A New Framework for the Gulf of Mexico EcoHealth Metrics

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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 begin here 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.

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).

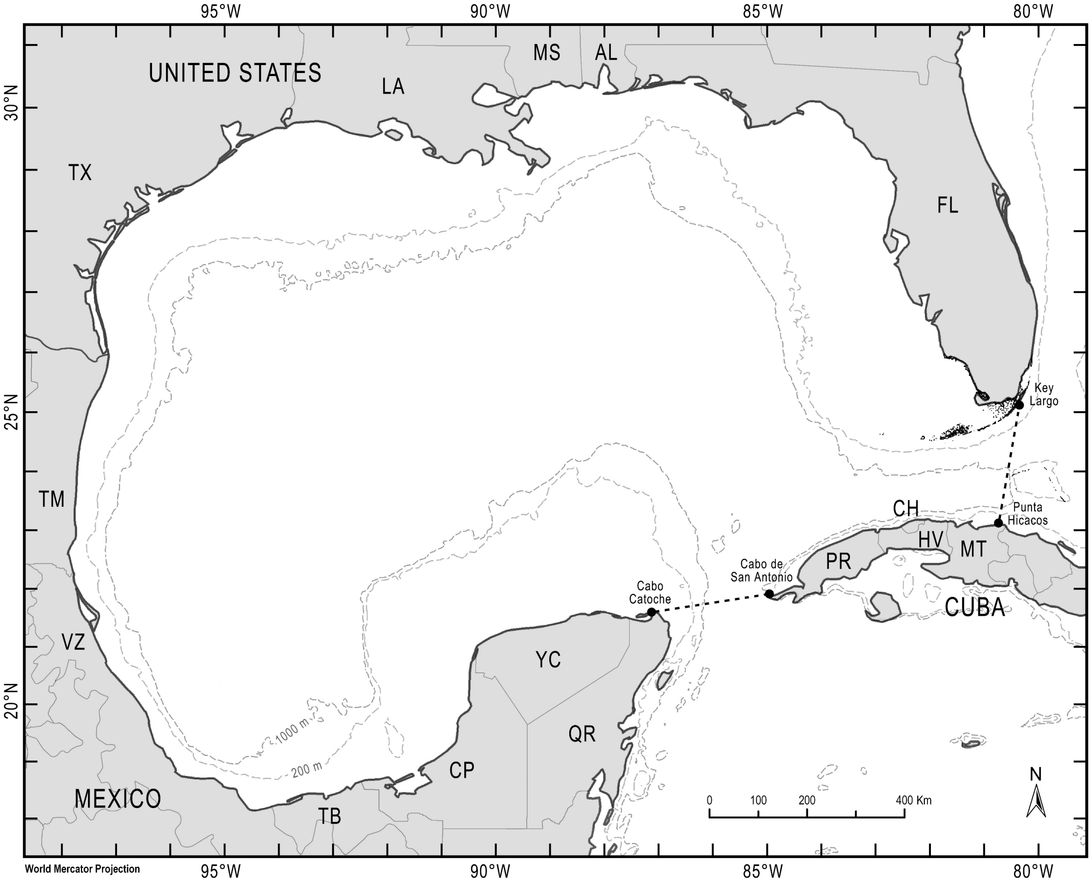


Figure 1a. The Gulf of Mexico, delimiting the geographic boundaries considered in the Gulf EcoHealth Metrics. Abbreviations for the states (counterclockwise) from Florida: FL = Florida, AL = Alabama, MS = Mississippi, LA = Louisiana, TX = Texas, TM = Tamaulipas, VZ = Veracruz, TB = Tabasco, CP = Campeche, 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

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. Our vision of the Gulf EcoHealth Metrics 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.

The intent of the present white paper is to describe a new conceptual framework that we have developed for the Gulf EcoHealth Metrics, providing the point-of-departure for the project's series of workshops.

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*

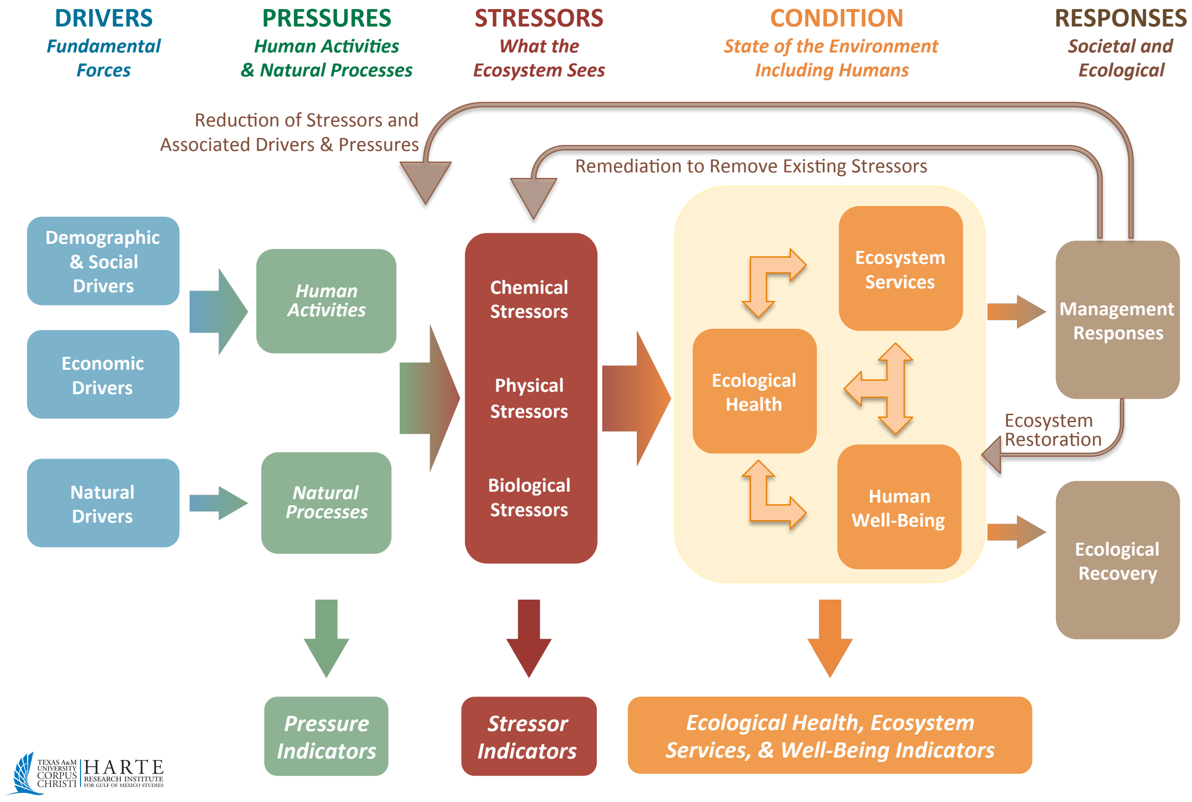
Based on this literature review of conceptual frameworks and indicators for assessing environmental health, we concluded that developing an assessment framework for an ecosystem of the scale and complexity of the Gulf of Mexico, and with the diversity of audiences that need to be informed, requires a 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]). Thus 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 2), 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$_4$.

