Indicators and Assessment Framework for Ecological Health and Ecosystem Services

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Introduction

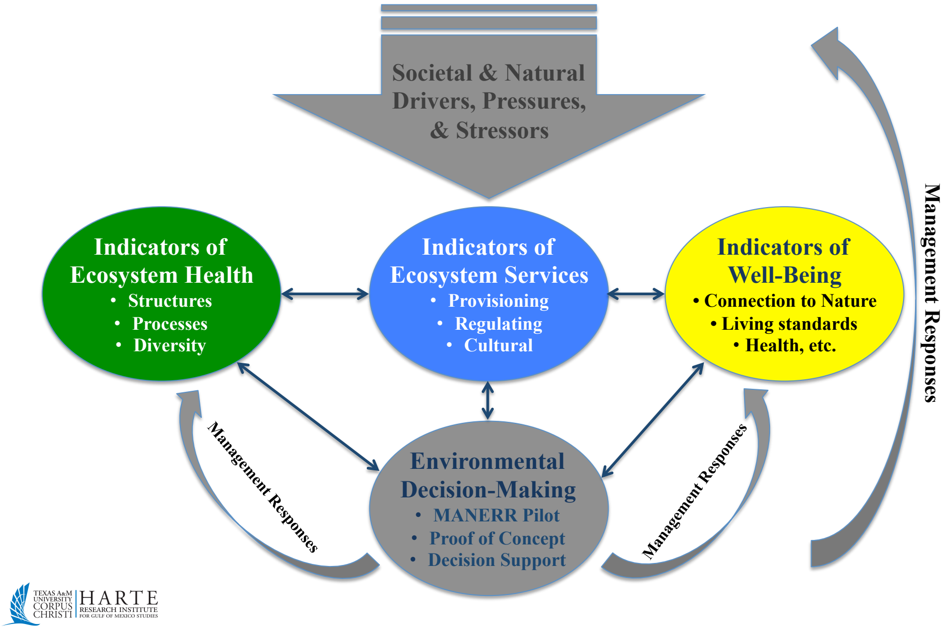
The Harte Research Institute for Gulf of Mexico Studies has undertaken a multi-faceted project to develop and implement an integrated indicators and assessment framework, which we term the *Gulf EcoHealth Metrics*, to characterize the health of the ecosystems of the Gulf of Mexico, including their linkages 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. 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.

As an important component of this initiative, we have begun a project sponsored by the NOAA RESTORE Science Program to enhance the EcoHealth Metrics conceptual framework with explicit connections among coastal ecological processes and ecosystem services and human well-being in communities that live along the Gulf of Mexico. Additionally, this framework is embedded within a decision-making process, with the aim of providing science-based information and understanding to identifying and assessing management policies and actions. The present white paper is intended as a point-of-departure for this project, providing an overall conceptual framework for characterizing ecological health and ecosystem services and their linkages to human well-being in support of resource management needs (Figure 1).

In this coupled human-ecological framework, anthropogenic and natural drivers, pressures, and stressors impinge on ecosystems, causing effects on ecological health (i.e., changes to ecological structure, processes, and/or diversity) and associated effects on ecosystem services that link ecological and societal systems. Management actions feed back to the ecological systems and associated ecosystem services. This integrated assessment/decision framework provides a scientific basis for designing and assessing environmental management policies affecting drivers and pressures, aimed specifically at reducing or mitigating environmental stressors in order to achieve ecosystem health and sustainability and to provide essential ecosystem services that enhance human well-being. We seek a blend of both the conceptual and the practical, so that the product from this research project will be a set of indicators and associated integrated assessment and decision framework with direct applicability and utility to support resource managers in achieving a healthy and sustainable Gulf of Mexico.

This project began with a survey and critical evaluation of existing ecological health and ecosystem services indicators, their links to human well-being, and assessment/decision frameworks for their applicability and utility in managing the restoration and sustainability of the Gulf. From this we have developed an integrated assessment and decision framework, along with associated indicators, for characterizing ecological health and ecosystem services and their links to human well-being, designed to meet the management needs for Gulf restoration and sustainability. We will test this approach in a proof-of-concept application to the Mission-Aransas National Estuarine Research Reserve (Mission-Aransas NERR). We will then evaluate the results and lessons learned from the Mission-Aransas Reserve pilot study for broader applicability and utility towards sustainability of a healthy Gulf of Mexico.

Figure 1. Linking Ecosystem Health, Services, and Well-Being



Need for characterizing the Gulf of Mexico and connectivity to society

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 2a). 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 socio-economic environment is as vibrant and diversified as the natural environment. The total population in the coastal region of the three countries surrounding the Gulf is approximately 50 million people, with close to half of that living in counties of 200,000 people or greater. It is home to a healthy shipping industry with six of the top ten ports in the US and four of the top ten ports in Mexico (by weight) calling the Gulf home. Oil and gas exploration and production are important in all three countries. The Gulf states and the Federal offshore area accounted for 54% of oil production in the US, and the Gulf of Mexico offshore area accounted for 75% of Mexico's production (Yoskowitz et al. 2013).

