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Ecological resilience indicators for salt marsh ecosystems

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Chapter 2. Ecological Resilience Indicators for Salt Marsh Ecosystems

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Ecosystem Description

Salt marshes are coastal ecosystems within the intertidal zone, characterized by hypoxic, saline, soil conditions and low biodiversity. Low diversity arises from frequent disturbance and stressful conditions (i.e., high salinity and hypoxia), where vegetative reproduction and low competition result in mostly monotypic stands, with some differences in plant community influenced by flooding regime (described below). While there are several types of salt marshes in the Northern Gulf of Mexico (NGoM), ranging from low to high salt marshes and salt flats (Tiner, 2013), *Spartina alterniflora*–dominated salt marshes in the Coastal and Marine Ecological Classification Standard (CMECS) Low and Intermediate Salt Marsh Biotic Group (FGDC, 2012) are the most extensive and are the focus of this project. These salt marshes are classified as “Gulf Coast Cordgrass Salt Marsh” (CEGL004190; USNVC, 2016). Within the NGoM region, some salt marsh areas are dominated by other species such as *Spartina patens* and *Juncus roemerianus*, which both occupy higher elevations in high-precipitation zones (e.g., Louisiana, Alabama, Mississippi, and Florida). In lower precipitation regions (southern Texas), hypersaline conditions often develop yielding communities of succulent salt marsh plants (*Batis* and *Salicornia* spp.). In climatic zones with warmer winter temperatures, temperate salt marshes naturally transition to mangrove (generally in the southern Gulf of Mexico range) or, in areas with lower precipitation, to salt flats (generally in western part of the study area).

