

Chapter 1. Project Overview

Introduction

To achieve the goal of sustaining healthy, diverse, and resilient coastal and marine habitats and living marine resources (LMRs) in the Northern Gulf of Mexico (NGoM), resource managers need a way to take the pulse of this vast ecosystem to evaluate its health and its ability to provide needed ecosystem services. Managers need good indicators that track the condition of ecosystems and are sufficiently sensitive to stressors and their effects on LMRs, such that changes in these indicators inform management strategies. Finding the right metrics that indicate ecosystem condition and that support the delivery and management of sustainable ecosystem services and LMRs requires an understanding of how Gulf ecosystems function and how drivers and stressors impact their condition and services.

A comprehensive set of consistently and broadly monitored indicators that inform these needs is not available for the NGoM. Although current inventory and monitoring programs use indicators that provide status and trend information for a variety of biological and socio-economic resources, most are focused on specific geographies defined by institutional or agency mandates that address the needs of their jurisdiction. As a result, the output of these monitoring programs is at best uneven across the range of ecosystems, hindering our ability to support sustainable ecosystem and LMR management. Thus, despite large investments in time and money, the effectiveness of these programs in addressing critical management questions across necessary spatial and ecological scales is unclear. A coordinated effort and structured framework is needed to review and improve the scope and outputs of existing monitoring programs, so they can be maximally effective in providing the information needed to efficiently support sustainable ecosystems and LMRs.

Often, the identification of indicators has been limited to either indicators of the ecological condition or integrity of an ecosystem (such as indicators for species diversity or water quality), or indicators of the services that an ecosystem provides (such as fishing, tourism, or energy production). But this limits our understanding of the interaction between natural processes and human uses. There is now strong recognition that an inventory and review of indicators should use a framework that includes both the condition of key ecosystem types in the NGoM and the variety of ecosystem services that they provide (National Research Council, 2014). Such an approach can be achieved using a framework grounded in the concept of ecological resilience. Classically, *resilience* has been defined as a “measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables” (Holling, 1973). As defined, this concept largely corresponds to ecological integrity; that is, an assessment of the degree to which, under current conditions, the structure, composition, function, and connectivity of an ecosystem corresponds to reference conditions and is within the bounds of natural or historic disturbance regimes (Parrish et al., 2003; Faber-Langendoen et al., 2016). But the concept of resilience can be expanded to include both human and natural processes and disturbances within what are termed “social-ecological systems;” namely, linked systems of people and nature (Berkes and Folke, 1998; Lloyd et al., 2013). Ecological resilience is thus a measure of the persistence of systems and their ability to maintain ecological integrity and provide ecosystem services while absorbing changes and disturbances. Here, we apply an innovative Ecological Resilience Framework (ERF) that integrates information on ecosystem drivers,

structure and function and ecosystem service provision to make recommendations for a set of ecosystem indicators that should be monitored to assess ecosystem resilience.

The Ecological Resilience Framework (Figure 1.1) emphasizes the two major dynamic components of ecological resilience—ecological integrity and ecosystem services (Berkes and Folke, 1998; Lloyd et al., 2013). The Framework consists of:

- **Conceptual Ecological Models (CEMs)** that identify the critical ecosystem drivers and functions and specify the linkages between them that ultimately effect ecosystem services.
- **Indicators with specific metrics** determined within the context of the CEMs that can be monitored at the site level to assess the ecological integrity of the ecosystem and its capacity to provide ecosystem services.
- **Metric ratings with quantifiable assessment points** that allow evaluation of ecological condition and capacity for provision of ecosystem services across sites and over time.

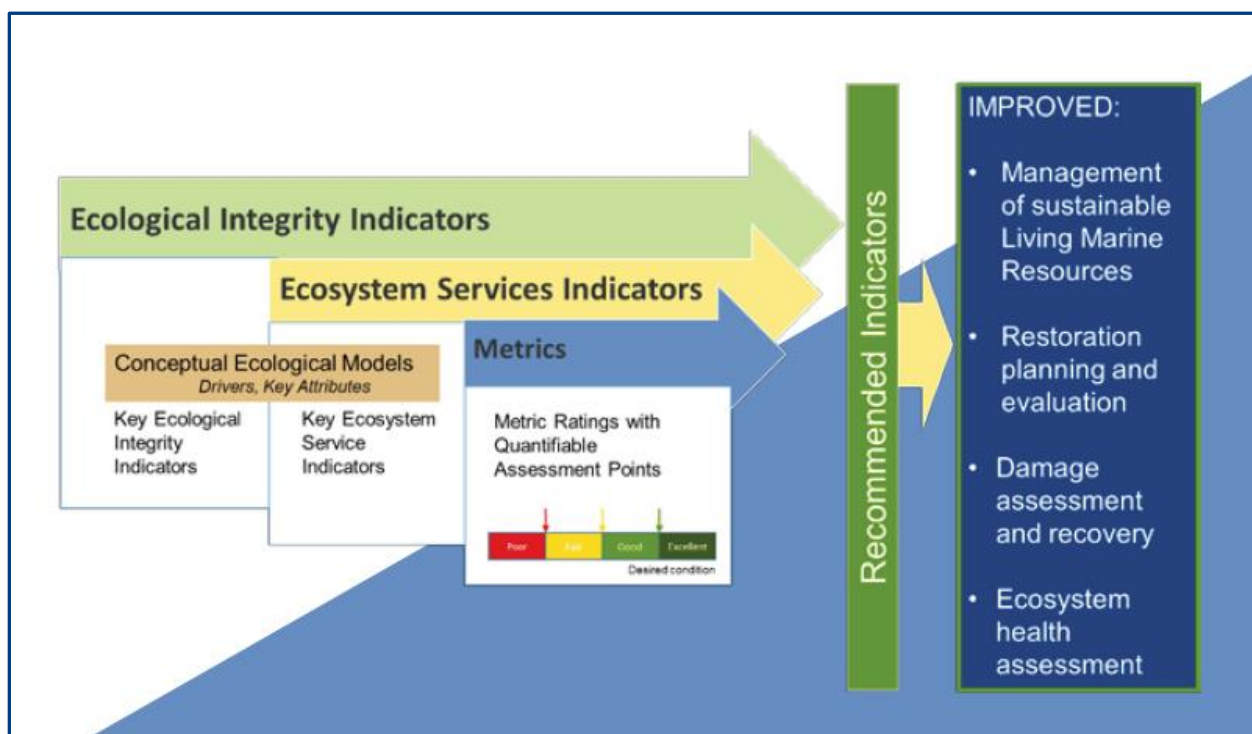


Figure 1.2. Ecological Resilience Framework. The framework incorporates both ecological and ecosystem services indicators that guide managers in their assessment of the ecological resilience of Living Marine Resources.

The primary objective of this project was to develop and apply the ERF in order to recommend a set of scientifically rigorous indicators that are practical to monitor for the five major ecosystem types in the NGOM. A second objective was to complete programmatic and spatial analyses to assess the degree to which the recommended indicators are currently being monitored by existing programs in the NGOM to identify gaps in monitoring and opportunities for additional data collection.

Ideally monitoring of these indicators will deliver essential information to managers that will result in healthier, more diverse, more resilient and sustainable ecosystems and LMRs in the NGoM. We expect that this work will support the following management needs:

Management of sustainable ecosystems and LMRs: Having indicators that track the linkage between drivers/stressors, ecosystem condition, and the ecosystem services they provide will help managers decide which management activities will likely have the most impact towards meeting their management goals.

Damage Assessment and Recovery Planning: Once programs are in place to monitor the key indicators, this information will support the establishment of baseline ecosystem condition and ecosystem service status information and will provide the information needed to detect impacts of major disturbance events. The CEMs and metric ratings can help managers develop ecologically appropriate recovery plans.

Restoration Planning and Evaluation: Ecosystem integrity indicators can be used to assess the overall success of restoration efforts and they provide a means for tracking the progress made in restoring an ecosystem back to desired levels of ecological integrity and ecosystem services. Having NGoM-wide indicator information on each ecosystem will also support the effective allocation of funds for restoration where the conditions warrant the greatest need.

Ecosystem Health Assessments: The ERF is a necessary precursor to the development of reporting briefs and scorecards for both local and Gulf-wide ecosystem health. After programs are in place that monitor the key indicators of each ecosystem throughout the NGoM, we will have a means of assessing the overall health of the NGoM.

[Project Area](#)

The area for this study covers the Northern Gulf of Mexico (NGoM) including the coastal and nearshore areas of Texas, Louisiana, Mississippi, Alabama and Florida (Figure 1.2). The project area extent boundary was derived from the NOAA Coastal Assessment Framework (CAF) GIS dataset. The CAF provides a consistently derived, watershed-based digital spatial framework for managers and analysts to organize and present information on the nation's coastal, near-ocean, and Great Lakes' resources. The landward extent follows the watersheds that drain directly into an estuarine or marine water body. The drainage areas are based on the USGS Watershed Boundary Dataset, Hydrologic Unit 8 (HUC8) level boundaries. The seaward extent was derived from the NOAA 200 m contour in the NGoM. This polygon encompasses the full project area of analysis of ecosystem distribution and for monitoring programs in the NGoM.