The Gulf's watershed comes from five countries and covers 56% of the continental US (USEPA 2011), 40% from the Mississippi River Basin alone (Figure 2b). 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 seven decades (Couvillion et al. 2011). As a result of natural and anthropogenic pressures, the Gulf's estuaries have become increasingly degraded for both human use and aquatic life. Threats to the health of the Gulf include (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;
- hypoxia offshore of the Mississippi River Delta;
- 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;
- 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 x 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 x 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). It is to meet this challenge that the present series of activities in support of an EcoHealth Metrics have been undertaken.

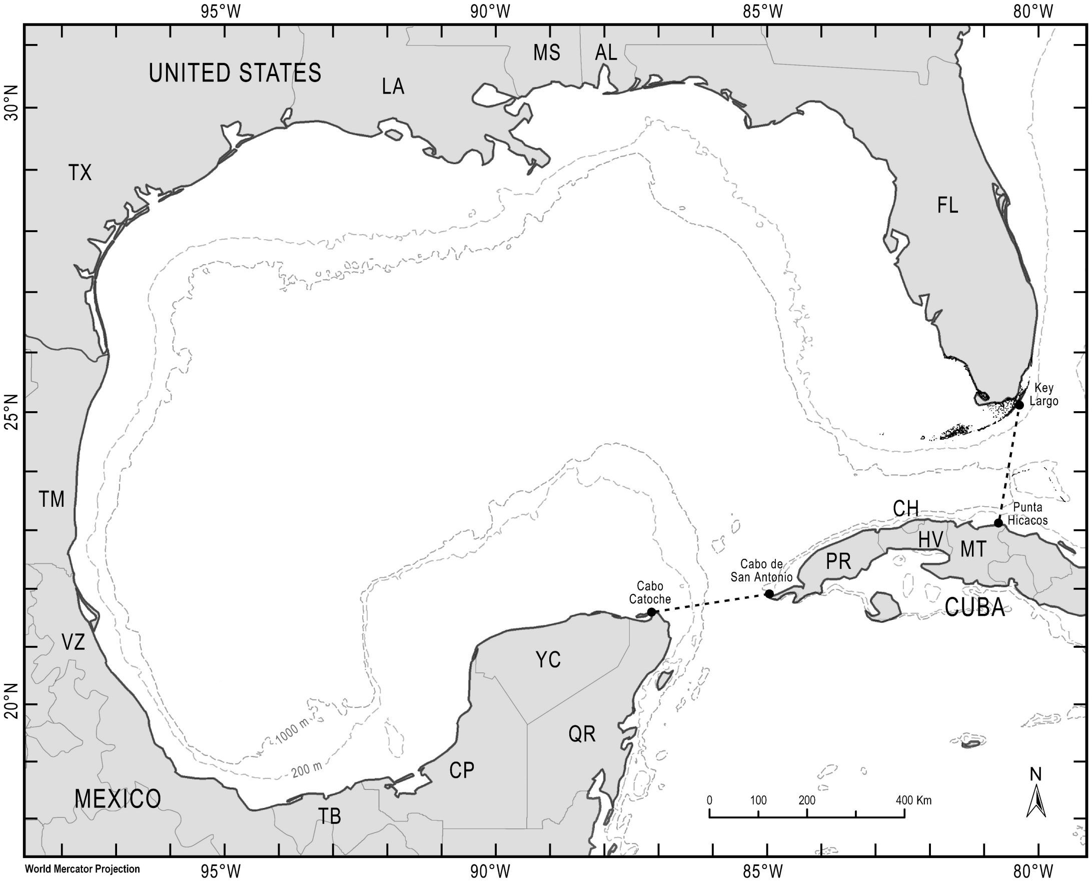


Figure 2a. The Gulf of Mexico, delimiting the geographic boundaries considered in the Gulf EcoHealth Metrics. Abbreviations for the states (counterclockwise) from Florida: FL = Florida, AL = Alabama, MS = Mississippi, LA = Louisiana, TX = Texas, TM = Tamaulipas, VZ = Veracruz, TB = Tabasco, CP = Campeche, 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 2b. Map of the Gulf of Mexico watershed