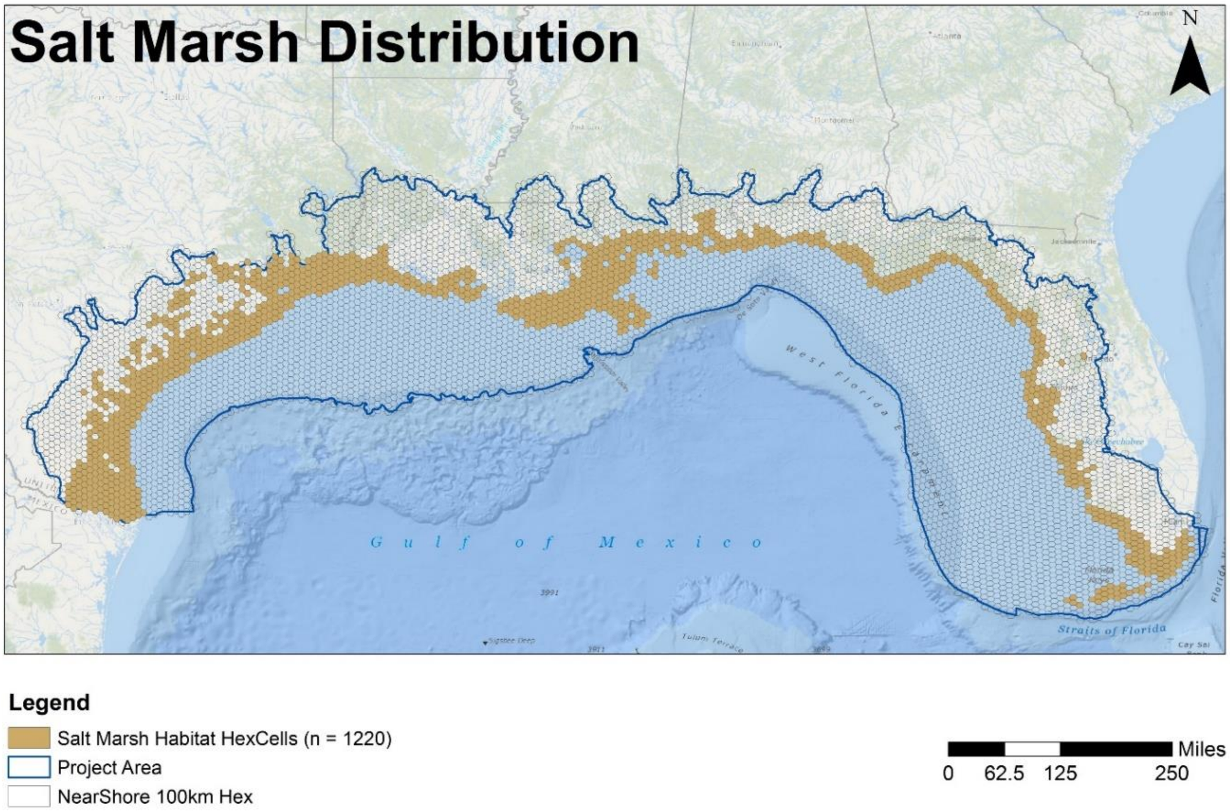


Figure 2.10. Distribution of salt marsh ecosystem within the Northern Gulf of Mexico

Low elevation salt marshes are widely distributed throughout the NGoM (Figure 2.1). This area contains roughly 60% of marshes in the contiguous United States, partially due to the presence of the large river deltas (Mitsch and Gosselink, 2007), which are also areas that are heavily developed by humans. Consequently, NGoM salt marshes are exposed to natural and anthropogenic disturbances (direct and indirect), including sea-level rise, terrestrial nutrient runoff and pollutants, and human land use change. These forces have resulted in historic widespread loss of wetlands. For example, since European settlement, Louisiana may have lost 25 to 50% of its salt, brackish, and freshwater coastal marshes (Tiner, 2013). Unfortunately, loss of coastal wetland habitats impedes ecosystem function and subsequent ecosystem services that sustain NGoM coastal communities, notably coastal protection, commercial and recreational fisheries, carbon sequestration, and water quality regulation.

Despite multiple threats to salt marsh biota, salt marshes are resilient systems. While salt marshes can rapidly subside, potentially resulting in wetland loss (transition to open water), subsidence can be compensated for by wetland elevation gains (Cahoon, 2015). Accretion-facilitated elevation gains may fully compensate for elevation losses from sea-level rise and subsidence, or just delay submergence. However, even with relatively high rates of accretion, marshes can still be lost when overcome by higher additive rates of sea-level rise and subsidence (i.e., relative sea-level rise). Accretion rates are maintained by high rates of primary production, low rates of organic matter decomposition, and tidal transport of suspended sediment onto the marsh surface (Cahoon et al., 2006). The high-frequency disturbance regime of an intertidal zone is also regulating and provides regular flushing and renewal of the surface and subsurface conditions. This resilience is a necessary characteristic of salt marsh ecosystems, because of the dynamic landscape they occupy. While anthropogenic activity has introduced new stressors/disturbances and augmented natural ones, the capacity for system adaptation must be considered when assessing how these stressors impact system integrity. However, the transition to open water is a state from which there is lower probability of recovery to marsh (Stagg and Mendelssohn, 2011); thus, low-marsh ecosystems (dominated by *S. alterniflora*) are more vulnerable and deserve closer monitoring effort.

To understand the ecological and human processes that affect the NGoM salt marshes, we developed a conceptual ecological model. We present the model as a diagram (Figure 2.2) that accompanies the following description of salt marsh ecosystem attributes or factors and their interactions. This diagrammatic representation of the ecosystem was designed to guide the selection of indicators of the ecosystem condition and associated services. In the following narrative, we describe the most direct or strongest linkages between the ecosystem components, including those between ecosystem processes and the largely external environmental drivers, such as climatic, hydrogeomorphic, and anthropogenic drivers. From a monitoring perspective, these linkages are particularly important because they illustrate how indicators that track one factor within the ecosystem can directly and indirectly serve as indicators of the overall ecosystem condition. Condition of the overall system can be assessed by monitoring factors and functions that contribute to ecosystem services. Accordingly, this framework focuses on *S. alterniflora* systems, but the metrics are applicable to monitoring and assessing all salt marsh ecosystem types.