Figure 1.3. Project area extent along the Northern Gulf of Mexico

Ecosystem Types

We used the ERF to develop indicators for five NGoM ecosystems: salt marsh, mangrove, seagrass, oyster beds/reefs, and coral reefs/coral colonized substrates. We followed the Coastal and Marine Ecological Classification Standard (CMECS; FGDC, 2012) for each ecosystem definition as noted below. We also note the related units in the US National Vegetation Classification (USNVC, 2016) where applicable.

Salt Marsh Ecosystems

Salt marshes are coastal wetland ecosystems within the intertidal zone, characterized by hypoxic, saline soil conditions and low biodiversity. The NGoM region contains roughly 60% (2,211,674 acres in 2009) of salt marsh in the contiguous United States, partly due to the presence of the large river deltas (Dahl, 2013). While there are several types of salt marshes in the NGoM, ranging from low to high salt marshes, salt flats and brackish marsh (Tiner, 2013), the smooth cordgrass (*Spartina alterniflora*) low salt marsh is the most extensive and is the focus of this description. This type is classified under the “Low and Intermediate Salt Marsh Biotic Group” in CMECS (FGDC, 2012), and as “Atlantic & Gulf Coastal Low Salt Marsh (G122), especially Gulf Coast Cordgrass Salt Marsh (CEGL004190),” in the USNVC (2016).

Mangrove Ecosystems

Mangrove ecosystems are coastal wetland ecosystems dominated by mangrove species that are typically found in the intertidal zone, characterized by frequently flooded saline soil conditions. The majority of the approximately 500,000 acres of mangrove ecosystem in the United States occurs in the NGoM, and almost all of that is in Florida, with over 90 percent in the four southern counties of Lee, Collier, Miami-Dade, and Monroe. Scattered stands and individuals occur north and westward into

Louisiana and Texas (Osland et al., 2016). The three common mangrove species are: black mangrove (*Avicennia germinans*), white mangrove (*Laguncularia racemosa*), and red mangrove (*Rhizophora mangle*). The mangrove system described in this project includes Tidal Mangrove Shrubland and Tidal Mangrove Forest as classified in CMECS (FGDC, 2012). It is classified as Caribbean Fringe Mangrove (G004) in the USNVC (2016), with a variety of distinct associations, based on species dominance and ecological setting.

Seagrass Bed Ecosystems

Seagrasses are marine angiosperms, typically with long strap-like leaves, found in many shallow coastal and oceanic waters around the world. These plants are found in intertidal or subtidal zones, down to depths of about 50 m. They are widely dispersed, extending from the tropics to the Arctic Circle. Despite their large geographic extent, seagrass beds have low species biodiversity. Globally, there are approximately 60 seagrass species, six of which occur in the NGoM. The three most prevalent species, *Thalassia testudinum*, *Syringodium filiforme*, and *Halodule wrightii* can form monospecific stands or mixed assemblages. The areal extent of seagrass beds in the NGoM comprises nearly half of total seagrass coverage in the United States of America. This ecosystem is classified as “Seagrass Bed Biotic Group” in CMECS (FGDC, 2012).

Oyster Ecosystems

Oyster reefs are intertidal or subtidal biogenic structures formed by living oysters that provide habitat with significant structural complexity (Galtstoft, 1964; Chestnut, 1974). Eastern oysters, *Crassostrea virginica*, are natural components of estuaries along the NGoM and mostly tend towards forming reefs. For this project we include “Oyster Reef Biotic Group,” “Oyster Beds,” and “Attached Oysters Biotic Group” as defined by CMECS (2012). An oyster reef system is an area of ecologically connected reefs or beds and oyster shell dominated bottom, and may include small areas of bare mud, sand or shelly substrates that offer benefits to neighboring submerged aquatic vegetation, marsh grass and mangrove habitats. While reefs are normally an integral part of such diverse landscapes (Puckett and Eggleston, 2012), oysters also occur as beds—areas of oyster shell bottom with low densities of live oysters (1–10 m⁻²). Oyster ecosystems occur in all states in the NGoM.

Coral Ecosystems

Coral reefs are composed of large, limestone-building, colonial organisms in the phylum *Cnidaria*. In the NGoM, corals are mostly found in shallow waters within the photic zone, though some deepwater varieties exist. For this project we include the Shallow/Mesophotic Reef Biota Subclass and the Attached Corals Biotic Group as defined by CMECS (FGDC, 2012). Temperature limitations constrain corals to 30 degrees north and south of the equator. Typical tropical reef systems, with high topographic complexity, accretion, and diversity are rare in the NGoM. The NGoM is more temperate and corals are at the northern limit of their range. Because abiotic aspects limit growth of coral communities in the NGoM, the coral ecosystems on hardbottom are often composed of a mixture of scleractinian corals, sponges, octocorals, and hydrozoan corals and may or may not exhibit reef structure.

Methods

Development of an Ecological Resilience Framework

Process Overview

We developed indicators of ecological resilience for the five major ecosystems, using the Ecological Resilience Framework outlined above. Our project team was organized into eight working groups (see Appendix I for working group members):

Methodology Development and Application Working Group – This working group was responsible for development, refinement and consistent application of the methodology. They provided oversight and were engaged with all other working groups to ensure consistency and quality across the final products. The methodologies used by the various working groups are described in the next section.

Ecosystem Specialist Working Groups – These five working groups (one group for each ecosystem) were responsible for Conceptual Ecological Models (CEM), Indicator, and Metric Rating development, and ecosystem narrative writing.

Ecosystem Service Working Group – This working group was responsible for providing ecosystem service indicator and metric rating development for all five ecosystems, and integrating them into the CEM.

Monitoring Program Inventory and Analysis Working Group – This working group conducted the monitoring program inventory, programmatic and spatial analyses, and published inventory results.

As a first step, each ecosystem specialist working group created a draft CEM and list of potential ecological integrity indicators, then worked with the ecosystem services working group to expand the CEM to include ecosystem services indicators. They invited ecosystem experts to form a panel of 4–7 individuals to support and evaluate their work (see Appendix II for the list of expert panel participants). The expert panels were convened in two workshops to refine the CEMs and the list of indicators for the ERF and to help identify specific metrics and metric ratings for each indicator. The first workshop focused on one ecosystem—salt marsh—which allowed us to test and refine the methodology and products. During the second workshop we applied the refined methodology to the remaining four ecosystems. During each workshop, participants reviewed and refined the CEM and reorganized the draft indicator list as needed. Using a consistent set of evaluation criteria, they then assessed each existing indicator according to its utility for demonstrating the ecological integrity of the ecosystem and informing the ecosystem services and management of associated LMRs. They also considered practicality and cost effectiveness of monitoring each indicator. After the final set of indicators and metrics were identified, the ecosystem working groups revised the CEMs and list of indicators and metrics. They also completed metric rating tables with assessment points for each metric, based on supporting literature and their expert judgment.

For each ecosystem, the ecosystem working group produced 1) a CEM, with 2) a recommended set of ecological integrity and ecosystem service indicators and metrics, and 3) metric ratings. For each ecosystem we provided a narrative that describes the major ecosystem components and the linkage between them. Details on the development of each of these components of the ERF are provided in the following sections.

Conceptual Ecological Models

Conceptual Ecological Models (CEMs) are widely used to describe ecosystem structure, function and dynamics and to help identify indicators that track the system's response to disturbances (Mitchell et al., 2014). CEMs are an effective tool for developing consensus regarding a set of working hypotheses that explain ecosystem processes. They can also be used to specify linkages between ecosystem condition and LMR management needs to support communication between science and management (Tierney et al., 2009; Mitchell et al., 2014). We developed CEMs for the five major ecosystems based on existing literature, previously developed models, and expert opinion to identify the most critical drivers and key ecosystem functions and services. Our CEMs are narrative-based, non-quantitative models, including both descriptive text and a diagram that highlight the major anthropogenic and natural drivers, key ecological factors and ecosystem service attributes. Figure 1.3 provides the general framework we used for each CEM. The terminology for the CEMs is provided in Box A. In each CEM narrative, we described the most direct or strongest linkages between the ecosystem components, including those between ecosystem processes and structure and the largely external environmental drivers, such as climate, hydrogeomorphology, and anthropogenic influences (both positive and negative).

