessment/Decision Framework for EcoHealth Metrics—** The EcoHealth Metrics initiative required development of a new assessment framework and associated set of indicators to characterize the ecosystem health of the Gulf of Mexico, commensurate with the scale and complexity of the Gulf. The assessment framework that we have developed is an integration of previous ecological risk- and environmental management-based frameworks for assessing ecological health. This integrated framework is termed $DPSCR_{4,}$ Drivers-Pressures-Stressors-Condition-Responses. Here, anthropogenic and natural *Drivers* are the fundamental forces driving the coupled human-environment system (e.g., industry, climate change), leading to *Pressures*, which are human activities and natural processes (e.g., oil/gas extraction, coastal development, sea-level rise). These in turn generate the chemical, physical, or biological environmental *Stressors* (e.g., toxic chemicals, habitat alteration, invasive species) that directly impinge on ecosystems. The environmental stressors cause effects on ecological *Condition* (i.e., changes to ecological structure, processes, and/or diversity). These effects are characterized on system-specific valued ecosystem components (VECs) that are designed to reflect ecologically significant changes to the essential characteristics of the ecosystem. Our framework has been extended explicitly to address ecosystem services and associated effects on human well-being, thus reflecting the complete coupled ecological-societal system. Management actions feed back to the ecological systems and associated ecosystem services through four types of *Responses*: 1) *Reduction of stressors* through regulation or other constraints on the associated drivers and pressures (e.g., land use policies, air pollution regulations); 2) *Remediation* through removal of existing stressors (e.g., clean-up of oil spills or toxic chemical sites); 3) *Restoration* of damaged ecosystems (e.g., planting of seagrasses); and 4) *Recovery* of ecosystems through natural processes once stressors are reduced or eliminated. From this conceptual framework are derived the specific indicators for use in characterizing ecological condition and the progress, or lack thereof, towards achieving ecological health and sustainability goals. Furthermore, the framework's tiered hierarchical structure communicates the EcoHealth Metrics 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. The $DPSCR_4$ framework is documented in Section II.

3. **Initiate Texas Pilot Project —** As a demonstration and proof-of-concept pilot project, we focused on Texas coastal ecosystems for EcoHealth Metrics development and data acquisition, as reported here in the Texas Coast Report Card and EcoHealth Metrics Technical Support Document. The Texas coastal region was partitioned into its constituent ecological habitats and cross-cutting components (focused initially on fisheries, oyster reefs, seagrass communities, and resident and migratory birds), and a set of habitat-specific risk-based conceptual ecosystem models (CEMs) were constructed to graphically capture the relationships between stressors and effects on the valued ecosystem components of each (for examples of this type of conceptual model, see Cormier et al. 2000, Gentile et al. 2001, Ogden et al. 2005a, b). The conceptual modeling process involved scientists, managers, and stakeholders to ensure that the drivers and pressures were adequately identified and long-term sustainability goals appropriately defined. These conceptual models were then used to fully define the $DPSCR_4$ framework and indicators for each habitat and cross-cutting component. Existing data were acquired to populate the EcoHealth Metrics for the selected ecosystems of interest, along with appropriate techniques and tools for communicating the Texas EcoHealth Metrics to various targeted audiences. The Texas Coast Report Card is presented in Section III; the Technical Support Document is presented in Appendix A, and the CEMs are provided in Appendix B.

4. **Develop Regional Gulf EcoHealth Metrics —** Now that the Texas pilot has been completed, we propose next to apply the methodology and lessons learned to subsequent regions, e.g., Northern Gulf Coast EcoHealth Metrics, Eastern Gulf Coast EcoHealth Metrics, etc. The following components are envisioned:

   - **Texas EcoHealth Metrics —** The next steps for the EcoHealth Metrics for Texas are: a) to enhance the existing metrics through development of additional databases on ecological condition; b) develop similar databases on the stressors of importance to each system; and c) incorporate other coastal systems of importance in Texas, in particular coastal marshes and mangroves. The initial Texas seagrass EcoHealth Metrics demonstrated a paucity of essential data on seagrass spatial extent and health; thus, one important activity would be to build upon the seagrass mapping and monitoring plans developed for Texas a decade ago but never implemented. Another envisioned project would examine coastal marshes and the mangrove/marsh ecotone utilizing a satellite- and aerial-based hyperspectral imagery as a synoptic indicator for sea-level rise across Texas and the northern Gulf. Expansion of condition and stressor databases will require enhanced linkages to relevant federal and state agencies, non-governmental organizations, and other potential sources of environmental data.
   - **Northern and Eastern Gulf Coast EcoHealth Metrics —** We believe the next step in expanding EcoHealth Metrics Gulf-wide is to tailor our framework to the coastal ecosystems of Florida that comprise the eastern Gulf of Mexico. The process we envision is to convene a workshop that engages knowledgeable

practitioners to: develop Florida-specific EcoHealth Metrics for important coastal ecosystems; develop conceptual models of the coupled human-ecological systems for those ecosystems; rank the pressure-stressor-VEC relationships as they exist in Florida; identify specific indicators and metrics and potential data sources; initiate a Florida EcoHealth Metrics communications strategy; and transfer the methodology and approach to an appropriate Florida-based institution. A subsequent step would be to follow the same process, but focused on the unique coastal ecosystems of Louisiana, with their particular vulnerability to sea-level rise and to petrochemical-related stressors, as well as a separate activity characterizing the similar coastal ecosystems that extend from coastal Mississippi through the Florida panhandle.

- **Mexican Coast EcoHealth Metrics —** The Mexican Gulf of Mexico shoreline is predominantly sandy beach habitat with some rocky seashores in Veracruz and Campeche. Over 35 coral reefs exist in offshore waters, and over 20 coastal lagoons and estuaries extend from Texas to the Caribbean in this region. Mangroves line lagoon and estuary shorelines and seagrass beds and oyster reefs are present in some. Fisheries data are the only long-term biotic datasets available in Mexico, and report card activity there should include collaboration with academic institutions, and federal and state agencies.
- **Cuban Coast EcoHealth Metrics —** Cuba's northwestern shoreline from its far western tip to Punta Hicacos, just east of Havana, constitutes the island's Gulf of Mexico region. Coral reefs are common on the narrow continental shelf, and seagrasses exist near shore. The coastline is mostly sandy beaches with scattered limestone rocky shores. There are some barrier islands, which protect extensive mangrove lagoons, and several small estuaries with mangrove shorelines. Fisheries data are the only long-term biotic datasets available in Cuba, and report card activity there should include collaboration with academic institutions, and federal and provincial agencies.
- **Cross-Cutting Gulf-Wide and Pelagic EcoHealth Metrics —** A cross-cutting Gulf EcoHealth Metrics initiative would begin by extending the Texas bird and fisheries report cards throughout the Gulf of Mexico, integrating databases from other states and regions with synoptic databases such as Cornell Lab of Ornithology's eBird. Two key at-risk components from the *Deepwater Horizon* oil spill require attention: a new project needs to be developed on Gulf marine mammals, a critically important cross-Gulf valued ecosystem component; and similarly, the continental slope and abyssal benthic ecosystems are essential but largely unknown components of the greater Gulf of Mexico ecosystem. We also envision explicit linkages to large-scale remote-sensing atmospheric and oceanographic observing systems that are commensurate with the spatial scale of the open Gulf of Mexico.