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 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 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.

Figure 2. Integrated Assessment/Management Framework (DPSCR$_4$)



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 3).

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 3. 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.

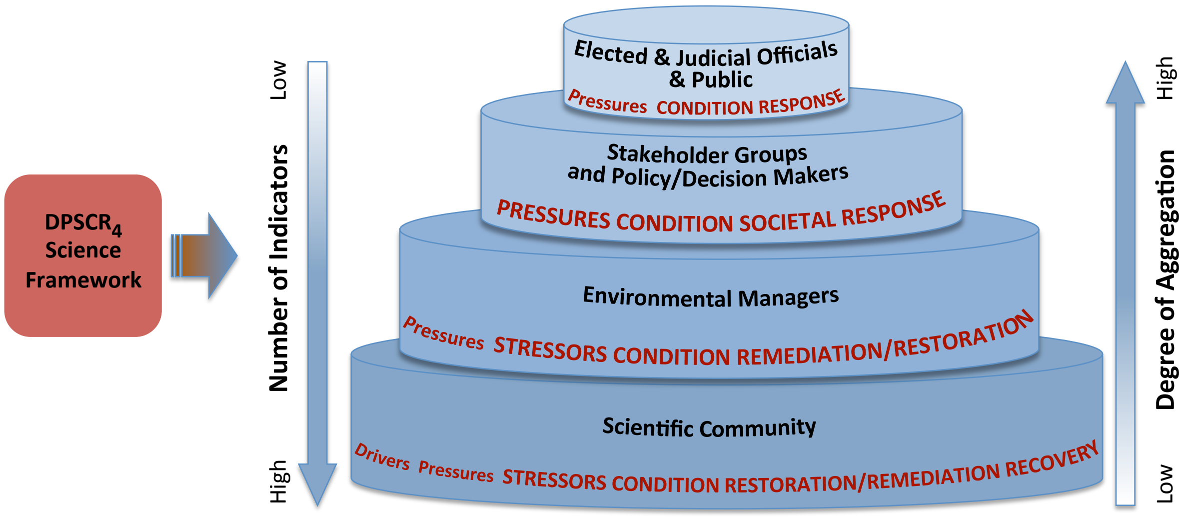
The next lower level is the realm of people who make or attempt to influence environmental decisions and policy. This tier emphasizes impacts from pressures on the environment and specific societal responses to mitigate impacts by managing pressures. This level requires more information because the audience 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.

Figure 4. Gulf EcoHealth Metrics
Hierarchical Reporting Structure for Various Audiences



The hierarchical structure also facilitates aggregation across spatial and ecological scales (Figure 5), 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.

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.