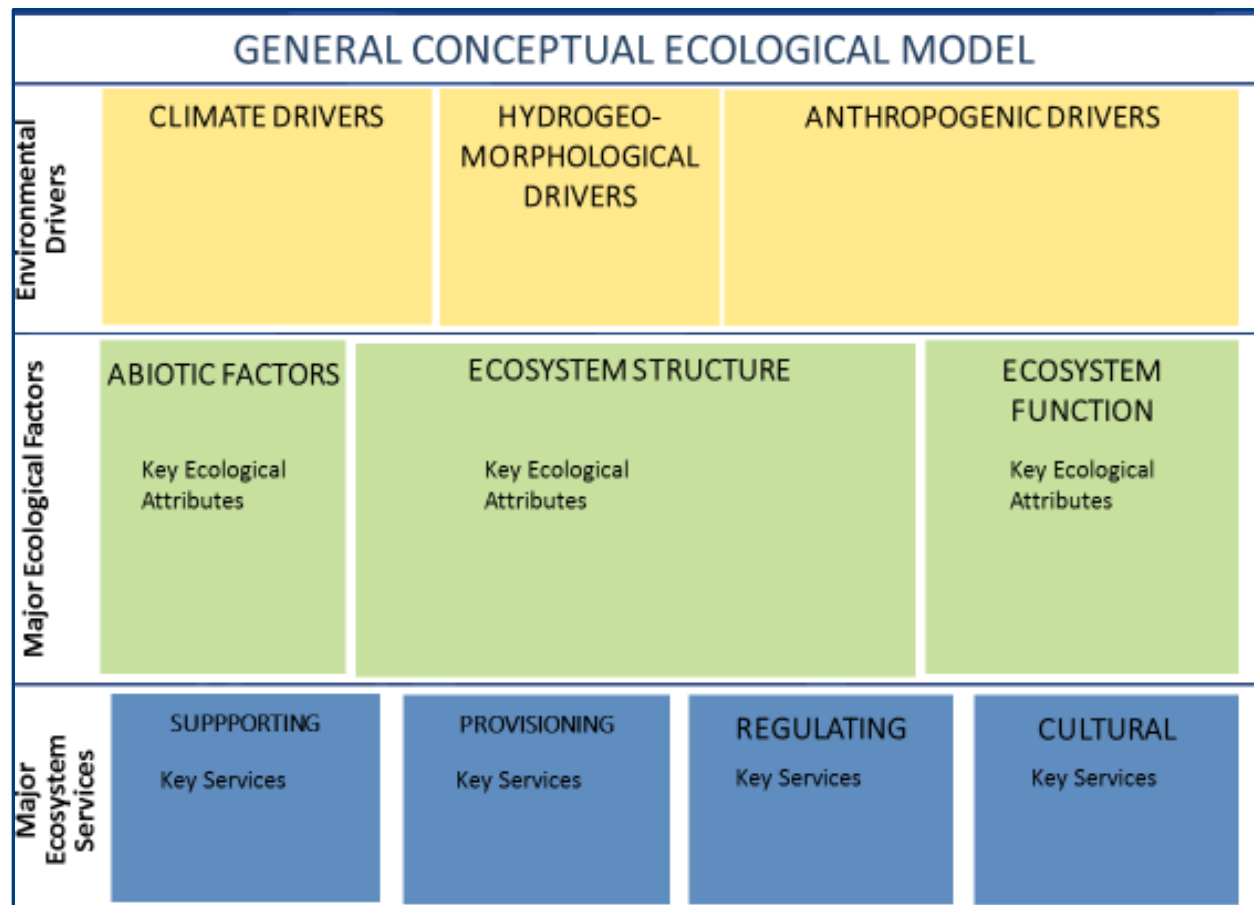


Figure 1.4. The CEM includes the primary drivers (yellow boxes), major ecological factors and key ecological attributes (green boxes), and major ecosystem services and key ecosystem services (blue boxes).

BOX A. Terminology for Conceptual Ecological Models

Environmental Drivers are major external driving forces such as climate, hydrology, and anthropogenic activities that have large-scale influences on natural ecosystems.

Major Ecological Factors (MEF) and **Major Ecosystem Services (MES)** broadly describe the ecological characteristics of the ecosystem.

Major Ecological Factors:

Abiotic Factors: includes physical and chemical attributes that are characteristic of the system.

Ecosystem Structure: includes biological structure, and landscape structure attributes.

Ecosystem Function: includes ecosystem processes of the system, such as productivity and decomposition.

Major Ecosystem Services: We used the categories developed by the Millennium Ecosystem Assessment (MEA 2005) to describe major ecosystem services.

Supporting: includes benefits to the ecosystem itself; i.e., plants, animals and their habitats, that are needed for the system to persist and that are the foundation for other ecosystem services. Supporting services indicators partly overlap with ecological integrity indicators.

Provisioning: includes goods and services provided directly by the system which benefit people and include food, water and other resources, such as genetic materials and medicinal sources.

Regulating: includes benefits received from natural regulation of ecological factors, such as water quality and flood and disease control.

Cultural: are the benefits that provide cultural experiences, and contribute to human mental, physical, and spiritual well-being, such as recreation.

Key Ecological Attributes (KEAs) and **Key Ecological Services (KESs)** of an ecosystem are subsets of major ecological factors or services that are critical to a particular aspect of the ecosystem's response to both natural ecological processes and anthropogenic disturbances and the services it provides. Alterations to KEAs can lead to the degradation or loss of that ecosystem and its services. KEAs and KESs are helpful for detailed models of specific ecosystem types. For example, salt marsh KEAs within the Ecosystem Function MEF include biogeochemical cycling, secondary production, primary production, decomposition, and elevation change. Typical KESs include nursery/habitat, nutrient reduction, disturbance regulation (e.g., protection of coastline and built infrastructure), water quality, and recreational fisheries.

Indicators and Metrics

Indicators are a select subset of measurable ecosystem features or processes whose values are indicative of the integrity or services of the larger ecological system to which they belong. We used the CEMs for each of the five ecosystems to identify the key indicators that describe the condition of an ecosystem and its ability to deliver ecosystem services. We use the terms “ecological integrity indicators” and “ecological condition indicators” interchangeably to specify indicators that track Key Ecological Attributes. We use the term “ecosystem service indicators” to specify indicators that track Key Ecological Services.

We adopted the Ecological Integrity Assessment methods developed by NatureServe and partners (Unnasch et al., 2009; Mitchell et al., 2014; Faber-Langendoen et al., 2016a,b) as the basis for selecting ecosystem integrity indicators. Through the workshop process described above, we evaluated each indicator according to the criteria identified in Table 1.1. Those that met the most criteria were included in our final list. Because any given indicator may vary in its ability to serve as a warning sign, we identified multiple indicators for each ecosystem. By using multiple lines of evidence from multiple indicators, managers can be more confident in the kind of management actions needed. The result was a set of ecologically relevant, practical indicators of ecological resilience. An example of the CEM and selected indicators is provided in Figure 1.4.

Table 1.6. Indicator Evaluation Criteria

Evaluation Criteria	Definition
Informative of ecological condition	Documented (scientifically) relationship to ecological integrity – i.e. the structure, composition, function and connectivity of an ecosystem.
Detects long term trends	High signal: noise ratio (sensitive to detecting long-term trends and insensitive to short-term variability, such as differences associated with short-term weather patterns and time since disturbance).
Repeatable	Can be measured with a methodology that provides consistent results by different observers. Low susceptibility to bias. Relatively easy to standardize measurement or observation of indicator across observers.
Precision suitable for analyses that support management applications	Can be quantified with selected sampling design with sufficient level of precision at scale(s) relevant to management needs.
Can be easily understood and applied by managers	Can be applied by trained managers with undergraduate or master's level knowledge of relevant resource management. Does not require specialized expertise to apply.
Applicable at multiple scales	Applicable to management at multiple scales (plot to Gulf-wide). Characterization of indicator at one scale can be extrapolated to other scales (assuming an appropriate sampling design) in order to facilitate interpretation of current condition or provision of services.
Applicable to multiple management objectives	Can be consistently applied to address multiple management objectives including Living Marine Resources.

Evaluation Criteria	Definition
Low cost for data collection	Cost, including field and analysis expense and time, necessary to obtain the required number of measurements with a sufficient level of precision, accuracy and repeatability (across years) is relatively low.
Currently collected in the NGoM	Currently collected in the NGoM by existing monitoring programs.
Can be collected more cheaply by remote sensing	Remote sensing detection currently or soon possible with high resolution imagery or satellite imagery, at less than field cost at observation or plot level.

A major contribution of this work was to identify the linkages between ecological integrity and ecosystem services. The descriptions of these linkages were particularly important because they illustrated how indicators that track one factor within the ecosystem can directly and indirectly serve as indicators of the service of a given site. In some cases, the linkages were so strong that we selected the same metric to indicate both ecological integrity and ecosystem service provision. For example, scallop production is an excellent indicator of both secondary production and of food production in seagrass ecosystems.

For ecosystem services indicators, we identified the ecological factors that can be measured to assess the capacity of a given site to provide those services. In many cases it's very difficult to measure the direct contribution of a given ecosystem to a particular human benefit. For example, several of the ecosystems we studied are known to provide nursery habitat for commercially important fish species, but it is extremely difficult to track the juvenile fish from a given site within an ecosystem all the way to human consumption. In this case, we recommended collecting data on the density of commercially or recreationally important juvenile fish species at a site.