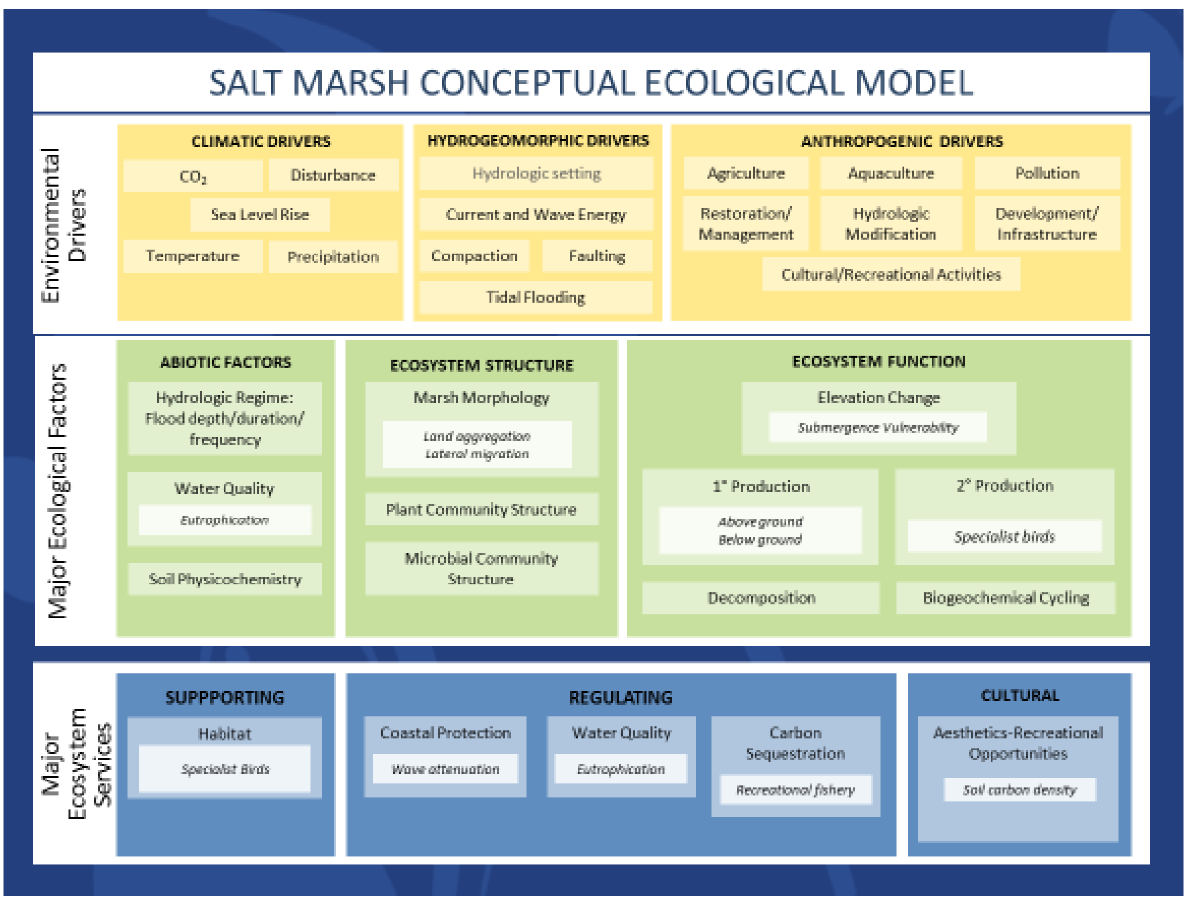


Figure 2.11. *Salt Marsh Conceptual Ecological Model*

Factors Involved in Ecological Integrity

Abiotic Factors

Hydrologic Regime – Flood depth/duration/frequency

Hydrologic regime is often quantified as flood depth, duration, and frequency, and the variability surrounding those parameters. Hydrologic regime is heavily influenced by external forcing—precipitation, river flows, and tidal fluctuations (and less frequently by storm surges)—imposed on the landscape topography, resulting in spatially and temporally varying water levels. Hydrologic regime determines habitat zonation, ecosystem productivity, physicochemical conditions, ecosystem structure, and marsh morphology (Mitsch and Gosselink, 2000).