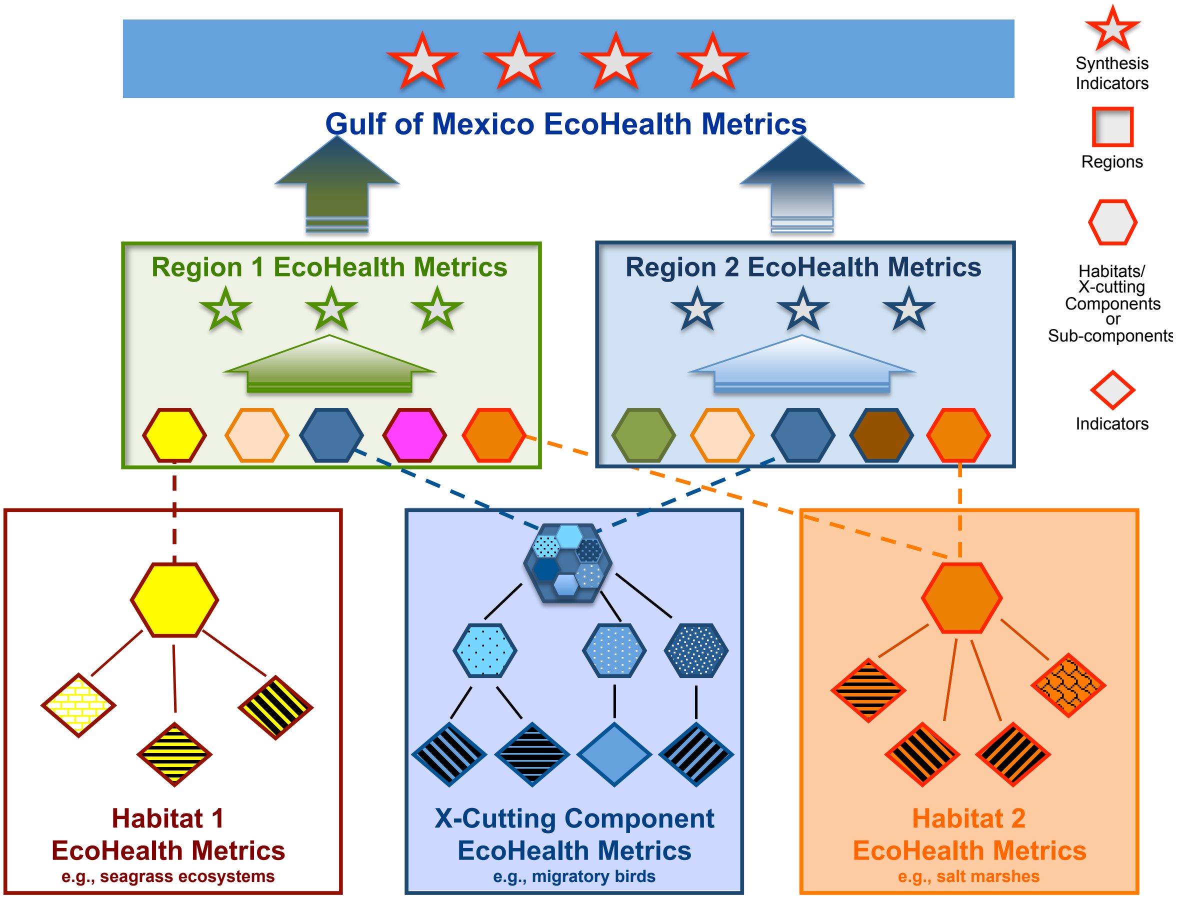


Figure 5. Aggregation scheme for elements of the Gulf of Mexico EcoHealth Metric.

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 6):

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.

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 7), 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).

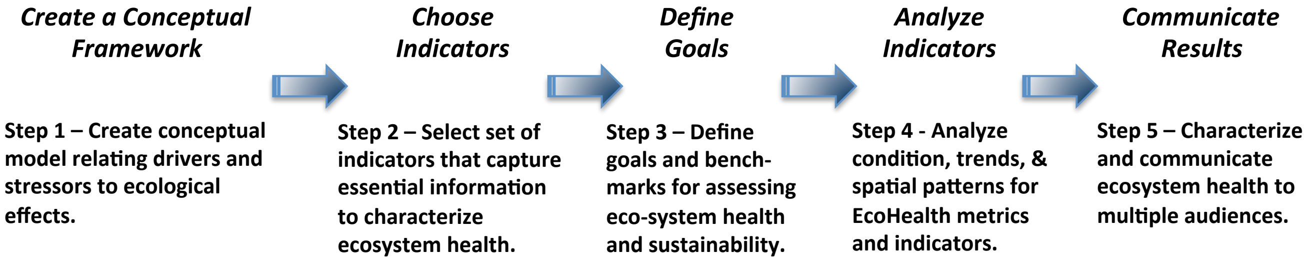


Figure 6. Five-Step Process for Constructing EcoHealth Metrics

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.

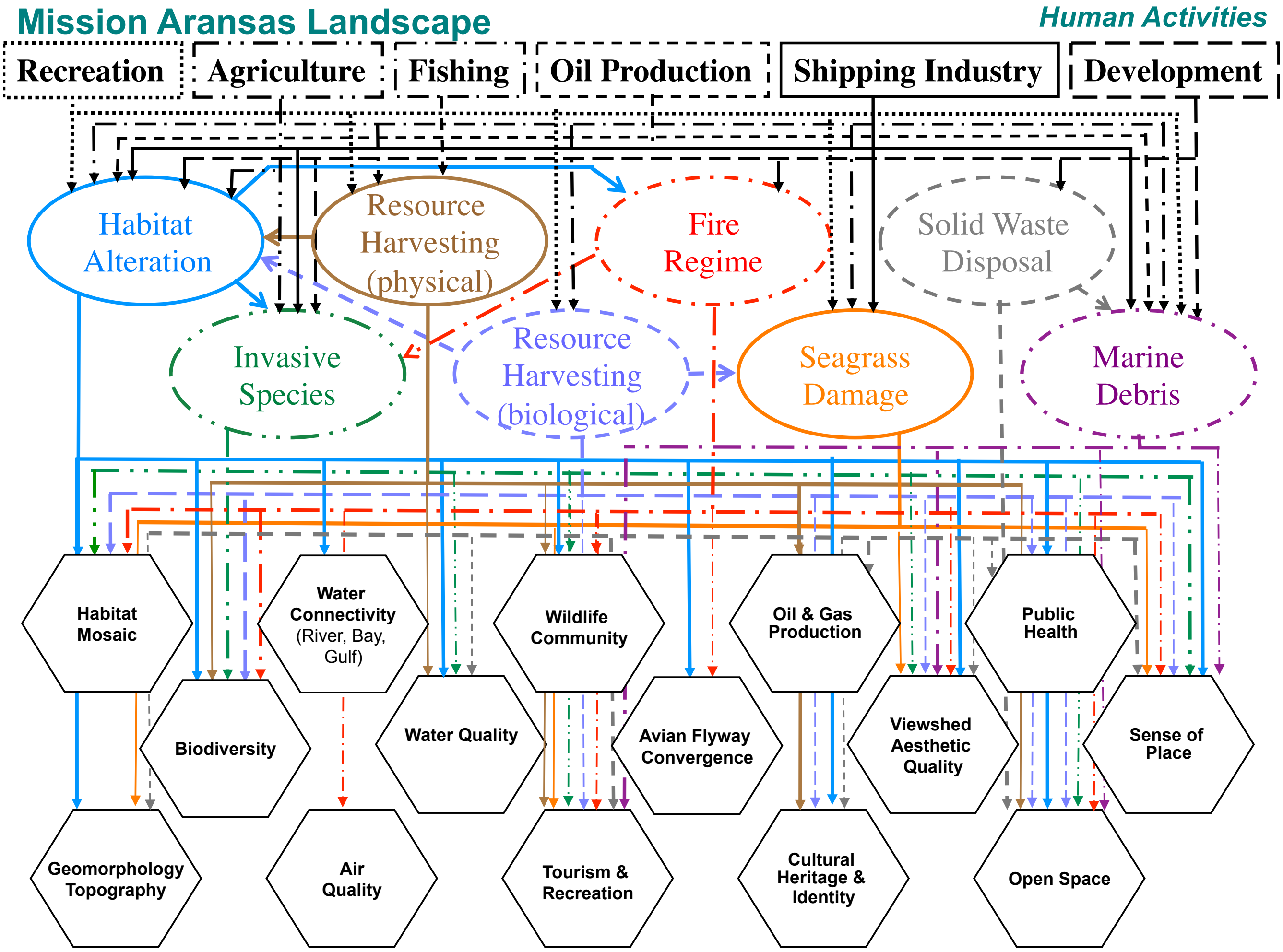


Figure 7. Example conceptual ecosystem model (CEM) for the Mission-Aransas National Estuarine Research Reserve.