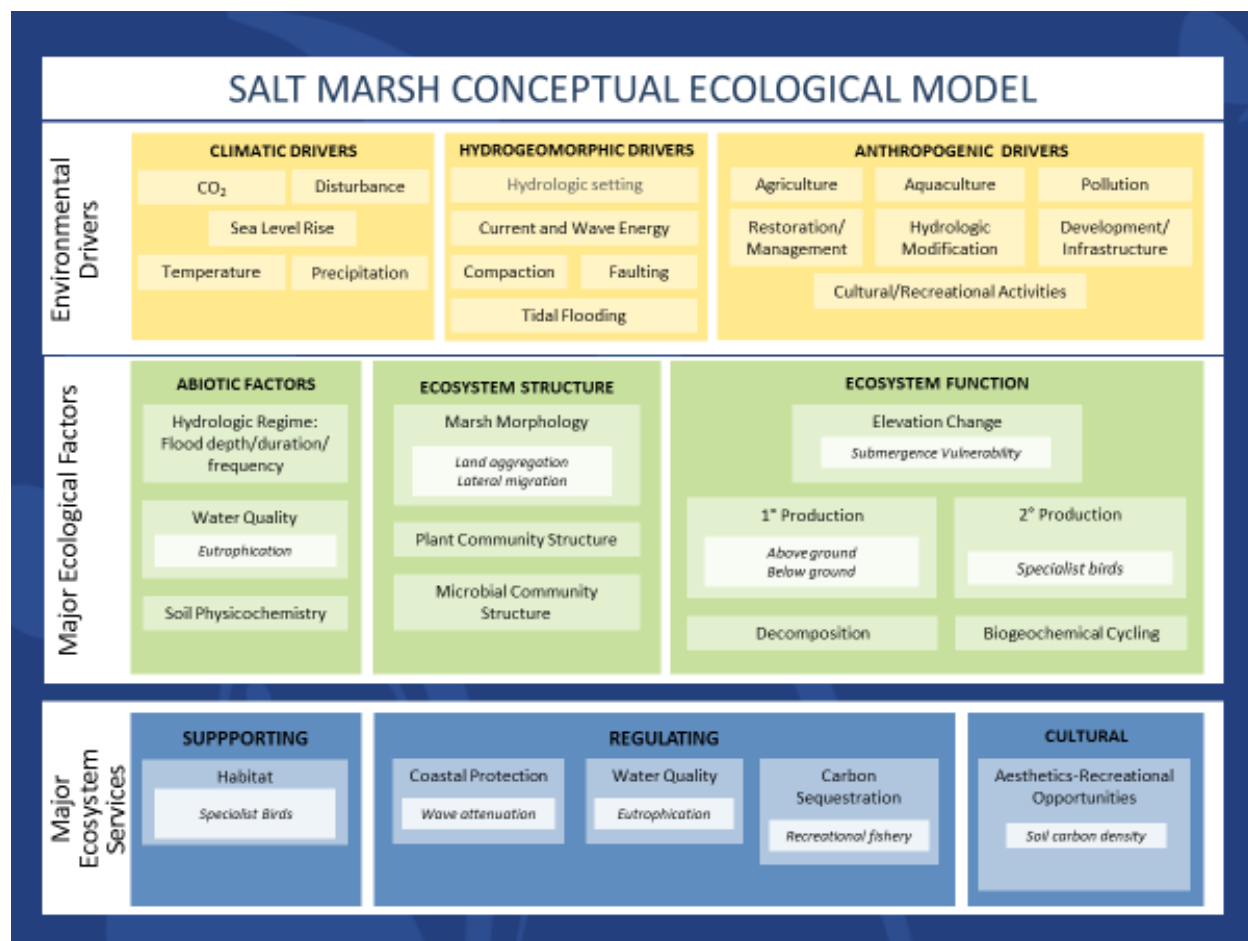


Figure 1.5. Example CEM with indicators. The terms in the white boxes are the indicators identified for a key attribute. Ecological integrity indicators are those associated with Major Ecological Factors (green boxes). Ecosystem services indicators are those associated with Major Ecosystem Services (blue boxes).

For each indicator, we identified the metrics and measures that are used to assess and monitor them. **Metrics** are quantified forms of indicators that inform the relative condition or services of the ecosystem. **Measures** are the data actually measured in the field and used to calculate the metric. For example, in salt marsh ecosystems, *measures* of stem height are needed to calculate the *metric* of aboveground live biomass stock for the Aboveground Primary Production *indicator*. Note: In some instances, the name of the indicator and metric are the same, which simply reflects that the indicator is best known by the name of the metric used to assess it.

Metrics may vary considerably in the ease and cost of data collection. We assessed each metric by assigning it to a “**Tier**,” which describes level of intensity of effort required to document a metric. Tier 1 metrics use data that are relatively easy to collect and apply, such as may be available from remote sensing imagery or data loggers. Tier 2 typically requires rapid field collection that can be collected in less than half a day. Tier 3 typically requires intensive field collection that takes a day or more to collect. Although low cost data collection is ideal, we did not exclude indicators if they fell into Tier 3. The working groups and expert panelists agreed that some Tier 3 metrics are worth the effort required for data collection because of the valuable information on ecosystem condition that they can provide.

Metric Ratings and Assessment Points

A major reason for implementing an environmental monitoring program is to provide early warning of abnormal conditions, impending concerns, or potential shifts in resource values relative to management goals (Bennetts et al., 2007). An indicator-based approach is a well-tested means to provide these early warnings, particularly when metric ratings with specific assessment points are provided for the indicators. **Metric Ratings** indicate how the measured values are informative of the integrity of the ecosystem (e.g. Excellent, Good, Fair, Poor). They are determined by quantifiable **Assessment Points**, which are specified ranges in a measure that distinguish expected or acceptable conditions from unacceptable conditions that warrant further evaluation or management action. They represent pre-selected points along a continuum of indicator values that provide an assessment of the status or trend of a resource (Bennetts et al., 2007). Assessment points are critical for providing guidance to managers on how the ecosystem is changing and whether management actions should be taken (Figure 1.5).

Assessment points may also represent ecological thresholds; that is, where relatively small changes in an indicator value lead to substantial changes in a system, below or above which it may be hard to recover (Bennetts et al., 2007; Carter and Bennetts, 2007). We chose to use the more generic term “assessment point” over the term “ecological threshold” for this study because the specific ecological thresholds are often unknown or uncertain for many indicators.

To be meaningful, assessment points must represent a quantitative or semi-quantitative value and avoid ambiguity about whether a given point has been reached. They may represent the measure or value of a given indicator at a given point in time, the value of a derived or aggregated measure or index; or the rate of change for the value of a given indicator (see Carter and Bennetts, 2007).

Each ecosystem team developed quantitative metrics and assessment points from the literature, known values from existing sites, and from the expert panelists, and documented the rationale for their selection. For example, the salt marsh team identified “Primary Production” as a KEA for Salt Marsh, and “Above Ground Primary Production” as its best indicator. Although there were multiple ways to measure this indicator, the salt marsh team concluded that the best (i.e. most cost-effective, reliable, and widely used) metric was Aboveground Live Biomass Stock. They consulted the literature and experts to develop the metric ratings and assessment points to track declining levels of aboveground primary production (Table 1.2). The Fair assessment point may or may not trigger any action, because recovery may occur through natural processes, but the Poor should trigger action, because these levels indicate that the system may be failing and may not be able to recover its production levels (Figure 1.5).

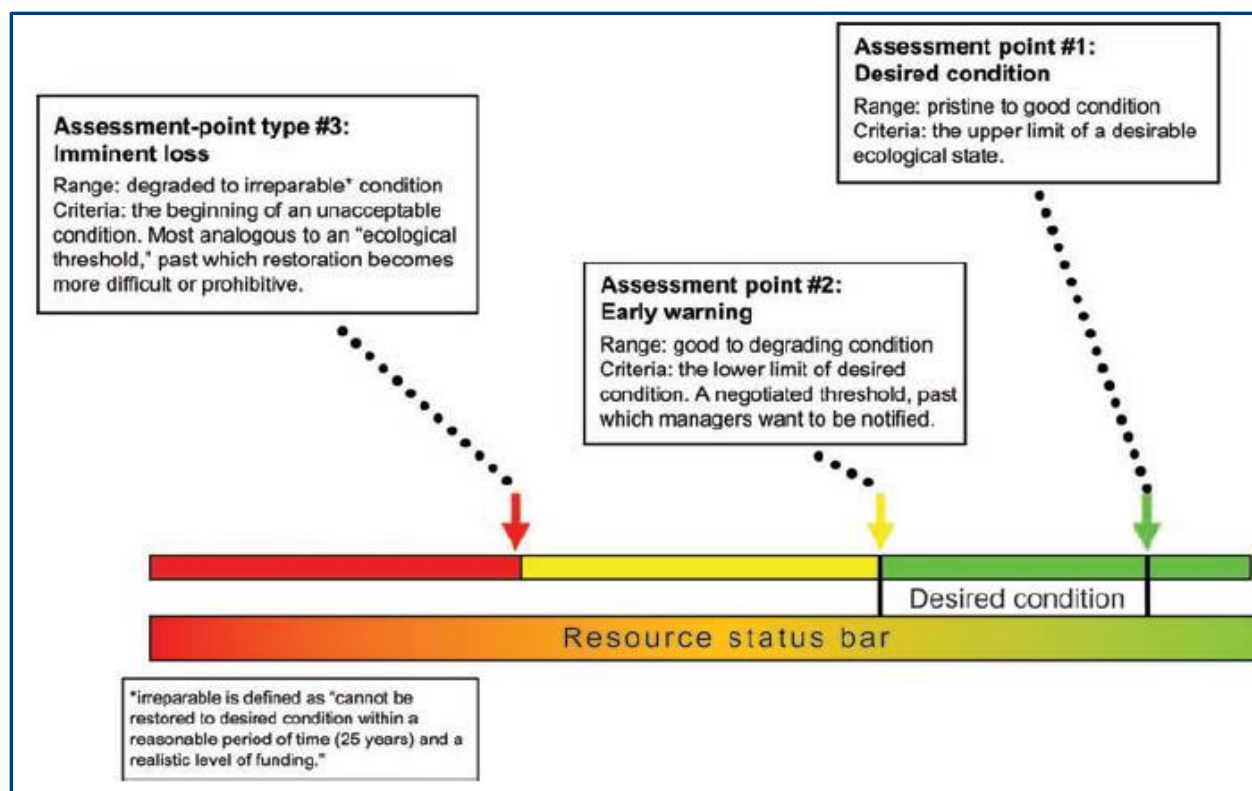


Figure 1.6. Assessment Point Concept (from Carter and Bennetts, 2007)