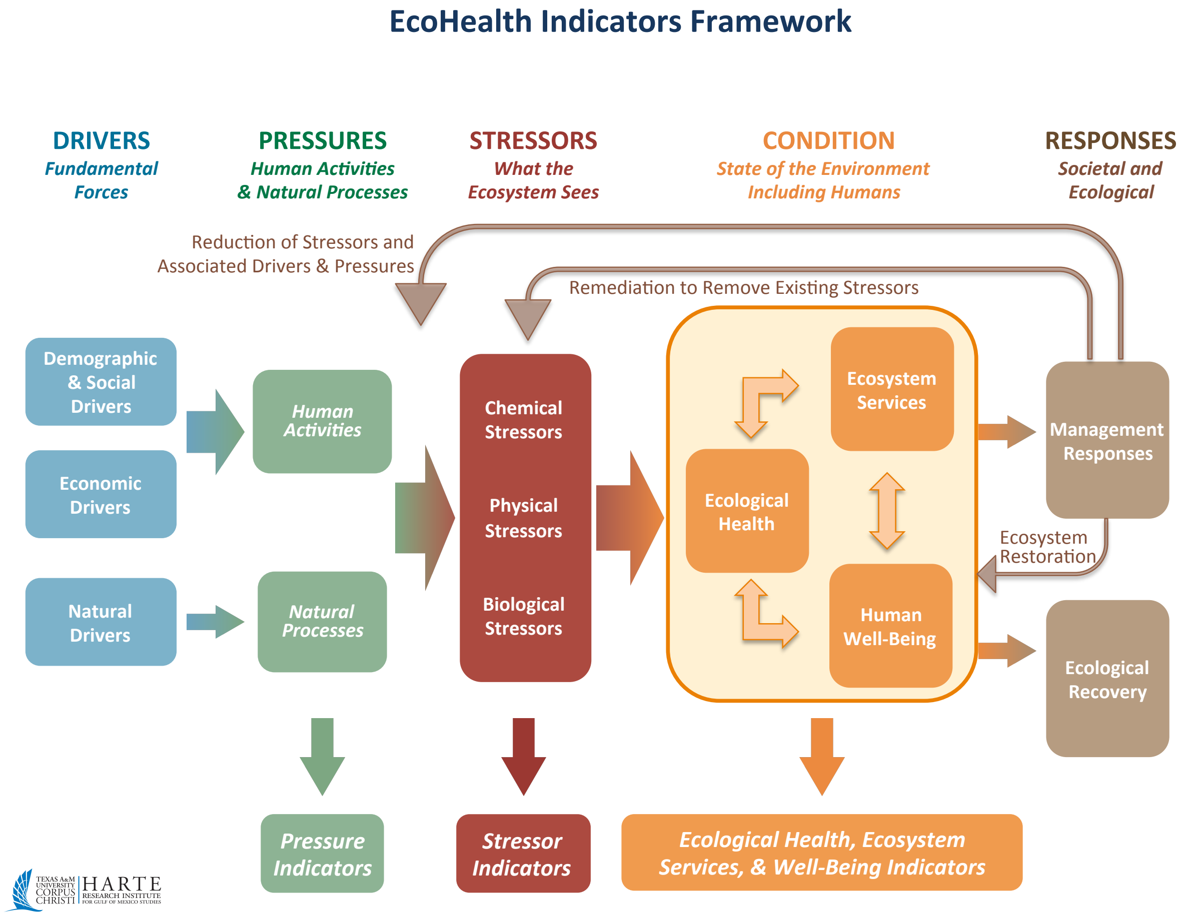
Ecosystem health assessment framework

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), 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; Barrett et al. 1976) and its derivatives, ecological indicators and ecological risk assessment (e.g., Kelly and Harwell 1990; USEPA 1992, 1998; Gentile et al. 1993; Harwell et al. 1999; Dale and Beyeler 2001; Suter 2007; Cormier and Suter 2008; Reiter et al. 2013). 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. The second approach is based on the Drivers-Pressures-State-Impacts-Response (DPSIR) framework (EEA 1999; Weber 2010), which is 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). We have concluded that developing an ecosystem assessment framework for a system 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, i.e., a synthesis of the ecological-risk-based and DPSIR approaches. Details are provided in a companion white paper; following is a brief overview.

The synthesis framework that we have developed (Figure 3) consists of *Drivers*, *Pressures*, *Stressors*, *Condition*, and *Responses* elements. The latter constitute both *societal responses*, i.e., changes in the societal system, and *ecological responses*, i.e., changes in the ecological system, and 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). The acronym for this new framework is DPSCR$_4$.

In this construct, 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. 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, thereby able to inform interested audiences at all levels. Additionally, 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.

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, and we provide a few illustrative examples specific to the Gulf of Mexico (Figure 4).



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, 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; recreation and tourism; and the anthropogenic components 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, 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.

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 or hydrologic alterations; altered sedimentation or salinity regimes; drought; hypoxia. Examples of biological stressors include invasive and exotic species; over-fishing or over-harvesting; pathogens and disease; harmful algal blooms. Stressors may secondarily generate other stressors; e.g., hydrologic alterations can lead to hypoxia, invasive species, and altered regimes of flooding, sedimentation, turbidity, and salinity.