The hydrologic regime is largely determined by site position within the intertidal range. Lower elevation results in more frequent and deeper flooding. However, relationships between elevation and sea level are dynamic, because both elevation and sea level are constantly changing. Thus, for a marsh to be stable, relative sea-level rise must be matched by elevation gain (Reed, 1995). The processes controlling elevation gains (and losses) are discussed below.

River flows, tidal fluctuations, and precipitation are a function of climate and geomorphological setting, differing geographically and likely to change over time. Climate primarily affects precipitation amount, thereby influencing local salinity.

Hydrologic regime can be directly modified by anthropogenic activity, including coastal engineering (e.g., channelization reducing water transit times) or upstream modification of rivers (Kennish, 2001). Both sea-level change and tectonic subsidence contribute to a regional trend of deeper flooding and higher rates of relative sea-level rise; given the timescales of these processes, this trend will continue (Kennish, 2001).

Water Quality

Water quality is affected by all the external factors that influence hydrologic regime, in addition to internal ecological functioning of the salt marsh. The geomorphic setting of the wetland is important in determining wetland type and the dominant sources of water a wetland receives (Brinson, 1993). Important components of water quality in salt marshes are salinity, total suspended solids (TSS), and nutrient load—particularly those contributing to eutrophication. These same three factors are necessary elements of salt marsh ecological function but can become stressors to the system at higher concentrations. Eutrophication is the excessive enrichment of nutrient concentrations in a body of water, often resulting from agricultural runoff and/or urban effluents high in nitrogen and phosphorus. Eutrophication directly affects soil chemistry, geomorphology, and plant growth; in coupled aquatic ecosystems, eutrophication often leads to algal blooms that inhibit secondary growth and production (Smith, 2003). Anthropogenic activity, especially agricultural development, increases nutrient loading, which can stimulate primary production, but also increases system vulnerability by altering biogeochemical cycles, community structure, and carbon allocation within wetland plants (Deegan et al., 2012).

Although water quality can be dominated by relatively short-term variations (e.g., most sediment transport occurs with infrequent extreme events), impacts of stochastic events are less understood and inherently less predictable (or assessable) than the long-term trends in water quality from human activity. For example, river flow dynamics determine TSS transport, but levees can affect the velocity with which sediment exits a river system, dams upstream can reduce the natural levels of sediment transport (Tockner et al., 1999), and channels and canals through the landscape can also reduce the deposition of sediment on marshes.

Soil Physicochemistry

The physical and chemical properties of soil are strongly related to the hydrogeomorphic setting. Topography and hydrologic regime (including water quality) determine the depositional setting, ultimately determining where and how much accretion occurs. Surficial accretion of sediments occurs through the deposition of allochthonous and autochthonous carbon and the deposition of mineral sediments. High mineral content soils, which generally result from proximity to a mineral sediment source (e.g., rivers), have higher bulk density and lower organic matter (Morris et al., 2016). In general, lower mineral content soils (i.e., higher organic) are more vulnerable to collapse due to decomposition (Swarzenski et al., 2008). High mineral content soils also tend to have higher nutrient concentrations, which may stimulate production (Mitsch and Gosselink, 2007). However, elevated nutrient concentrations may not be optimal for system sustainability, because although nutrient enrichment in coastal wetlands increases aboveground production (leaves, stems) of foundation plant species, belowground foraging, and thus root production, decreases. Reduction in belowground biomass leads to bank erosion or collapse of marsh platforms (Deegan et al., 2012). Belowground production and accretion of organic matter are important processes that contribute to the maintenance of marsh elevation (Stagg et al., 2016).