Table 1.7. For Salt Marsh Aboveground Live Biomass Stock, the assessment points establish the range of biomass values that pertain to a particular level of integrity.

Salt Marsh Metric Rating	
Rating	Aboveground Live Biomass Stock Assessment Points
Good/Excellent	Standing Biomass > 600 g m ⁻²
Fair	Standing Biomass 300–600 g m ⁻²
Poor	Standing Biomass < 300 g m ⁻²

Analysis of Existing Monitoring Efforts

Current availability of data for the indicator was one of the criteria we used to evaluate each indicator. To assess the degree to which the recommended indicators for each ecosystem are currently being collected by monitoring programs across the NGoM, we completed the following steps for each ecosystem:

- Compiled ecosystem range maps, and created a distribution map of each ecosystem across the NGoM.
- Inventoried existing monitoring programs and identified the data that they collect
- Analyzed the metadata of indicators from the monitoring programs to identify the programs that collect data on our recommended indicators

- Completed a spatial analysis of the monitoring programs that collect data for each indicator to assess the degree of implementation of the indicators geographically across the NGoM
- Published the spatial analyses and supporting data for each indicator of each ecosystem on a publicly available website

Each of these steps is described further below. Note that evaluating whether an indicator is “currently collected in the NGoM” (see Table 1.1 above) is one of several criteria used to evaluate candidate indicators. Not all recommended indicators scored highly on this criterion. The indicators that scored low on this criterion, but were still recommended by our evaluation, are included because they met other important evaluation criteria in Table 1.1. Despite their not being collected by existing programs, we recommend that their use be expanded in the NGoM. Thus, our analysis emphasizes gaps in indicator data coverage and highlights the need for additional monitoring efforts.

Ecosystem Range Maps

To create the ecosystem range maps, we compiled and adjusted readily available spatial ecosystem data from sources throughout the NGoM. Mapped ecosystem data were available from multiple sources both at the state level and NGoM regional level but varied in extent and scale. The primary sources we used included NOAA Environmental Sensitivity Index, NOAA Office for Coastal Management (formerly Coastal Services Center), NOAA National Marine Fisheries Service, FWS National Wetlands Inventory, Texas Parks and Wildlife Office, Texas General Land Office, Florida Wildlife Commission/Florida Wildlife Research Institute, Louisiana’s Statewide GIS Atlas, among others. See Appendix III for a complete listing of the data used to compile distribution maps for each ecosystem.

For each ecosystem we linked the source units to match CMECS unit definitions. This was particularly important for National Wetland Inventory (NWI) maps, where multiple source classification codes intersect with CMECS units. For mangrove ecosystem types, some of the NWI mapping units are broader than the corresponding CMECS units. For example, the NWI map unit E2SS3 – Estuarine Intertidal Broad-Leaved Evergreen Scrub Shrub includes mangroves as well as other evergreen shrubs that are not mangroves. There is not enough information on the NWI maps to make a clear separation. We had to decide whether to potentially over-identify or under-identify mangrove sites. We opted to include these more broadly defined units in our map, so it is probable that the mangrove map over-estimates mangrove distribution. A small subset of the highlighted hexagons, especially in the northern regions of the NGoM may not include mangroves. The NWI codes that we included in each map are provided in Appendix III.

Inventory of Existing Monitoring Programs

We completed an inventory of existing indicators (both ecological and ecosystem services) for the five ecosystem types, starting with the Ocean Conservancy’s geodatabase that contained a long-term monitoring program inventory and associated information on these NGoM ecosystems (Love et al., 2015). The Ocean Conservancy inventory captures information on individual monitoring efforts obtained through meetings with resource experts and a review of primary literature and monitoring plans. Ocean Conservancy met or corresponded with nearly 300 individuals from federal and state agencies, academia and nonprofits. These communications were essential to compiling information on the geographic and temporal scope, sampling methods, and focal species of long-term monitoring programs

in the NGoM. The inventory of monitoring includes information, or metadata, about environmental programs that conduct systematic monitoring of natural resources in the NGoM. Only programs that produce publicly accessible information were included. This inventory was built upon a previous effort to document all monitoring programs with a minimum five-year data record. To augment the Ocean Conservancy inventory, we reviewed additional sources including the Gulf GAME catalog (<http://research.myfwc.com/game/search.aspx>), the Gulf of Mexico Data Atlas (www.gulfatlas.noaa.gov), Data Basin (www.databasin.org), the Gulf of Mexico Research Initiative's master research database, and GRIIDC (Gulf of Mexico Initiative Information and Data Cooperative – <https://data.gulfresearchinitiative.org/>). For this project, we removed the minimum data record requirement and identified additional, shorter-term programs that collect data for the five target ecosystem types. There are likely additional environmental monitoring efforts in the coastal or offshore areas of the NGoM that were not documented in this inventory because they were either not relevant to the project's goals or were not identified during the process.

Metadata in the monitoring program inventory includes information on the program that manages the sampling effort, contact information, the parameters that are monitored, sampling frequency and the length of the data record. For a large subset of programs in the inventory, the spatial sampling footprint for the program was assembled in a GIS layer and maintained as a separate geodatabase. The spatial data set included programs assessed in the original Ocean Conservancy monitoring assessment (Love et al., 2015) and any additional programs that were identified during this project. The sampling footprint was either provided directly by the monitoring program in the form of coordinates or sampling boundaries or it was estimated from published descriptions. The final monitoring inventory and spatial sampling extents (or spatial footprints) were compiled via a Microsoft Access database and an Environmental Systems Research Institute geodatabase and are linked by the ID field common to each file.

Assessment of Monitoring Program Inventory

The Ocean Conservancy monitoring database contains data on a broad number of ecosystems and many different types of monitoring programs (e.g. sediments, water quality, habitats, etc.). To hone in on the relevant programs for our study, we first searched the Ocean Conservancy monitoring database for all programs that collected any type of data for each ecosystem (e.g. Coral = True), and used that information to create a list of monitoring programs that collect data for each ecosystem. We then searched for potential metrics that corresponded with our recommended indicators by using sets of keywords. We excluded some monitoring programs from the list if:

1. they were research studies, restoration programs, or harvest activities that manipulated ecosystem variables;
2. they were not focused on ecological integrity indicators, or the data collected were not relevant to this work (e.g., soil profile data);
3. there wasn't enough information about the variables collected to discern whether they were a good match (e.g., we excluded bird counts that did not specify monitoring for specific species); or
4. there was no evidence that a data set was collected for the purpose of monitoring a specific ecosystem (e.g., we excluded general water quality monitoring programs where it was unclear whether the monitoring sites were in the same location as a given ecosystem).

For example, our initial search of the inventory database returned 40 monitoring programs that collected data for seagrasses. We excluded two of these programs because one was a research study that manipulated variables, and the second did not provide enough information on the variables collected. Therefore, the total number of relevant seagrass monitoring programs that we included in the NGoM was 38.

Using these screening criteria, we developed a list of monitoring programs where the keyword search resulted in a match for our metric. We then calculated the percentage of relevant monitoring programs that collect data for each metric ($n\% = \text{number of programs collecting data for the metric} / \text{total number of relevant monitoring programs}$). In the following ecosystem indicator narratives, we note this as the “Programmatic” implementation. Note that for several of the metrics, there were no instances of monitoring activity in the NGoM. This was particularly true for many of the ecosystem services metrics. At this time, we don’t know whether this is an artifact of the program inventory methodology, a result of the way ecosystem services monitoring programs report their activities, or whether they are truly not monitored. See Appendix IV for a list of the monitoring programs that collect information for each metric.