5. **Integrated Gulf EcoHealth Metrics —** The final implementation of the EcoHealth Metrics for the Gulf of Mexico is envisioned to be the development of an integrated framework that incorporates each of the regional EcoHealth Metrics into a comprehensive assessment of the health of the Gulf of Mexico and its progress, or lack of progress, towards achieving sustainability goals. A series of new

methodological advances, along with development of new environmental databases including synoptic observations and monitoring, will be necessary to attain this goal.

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II. $DPSCR_4$ Framework for EcoHealth Metrics Assessment-Decision Process

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Abstract
The purpose of the EcoHealth Metrics initiative is to develop an assessment framework and associated set of indicators to characterize the ecosystem health of the Gulf of Mexico. The assessment framework presented here has been developed as an integration of previous ecological risk- and environmental management-based frameworks for assessing ecological health, commensurate with the scale and complexity of the Gulf. This conceptual framework is designed to identify the natural and anthropogenic drivers, pressures, and stressors impinging on ecosystems and the ecological conditions that result. Four types of societal and ecological responses are also identified, including 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 for use in characterizing ecological condition and the progress, or lack thereof, towards achieving ecological health and sustainability goals. Furthermore, a tiered hierarchical structure is presented to communicate the EcoHealth Metrics 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. A five-step process for constructing the EcoHealth Metrics is detailed: 1) Create the conceptual model for the ecosystem; 2) Select EcoHealth Metrics indicators; 3) Define goals and benchmarks for assessing ecosystem health and sustainability; 4) Analyze the indicators to characterize condition and trends; and 5) Communicate results to the appropriate audiences. Ultimately the EcoHealth Metrics will apply to the entire Gulf of Mexico and all its constituent regions and ecosystems, but we began by focusing on the conceptual framework and assessment methodology and the initiation of a proof-of-concept pilot project focused on the coastal ecosystems of Texas.

History of ecological health assessment frameworks
The EcoHealth Metrics research project builds upon existing indicators and assessment frameworks for ecological health to develop a new, more integrative, management-driven framework that connects ecological sustainability and human well-being to ecological health and ecosystem services. Environmental assessment indicators and frameworks are becoming more 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 Gulf of Maine ecosystem indicators partnership (Mills 2006), Chesapeake Bay Report Card (Williams et al. 2009, 2010; IAN 2013), US National Coastal Condition Report (USEPA 2012), Florida Keys Ecosystem Report Card (NOAA 2011), Ocean Health Index (Halpern et al. 2012), San Francisco Bay Index (PEEIR 2005), scorecards for Marine Protected Areas (CEC 2011), Southeast Queensland

healthy waterways report cards (Pantus and Dennison 2005), Mississippi River report card (americaswatershed.org), and Australia's Great Barrier Reef Report Card (Australian and Queensland Governments 2010) are a few examples of indicators and assessments being used to inform the public and decision-makers about the health and sustainability of coastal ecosystems.

We have conducted a review of the frameworks for these and many other environmental assessments as well as the literature on ecological indicators, ecological recovery, and stress ecology. Two approaches dominate, the first derived from the perspective of stress ecology (e.g., Odum 1969, 1985; Holling 1973; Barrett et al. 1976) and its derivatives, ecological indicators and ecological risk assessment (e.g., Kelly and Harwell 1989, 1990; Gentile and Slimak 1990; USEPA 1992, 1998; Gentile et al. 1993; Environment Canada 1993; Harwell 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 various 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, the 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 (see, for instance, FAO [undated]).

The second approach is based on the Pressure-State-Response (PRS) framework (OECD 1991, 1993) and its derivative, the Drivers-Pressures-State-Impacts-Response (DPSIR) framework (EEA 1999; Weber 2010). In the OECD PSR framework, *Pressures* are broad categories of human activities (e.g., energy, agriculture) but explicitly excluding natural processes; *State* is the quality and quantity of the environment and natural resources; and *Response* is how society responds to changes in state through environmental and economic policies. The Organization for Economic Co-operation and Development (OECD), created under the Marshall Plan in the aftermath of World War II, provides advice and promotes policies to improve economic development and social well-being in Europe (see www.oecd.org), but it has no legal, regulatory, or management authority. Consequently, this framework was initially developed by economists and policy analysts for policy makers, aimed at a broad-scale view of general relationships between human pressures and the environment, rather than at scientific understanding of cause-effect relationships or specific steps for environmental management (FAO undated).

The European Environmental Agency (EEA), an agency of the European Union with the mission to provide the environmental agencies of member nations with independent information to be used in developing and implementing environmental management policies (see eea.europa.eu), extended the OECD PSR framework to a more practical and scientifically sound basis. In the EEA's DPSIR framework, *Drivers* are the fundamental forces causing *Pressures* which 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 initially also excluded natural processes, except for climate change, but more recent applications have relaxed that exclusion (e.g., Weber 2010). DPSIR has been adopted by the United Nations, European Union, and some US agencies, as 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 or DPSIR approach, 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.

Irrespective of the framework used for assessing environmental condition, the specific indicators to measure have also been a topic of considerable research and discussion over the past three or four decades. Consequently, there is an extensive literature on ecological indicators (e.g., since 2001, a peer-reviewed journal, *Ecological Indicators*, has been dedicated to the topic; see also MacKenzie et al. 1990). Some of the early literature on ecological indicators (e.g., Kelly and Harwell 1989, 1990; Gentile and Slimak 1990; Hunsaker and Carpenter 1990; Cairns et al. 1993) explored the utility and classes of ecological indicators in different applications and criteria for selecting indicators. Other publications proposed specific indicators or indices: for example, Karr (1981) proposed a fish community-based index of biotic integrity that has been widely used to assess stream health condition; Landres et al. (1988) discussed the utility and limitations of vertebrates as indicator species, a central approach used by the US Fish & Wildlife Service to characterize wildlife habitat quality. Ecological indicators have been suggested from the molecular (e.g., Goksøyr and Förlin 1992) to the landscape levels (e.g., Hunsaker et al. 1990). Clearly, there is a plethora of indicators that could be used to characterize ecological health, but a key issue is identifying the set of indicators that are most efficacious for understanding ecological condition and informing environmental management. We suggest that the specific sets of indicators to be used will logically emerge from the proposed integrated assessment/decision framework discussed in the next section.