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

- *intrinsic importance* – key: indicator is the endpoint
  - example: economically important species; endangered species
- *early-warning indicators* – key: rapid indication of effects
  - quick response time
  - low signal-to-noise ratio; low discrimination
  - screening tool; accept false positives
- *diagnostic indicators* – key: reliability in predicting effects
  - high stressor-specificity
  - high signal-to-noise ratio
  - minimize false positives
- *process/functional indicators* – key: process is the endpoint
  - monitoring other than biota (e.g., decomposition rates)

CRITERIA FOR SELECTING INDICATORS

- *signal-to-noise ratio*
  - sensitivity to stressor
  - intrinsic stochasticity
- *rapid response*
  - early exposure
  - quick dynamics (e.g., short life span)
- *reliability/specificity of response*
- *ease/economy of monitoring*
  - available field protocols
  - pre-existing database
  - low-cost tools
- *relevance to the endpoint*
  - answers the "so what?" question
- *feedback to management*

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

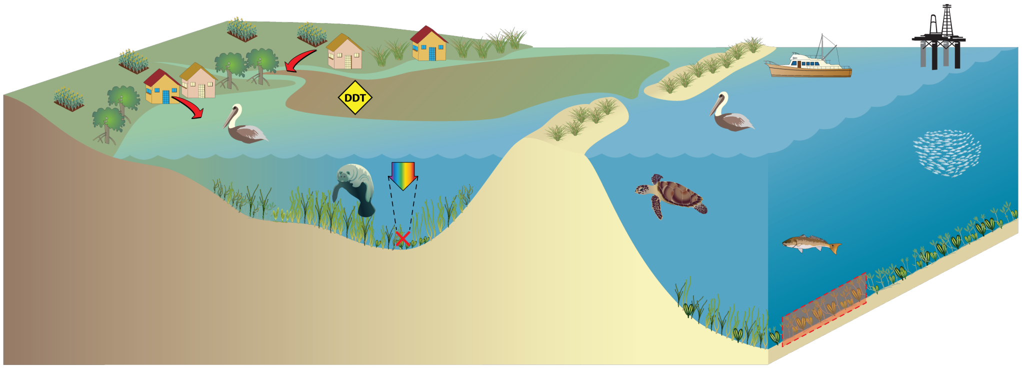
4.) *Characterize results* — Once data and thresholds are established, there are several options for characterizing the condition of the VECs. In general, indicator values are evaluated against specific goals, benchmarks, or thresholds. These may be standardized into assigned condition categories, and 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 (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 7 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 7 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 8a and 8b represent a similar ecosystem presented more appropriately in less detail 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



Contaminants, in particular DDT, reduced Brown Pelican populations prior to the chemical being banned in the USA in 1972. Brown Pelican populations rebounded but habitat alterations continue to be a threat to the population.

Urban development and agriculture runoff lead to turbidity and nutrient inputs into shallow coastal waters. Various seagrass species are adversely affected by reduced light, reducing seagrass area.

Figure 8a. Example conceptual model of a Gulf coastal ecosystem targeted at decision-makers and the public (from McKinney et al. 2011).

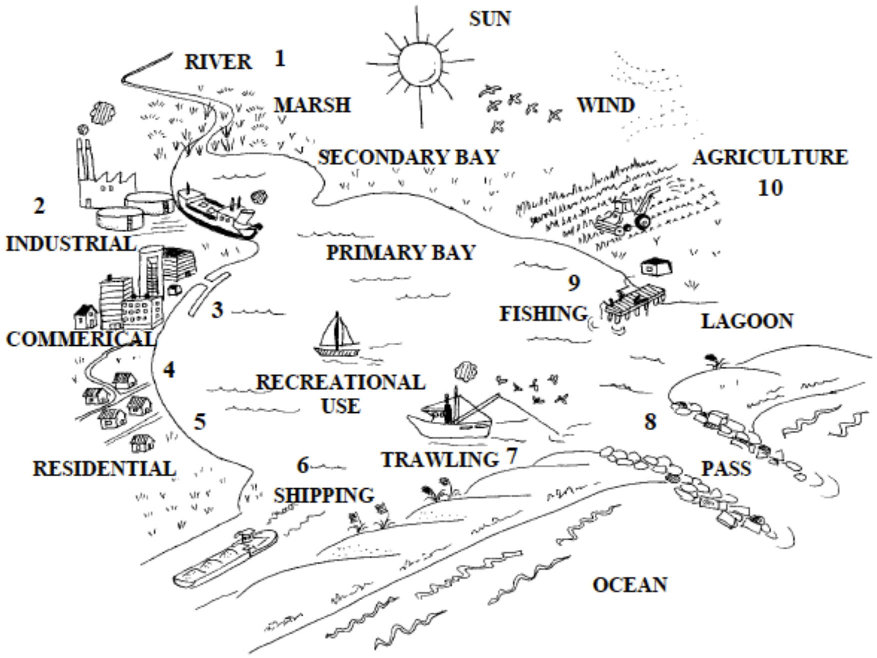


Fig. VI.1B. The role of humans in the CCBNEP Bay Area System. Human activities can impact the bay ecosystem in a variety of ways, most of which tend to have harmful effects on the productivity and diversity of the ecosystem. 1 – Impounding rivers cut off fresh water inflow to the bay. 2 – Industry can 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 8b. 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).