Spatial Analysis of Existing Efforts

To determine the geographic extent and distribution of collection of data for each metric, we used the monitoring inventory geodatabase to map the spatial footprint of monitoring programs that collect data for each metric, and we overlaid that information on its corresponding ecosystem range map (Figure 1.6). Spatial footprint data were not available for some monitoring programs and the spatial footprints were very large for a few national or regional monitoring programs and did not identify specific sampling sites (e.g. the spatial footprint for the National Lidar Survey includes the entire GOM). We did not map the spatial extent of the programs in either of these cases, but did include these programs in our analysis of programmatic implementation described above.

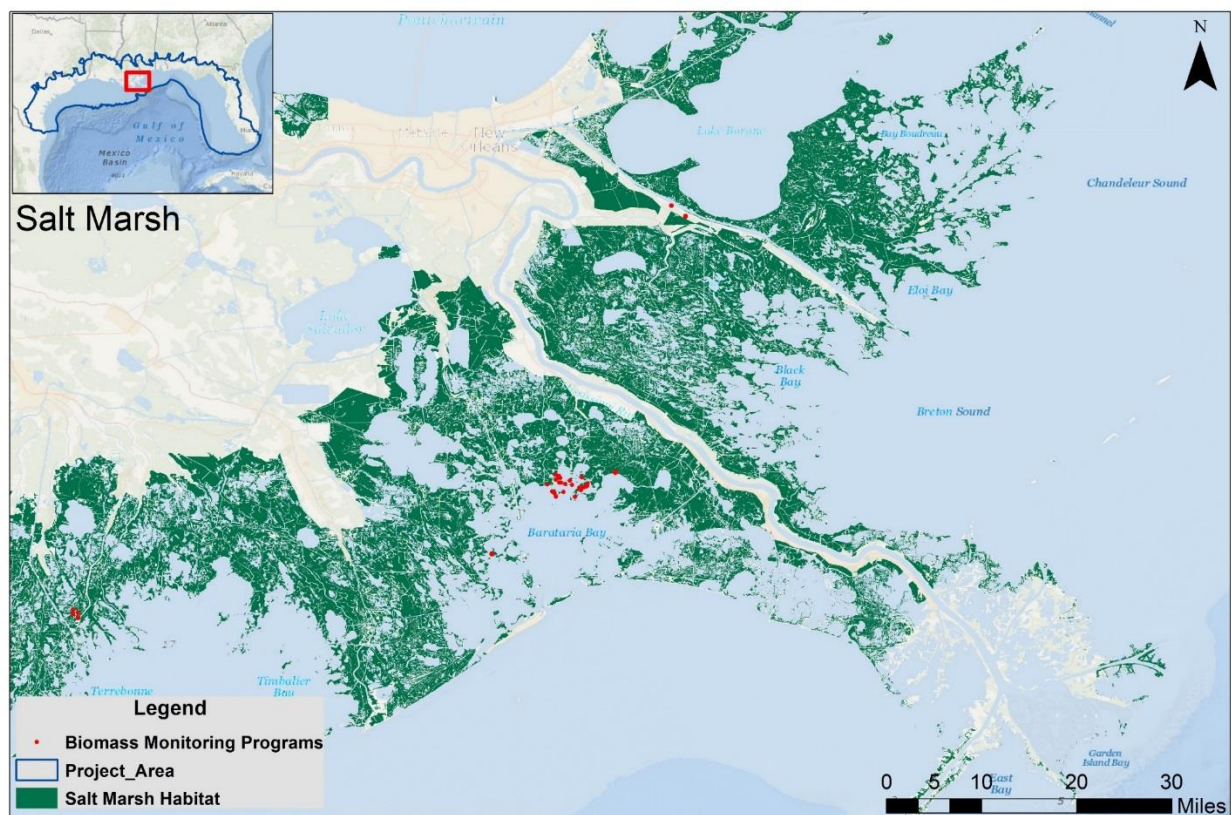


Figure 1.7. This map shows salt marsh distribution (green) with the spatial footprints of the collection sites for the Aboveground Live Biomass Stock metric (red).

To provide a consistent spatial unit of analysis, we created a 100 km² hexagon grid for the study area using DGGRID software (<http://www.discreteglobalgrids.org/software/>). To create the generalized ecosystem distribution map, we shaded the hexagons in the study area if they contained any mapped occurrence of the ecosystem. Shaded hexagons demonstrate presence of the ecosystem in the 100 km² hexagon area. We then highlighted hexagon cells where there was at least one instance of the metric being collected in that area (Figure 1.7) and calculated the percentage of ecosystem hexagons where each indicator is monitored ($n\% = \text{number of hexagon cells where the indicator is collected} / \text{total number of hexagon cells with the ecosystem}$). We then rated each of the indicators according to the scale in Table 1.3. We also described the geographic distribution of the data collection for each metric (e.g., throughout the range, only in certain states, clustered in certain areas, etc.). We refer to these calculations as “Geographic” implementation in the following ecosystem narratives.

Table 1.8. Rating scale for geographic extent of each metric

Well collected	Monitored in more than half of the hexagons
Moderately well collected	Monitored in 25-49% of the hexagons
Less well collected	Monitored in 10-24% of the hexagons
Not well collected	Monitored in <10% of the hexagons

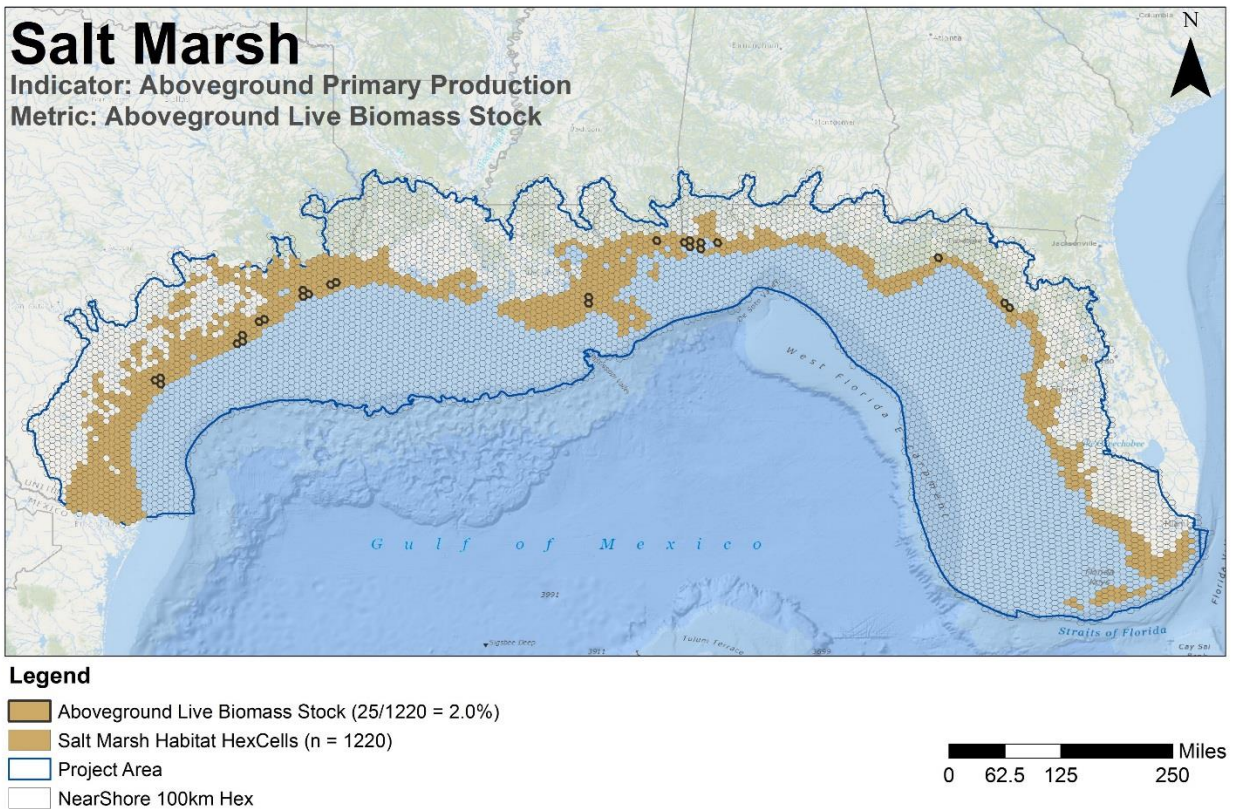


Figure 1.8. Spatial distribution of salt marsh habitat and Aboveground Live Biomass Stock Metric by 100 km² hexagon. Note that neither the shaded hexagons nor the highlighted hexagons demonstrate the density of the ecosystem or metric respectively (i.e., there could be one or more sites within the cell where the ecosystem occurs or where a program is collecting data for the metric).

To get a sense of the overall monitoring effort for the recommended metrics for each ecosystem, we also mapped the density of monitoring efforts and calculated the percentage of hexagons where at least one metric is monitored (Figure 1.8).