DPSCR$_4$ Framework — *Need for a New Synthesis Framework*

Based on this literature review of conceptual frameworks and indicators for assessing environmental health, we concluded that developing an assessment framework for an ecosystem of the scale and complexity of the Gulf of Mexico, and with the diversity of audiences that need to be informed, requires a new conceptual framework that builds upon the strengths of the existing frameworks while avoiding their deficiencies. We propose that this new framework should be a synthesis of the ecological-risk-based and DPSIR approaches. The advantage of the risk-based, stress-effect approach is its focus on defining the causal relationships between stressors and ecological effects, i.e., how the things that an ecosystem "sees" (the environmental stressors) cause changes in the state of ecological attributes that are important ecologically and/or societally. This risk-based approach avoids the potential deficiency of the OECD PSR or the EEA DPSIR approach, in which pressures are often defined at such a broad level that their relationships to the state of the environment are only correlative instead of causal, and thus environmental management decisions may be inadequately science-based. On the other hand, the advantage of the DPSIR approach is that it avoids a potential limitation of the stress-effects approach, where there may be simply too many cause-effect relationships at very large scales (e.g., national or larger) to manage each one separately (FAO [undated]). Therefore, this approach is more attuned to the needs of decision-makers, stakeholders, and the public when addressing environmental issues on such large scales, and perhaps more attuned to reporting on health at the level of resolution that is relevant to those audiences.

The synthesis framework that we propose is a merging of the two, consisting of *Drivers*, *Pressures*, *Stressors*, *Condition*, and *Responses* elements (Figure 1), each of which is defined below in the specific context of the new framework. Additionally, the *Responses* component in our framework is divided into two categories, *societal responses*, i.e., changes in management within the societal system, and *ecological responses*, i.e., changes in the ecological system. These are further partitioned into *Reduction* of stressors and associated pressures (such as through regulations limiting discharges of pollutants or controlling land use); *Remediation* (actions aimed at directly reducing existing contaminant stressors, such as oil spill clean-up or toxic waste removal); *Restoration* (actions to directly renew or restore a damaged or altered ecological system, such as planting trees or reconstructing wetland habitats); and *Recovery* (natural ecological processes of recovery once the stressor is gone, such as an injured population returning to its pre-event condition). To accommodate the stressor *Reduction,* stressor *Remediation,* ecological *Restoration*, and ecological *Recovery* aspects, the acronym for this new framework is $DPSCR_4$.

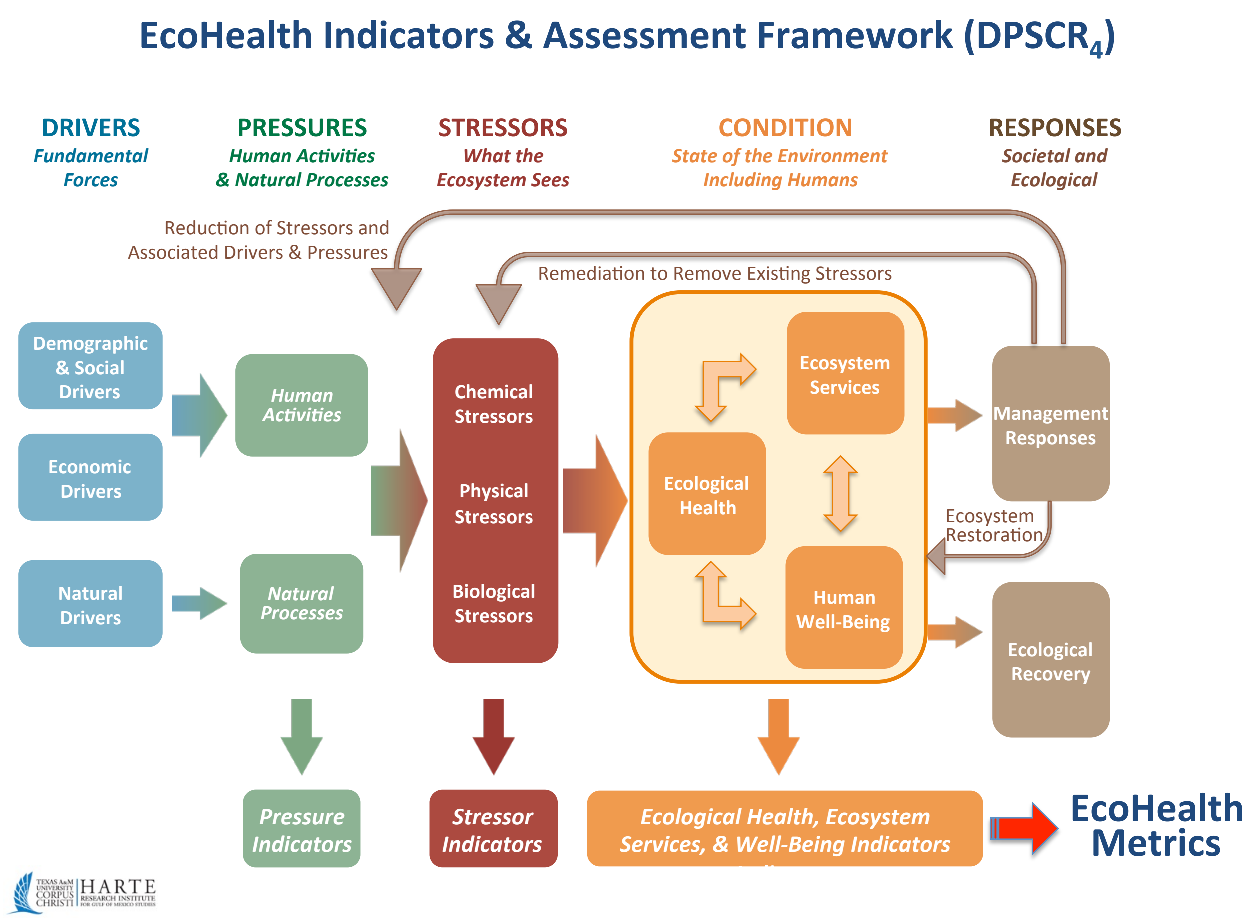

Figure 1.

There are several advantages of this new construct. For example, the full sequence of causal relationships is delineated from the ultimate source (fundamental societal or natural drivers) through their 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 scaling taking these relationships from the broad scale down to the specific cause-effect process, the Gulf EcoHealth Metrics framework can characterize the system simultaneously from the big-picture policy level to the specific cause-effect hypothesis-driven scientific level and back. When nested within a hierarchy of reporting levels, as discussed below, 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, or as things change over time or space. Consequently, the EcoHealth Metrics can become both responsive to new needs or questions and useful in identifying uncertainties and new areas of research or monitoring. Finally, the $DPSCR_4$ provides the basis and rationale for identifying the specific sets of indicators in the EcoHealth Metrics for pressures, stressors, and condition, the particular suite of attributes desired for each indicator, and insights into the societal actions that could be implemented to achieve ecological health.