Prolonged inundation from tidal flooding of salt marsh soils promotes hypoxic conditions (Mendelssohn and Seneca, 1980). Although hypoxia can inhibit primary production, salt marsh vegetation have adapted to hypoxic conditions by oxidizing the rhizosphere (Armstrong, 1979). Furthermore, hypoxic conditions limit decomposition of organic matter and thus enable organic matter accumulation (Day and Megonigal, 1993), providing elevation capital that stimulates production and maintenance of salt marsh elevation through hydrogeomorphic feedback loops (Kirwan et al., 2016). Nonetheless, despite flooded, anoxic, conditions, decomposition of organic matter does occur through anaerobic respiration pathways and facilitates energy flow through the detrital community (Stagg et al., 2017).

Salinity is a dominant feature of soil physicochemistry, acting as a natural stressor that salt marsh biota necessarily tolerate. Nonetheless, if salinity is high enough, it can reduce the height and production of vegetation through both direct ionic stress and competitive inhibition of ammonium uptake (Haines and Dunn, 1976; Bradley and Morris, 1991). Salinity can vary temporally and spatially as a function of precipitation and proximity to freshwater sources, and in sensitive areas, small changes in precipitation can cause large changes in cover of foundation plant species (Osland et al., 2014). The dramatic precipitation gradient across the NGoM, from Texas to Louisiana, is an example of such an ecological transition zone, where changes in precipitation and salinity can lead to a change in dominance from *S. alterniflora* (12–35 PSU) to halophytic succulent shrubs (> 35 PSU) and salt flats (up to 100 PSU), although the majority of low tidal saline wetlands along the NGoM are herbaceous, *S. alterniflora* marshes.

Ecosystem Structure

Marsh Morphology

Despite low species diversity, marsh morphology can be very complex due to geographic setting, with secondary effects from the competing factors of deposition and erosion, both of which are affected by both natural and anthropogenic factors.

Perhaps the largest source of geomorphic variation in coastal environments is the proximity to a river delta. River deltas commonly support large marsh complexes because of high sediment effluxes. Within salt marshes, sediment and other materials are transported through sinuous natural channels, across areas of open water, and over mudflats to the adjacent vegetation. Interior areas, which are generally lower in elevation, are more susceptible to submergence and transition to open water, resulting in a disaggregated landscape (i.e., highly heterogeneous with impeded connectivity across the marsh). Landscape change can also occur through lateral erosion and migration (Fagherazzi et al., 2013), which may occur in rapid pulses from storm influences (Guntenspergen et al., 1995).

Human effects on landscape structure are prominent. Indirect anthropogenic activities that affect hydrology and water quality trickle down to affect marsh morphology (e.g., transport of sediment and nutrients from upstream affect marsh geomorphic processes [Kennish, 2001]). However, human activity also directly modifies marsh morphology. Infrastructure (including roads, pipelines, dams, oil and water wells, power and telecommunication cables, and many other human structures or modifications to the environment that do not represent a complete conversion of salt marsh habitat to another land use type) can have significant effects on salt marsh habitat connectivity. Depending on the type and nature of infrastructure present, it may directly affect water and material flow, produce a barrier to plant and/or animal migration, and contribute to habitat fragmentation. The development of channels can alter water and sediment flows into and out of the marsh, as well as alter species corridors (Turner, 2010). Oil removal can directly drive subsidence (Kennish, 2001). Furthermore, the presence of the oil industry presents a risk of unintentional release of petrochemicals with potential effects on geomorphic stability (DeLaune et al., 1979b). Since belowground biomass affects sediment cohesion (Turner, 2010), the loss of vegetation, whether through petrochemical pollution (Culbertson et al., 2008) or other processes, results in less protection of surface sediments from erosive forces (Kadlec, 1990).

Plant Community Structure

The community structure of *S. alterniflora*–dominated salt marsh vegetation is simple compared to many other ecosystems. Most low salt marshes across the region are monotypic stands of *S. alterniflora*. While the focus of this work is the NGoM, the range of *S. alterniflora* extends across most of the Atlantic and NGoM coasts, from Canada to Argentina. Height variations within these stands are common, with interior marsh areas having lower vegetation and edges having taller vegetation. The tall (~1.5m) herbaceous vegetation creates a dense habitat, both aerially and below ground, that provides habitat for fish, shellfish, and birds. Vegetative reproduction (rather than sexual reproduction) helps maintain a dense monotypic stand structure (Anderson, 1974).