Figure 4. 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***

Ecological Condition is the state of the ecosystem, also considered its "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, under one classification scheme, 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). 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. Both ecological and societal indicators will be explored in more depth below.

Responses constitute regulatory actions and other interventions to reduce stressors or facilitate ecological processes, including *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).

The environment and human well-being

To provide managers with an understanding of how human populations utilize and benefit from coastal ecosystem services in the Gulf of Mexico, we have compiled and assessed existing environmental, social, and economic indicators that best reflect the utilization of ecosystem services by coastal human communities in the Gulf of Mexico, while examining gaps in available data, as well as indicators of human well-being. Our work to date has focused on developing indicators of provisioning, regulating, and cultural services and their linkages to ecological health through supporting ecological services. However, for the current project we will extend beyond this traditional classification of ecosystem services provided by the Millennium Ecosystem Assessment (2005) to explore the more recent generic ecosystem services assessment endpoints (Munns et al. 2015) and particularly the Final Ecosystem Goods and Services classifications (Landers and Nahlik), the latter of which focuses on the service most relevant to a specific beneficiary. Our initial review of the literature provides the following overview.

Over recent decades, the concept of well-being has been operationalized across a wide range of frameworks and dimensions within social, public health, economic, and environmental sectors (McLean 2014). The Organisation for Economic Co-operation and Development (OECD) Social Indicator Programme (Sawyer and Wasserman 1976; OECD 2014), Millennium Ecosystem Assessment (MEA) (MEA 2005), Human Development Index (UNDP 1990), and World Health Organization (WHO) Five Well-Being Index (Bech 2012) have served as the main templates for assessments (King et al. 2014). In most cases, well-being refers to the assessment of the objective and/or subjective status of a human population (White 2010; Coulthard et al. 2011; Dillard et al. 2013; Weeratunge et al. 2014; King et al. 2014). For example, well-being components in MEA (2005) include basic material for a good life, health, good social relations, security, and freedom of choice and action. Objective components refer to the material conditions (infrastructure, assets, or resources) that support life standards and livelihoods, usually captured in national- and state-level statistics (Wellman et al. 2014), incorporating macroeconomic variables like GDP, income, and wealth (UNDP 1990; OECD 2014). Subjective components present additional complexity, e.g., individual valuations, perceptions, and experiences regarding circumstances of life, often captured by profiles and household-level surveys (Camfield and Skevington 2008; Dillard et al. 2013). Examples of indicators of subjective well-being are happiness and satisfaction (Costanza et al. 2007; Day and Okey 2014). Finally, well-being assessments are beginning to incorporate a third relational dimension, encompassing capabilities, personal relationships, and cultural, political, and social identities (White 2010; Coulthard et al. 2011; Britton and Coulthard 2013; Weeratunge et al. 2014). The relational dimension characterizes well-being as not only an outcome, but also a process where people actively shape their interactions with the environment (termed *agency*; Camfield et al. 2009; Brown and Westaway 2011; King et al. 2014).

Recent studies in socio-ecological systems consider the interconnectedness of the biophysical and socio-cultural dimensions of ecosystems (Bowen and Riley 2003; Nobre 2011; Armitage et al. 2012;

King et al. 2014). Within this perspective, well-being is considered a product of the interactions among human, social, built, and natural capital (Smith et al. 2013; Costanza et al. 2014) and is significant to sustainable development (Engelbrecht 2009). However, most analyses of well-being in government, management, and policy contexts predominantly focus on objective rather than relational dimensions. Studies rarely measure the interaction between social and ecological systems or attempt to quantify the degree to which agency or social participation may affect well-being (Brown and Westaway 2011; Le Gentil and Mongruel 2015).

The use of social indicators to characterize well-being is a recent development in coastal and ocean management (Bowen and Riley 2003; Weeratunge et al. 2014; Biedenweg et al. 2014). Since the 1970s, socioeconomic impact assessments of environmental policies have been required by legal mandates, and several federal agencies (e.g., US Forest Service, US Environmental Protection Agency [USEPA], NOAA) subsequently began collecting data and developing socioeconomic monitoring tools (Dobson et al. 2005; Pollnac et al. 2006; Prokopy et al. 2009; Abbott-Jamieson and Clay 2010). Exploration of the sociocultural and subjective domains of resource use has been limited (Sepez et al. 2006), and only a few studies have quantified human well-being or vulnerability among fishing communities (Jepson 2007; Jacob and Jepson 2009). However, in the past five years, well-being variables have been increasingly included in ocean and coastal management because of changes in economic and environmental conditions and an emphasis on the human dimensions of ecosystems (Charles and Wilson 2009; Norman et al. 2012; Kittinger et al. 2012; Breslow et al. 2013; McLean 2014).