Implementation

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 incorporating these series of activities over the next few years:

- Initiate Texas Pilot Project — a demonstration and proof-of-concept pilot project for EcoHealth Metrics development and data acquisition will initially focus on Texas coastal ecosystems.
- Partition the Gulf of Mexico into discrete units — this will reduce the scale of the problem to manageable levels by segmenting the Gulf into regions, ecosystem/habitat types, and cross-cutting components.
- Develop Regional Gulf EcoHealth Metrics — we will apply the methodology and lessons learned from the Texas pilot to the other regions of the Gulf.
- Develop Cross-Cutting Gulf EcoHealth Metrics — we will also apply the methodology and lessons learned to the cross-cutting components of the Gulf, such as migratory birds and marine mammals.
- Develop Integrated Gulf EcoHealth Metrics — the longer-term objective is to integrate the component EcoHealth Metrics into an overall assessment/decision framework for the Gulf of Mexico.

Texas Pilot Project

Coastal Texas and its watersheds provide an excellent model of the entire Gulf of Mexico for developing EcoHealth Metrics because of the diversity and complexity of its ecosystems, human communities, and associated environmental pressures and stressors. Consequently, we have chosen the Texas Pilot Project as a proof-of-concept evaluation of the framework and its implementation. We will begin with a workshop to partition this region into its constituent ecological habitats and to identify the full suite of pressures and stressors that impinge on coastal Texas ecosystems. This initial workshop will consist of scientists, stakeholders, and Texas environmental managers; collectively they have expertise and experience in integrated assessment/decision methodologies, ecological indicators and metrics, the ecosystems of Texas and the services they provide, human activities affecting the region, and environmental management issues of current or prospective concern. Selection of the workshop invitees will ensure that the ecosystems, habitats, drivers, pressures, stressors, and VECs of the Texas coastal region are correctly identified and characterized, that appropriate existing or prospective data and metrics are considered, and that the management issues and long-term sustainability goals are adequately defined.

The first task of the initial workshop will be to review the $DPSCR_4$ framework and hierarchical structure, as described to participants in this white paper. Participants will identify the major ecosystems, habitats, cross-cutting ecological components, and drivers and pressures of concern for coastal Texas. Workshop participants will then evaluate and modify a set of habitat-specific risk-based conceptual ecosystem models (CEMs), similar to Figure 7 above, that have been previously developed to identify the stressors and valued ecosystem components of each habitat and characterize the strengths of the relationships between each stressor and effects on each VEC of each habitat. Similarly, the workshop participants will evaluate the driver/pressure/stressor-effects relationships for each identified VEC of the cross-cutting components of the Texas coastal ecosystems, such as migratory birds. Finally, the workshop participants will identify candidate indicators and data sources that might be utilized for the Texas EcoHealth Metrics. Subsequent to the workshop, the EcoHealth Metrics Team will graphically capture these components into the $DPSCR_4$ framework for the region. We will then select specific indicators for each habitat and cross-cutting component of Texas as well as the important pressures/stressors. In parallel, the Harte Research Institute will initiate data acquisition and analyses and related studies, with the objective over time to populate candidate EcoHealth Metrics for selected ecosystems of interest in the pilot study.

Additionally, the EcoHealth Metrics team will begin to explore appropriate techniques and tools for communicating the Texas EcoHealth Metrics and assessments to various targeted audiences. A report will be prepared that describes the results of the initial pilot workshop and the post-workshop activities.

A subsequent workshop will consider the EcoHealth Metrics structure and data as they have developed, providing adjustments as needed for continuing the process of Texas EcoHealth Metrics development and implementation. This workshop will review and refine the DPSCR$_4$ framework for the region, the candidate indicators and metrics, results of initial analyses and assessments, and proposed communications strategies and tools. Additionally, plans will be made for subsequent activities towards finalizing and implementing the Texas EcoHealth Metrics. Following this workshop, an interim report will be prepared to overview the Texas pilot study, discuss next steps in the Texas EcoHealth Metrics development and implementation process, and provide guidance for developing similar regional-scale EcoHealth Metrics for other regions of the Gulf of Mexico.

Partitioning the Gulf of Mexico

A separate activity will partition the Gulf into manageable units, each of which will have a separate EcoHealth Metrics construct, indicators, and metrics. This task will also begin with a workshop consisting of scientists, stakeholders, and environmental managers, but drawn from a larger constituency with experience in the greater Gulf of Mexico, rather than primarily focused on Texas coastal ecosystems. The workshop participants will be provided with the white paper with background on the DPSCR$_4$ framework and hierarchical structure, plus they will have at least an initial report on the nature, results, and lessons learned from the Texas pilot study. The participants will be asked to identify all of the major ecosystems, habitats, and cross-cutting ecological components of concern for the Gulf, focusing not only on the US Gulf coast, but also Mexico and Cuba. They will then be asked to disaggregate the Gulf into component regions based on ecological, geographical, and political factors. The regional and cross-cutting component demarcations will be designed to ensure that the entire Gulf is appropriately represented. Additionally, the participants will be asked to identify candidate VECs, indictors, data sources, and metrics for further consideration in the regional and cross-cutting EcoHealth Metrics. Finally, they will explore candidate methods and tools for reporting EcoHealth assessment results to intended audiences. Results from the partitioning workshop will be documented in a report that will inform the subsequent activities.

Develop Regional and Cross-Cutting Gulf EcoHealth Metrics

Using the Texas pilot project as guidance, each of the regions and cross-cutting components will follow a similar process, involving workshops, development of CEMs and resultant DPSCR$_4$ frameworks and hierarchical structures, and identification of candidate indicators and metrics for further exploration and implementation. The staging and scale of each of these projects will depend on the availability of funding and the lessons learned from previous efforts. We envision that this development and implementation process will unfold over a period of several years, and once established, will evolve into continuing monitoring and assessment programs. As these progress, refinements will occur in the methods and tools for reporting EcoHealth Metrics and assessment results to intended audiences, and opportunities will be sought to integrate these EcoHealth Metrics into environmental decision-making processes.