Higher elevation areas can have different species composition. Compared to low marsh, higher elevation zones can be more saline in drier climates, due to evaporative concentration of salts, or less saline in higher rainfall areas, due to frequent flushing of salts by fresh rainwater. *Spartina patens* and *Juncus* species are common to less saline areas or areas that are less frequently inundated (high marsh). Other halophytic succulents including *Salicornia* spp (Anderson, 1974) are common in drier climates or impounded areas that can yield hypersaline soils, also often associated with high productivity algal mats (Zedler, 1980).

Microbial Community Structure

Salt marsh microorganisms are composed of fungi, bacteria, and other microorganisms that occupy the rhizosphere and litter layers. Microbial processes, mediated through soil reduction-oxidation status, control the major nutrient cycles (C, N, S) and provide an energy source that impacts decomposition of organic matter, nutrient mineralization, phytotoxin availability, and ultimately landscape-level productivity. Thus, microbial communities are essential to the ecological functioning of salt marshes. Studies have shown that microbial communities, or at least the fluxes they control, can be fairly resilient against pollution effects (DeLaune et al., 1979b; Li et al., 1990). However, natural disturbances, such as sea-level rise, have the potential to alter soil respiration through changes in microbial community composition and function (Chambers et al., 2013).

Ecosystem Function

Elevation Change

Elevation change is an essential function for the sustainability of salt marsh ecosystems, but interpretation of that change should be placed in the context of sea level, sea-level change, and tidal variability (Cahoon, 2015). Elevation deficits occur with sea-level rise and surface erosion and subsidence, which is influenced by decomposition of organic matter and compaction of sediments (Cahoon and Turner, 1989), subsurface withdrawals (e.g., water, oil, gas), and geologic activity (Kennish, 2001). Elevation gains occur by accretionary processes of sediment deposition and *in situ* biomass production contributing to organic accretion (Cahoon et al., 2006). Thus, in a sustainable salt marsh, elevation relative to sea level must be in balance (Cahoon, 2015). However, organic accumulation and sedimentation rates are dependent on tidal flooding and the relative elevation within the tidal range; accordingly, areas with a smaller tidal range, such as those in the NGoM, are more vulnerable to sea-level rise (Kirwan and Megonigal, 2013). For example, spring tidal ranges in the NGoM vary from approximately 0.3 m in south Texas to 1 m in south Florida, whereas elsewhere on the Atlantic and Pacific coasts, tidal ranges vary from 1 to > 3 m (Tiner, 2013). Despite high productivity in the NGoM region (Kirwan et al., 2009), total accretion rates are generally low (Neubauer, 2008) because of aforementioned alterations to allochthonous sediment supply.

Primary Production

Salt marshes can be highly productive ecosystems (Mitsch and Gosselink, 2007), and the NGoM *S. alterniflora* salt marshes are among the most productive salt marshes in the U.S. (Kirwan et al., 2009). Other salt marsh systems (e.g., succulents) tend to have less productive vegetation, but these wetlands often contain algal mats that can have high productivity (Zedler, 1980). Total primary production in plants is allocated across many different components: leaf, stem, root, and seed/fruit production; root exudates (which contribute to soil respiration); and photorespiration and maintenance respiration (Chapin et al., 2002). Aboveground biomass is the most visible component; however, it is not necessarily proportional to other components. For example, increased nutrients can increase aboveground biomass but dramatically decrease belowground production (Deegan et al., 2012). Primary production is a function of the availability of resources, capture of resources, and efficiency in use. Given that light and carbon dioxide are primary resources contributing to production, changes in climate may have major effects on production. However, shorter-term variations in productivity are mostly an effect of seasonal variation, direct anthropogenic effects, and hydrogeomorphic influences.