Elements and Definitions of $DPSCR_4$

The terminology that we have incorporated into the $DPSCR_4$ framework includes terms that have been used elsewhere in similar contexts, but there is often inconsistency across the literature in usage of many of these terms. Consequently, to ensure clarity, we define each element here to provide the specific meaning of the words as they are used in the $DPSCR_4$ framework. Additionally, we provide a few examples of various components of the $DPSCR_4$ framework using information specific to the Gulf of Mexico to illustrate the process (Figure 2).

Drivers are the fundamental forces, natural or anthropogenic, that ultimately drive the system. 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., agriculture, urbanization, industrial and energy development; and natural drivers, e.g., the unequal distribution of solar energy across latitudes. Drivers tend to be large-scale, long-term forces that are not easily controlled or diverted.

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 aquaculture; geophysical resource harvesting such as oil exploration and mining; biological resource harvesting such as fishing and forestry; coastal development; marine transport; recreation and tourism; flood control; and the anthropogenic component of global climate change and sea-level rise. Natural processes include ocean dynamic processes, such as upwelling and currents; climate processes, such as jet stream dynamics, monsoons, and El Niño-Southern Oscillations; sediment dynamics such as erosion, subsidence, and sedimentation; episodic events such as earthquakes, tsunamis, and hurricanes; and the natural processes component of global climate change and sea-level rise.

Figure 2. Example DPSCR$_4$ Elements for the Gulf of Mexico

DRIVERS	PRESSURES	STRESSORS	CONDITION		RESPONSES
Natural & Anthropogenic *These are the fundamental forces*	Human Activities & Natural Processes *These are what cause stressors*	Anthropogenic & Natural *These are what the ecosystem sees*	Condition of the Environment Assessed on Valued Ecosystem Components *Ecological state is compared against desired condition*		Societal & Ecological *Reduction, Remediation, Restoration, & Recovery*
ECONOMIC DRIVERS • Industry • Agriculture • Development	**HUMAN ACTIVITIES — *Resource Extraction:*** • Commercial Fishing • Recreational Fishing • Oil/Gas Extraction • Groundwater Usage	**BIOLOGICAL STRESSORS:** • Invasive Species • Overfishing • Altered Genetics • Pathogens • Harmful Algal Blooms	***Fish & Wildlife VECs*** • Fisheries Populations • Avian Populations • Marine Mammals • Sea Turtles • Endangered Species • Economic Species	***Goal: Sustainable Fish / Wildlife Communities***	**POLICIES TO REDUCE STRESSORS:** ***Managing Drivers/Pressures*** • Environmental Regulations • Land Use Management • Fisheries Management • Environmental Education • Conserve Special Places
DEMOGRAPHIC & SOCIAL DRIVERS • Population Growth • Urbanization • Politics	**HUMAN ACTIVITIES — *Physical:*** • Coastal Development • Dredging • Shoreline Structures • Transportation • Channelization • Land Use Change • Dams	**PHYSICAL STRESSORS:** • Habitat Alteration • Hydrological Alteration • Changes in Salinity • Changes in Climate • Suspended Sediment • Noise • Ocean Acidification • Hypoxia	***Habitats:*** • Wetlands • Mangroves • Oyster Reefs • Seagrasses • Coral Reefs • Barrier Islands • Freshwater & Tidal Marshes	***Goal: Restore and Sustain Productive Habitats***	**REMEDIATION:** ***Removing Existing Stressors*** • Clean-up Oil Spills • Clean-up Chemical Spills **RESTORATION:** ***Restoring Ecosystems*** • Plant Seagrasses • Restore Freshwater Flows • Increase Wetland Habitats • Remove Invasive Species
Natural Drivers	**NATURAL PROCESSES:** • Climate Processes • Ocean Dynamics • Ecosystem Dynamics • Sea-Level Rise	**CHEMICAL STRESSORS:** • Nutrient Inputs • Pesticides • Endocrine Disrupters • Chemical/Petroleum Spills	***Ecological Features:*** • Connectivity of Gulf with Coastal Rivers • Landscape Mosaic • Biodiversity	***Goal: Restore Ecological Features***	**ECOLOGICAL RECOVERY:** ***Ecological processes to return to healthy conditions***

Stressors are what the ecosystem directly experiences, i.e., the physical, chemical, or biological factors that can directly cause an ecological effect. Stressors are the critical point of intersection between the drivers/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 chemical stressors include oil and chemical spills, altered nutrient inputs, pesticides, and other xenobiotics. Example of physical stressors include habitat alteration and loss; altered sedimentation and light regimes; altered salinity regimes; drought; hypoxia; and hydrologic alterations. Examples of biological stressors include invasive and introduced exotic species; over-fishing or over-harvesting; pathogens and disease; harmful algal blooms; and altered genetics. Stressors may secondarily generate other stressors; e.g., 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 becomes a stressor 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 it may involve something novel to the ecosystem, such as toxic xenobiotic 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 one 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, often termed *Assessment Endpoints* (UPEPA 1998) or *Valued Ecosystem Components* (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 done, 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. 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 consists of ecological services, including provisioning services (e.g., fish stocks), regulating services (e.g., loss of carbon storage associated with habitat loss), and cultural services (e.g., environmentally related recreation and tourism) (UNEP WCMP 2011; Egoh et al. 2012; Hattam et al. 2015).

There is not a unique set of VECs that could be selected for an ecosystem, but the set should be selected such that if there is a significant change in the ecosystem, it would be manifested in one or more VECs and, conversely, if there is a change in one or more VECs, then the ecosystem can be considered to be changed. This obviates the problem that any stressor, no matter how small, may change some aspect of the ecosystem; our focus, however, is on identifying only ecologically significant effects (Gentile and Harwell 1998). Properly selected VECs can be both an aid in reducing the dimensionality of the ecosystem characterization problem to a manageable level and a means to distinguish those changes that matter from those that do not.

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:

- VEC *water quality*: indicators chlorophyll *a*, transparency, total suspended solids;
- VEC *coral community health*: indicators coral cover, juvenile recruitment, algal cover, coral composition;
- VEC *seagrass community health*: indicators areal extent, seagrass density, nutrient status, community composition;
- VEC *habitat mosaic*: indicators 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. It is the indicators that will form the foundation of the Gulf EcoHealth Metrics, including not only indicators characterizing the VECs, but also indicators characterizing the stressors and pressures, thereby identifying risks to the environment and/or possible causes for observed effects, as well as targets for responses to reduce stressors and improve environmental health. Additionally, the particular levels or trends characterized in 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 quantitative ecological health metrics, such as grades, scores, or indices.

Responses: The *Response* in the original PSR and DPSIR frameworks was meant to capture feedbacks by society 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 both such regulatory actions and other interventions to reduce stressors or facilitate ecological processes. Four types of *Responses* are identified: *Reduction* of stressor sources*, Remediation* of existing stressors*,* ecological *Restoration*, and ecological *Recovery*.

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 like enhanced educational programs focused on the environment, or providing consumers with clearer information on the source and safety of seafood in the markets, among many other examples.