Because they provide a link among ecological, social, and economic systems (Böhnke-Henrichs et al. 2013; Hattam et al. 2015), it is crucial to assess the status of ecosystem services. However, at present, there is no consensus in the literature on indicators to be used to quantify ecosystem services. Many different typologies of ecosystem services indicators have been presented, e.g., UNEP WCMC (2009), Staub et al. (2011), Liquete et al. (2013), Brown et al. (2014), Burkhard et al. (2014), Villamagna et al. (2014), and Hattam et al. (2015). Most current ecosystem services indicators are in the categories of provisioning (e.g., fish stocks) and regulating (e.g., loss of carbon storage associated with habitat loss) (UNEP WCMC 2011; Egoh et al. 2012; Hattam et al. 2015), including in the coastal and marine environment (Liquete et al. 2013). Recreation and tourism have the most cultural services indicators (Hattam et al. 2015). Several studies propose to distinguish between supply and delivery indicators (UNEP-WCMC 2009), while also considering specific indicators to measure the contribution to human well-being (Brown et al. 2014); or potential, flow, and demand indicators (Burkhard et al. 2014); or ecosystem services, ecological function, and benefit indicators (Hernandez-Morcillo 2013; Hattam et al. 2015); or capacity, flow, and benefit indicators (Liquete et al. 2013). Benefit indicators are usually used for cultural services such as inspirational, educational, and recreational services and are only weakly linked to ecological functions (Hernández-Morcillo et al. 2013; Liquete et al. 2013; Hattam et al. 2015). Recreation and tourism have the most cultural services indicators (Hattam et al. 2015). Additionally, ecosystem services themselves could be used as indicators for human well-being (Muller and Burkhard 2012).

Many existing ecosystem services indicators are actually ecological indicators reflecting ecological functions or processes (Feld et al. 2009; UNEP WCMC 2011; Hattam et al. 2015); others provide a link between changes in ecological functions and changes in the provision of benefits, thus linking them to human well-being (Böhnke-Henrichs et al. 2013). Some contend that current ecosystem services indicators are inadequate to represent the benefits ecosystems provide, especially for regulating and cultural services (Brown et al. 2014; European Commission 2014). It has been suggested that a suite of essential indicators be used for ecosystem assessment and to understand changes in the provision and uses of ecosystem services (Kelly and Harwell 1990; Dale and Beyeler 2001; UNEP WCMC 2011; Brown et al. 2014). These indicators should represent changes in functions, services, and benefits or realized uses; only in this way can changes in well-being be traced back to ecological changes (Kelly and Harwell 1990; Gentile and Slimak 1990; Johns et al. 2014; Hattam et al. 2015). However, the challenge is not only identifying and selecting appropriate ecosystem services indicators, but also making sure that they are included in monitoring and reporting systems (Brown et al. 2014).

While keeping in mind the validity of each of these indicators and approaches, for this project we expand beyond just using the classification provided by the MEA (2005), which considers four categories of ecosystem services, and explore the utility of two more recent approaches developed by the USEPA, the generic ecosystem services assessment endpoints (Munns et al. 2015) and the Final Goods and Services methodology (Landers and Nahlik 2013). In particular, considering the final goods and services provided by the ecosystem will enable us to create clearer links between ecological health and human well-being.

Indicators for assessing ecological health, ecosystem services, and human well-being

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, and 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. Recent literature has focused on methods to derive more synthetic indicators through appropriate aggregation of data into indices and composite indicators (Pollesch and Dale 2015). 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 ecological indicators will logically emerge from the $DPSCR_4$ framework imbedded within the integrated assessment/decision framework discussed below.

Our approach to identifying appropriate indicators is to align them to the pressures, stressors, and ecological endpoints including ecosystem services, i.e., selecting indicators to characterize the causal factors and ecological effects from natural processes and human interactions with the environment (Kelly and Harwell 1989, 1990; Gentile and Slimak 1990). For pressures and associated stressors, the indicators are often direct measurements of the agent itself, or its trends over time, such as water turbidity, concentrations of toxic chemicals in effluents, or extent of habitat alteration. For the ecological endpoints, indicators vary considerably by the nature of the endpoint and its position in ecological hierarchy. In some cases, the indicator is the endpoint itself (e.g., an endangered species), but in others, surrogate measures or metrics are more appropriate, i.e., the indicator(s) characterizes the condition of the ecological endpoint. Table 1 illustrates some of the types of ecological endpoints that may reflect ecological effects.

Kelly and Harwell (1989, 1990) listed categories of ecological indicators (Table 2) and noted the importance of matching the type of indicator used to the purpose intended. For example, an *early-warning indicator* is one that should alert the potential for effects before they become fully manifested; as such, it is important to raise a flag, even if it turns out to be a false signal (an example might be a biochemical marker that indicates a chemical stress without specifying the nature of the particular chemical). By contrast, a *diagnostic indicator* may require more time or expense to measure, but it should particularly avoid false positives as it is meant to be a reliable indicator showing that if effects are occurring, they are caused by a specific stressor.