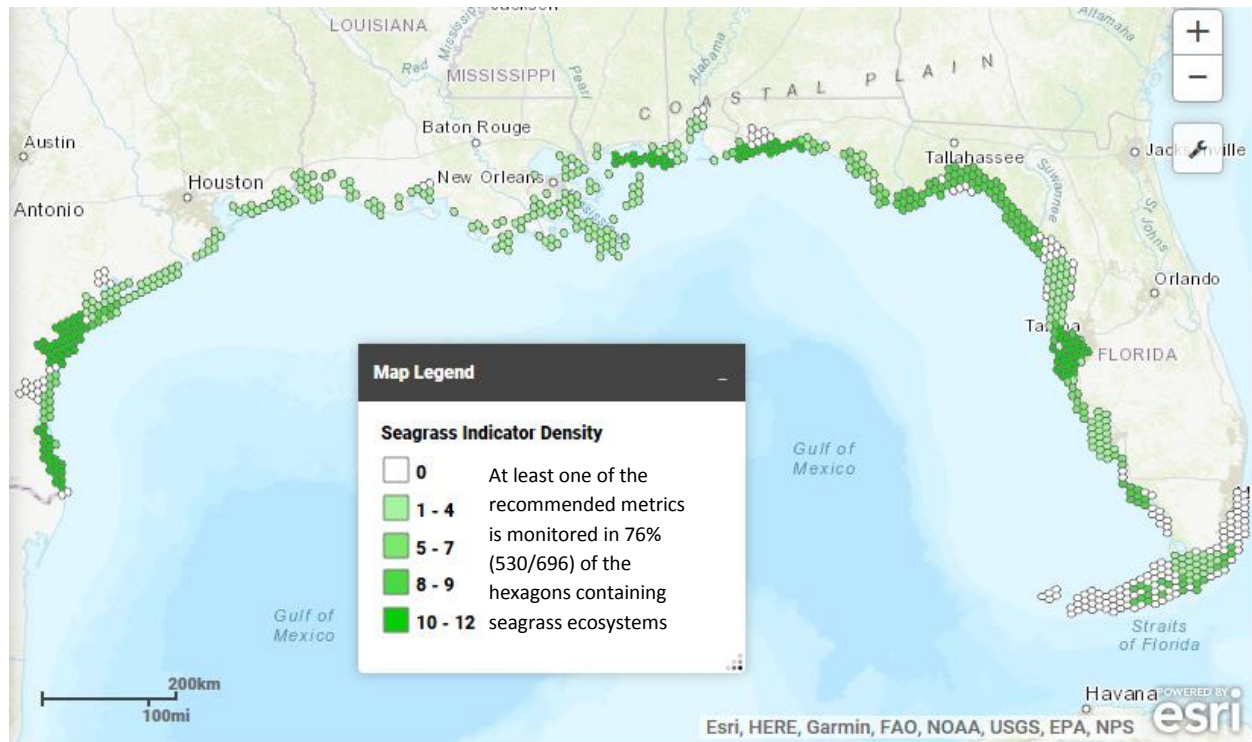


Figure 1.9. Density of the recommended indicators being collected in seagrass ecosystems in the NGoM

Publication of Spatial Analyses and Downloadable Data

We published the spatial analyses and resulting maps and made them publicly available via the Coastal Resilience Decision Support Tool (CRDST) (<http://maps.coastalresilience.org/gulfmex/>). The project geodatabase containing all spatial data is also available for download from that site.

Results

The lists of the indicators and metrics for each ecosystem in the context of the key factors from the CEMs are provided in Tables 1.4–1.8 below. Complete ecosystem narratives are provided in the following chapters.

Chapter 2: Ecological Resilience Indicators for Salt Marsh Ecosystems

Chapter 3: Ecological Resilience Indicators for Mangrove Ecosystems

Chapter 4: Ecological Resilience Indicators for Seagrass Ecosystems

Chapter 5: Ecological Resilience Indicators for Oyster Ecosystems

Chapter 6: Ecological Resilience Indicators for Coral Ecosystems

Table 1.9. Summary of Salt Marsh Metrics Based on the Conceptual Ecological Model

SALT MARSH ECOSYSTEMS			
Function & Services	Major Ecological Factor or Service	Key Ecological Attribute or Service	Indicator/Metric
Sustaining/ Ecological Integrity	Abiotic Factors	Hydrologic Regime: Flood Depth/Duration/Frequency	--
		Water Quality	Eutrophication/ <i>Basin-wide Nutrient Load (Total Nitrogen, Total Phosphorus)</i>
		Soil Physicochemistry	--
	Ecosystem Structure	Marsh Morphology	Land Aggregation/ <i>Aggregation Index (AI)</i> Lateral Migration/ <i>Shoreline Migration</i>
		Plant Community Structure	--
		Microbial Community Structure	--
	Ecosystem Function	Elevation Change	Submergence Vulnerability/ <i>Wetland Relative Sea Level Rise (RSLR_{wet}) and Submergence Vulnerability Index (SVI)</i>
		Primary Production	Aboveground Primary Production/ <i>Aboveground Live Biomass Stock</i>
			Belowground Primary Production/ <i>Soil Shear Stress</i>
		Secondary Production	Specialist Birds/ <i>Clapper Rail and Seaside Sparrow Density</i>
		Decomposition	--
		Biogeochemical Cycling	--
Ecosystem Services	Supporting	Habitat	Specialist Birds/ <i>Clapper Rail and Seaside Sparrow Density</i>
	Regulating	Coastal Protection	Wave Attenuation/ <i>Percent Wave Height Reduction per Unit Distance</i>
		Water Quality	Nutrient Reduction/ <i>Basin-wide Nutrient Load (Total Nitrogen, Total Phosphorus)</i>
		Carbon Sequestration	Soil Carbon Density/ <i>Soil Carbon Density</i>
	Cultural	Aesthetics-Recreational Opportunities	Recreational Fishery/ <i>Spotted Seatrout Density and Recreational Landings of Spotted Seatrout</i>

Table 1.10. Summary of Mangrove Metrics Based on the Conceptual Ecological Model

MANGROVE ECOSYSTEMS			
Function & Services	Major Ecological Factor or Service	Key Ecological Attribute or Service	Indicator/Metric
Sustaining/ Ecological Integrity	Abiotic Factors	Minimum Temperatures	--
		Soil Physicochemistry	--
		Hydrologic Setting	Eutrophication/ <i>Basin-wide Nutrient Load (Total Nitrogen, Total Phosphorus)</i>
			Connectivity/ <i>Multi-metric</i>
	Ecosystem Structure	Plant Community Structure	Stand Health/ <i>Foliage Transparency</i>
			Regeneration Potential/ <i>Propagule, Seedling, Sapling Presence</i>
		Landscape Structure	Land Aggregation/ <i>Aggregation Index (AI)</i>
			Land Cover Change/ <i>Land Cover Change Rate</i>
		Microbial Community Structure	--
	Ecosystem Function	Elevation Change	Submergence Vulnerability/ <i>Wetland Relative Sea Level Rise (RSLR_{wet}) and Submergence Vulnerability Index (SVI)</i>
		Primary Production	--
		Decomposition	--
		Secondary Production	Fish Habitat/ <i>Killifish Species Diversity</i>
			Invasive Species/ <i>Presence (Multiple Species)</i>
		Biogeochemical Cycling	--
Ecosystem Services	Supporting	Habitat	Status of Macrofauna Populations/ <i>Density of Juvenile Common Snook</i>
	Provisioning	Food	Status of Snapper-Grouper Complex Commercial Fishery/ <i>Density of Gray Snapper and Annual Commercially Landed Weight of Gray Snapper (Lutjanus griseus) in the Gulf of Mexico States and/or Federal Waters</i>
	Regulating	Coastal Protection	Erosion Reduction/ <i>Shoreline Change</i>
		Water Quality	Nutrient Reduction/ <i>Basin-wide Nutrient Load (Total Nitrogen, Total Phosphorus)</i>
		Carbon Sequestration	Soil Carbon Storage/ <i>Mangrove Height</i>
	Cultural	Aesthetics-Recreational Opportunities	Recreational Fishery/ <i>Density of Juvenile Common Snook</i>

Table 1.11. Summary of Seagrass Metrics Based on the Conceptual Ecological Model

SEAGRASS ECOSYSTEMS			
Function & Services	Major Ecological Factor or Service	Key Ecological Attribute or Service	Indicator/Metric
Sustaining/ Ecological Integrity	Abiotic Factors	Water Quality	Transparency/ <i>Percent Surface Irradiance</i>
			Phytoplankton Biomass/ <i>Chlorophyll a Concentration</i>
			Sediment Load/ <i>Total Suspended Solids</i>
		Soil Physicochemistry	--
	Ecosystem Structure	Abundance	Change in Areal Extent/ <i>Areal Extent</i>
			Change in Cover/ <i>Percent Cover</i>
		Plant Community Structure	Seagrass Species Composition/ <i>Species Dominance Index</i>
		Morphology	Shoot Allometry/ <i>Leaf Length</i>
			Shoot Allometry/ <i>Leaf Width</i>
		Chemical Constituents	Nutrient Content/ <i>Nutrient Limitation Index</i>
			Stable Isotope Ratios/ $\delta^{13}C$ and $\delta^{15}N$
	Ecosystem Function	Secondary Production	Scallop Abundance/ <i>Scallop Density</i>
		Carbon and Nutrient Sequestration	--
		Biogeochemical Cycling	--
		Primary Production	--
Ecosystem Services	Supporting	Habitat	Scallop Abundance/ <i>Scallop Density</i>
	Provisioning	Food	Scallop Abundance/ <i>Scallop Density</i>
	Regulating	Coastal Protection	Erosion Reduction/ <i>Shoreline Change</i>
		Water Quality	--
		Carbon Sequestration	--
	Cultural	Aesthetics-Recreational Opportunities	Recreational Fishery/ <i>Spotted Seatrout Density and Recreational Landings of Spotted Seatrout</i>