Remediation is the set of actions specifically aimed at reduction or elimination of a chemical stressor that has been released into the environment. This component was added to the framework to reflect the suite of clean-up (i.e., remedial) activities, often implemented under Natural Resources Damage Assessment (NRDA) regulations (derived from CERCLA [1980]) and the Oil Pollution Act of 1990 (OPA 90) regulations (NOAA 1996a, 2010).

Restoration is where 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.

The final "R" in our framework differs from the others in that it involves the natural ecological *Recovery* processes of an ecosystem, usually once a stressor has been eliminated or reduced below adverse effects levels. *Recovery* reflects ecological resilience, i.e., 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. 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).

Gulf EcoHealth Metrics Reporting Structure

The DPSCR$_4$ EcoHealth Metrics framework needs to be further structured to inform a diversity of audiences with differing concerns and levels of scientific understanding, and to accommodate multiple scales and ecological hierarchy. An assessment hierarchy (Figure 4), which we colloquially term the "wedding cake", reflects the differing types of audiences to be informed by an ecosystem health assessment, from the top level of officials and the general public down to the environmental scientific community. The $DPSCR_4$ framework overlays this structural hierarchy, emphasizing tier-relevant components and indictors.

The top level is the target of the original OECD PSR framework, 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.

The next lower level is the realm of people who make or attempt to 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.

Next is the level of hands-on environmental managers, e.g., managing a park or conservation lands. These individuals need to understand a diversity of environmental issues relevant to their specific locations or ecosystem types. Consequently, it is important for this audience to understand the specific stressors and impacts those stressors have on their ecosystems, and specific remediation/restoration activities they might implement 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 effects constitute adverse health compared to baseline or benchmark conditions; remediation/restoration activities to improve the health of the environment; 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.

This hierarchical structure not only reflects differing issues of concern and levels of understanding, but also 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. The $DPSCR_4$ hierarchy provides the template for this two-way information exchange to occur and ultimately may lead to more efficacious acquisition and utilization of research and monitoring data.

The hierarchical structure also facilitates aggregation across spatial and ecological scales (Figure 4), an essential aspect for characterizing the health of such a large and complex ecosystem as the Gulf of Mexico. The Gulf can be partitioned into several regional-scale subunits based on geographical, ecological, and/or political boundaries; indeed, different regions might be delineated for different purposes. The regional-scale indicators are then integrated into an overall Gulf of Mexico EcoHealth Metrics, not just by averaging the values of the regional indicators, as this could simply average out the important information needed to characterize the health of the system. Rather, both spatially explicit indicators, showing how the health varies over space, and new integrative indicators are needed to characterize ecosystem health in ways that are uniquely informative.

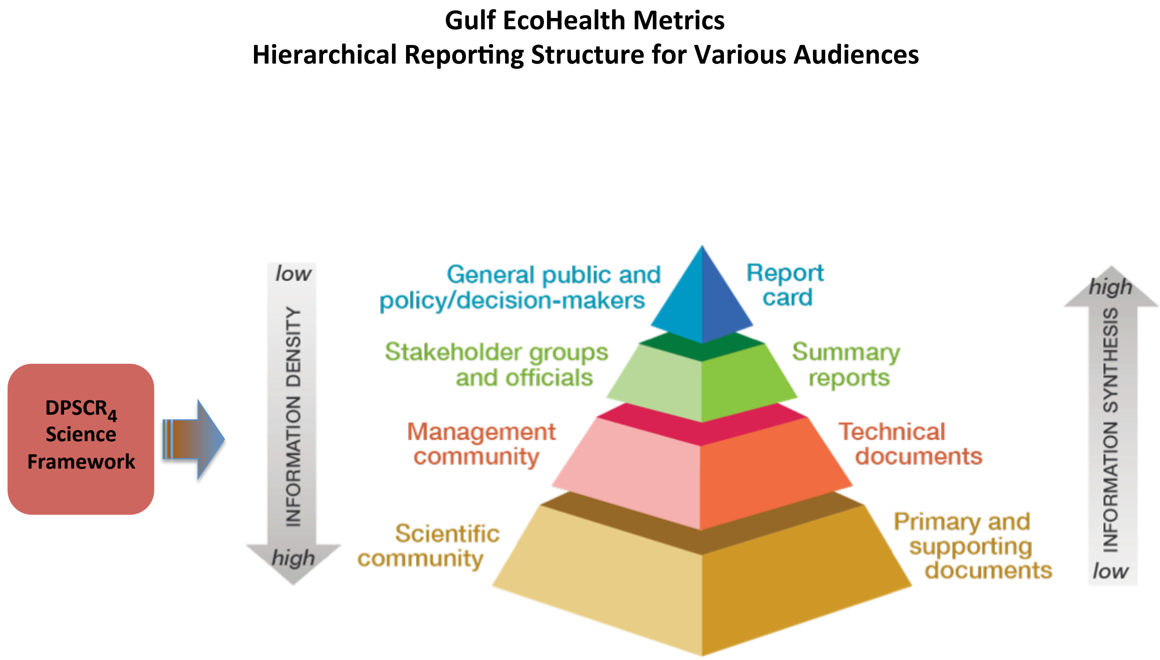

Figure 3.

Within each region are delineated specific habitat types of concern, like seagrass or salt marsh communities, and within each habitat are identified the specific set of relevant VECs and associated indicators. Figure 5 shows how one habitat type may be a component of more than one region. Moreover, other cross-cutting ecological components exist that are not spatially fixed like habitats, yet are very relevant to ecosystem health, such as migratory birds and marine mammals. As one integrates cross-cutting and habitat-specific indicators into regions, spatially explicit and/or integrative indicators are developed to characterize the ecosystems health.

At the lowest tier of the hierarchy, the indicators that are the ultimate foundation of the Gulf EcoHealth Metrics are specific qualitative or quantitative metrics that reflect the relevant characteristics of each VEC and each pressure and stressor over time and space. The utility of each indicator relates to 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, 1999a), can provide the foundation for understanding the dynamics of each VEC, its trajectory over time and space, and its health or recovery status.