Develop Integrated Gulf EcoHealth Metrics

Beginning with the Texas EcoHealth Metrics development process, we will also initiate activities to develop new, integrative tools for ecosystem characterization and assessments. We will seek to integrate across regions and cross-cutting components. Ultimately, the goal is to have a fully integrated EcoHealth Metrics that can inform the longer-term restoration and sustainability of the whole Gulf of Mexico.

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References Cited

Australian and Queensland Governments. 2010. *Great Barrier Reef First Report Card 2009 Baseline Reef.* Water quality protection plan. Reef Water Quality Protection Plan Secretariat.http://ian.umces.edu/press/assessment/great_barrier_reef/. Accessed 3 December 2013.

Barrett GW, Van Dyne GM, Odum EP. 1976. Stress ecology. *BioScience* 26: 192–194.

Cairns J, McCormick PV, Niederlehner BR. 1993. A proposed framework for developing indicators of ecosystem health. *Hydrobiologia* 236: 1–44.

Carter GA, Lucas KL, Biber PD, Criss GA, Blossom GA. 2011 Historical changes in seagrass coverage on the Mississippi barrier islands, northern Gulf of Mexico, determined from vertical aerial imagery (1940-2007). *Geocarto International* 26(8): 663–673.

CCBNEP. 1996. *A Conceptual Ecosystem Model of the Corpus Christi Bay National Estuary Program Study Area.* CCBNEP-08. Corpus Christi Bay National Estuary Program, Corpus Christi, TX.

CEC (Commission for Environmental Cooperation). 2011. *A Guide to Ecological Scorecards for Marine Protected Areas in North America*. North American Commission for Environmental Cooperation, Montreal, Quebec, Canada. www3.cec.org/islandora/en.

CERCLA (Comprehensive Environmental Response, Compensation and Liability Act of 1980) 43CFR11.14. www.gpoaccess.gov/cfr/.

CERP (Comprehensive Everglades Restoration Plan). 2012. *2012 System Status Report Interim Update December 2012*. www.evergladesplan.org/pm/ssr_2012/ssr_main_2012.aspx.

CCME (Canadian Council of Ministers of the Environment). 1996. *A Framework for Ecological Risk Assessment: General Guidance.* PN 1195. Environment Canada, Ottawa, Ontario, Canada.

CERCLA (Comprehensive Environmental Response, Compensation and Liability Act of 1980). 43CFR11.14.

Cormier SM, Smith M, Norton S, Nieheisel T. 2000. Assessing ecological risks in watersheds: a case study of problem formulation in the Big Darby Creek Watershed, Ohio, USA. *Environmental Toxicology & Chemistry* 19: 1082–1096.

Couvillion BR, Barras JA, Steyer GD, Sleavin W, Fischer M, Beck H, Trahan N, Griffin B, Heckman D. 2011. *Land Area Change in Coastal Louisiana from 1932 to 2010*. Pamphlet to accompany Scientific Investigations Map 3164, US Geological Survey, Reston, VA.

Dale VH, Beyeler SC. 2001. Challenges in the development and use of ecological indicators. *Ecological Indicators* 1: 3–10.

Davis SM, Ogden JC. 1994. Towards ecosystem restoration. In: Davis SM, Ogden JC (eds) *Everglades, The Ecosystem and Its Restoration*. St. Lucie Press, Delray Beach, FL, pp 769-796.

Doren RF, Best GR (eds). 2009. Indicators for Everglades restoration. Special issue of *Ecological Indicators* 6 (Suppl): S1–S160.

Doren RF, Trexler JC, Gottlieb AD, Harwell MC. 2009. Ecological indicators for system-wide assessment of the greater Everglades ecosystem restoration program. *Ecological Indicators* 9S: S2–S16.

EEA (European Environmental Agency). 1999. *Environmental Indicators: Typology and Overview*. EEA Technical Report no. 25. EEA, Copenhagen, Denmark.

Egoh B, Drakou EG, Dunbar MB, Maes J, Willemen L. 2012. *Indicators for Mapping Ecosystem Services: A Review*. European Commission. EUR 25456 – Joint Research Centre – Institute for Environment and Sustainability Luxembourg: Publications Office of the European Union

FAO (Food & Agriculture Organization of the United Nations) (undated) Pressure-State-Response Framework and Environmental Indicators.

www.fao.org/ag/againfo/programmes/en/lead/toolbox/Refer/EnvIndi.htm#Indicators.

Felder DL, Camp DK, Tunnell JW Jr. 2009. An introduction to Gulf of Mexico biodiversity assessment. In: Felder DL, Camp DK (eds) *Gulf of Mexico Origin, Waters and Biota: Volume 1 Biodiversity*. Texas A&M University Press, College Station, TX, pp 1–12.

Gentile JH, Harwell MA. 1998. The issue of ecological significance in ecological risk assessments. *Human & Ecological Risk Assessment* 4: 815–828.

Gentile JH, Harwell MA, van der Schalie W, Norton S, Rodier D. 1993. Ecological risk assessment: a scientific perspective. *J Hazardous Materials* 35: 241–253.

Gentile JH, Harwell MA, Cropper WP Jr, Harwell CC, DeAngelis D, Davis S, Ogden JC, Lirman D. 2001. Ecological conceptual models: a framework and case study on ecosystem management for South Florida. *J Science & the Total Environment* 274: 231–253.

Gentile JH, Slimak MW. 1990. Endpoints and indicators in ecological risk assessment. Pages 1385–1397 *in*: MacKenzie DH, Hyatt DE, McDonald VJ (eds). *Ecological Indicators*, Vol. 2, Elsevier Applied Science, NY.

Goksøyr A, Förlin L. 1992. The cytochrome *P*-450 system in fish, aquatic toxicology and environmental monitoring. *Aquatic Toxicology* 22(4): 287-311.

Griffith JA, Hunsaker CT. 1994. *Ecosystem Monitoring and Ecological Indicators: An Annotated Bibliography*. EPA/620/R-94/021. USEPA Office of Research and Development, Environmental Research Laboratory, Athens, GA.

Halpern BS, Longo C, Hardy D, et al. 2012. An index to assess the health and benefits of the global ocean. *Nature* 488: 615–620 with suppl.