Table 1. Types of Ecological Endpoints across Hierarchical Scales (from Kelly and Harwell 1989)

Human Health
• *vector for exposure to humans*
 	
Species-Level Endpoints
• *direct interest* – economic, aesthetic, recreational, nuisance, endangered species
• *indirect interest*
  o bi-species effects (e.g., predation, competition, pollination)
  o habitat role of species
• *ecological role*
  o trophic relationship (e.g., primary producers)
  o functional relationship (e.g., habitat engineers)
  o representative of guild
  o critical or keystone species
	Community-Level Endpoints
	• *food-web structure*
	• *species diversity*
	• *biotic diversity*
	• *community composition*
	
	Ecosystem-Level Endpoints
	• *ecologically important process (ecosystem services)*
	• *economically important process (ecosystem services)*
	• *water quality*
	• *habitat quality*
	
	Landscape-Level Endpoints
	• *habitat mosaic*

Table 2. Purposes of Ecological Indicators and Criteria for Selecting Them
(modified from Kelly and Harwell 1989)

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*

Major problems may ensue if an early-warning indicator is applied as if it is diagnostic of a particular stressor (e.g., see Harwell and Gentile 2014 for misuse of the biomarker CYP1A, a non-specific indicator of exposure to toxic chemicals, in assessing ecological recovery following an oil spill). On the other hand, using only diagnostic indicators may result in an effect being fully realized before any remedial action can be implemented. Consequently, Kelly and Harwell (1990), Cairns (1993), Dale and Beyeler (2001), Niemi and McDonald (2004), among others, have called for an appropriate suite of indicators to be used. We propose here that such an approach is imperative for assessing the health and sustainability of ecosystems with the complexity of the coastal Gulf of Mexico. We suggest that the new integrated assessment and decision framework to emerge from the proposed research project will specifically address that need by identifying the appropriate mix of indicators necessary to reflect the sets of pressures and stressors impinging on Gulf coastal ecosystems, to characterize the ecological conditions that result, including effects on ecosystem services, and to assess the efficacy of resource management alternatives.

Environmental Decision Frameworks

The complex and interconnected nature of coastal and marine ecosystems creates unique challenges to integrating multiple categories of indicators into the decision process; example issues include attributing impacts to a particular human activity or stressor, determining how changes in ecosystem structure and function translate to a loss of ecosystem services, and understanding how effects on ecosystem services in turn may impact social well-being (Burkhard et al. 2013). Consequently, effective environmental management requires a holistic approach that integrates ecosystem and societal-based assessment and decision strategies (Levin et al. 2008). This holistic approach should allow the resource manager to identify not only the important risks to the environment but also how those risks will affect the services the ecosystem provides that ultimately influence societal well-being. Environmental management often involves managing tradeoffs for deciding the best alternative course of action for mitigating risks and for restoring health and sustainability. Such risks may involve the structure and function of the ecosystem as a whole (such as at the landscape level) or specific ecological components (e.g., specific habitats or populations), and may derive from natural processes and/or human activities (Elmqvist et al. 2011). Employing a formal decision-support process is a powerful strategy for framing and addressing management questions because it allows the problem to be deconstructed and examined using a variety of analysis methods and models (Raiffa 1968; Clemen 1996). In addition, decision-support frameworks help manage complexity and uncertainty while making use of as much available information as possible (Clemen 1996; Hammond et al. 1999). A key issue is evaluating how each category of indicators can inform the decision process.

Most approaches to decision analysis we have reviewed in the literature include these four elements: 1) identifying and describing the problem and objectives; 2) identifying one or more alternative actions from which to choose; 3) analyzing expected consequences and trade-offs associated with each potential action relative to the objectives; and 4) once a decision is made, instituting appropriate monitoring to determine efficacy in attaining project goals (Lyons et al. 2008; Daily et al. 2009; Yoskowitz et al. 2013). We suggest the multi-step approach to identify the distinct roles for resource managers and scientists; allow stakeholders to articulate their goals and objectives and their relative importance; engage scientists to make predictions about the consequences of various actions; and assign management, scientist, and stakeholder groups appropriate roles in identifying potential actions that are both feasible and acceptable (Lyons et al. 2008). Upon existing decision frameworks as a point-of-departure, we will derive an approach that we will test in our pilot study on a management problem at the Mission-Aransas National Estuarine Research Reserve (Figure 4).