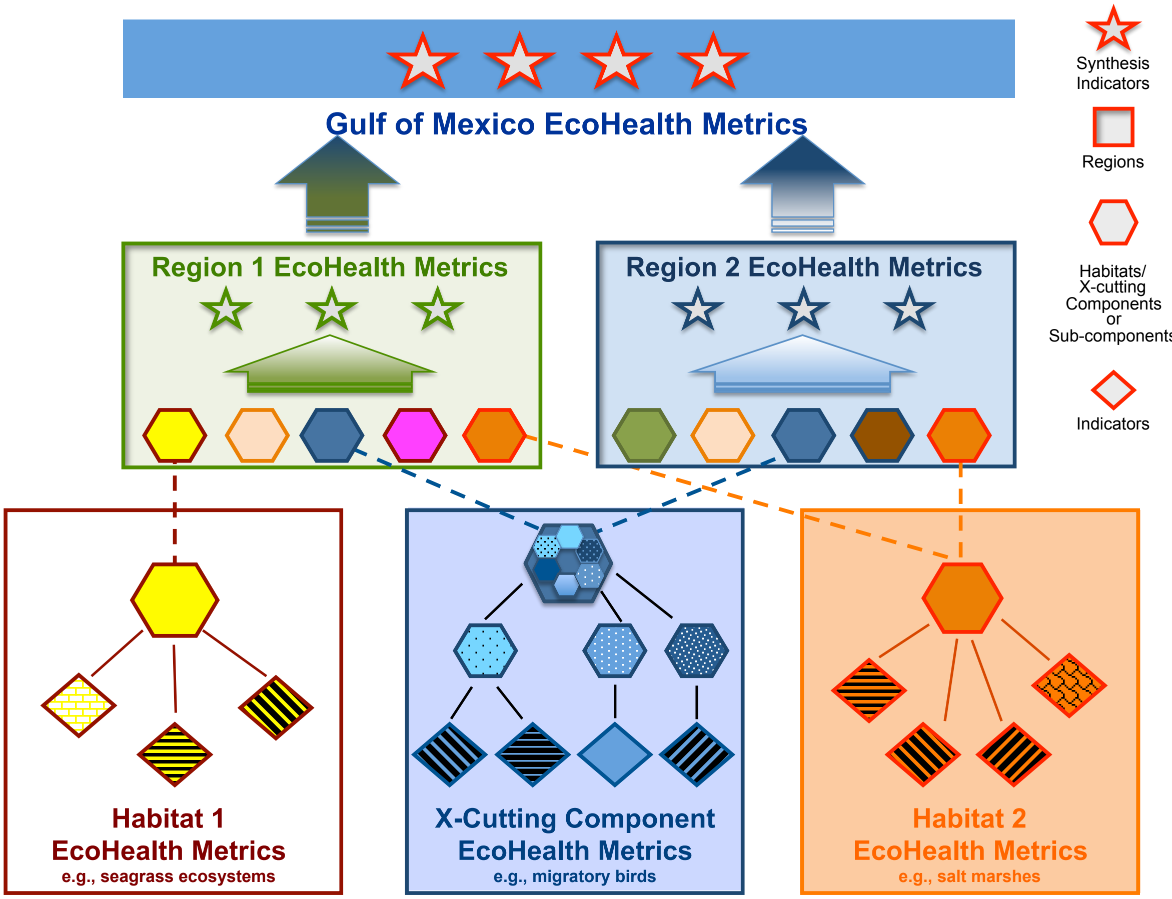

Figure 4. Aggregation scheme for elements of the Gulf of Mexico EcoHealth Metric.

Constructing the Gulf EcoHealth Metrics

The construction of the Gulf of Mexico EcoHealth Metrics using the $DPSCR_4$ framework is a complex process, emphasizing indicators for pressures, stressors, and condition/effects. It will follow the following steps (Figure 5):

1.) *Develop the conceptual framework for the EcoHealth Metrics* — This process involves disaggregating the Gulf into manageable reporting units, and developing conceptual models to define the specific elements of the EcoHealth Metrics. The Gulf will be partitioned into regions/subregions and habitat-based or cross-cutting components that comprise the Gulf ecosystems. The partitioning could be done based on political boundaries, geomorphic boundaries (e.g., coastal lagoons, estuaries), or biogeographical boundaries (e.g., tropical mangroves, warm temperate salt marshes); irrespective of the partitioning approach, the selected assessment regions should collectively cover the domain of the Gulf.

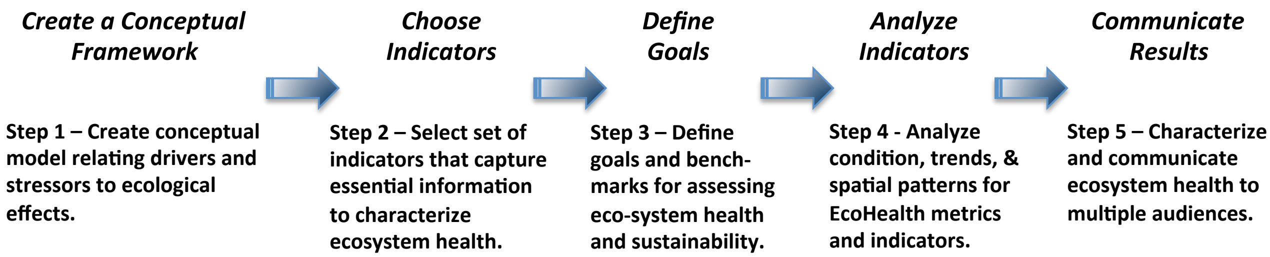

Figure 5. Five-Step Process for Constructing EcoHealth Metrics

Next, each region/subregion will be partitioned into its constituent ecological habitats. A set of habitat-specific risk-based conceptual models can then be constructed to graphically capture the relationships between stressors and effects on the VECs of each habitat; collectively, the conceptual ecosystem models (CEMs) for a region should reflect the connectivity among all the ecosystem components. In this type of conceptual model are shown the drivers/pressures for the system of concern, the environmental stressors that result from those pressures, the valued ecosystem components for each specific habitat within the region, and the causal links among each of these elements. In this type of CEM (Figure 6), the top tier (rectangles) are pressures, in this case human activities that impinge on the Mission-Aransas landscape (http://missionaransas.org/). The next tier (ovals) are 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 are the VECs identified for the landscape-level attributes of Mission-Aransas NERR, again showing the weighted linkages with the specific stressors that cause effects on the VEC. For additional examples of this risk-based class of conceptual ecosystem models, see Cormier et al. (2000), Gentile et al. (2001), and Ogden et al. (2005a, b).

Separately, a similar risk-based conceptual model will be constructed for each cross-cutting VEC, such as migratory birds and marine mammals, capturing the drivers and stressors that affect that component across the region- or Gulf-wide domain. The conceptual modeling process should involve scientists, managers, and stakeholders to ensure that the drivers and pressures are adequately identified and long-term sustainability goals are appropriately defined.

2.) *Select EcoHealth Metrics indicators* — From each risk-based conceptual model, indicators will be identified for the key relationships within the $DPSCR_4$ assessment framework. These indicators will be used for effective, spatially explicit reporting on the state of each VEC, pressure, and stressor. 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 pressure/stressors and for ecological condition. Moreover, indicators should be chosen with consideration of their use within the EcoHealth Metrics (see Table 1) (Kelly and Harwell 1989, 1990). For example, ecological indicators could include both early-warning indicators (i.e., red flags indicating potential harm, but with a potential for high false positives) and diagnostic indicators (i.e., reflecting specific effects from a particular stressor). Similarly, the set of pressure and stressor indicators should reflect both short-term variability and long-term conditions and trends.