Table 1.12. *Summary of Oyster Metrics Based on the Conceptual Ecological Model*

OYSTER ECOSYSTEMS			
Function & Services	Major Ecological Factor or Service	Key Ecological Attribute or Service	Indicator/ <i>Metric</i>
Sustaining/ Ecological Integrity	Abiotic Factors	Water Quality	Salinity/ <i>Salinity</i>
			Dissolved Oxygen/ <i>Dissolved Oxygen</i>
		Substrate Availability	Change in Percent Cover of Reef Substrate/ <i>Percent Cover of Reef Substrate</i>
		Acidification	--
	Ecosystem Structure	Disease	Disease Prevalence (Dermo)/ <i>Weighted Prevalence</i>
		Food Availability	--
		Reef Structure	Change in Reef Area/ <i>Area</i>
			Change in Reef Height/ <i>Height</i>
			Density of Live Oysters/ <i>Density of Live Oysters Relative to the Regional Mean</i>
		Oyster Larvae	--
		Predation	--
	Ecosystem Function	Habitat Provisioning	Species Richness/ <i>Number of Species per Unit Area</i>
			Resident Species/ <i>Biomass of Resident Species</i>
		Filtration	--
		Condition of Adjacent Habitat	--
		Nitrogen Removal	--
Ecosystem Services	Supporting	Habitat	Status of Macrofaunal Populations/ <i>Density of Naked Goby</i>
	Provisioning	Food	Oyster Fishery/ <i>Site Harvest Status and Commercial Oyster Landings</i>
	Regulating	Coastal Protection	Erosion Reduction/ <i>Shoreline Change</i>
		Water Quality	--
	Cultural	Aesthetics-Recreational Opportunities	Recreational Fishery/ <i>Perception of Recreational Anglers Fishing in the Area of Influence of Oyster Reefs</i>

Table 1.13. Summary of Coral Reef Metrics Based on the Conceptual Ecological Model

CORAL ECOSYSTEMS			
Function & Services	Major Ecological Factor or Service	Key Ecological Attribute or Service	Indicator/ <i>Metric</i>
Sustaining/ Ecological Integrity	Abiotic Factors	Water Quality	Nutrient Enrichment/ <i>Chlorophyll a Concentration</i>
			Light Attenuation/ <i>Water Transparency</i>
			Temperature Regime/ <i>Temperature Range</i>
			Carbonate Chemistry/ <i>Aragonite Saturation State</i>
		Substrate Attributes	--
	Ecosystem Structure	Benthic Community Structure	Epibenthic Sessile Community Structure/ <i>Living Biota Percent Cover</i>
			Grazing/ <i>Echinoid Abundance</i>
	Ecosystem Function	Benthic Community Condition	--
			Macroalgae/ <i>Macroalgal Percent Cover</i>
			Coral Disease/ <i>Disease Prevalence</i>
			Coral Bleaching/ <i>Bleaching Prevalence</i>
			Coral Mortality/ <i>Recent Mortality Prevalence and Old Mortality Prevalence</i>
		Connectivity	--
		Primary Production	--
		Secondary Production	--
		Tertiary Production	--
		Nutrient Cycling	--
		Environmental Condition	--
Ecosystem Services	Supporting	Habitat	Status of Macrofauna Populations/ <i>Live Stony Coral Cover</i>
	Provisioning	Food	Status of Snapper-Grouper Complex Commercial Fishery/ <i>Density of Red Snapper</i>
	Cultural	Aesthetics-Recreational Opportunities	Recreational Fishery/ <i>Density of Juvenile Common Snook</i>
		Educational Opportunities	Educational Program Participation/ <i>Number of Visitors of a Coral Reef Participating in an Education Program</i>

Discussion

The indicators that have been developed by NGoM ecosystem experts using the Ecological Resilience Framework (ERF) represent a major step towards achieving the goal of coordinating the monitoring efforts in the NGoM to support effective management of sustainable ecosystems and living marine resources (LMRs). The ERF is very timely, as billions of dollars will be spent on the management and restoration of NGoM ecosystems over the next twenty years. Implementing the indicators developed as part of the ERF will help ensure that this unprecedented level of funding significantly improves and sustains the ecological condition of the NGoM and its living marine resources. Ecosystem managers and restoration practitioners must monitor ecologically appropriate indicators to effectively evaluate the performance and impacts of their activities and guide adaptive management. They need access to baseline data and trends in the condition of sites to help them set ecologically valid restoration goals and monitor the performance of their projects. Decision makers need synthesized data to make decisions within timelines set by politics and law. Grant makers need data to evaluate whether proposed restoration and management activities are appropriate for the proposed sites and to measure the impacts of their investments across multiple sites. Indicator monitoring data from multiple restoration projects across spatial and temporal scales must be aggregated to assess the collective impacts of management and restoration activities and to provide an ecological accounting for the money spent. The RESTORE Council, NRDA Trustees, National Fish and Wildlife Foundation and several other granting and scientific institutions in the NGoM all have stated the need to report on monitoring results to measure the impacts of their management and restoration investments and communicate progress at scales beyond the single project level (NAS 2017). They call for making data publicly available to maximize utility of the data for multiple purposes.

The challenge to collect, aggregate, and share ecologically appropriate indicator monitoring data has been a major impediment to ensuring maximum impact and return on investments. Developing standards on what data to collect is the first step towards addressing the challenge. This report recommends a comprehensive set of ecologically-informed ecological resilience indicators that can be used to inform sustainable ecosystem and LMR management, damage assessment and recovery planning, restoration planning and evaluation, and ecosystem health assessment. Because they specify the linkage between ecological integrity indicators and ecosystem service provision indicators, they can also be used to help understand how management activities and disturbances may impact the benefits that the ecosystems provide to humans.

The indicators were developed for monitoring at the site level and can immediately be adopted by monitoring programs that have the need to understand condition and trends at this scale. Deployment of these indicators as a standard by multiple monitoring sites across the region would allow for Gulf-wide condition and trend assessment. The spatial analyses of monitoring efforts for each indicator in this report can be used to identify opportunities to begin reporting on regional baseline condition and trends for some indicators in the near term. The spatial analyses can also be used to identify the needs for additional coordination and data collection for some of the indicators.

Uptake of these standard indicators more broadly than the site level should be based on shared goals of the stakeholders in the region. Several efforts in the NGoM are being initiated to coordinate monitoring program efforts and support the synthesis of monitoring activities across the region. The Natural Resource Damage Assessment (NRDA) Trustee Implementation Group Cross-Trustee Implementation

Group (TIG) Monitoring and Adaptive Management work group, the RESTORE Council Monitoring and Assessment Program (CMAP), Gulf of Mexico Alliance (GOMA) Data and Monitoring Priority Issue Team, the Seagrass Monitoring Community of Practice (funded by GOMA), the Florida Department of Environmental Protection Coastal Program, and the Florida Panhandle Landscape Conservation Cooperative are all seeking to coordinate ecosystem monitoring efforts in the region and to synthesize monitoring information from multiple scales. The indicators and evaluation of current monitoring programs can be used by these efforts to guide the development and implementation of a set of indicators that can be collected and reported comprehensively across the region.

The aggregation of data on the recommended indicators from multiple monitoring programs will be required to provide data access to a wider community of practice and provide a means for understanding the collective impact of restoration and management activities and detect trends in ecological resilience at multiple scales over time. Additional work will be needed to aggregate data from monitoring programs to make this possible. Some data transformation and standardization methods may need to be developed to allow for aggregation of existing indicator data that have been collected with varying collection methods and sampling design. A data portal to aggregate the data to facilitate reporting will also be required. The technology now exists to create an open data portal that provides continuously updated, standardized and aggregated monitoring data that is easy to discover, understand and use. This technology supports data providers to standardize and publish their indicator monitoring and ecosystem distribution data to a common platform, while maintaining ownership and control of their own data. Standardized data flowing from multiple providers across multiple sites could be aggregated dynamically and used repeatedly. Development of such a solution would collectively save thousands of hours of time spent by those manually compiling data from scattered sources. Data reporting and visualization tools will also be required to support the uptake of data for use by decision makers. When fully operational, the indicators recommended in this report could be made available via visualization tools such as the NatureServe Biodiversity Indicators Dashboard (<http://dashboard.natureserve.org/>) and via the Gulf of Mexico Report Card being developed by the Harte Research Institute (<https://www.hartheresearchinstitute.org/news/gulf-mexico-report-card-track-and-share-health-gets-underway>). By so doing, managers and scientists will have access to the information needed to support effective management of sustainable ecosystems and LMRs in the Gulf of Mexico.

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