While assessment and decision frameworks are essential to environmental management and decision-making, challenges remain in implementation, especially integrating and linking multiple categories of indicators and determining how to place value on the services (Costanza et al. 1997; de Groot et al. 2010). Daily (2000) was the first to introduce an ecosystem services framework that explicitly integrated biophysical and social dimensions to environmental protection. As discussed previously, the United Nations' Millennium Ecosystem Assessment Report (MEA 2005) classified ecosystem services into four categories: provisioning, regulating, cultural, and supporting, and illustrated how these classes of ecosystem services are linked to natural and societal activities and to human well-being. This ecosystem services framework highlights the long-term role that healthy ecosystems play in the sustainable provision of human well-being, and economic development across the globe (Turner and Daily 2008). More recently, the USEPA (Landers and Nahlik 2013) proposed the FEGS approach in which ecosystem services are defined as “components of nature, directly enjoyed, consumed or used to yield human well-being” (Boyd and Banzhaf 2007). This approach reduces ambiguity and double-counting, facilitates creating links to human well-being, and attributes services to specific beneficiaries (Landers and Nahlik 2013).

Figure 4. Proposed Integrated Assessment & Decision Framework

Recent studies have advanced our understanding of the interdependency of ecosystems, their services, and well-being at a conceptual level, as detailed in the previous sections. Nevertheless, a series of challenges remain for structurally integrating these concepts into actual decision-making (Daily et al. 2009; de Groot et al. 2010; Yoskowitz and Russell 2015). An analysis of the role of spatial scales of ecosystem services (Hein et al. 2006) shows that stakeholders can have very different interests in ecosystem services at different spatial scales. Thus it is important to consider the scales of ecosystem services when formulating or implementing ecosystem management plans. For example, at the landscape level, the main challenge is often how to decide on the optimal allocation and management of the many different land-use options (Madden and Morehead 2011). Landscape functions (and services) have become an important concept in policy-making, as decision-makers have to deal with demand for landscape services from a broad range of stakeholders (de Groot et al. 2010). Assessing the trade-offs inherent in managing humans embedded in ecological systems is a key component of decision-support analyses. This requires an understanding of the nature of changes in ecosystem services that result from human activities and natural stressors, and the impact of these changes on human welfare.

Testing Assessment/Decision Framework and Indicators: Mission-Aransas NERR Pilot Project

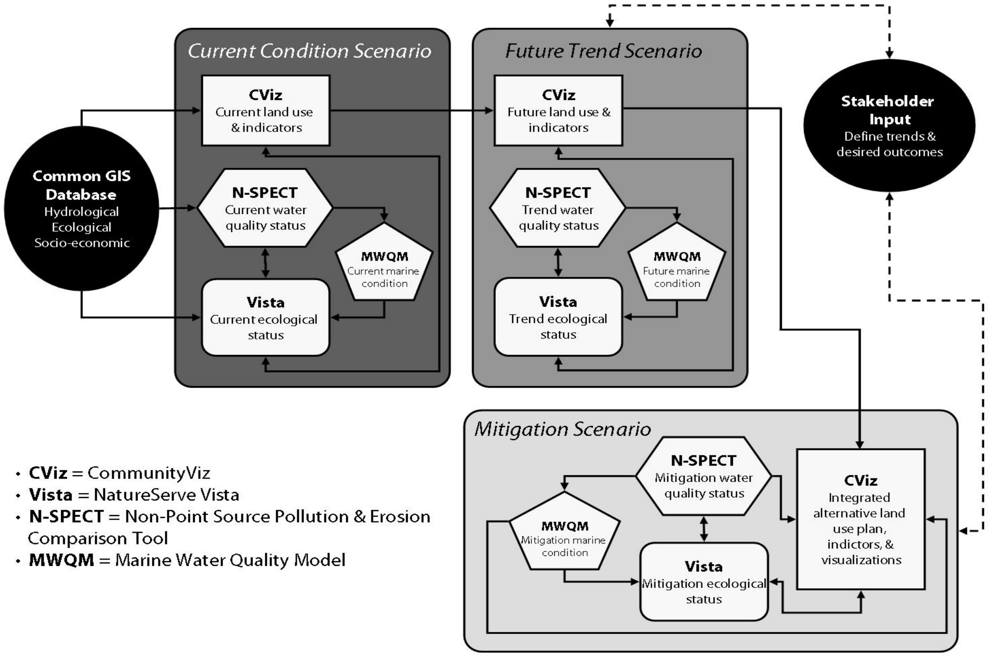
As noted previously, our objective is to finalize and test the integrated assessment/decision framework and associated indicators in a real-world environmental management application. This process will entail convening a workshop and a series of web-based conferences involving both natural and social scientists and resource managers to review, refine, and finalize the assessment/decision framework, and to identify associated ecological and ecosystem services indicators. We have previously developed ecological indicators and conceptual ecosystem models (CEMs) for each of the Gulf coast NERRs, including the Mission-Aransas Reserve, using the ecological risk-based construct, identifying for each habitat type, the relevant drivers, stressors, and VECs. At the workshop, we will revisit these CEMs with particular attention to expanding the societally relevant ecological endpoints to incorporate a more comprehensive set of VECs linked to ecosystem services and human well-being. We will utilize the USEPA relational browser for ecosystem services (available at http://www2.epa.gov/eco-research/ecosystems-services) as well as the USEPA tool for Final Ecosystem Goods and Services (https://gispub4.epa.gov/FEGS/) to assist workshop participants in considering a comprehensive set of relevant components. Drawing upon the expertise of participants with resource management experience, we will evaluate and modify as needed the proposed decision process (Figure 4). Finally, we will engage the workshop participants in expanding the CEM approach into the more comprehensive $DPSCR_4$ framework, with attention to how each of our ecosystem health, ecosystem services, and well-being indicators could inform the decision process. As a part of that process, we will re-examine the sets of VECs previously characterized for the Reserve, with emphasis on identifying additional endpoints for ecosystem services and human well-being, as discussed previously, and using the USEPA ecosystem services tools to assist this process. Similarly, we will follow the indicators selection criteria and guidance, discussed previously, to identify specific candidate indicators of pressures, stressors, ecological health, ecosystem services, and human well-being that can be used in the pilot study.