Harwell MA, Long JF, Bartuska AM, Gentile JH, Harwell CC, Myers V, Ogden JC. 1996. Ecosystem management to achieve ecological sustainability: the case of South Florida. *Environmental Management* 20: 497–521.

Harwell MA, Myers V, Young T, Bartuska A, Gassman N, Gentile JH, Harwell CC, Appelbaum S, Barko J, Causey B, Johnson C, McLean A, Smola R, Templet P, Tosini S. 1999a. A framework for an ecosystem integrity report card. *BioScience* 49: 543–556.

Harwell MA, Gentile JH, Bartuska A, Harwell CC, Myers V, Obeysekera J, Ogden JC, Tosini SC. 1999b. A science-based strategy for ecological restoration in South Florida. *Urban Ecosystems* 3: 201–222.

Harwell MA, Gentile JH, Cummins KW, Highsmith RC, Hilborn R, McRoy CP, Parrish J, Weingartner T. 2011. A conceptual model of natural; and anthropogenic drivers and their influence on the Prince William Sound, Alaska, ecosystem. *Human and Ecological Risk Assessment* 16: 672–726. Available online at: http://dx.doi.org/10.1080/10807039.2010.501011.

Harwell MA, Gentile JH, Parker KR. 2013. Characterizing ecological risks, significance, and recovery. Pages 383–419 in: Wiens JA (ed) *Oil in the Environment. Legacies and Lessons of the* Exxon Valdez *Oil Spill*. Cambridge University Press, Cambridge, UK.

Harwell MA, Gentile JH. 2014. Assessing sea otter risks and the *Exxon Valdez* oil spill: new scenarios, attributable risk, and recovery. *Human & Ecological Risk Assessment* 20(4): 889-916; available at DOI: 10.1080/10807039.2013.828513.

Hattam C, Atkins JP, Beaumont N, Börger T, Böhnke-Henrichs A, Burdon D, et al. 2015. Marine ecosystem services: Linking indicators to their classification. *Ecological Indicators* 49: 61-75.

Holling CS. 1973. Resilience and stability of ecological systems. *Annual Review Ecology & Systematics* 4: 1–23.

Hunsaker CT, Carpenter DE (eds). 1990. *Ecological Indicators for the Environmental Monitoring and Assessment Program.* EPA/600/3-90/060. US EPA Office of Research & Development, Research Triangle Park, NC.

Hunsaker CT, Levine DA, Timmins SP, Jackson BL, O'Neill RV. 1990. Landscape characterization for assessing regional water quality. Pages 997-1006, in: MacKenzie DH, Hyatt DE, McDonald VJ (eds). *Ecological Indicators*, Vol. 2, Elsevier, NY.

IAN (Integration & Application Network). 2007. *2006 Chesapeake Bay Report Card*. IAN, Center for Environmental Studies, University of Maryland, Cambridge, MD. http://ian.umces.edu/ecocheck/report-cards/chesapeake-bay/2006/.

IAN (Integration & Application Network). 2013. *2012 Chesapeake Bay Report Card.* IAN, Center for Environmental Studies, University of Maryland, Cambridge, MD. http://ian.umces.edu/ecocheck/report-cards/chesapeake-bay/2012/.

Joye, SB. 2015. Deepwater Horizon, 5 years on. *Science* 349(6248): 592–593.

Karr JR. 1981. Assessment of biotic integrity using fish communities. *Fisheries* 6: 21–27.

Kelly JR, Harwell MA. 1989. Indicators of ecosystem response and recovery. Chapter 2 *in*: Levin SA, Harwell MA, Kelly JR, Kimball KD (eds). *Ecotoxicology: Problems and Approaches*. Springer-Verlag, New York, NY.

Kelly JR, Harwell MA. 1990. Indicators of ecosystem recovery. *Environmental Management* 15: 527–545.

Kujawinski EB, Kido Soule MC, Valentine DL, Boysen AK, Longnecker K, Redmond MC. 2011. Fate of dispersants associated with the Deepwater Horizon oil spill. *Environmental Science & Technology* 45: 1298–1306.

Landres PB, Verner J, Thomas JW. 1988. Ecological uses of vertebrate indicator species: a critique. *Conservation Biology* 2: 316–328.

Levin PS, Fogarty MJ, Matlock GC, Ernst M. 2008. *Integrated Ecosystem Assessments*. US Department of Commerce, NOAA Technical Memorandum NMFS-NWFSC-92. NOAA, Washington, DC.

Mabus R. 2010. *America's Gulf Coast. A Long Term Recovery Plan after the Deepwater Horizon Oil Spill*. Report to the Gulf Coast Ecosystem Restoration Task Force. www.restorethegulf.gov.

MacKenzie DH, Hyatt DE, McDonald VJ (eds). 1990. *Ecological Indicators*, Volumes 1 and 2, Elsevier Applied Science, New York.

McKinney LD, Tunnell JW Jr, Harwell MA, Gentile JH, Dennison WC, Kelsey RH, Thomas JE. 2011. *A Vision for the Gulf of Mexico Report Card. Synopsis and Report Card Prototypes Prepared for the Gulf of Mexico Summit, Houston, TX, December 2010*. Harte Research Institute for Gulf of Mexico Studies, Texas A&M University-Corpus Christi, TX.

Mills, K. E. 2006. *A Strategy for Gulf of Maine Ecosystem Indicators and State of the Environment Reporting*. Gulf of Maine Council on the Marine Environment. (available at: http://www.gulfofmaine.org/2/esip-homepage).

Morton RA, Bernier JC, Barras JA, Ferina NF. 2005. *Rapid Subsidence and Historical Wetland Loss in the Mississippi Delta Plain: Likely Causes and Future Implications*. Open File Report 2005-1216, US Department of the Interior, US Geological Survey. http://pubs.usgs.gov/of/2005/1216/ofr-2005-1216.pdf.