Intermediate elevation (relative to the tidal range) is generally optimal for vegetation growth, with decreased production at both high and low elevations (Morris et al., 2002). Severe drought is associated with sudden marsh dieback (McKee et al., 2004). While freshwater inputs can augment production (Mitsch and Gosselink, 2007), extended flood events associated with sea-level rise can lead to salt marsh deterioration and submergence (Boesch et al., 1984). The effects of pollution are not well understood, but oil spills may result in dieback that constitutes a short-term dramatic decrease in production.

Secondary Production

Secondary production of salt marshes—dominated by birds, fish, invertebrates, and other soil microbiota—is affected by energy sources, habitat quality, and system connectivity. Salt marshes are particularly important as nurseries, providing many fish and birds with shelter not available in other aquatic and wetland systems. These factors, however, are dependent on marsh elevations and vegetation structure and production.

The same perturbations that affect vegetation and soils (pollution, submergence, and landscape modification) also affect habitat quality. Fragmentation of the landscape (by channels, or simply by marsh loss) can have major detrimental impacts on marsh bird species, such as clapper rail and seaside sparrow. The aquatic species (shellfish and fish) are highly dependent on the provisioning of decomposed organic matter and associated biogeochemical processes (Mitsch and Gosselink, 2007).

Decomposition

Secondary production in salt marshes largely relies on decomposition (herbivores use only a small fraction of live biomass) and the organic exports that support the ecosystem (Teal et al., 1986). The soil fungal and bacterial communities account for the majority of detrital decomposition (Teal et al., 1986), and the detritus is efficiently converted to bacterial biomass that contributes to cycling of other nutrients (Mitsch and Gosselink, 2007). In salt marshes, only ~5% of carbon produced *in situ* is exported from the system, indicating that the carbon either decomposes or is stored (Howes et al., 1985), illustrating the importance of decomposition for the overall functioning of the ecosystem.

Biogeochemical Cycling

Biogeochemical cycles are inexorably involved in all factors discussed above because of the chemical transformations and exchanges that occur. These transformations mostly occur in soil, largely facilitated by microbiota (Boon, 2006). Nitrogen cycles are especially distinct in wetlands because of the presence of both oxic and anoxic conditions, enabling nitrification and subsequent denitrification (Mitsch and Gosselink, 2007). In areas where nitrogen is unnaturally elevated, nitrogen cycling in wetlands can play an important role in reducing eutrophication.

The accretion of nutrient-rich sediments in marshes can allow for storage of nutrients, removing a portion from circulation. Accordingly, the conditions that allow long-term capture, storage, or transformation are essential to marsh maintenance, because they are part of the stabilization of sediments required for vertical accretion; that is, pedogenesis results in more stability than disaggregated sediments would otherwise have.

Biogeochemical cycling in marshes also affects production in the connected aquatic systems by controlling the chemistry of exports (N, P, and C concentrations and forms) into those systems. Less direct but important effects of biogeochemical cycling are the atmospheric fluxes of CO_2, CH_4, and NO_2 (Chmura et al., 2011), which alter atmospheric chemistry and radiative forcing.

Factors Involved in Ecosystem Service Provision

Salt marshes provide a wealth of supporting, regulating, provisioning, and cultural services that include soil and sediment (shoreline stabilization) maintenance, nutrient regulation and water quality, food provision, recreational opportunities, and hazard moderation (NAS, 2013). Their ability to provide these services can be compromised by stressors that degrade key ecological attributes. For example, salt marshes with good integrity accumulate sediments at rates that can keep the marsh in equilibrium with sea level. The suspended solids carried by tides over the marsh surface increase in part with the density and production of standing vegetation. In addition to surface deposition, production of organic matter, primarily of roots and rhizomes, contributes to the total accumulation rate (Stagg et al., 2016). Thus, declines in the indicator values of key ecological attributes related to marsh elevation, primary production, or root biomass translate into changes that will lower the ecosystem services of these marshes. A complete list of the services provided by salt marshes in the NGoM is provided by Yoskowitz et al. (2010). Below we provide an overview of the five most important Key Ecosystem Services that we included in the conceptual ecological model.