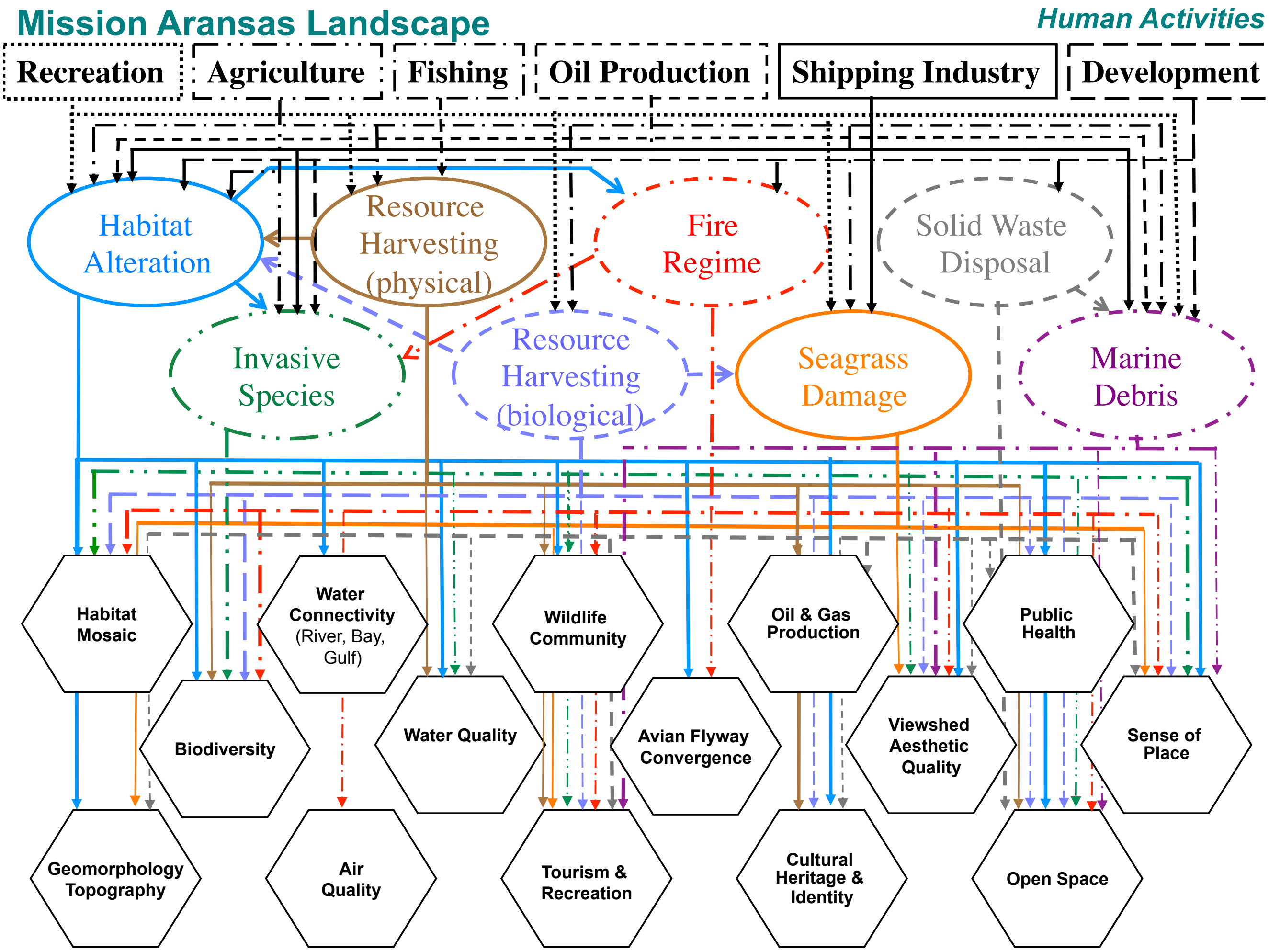

Figure 6. Example conceptual ecosystem model (CEM) for the Mission-Aransas National Estuarine Research Reserve.

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 towards the desired sustainable state (Harwell et al. 1999a). Additionally, thresholds may be identified that mark particular levels of health, often useful for communicating ecosystem condition. A quantitative or qualitative metric defining a desired condition or goal for each indicator should be established, allowing indicator metrics to be assessed and reported in the Gulf EcoHealth Metrics. 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 ≤ 2.0 mg•l^{-1} dissolved oxygen; 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. Thresholds can be "pass/fail" (e.g., does a measurement meet the threshold or not?), or they may array along a gradient in a multiple threshold scheme.

PURPOSES OF INDICATORS	CRITERIA FOR SELECTING INDICATORS

• *intrinsic importance* – key: indicator is the endpoint
  o example: economically important species; endangered species
• *early-warning indicators* – key: rapid indication of effects
  o quick response time
  o low signal-to-noise ratio; low discrimination
  o screening tool; accept false positives
• *diagnostic indicators* – key: reliability in predicting effects
  o high stressor-specificity
  o high signal-to-noise ratio
  o minimize false positives
• *process/functional indicators* – key: process is the endpoint
  o monitoring other than biota (e.g., decomposition rates)
	• *signal-to-noise ratio*
	  o sensitivity to stressor
	  o intrinsic stochasticity
	• *rapid response*
	  o early exposure
	  o quick dynamics (e.g., short life span)
	• *reliability/specificity of response*
	• *ease/economy of monitoring*
	  o available field protocols
	  o pre-existing database
	  o low-cost tools
	• *relevance to the endpoint*
	  o answers the "so what?" question
	• *feedback to management*

Table 1. Purposes of Indicators and Criteria for Selecting Them (modified from Kelly and Harwell 1989).

4.) *Characterize results* — Once data and thresholds are established, there are several options for characterizing the condition of the VECs. In general, 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 metrics for the VEC, pressure, or stressor. These may be spatially integrated into a characterization for the subregion or region of concern, and these in turn may be further integrated with other subregion/region results using an area-weighting approach.

Assessment metrics can be qualitative (e.g., alphabetic grades or stoplight colors), or quantitative based on numeric assessment values (e.g., achieving 90% of a target value). Overlain on each indicator metrics can be up/down arrows indicating trends of improvement, degradation, or no change in environmental condition from previous values. Qualitative characterizations are simple and easily comprehended, but may oversimplify conditions or not adequately allow for nuances. Numeric assessments can be more precise, but precision may be mistaken for accuracy, and numeric assessments can be overly precise given natural variability and uncertainty (e.g., reporting 3 significant digits would be misleading for a metrics with an interannual variability of 25%). Numeric assessments tend to be more technical, and therefore less understandable by some audiences but more useful for others. Various combinations of qualitative/quantitative indicators can be used, avoiding the pitfalls of a single approach.