The purpose of the Mission-Aransas Reserve case study is to examine the assessment/decision framework in a proof-of-concept pilot study focused on specific management issues of the Reserve, with intensive involvement of scientists and managers from the Reserve. In the pilot study, we will fully adapt the conceptual framework to the selected management issues; characterize the critical linkages between the ecological and societal systems; specify key indicators for assessing ecological health and ecosystem services and their linkages to well-being; identify management alternatives for assessment; apply geospatial ecosystem-based management tools to perform a scenario-consequence analysis of each management option in terms of ecological health, ecosystem services, and human well-being indicators; identify gaps in data and assessment tools needed for the key indicators; and consider how the ongoing environmental monitoring programs at NERRs might be expanded to include relevant ecosystem services and socioeconomic data.

At the workshop, we will begin the process of converting the selected Mission-Aransas Reserve management issues into specific scenarios for consequence analyses, a process that is expected to continue through a series of post-workshop web-based teleconferences with selected participants until sufficient scenario specificity is attained for the analyses.

The Mission-Aransas Reserve pilot study will unfold over the year or so following the initial workshop, involving scenario refinement, data acquisition, scenario-consequence analyses, and other activities coordinated using a series of web-based conferences. We anticipate using a suite of spatially explicit ecosystem-based management tools to evaluate specific scenarios, chosen as appropriate for the set of management issues selected; examples of such tools include NatureServe Vista, Open Nonpoint-Source Pollution and Erosion Comparison Tool (N-SPECT), CommunityViz, and Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST; Sharp et al. 2014). These tools allow users to map and evaluate changes in indicators of ecosystem health and ecosystem services in response to the changes in stressors from each of the selected scenarios. The exact combination of tools to be used will be determined following the selection and refinement of management scenarios and indicators. These geospatial tools mentioned above are all extensions to ESRI ArcGIS software and thus are able to interoperate with one another by utilizing the same software platform. Previous studies have shown the ability to interoperate these tools to evaluate indicators associated with multiple land-use scenarios in the Mission-Aransas Reserve watershed (Crist et al. 2009; Madden and Morehead 2011) (Figure 5). A common geospatial database will be developed to create and evaluate scenarios.

Figure 5. Integrated Ecosystem-Based Management Tools
(from Madden and Morehead 2011)



Although the exact information needed will depend on the decisions made at the Mission-Aransas Reserve pilot project workshop, we anticipate it may include land-use policy (e.g., zoning regulations), development trends (e.g., new residential developments), conservation elements (e.g., species of concern, cultural features), conservation goals (e.g., 95% of seagrass beds), and habitat/species viability requirements (e.g., water clarity requirements in seagrass beds). Ecological indicators will be related to habitat type, species habitat requirements, and water quality. Similarly, anticipated human well-being indicators include public health, cultural heritage and identity, tourism, and viewshed aesthetic quality.

Upon completion of the pilot proof-of-concept study at Mission-Aransas Reserve, we will prepare a summary document describing the assessment/decision framework, the issues examined in the pilot study, the scenarios and consequence analyses, and the results and lessons learned from the exercise. In subsequent and parallel activities associated with the EcoHealth Metrics initiative of the

Harte Research Institute, we intend to expand assessments to other NERRs of the northern Gulf; continue the Texas Pilot Project, an ongoing proof-of-concept effort for EcoHealth Metrics; partition the overall Gulf into regional systems and develop similar metrics for each region, including expansion into Mexico and Cuba; develop integrative metrics across the Gulf and its ecosystems; and explore and develop communications tools to present the EcoHealth Metrics to the diversity of targeted audiences concerned with the sustainability of a healthy and productive Gulf of Mexico.

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