NAS (National Academy of Sciences). 2012. *Approaches for Ecosystem Services Valuation for the Gulf of Mexico after the Deepwater Horizon Oil Spill. Interim Report*. Committee on the Effects of the Deepwater Horizon Mississippi Canyon–252 Oil Spill on Ecosystem Services in the Gulf of Mexico. National Research Council, National Academies Press, Washington, DC

NOAA (National Oceanic and Atmospheric Administration). 1996a. *Injury Assessment: Guidance Document for Natural Resource Damage Assessment under the Oil Pollution Act of 1990*. www.darrp.noaa.gov/library/1_d.html.

NOAA (National Oceanic and Atmospheric Administration). 1996b. *Restoration Planning: Guidance Document for Natural Resource Damage Assessment under the Oil Pollution Act of 1990*. www.darrp.noaa.gov/library/1_d.html.

NOAA (National Oceanic and Atmospheric Administration). 2010. *OPA Guidance*. www.darrp.noaa.gov/library/1_d.html.

NOAA (National Oceanic and Atmospheric Administration). 2011. *Florida Keys National Marine Sanctuary Condition Report 2011*. NOAA Office of National Marine Sanctuaries, Silver Spring, MD. http://sanctuaries.noaa.gov/science/condition/pdfs/fknms_highres.pdf.

NMFS (National Marine Fisheries Service). 2013. *Fisheries of the United States 2012. Current Fisheries Statistics No. 2012*. NOAA NMFS, Fisheries Statistics Division, Silver Spring, MD, USA. www.st.nmfs.noaa.gov/Assets/commercial/fus/fus12/FUS2012.pdf.

Odum EP. 1969. The strategy of ecosystem development. *Science* 164: 262–270.

Odum EP. 1985. Trends expected in stressed ecosystems. *BioScience* 35: 419–422.

OECD (Organisation for Economic Co-operation and Development). 1991. *Environmental Indicators: A Preliminary Set*. OECD, Paris, France.

OECD (Organisation for Economic Co-operation and Development). 1993. OECD Core Set of Indicators for Environmental Performance Reviews. *Environment Monographs No. 83*. OECD, Paris, France.

Ogden JC, Davis SM, Barnes T, Jacobs KJ, Gentile JH. 2005a. Total system conceptual ecosystem model. *Wetlands* 25: 955–979.

Ogden JC, Davis SM, Jacobs KJ, Barnes T, Fling HE. 2005b. The use of conceptual ecological models to guide ecosystem restoration in South Florida. *Wetlands* 25: 795–809.

OPA 90 (Oil Pollution Act of 1990) 15CFR990.30. www.gpoaccess.gov/cfr/.

Pantus FJ, Dennison WC. 2005. Quantifying and evaluating ecosystem health: a case study from Moreton Bay, Australia. *Environmental Management* 36: 757–771.

PEEIR (Pacific Estuarine Ecosystem Indicator Research Consortium). 2005. *The San Francisco Bay Index (Ecological Scorecard): A Tool for Summarizing Condition at Regional Scales*. University of California David Bodega Marine Laboratory & University of California Santa Barbara. www.bml.ucdavis.edu/PEEIR/Brochures/SFBay_Scorecard.pdf.

Rabalais NN, Turner RE, Scavia D. 2002. Beyond science into policy: Gulf of Mexico hypoxia and the Mississippi River. *BioScience* 52: 129–142.

Rapport DJ, Regier HA, Hutchinson TC. 1985. Ecosystem behavior under stress. *American Naturalist* 125: 617–640.

Stephan CE, Mount DI, Hansen DJ, Gentile JH, Chapman GA, Brungs WA. 1985. *Guidelines for Deriving Numerical National Water Quality Criteria for the Protection of Aquatic Organisms and Their Uses*. USEPA PB85-227048, USEPA Office of Research & Development, Environmental Research Laboratories, Washington, DC.
http://water.epa.gov/scitech/swguidance/standards/criteria/aqlife/index.cfm#final.

Suter GW, II (ed). 2007. *Ecological Risk Assessment*. Lewis Publishers, Chelsea, MI.

UNEP WCMP (World Conservation Monitoring Centre). 2011. *Developing Ecosystem Service Indicators: Experiences and Lessons Learned from Sub-global Assessments and Other Initiatives*. Secretariat of the Convention on Biological Diversity, Montréal, Canada. Technical Series No. 58, 118 pages.

USEPA (US Environmental Protection Agency). 1992. *Framework for Ecological Risk Assessment*. EPA/630/R-92/001. USEPA Risk Assessment Forum, Washington, DC.

USEPA (US Environmental Protection Agency). 1998. *Guidelines for Ecological Risk Assessment.* EPA/630/R-95/002F. USEPA Risk Assessment Forum, Washington, DC.

USEPA (US Environmental Protection Agency). 2011. *Gulf of Mexico Regional Ecosystem Restoration Strategy*. Gulf Coast Restoration Task Force. December 2011. http://archive.epa.gov/gulfcoasttaskforce/web/pdf/gulfcoastreport_full_12-04_508-1.pdf

USEPA (US Environmental Protection Agency). 2012. *National Coastal Condition Report IV.* EPA-842-R-10-003, USEPA Office of Research and Development/Office of Water, Washington, DC. http://water.epa.gov/type/oceb/assessmonitor/nccr/upload/0_NCCR_4_Report_508_bookmarks.pdf.

USEPA SAB (US Environmental Protection Agency Science Advisory Board). 2002. *A Framework for Assessing and Reporting on Ecological Condition: An SAB Report*. EPA-SAB-EPEC-02-009, EPA Science Advisory Board, Washington, DC.

Weber J-L. 2010. *Merging the Ecosystem Approach with the Conventional PSR/DPSIR Framework (Draft for Discussion).* ESA/STATISTICS/AC.228, EGM-FDES/1/16. Department of Economic and Social Affairs, Statistics Division, United Nations

Williams MR, Longstaff BJ, Buchanan C, Llanso R, Dennison WC. 2009. Development and evaluation of a spatially-explicit index of Chesapeake Bay health. *Marine Pollution Bulletin* 59: 14–25.

Williams MR, Finoso S, Longstaff BJ, Dennison WC. 2010. Long-term trends in water quality and biotic metrics in Chesapeake Bay: 1986-2008. *Estuaries & Coasts* 33: 1279–1299.