5.) *Communicate results* — The communication of results is the central purpose of the Gulf EcoHealth Metrics; it should be multifaceted and transparent, structured hierarchically into the wedding cake design described previously (see Figure 4). Each Gulf EcoHealth Metrics document should be a graphics-rich, synthesis document that aggregates results to create an easily understandable message about the overall health of the ecosystem. Hierarchy-appropriate graphics should illustrate the important attributes of the ecosystem and its links to humans. For example, the conceptual model of the Mission-Aransas ecosystem shown in Figure 6 is aimed at scientists, presenting in considerable detail the many habitats, drivers/pressures, VECs, and causal linkages among the pressures-stressors-effects of the Mission-Aransas NERR. However, while the sheer complexity of the Mission-Aransas required such great detail to adequately characterize the system (the illustration in Figure 6 is only one of 36 such graphics needed to fully represent Mission-Aransas), it would be prohibitively complex to inform the general public. By contrast, Figures 7a and 7b represent a similar ecosystem presented in less detail to more appropriately communicate to an audience of decision-makers and the public, with the commensurate need-to-know information captured in easier-to-understand graphics.

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. The Gulf EcoHealth Metrics should be readily accessible, such as through website access. The series of Chesapeake Bay Report Cards (e.g., IAN 2007, 2013; ecoreportcard.org) provide examples of the types of communications we envision.

Assessment results could be communicated on an annual and/or multi-year production and release cycle. Advantages to an annual cycle include keeping the status of the resource in the public eye, frequent tracking of progress (or lack of progress) toward achieving goals, and reflecting the inherent interannual variability in many environmental indicators (e.g., seasonality of climate and life cycles). However, many important processes and indicators do not appreciably vary interannually (e.g., land use change), and it can be prohibitive to maintain data collection, analysis, and reporting timelines to support an annual EcoHealth Metrics. Alternative reporting cycles involving multiple years (e.g., 5-year reporting cycle) allow more time for analysis and interpretation, enhanced clarity of trends, and the use of more integrative or longer response-time

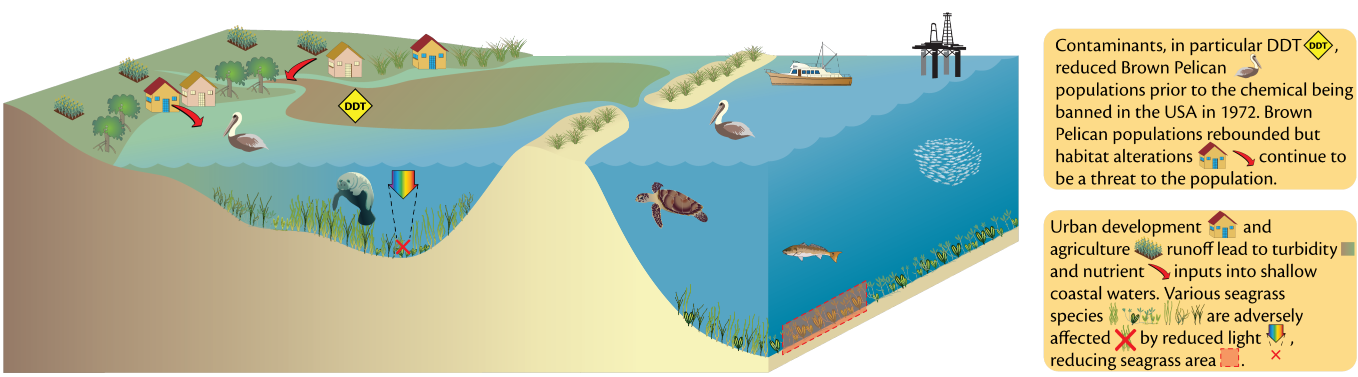

Figure 7a. Example conceptual model of a Gulf coastal ecosystem targeted at decision-makers and the public (from McKinney et al. 2011).

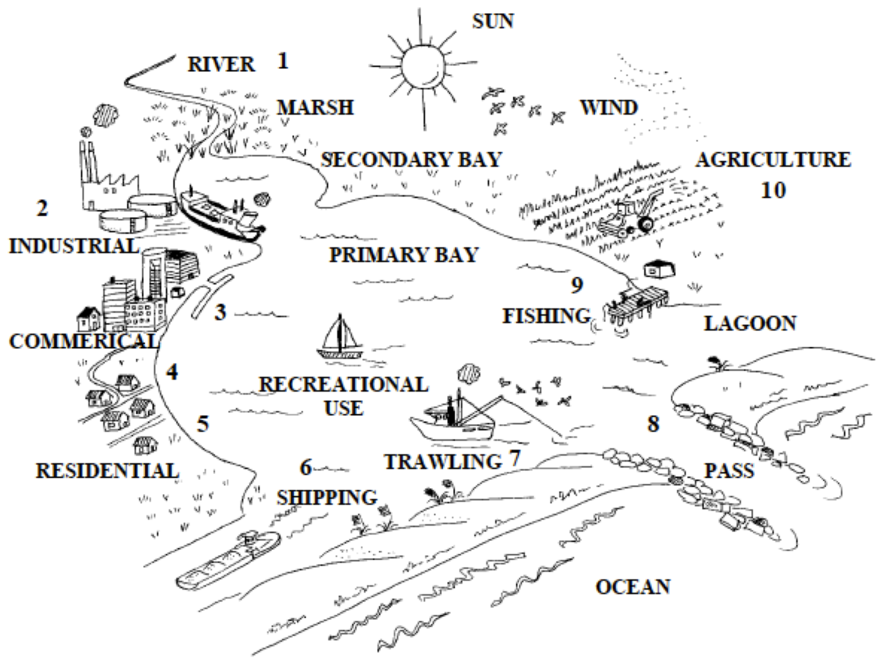

Fig. VI.1B. The role of humans in the CCBNEP Bay Area System. Human activities can impact the bay ecosystem in a variety of ways, most of which tend to have harmful effects on the productivity and diversity of the ecosystem. 1 – Impounding rivers cut off fresh water inflow to the bay. 2 – Industry can introduce toxic compounds to the air or water that can stress or kill many estuarine species. 3 – Construction on the shore of the bay destroys productive marsh habitats, and can increase turbidity. 4 – Runoff from cities can introduce contaminants to the bay and increase turbidity. 5 – Water treatment can bring high nutrients into the bay that may lead to eutrophication. 6 – Motor boats can scar seagrass beds and leak fuel. 7 – Trawling and dredging may disturb or kill the organisms living in sediment. Shrimping also produces by-catch. 8 – Creating or reinforcing passes, channels and causeways can alter estuarine circulation. 9 – Fishing may remove too many top predators from an ecosystem. 10 – Agriculture can introduce nutrients to the bay, through fertilizer or simple runoff, or can introduce toxins to the bay in the form of pesticides.

Figure 7b. Example conceptual ecosystem model showing major pressures affecting the Corpus Christi Bay National Estuary Program system (from CCBNEP 1996).

indicators. While we anticipate that the Gulf EcoHealth Metrics will be issued annually, more in-depth reporting will occur on a longer time cycle, similar to the series of Everglades System Status reports and updates (http://www.evergladesplan.org/pm/recover/recover.aspx).

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