Supporting

Habitat

Saltmarsh habitat is essential for healthy estuaries, fisheries, coastlines, and communities. These ecosystems provide nursery habitat, refuge, and other services for more than 75% of fisheries species, including commercially important shrimp, blue crab, and many finfish (NOAA, 2016). The ability of the salt marsh to provide habitat for commercially important species depends on the factors described for the “Secondary Production” Key Ecological Attribute above.

Regulating

Coastal Protection

Another important service of salt marshes is shoreline protection. Marshes protect the coast from erosion by attenuating wave action and trapping sediments. This is especially important as sea level rises due to climate change, and our coasts become more vulnerable in places where marshes are not present or are threatened (TNC and NOAA, 2011).

Water Quality

Salt marshes protect water quality by filtering runoff. Salt marsh vegetation enhances sediment deposition, thereby removing suspended solids from the water column (Leonard and Luther, 1995). Additionally, salt marsh vegetation reduces the nutrient load in the water column through uptake and metabolism of excess nutrients in estuarine systems (Mitsch and Gosselink, 2008).

Carbon Sequestration

As one of the most productive ecosystems in the world, salt marshes sequester millions of tons of carbon annually in their anoxic soils. They are considered one of the most powerful carbon sinks on the planet (Macreadie et al., 2013). Carbon is sequestered in their leaves, stems, and roots, which are buried by accumulated sediment. Carbon is eventually released through respiration, or by disturbances to the sediments, including through excavation, dredging, or severe storms, such as hurricanes. Carbon storage and sequestration in coastal wetlands are increasingly being valued as part of "blue carbon" initiatives (McCleod et al., 2011).

Cultural

Aesthetics/Recreational Opportunities

Marshes provide a unique and aesthetic landscape that benefits millions of people living on the coast (Barbier et al., 2011). Recreational fishing is one such benefit, as is bird watching.

Indicators, Metrics, and Assessment Points

Using the conceptual model described above, we identified a set of indicators and metrics that we recommend for monitoring salt marsh ecosystems across the NGoM. Table 2.1 provides a summary of the indicators and metrics proposed for assessing ecological integrity and ecosystem services of salt marsh ecosystems organized by the Major Ecological Factor or Service (MEF or MES) and Key Ecological Attribute or Service (KEA or KES) from the conceptual ecological model. Note that indicators were not recommended for several KEAs or KESs. In these cases, we were not able to identify a practical indicator based on our selection criteria. In some instances, the name of the indicator and the name of the metric are the same, which simply reflects that the indicator is best known by the name of the metric used to assess it. Below we provide a detailed description of each recommended indicator and metric(s), including a rationale for its selection, guidelines on measurement, and a metric rating scale with quantifiable assessment points for each rating.

We also completed a spatial analysis of existing monitoring efforts for the recommended indicators for salt marsh ecosystems. Figure 2.3 provides an overview of the overall density of indicators monitored. Each indicator description also includes a more detailed spatial analysis of the geographic distribution and extent to which the metrics are currently (or recently) monitored in the NGoM, as well as an analysis of the percentage of active (or recently active) monitoring programs that are collecting information on the metric. The spatial analyses are also available in interactive form via the Coastal Resilience Tool (http://maps.coastalresilience.org/gulfmex/) where the source data are also available for download.

***Table 2.14**. 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/*Basin-wide Nutrient Load (Total Nitrogen, Total Phosphorus)*
		Soil Physicochemistry	--
	Ecosystem Structure	Marsh Morphology	Land Aggregation/*Aggregation Index (AI)*
			Lateral Migration/*Shoreline Migration*
		Plant Community Structure	--
		Microbial Community Structure	--
	Ecosystem Function	Elevation Change	Submergence Vulnerability/*Wetland Relative Sea Level Rise ($RSLR_{wet}$) and Submergence Vulnerability Index (SVI)*
		Primary Production	Above Ground Primary Production/ *Aboveground Live Biomass Stock*
			Below Ground Primary Production/*Soil Shear Stress*
		Secondary Production	Specialist Birds/*Clapper Rail and Seaside Sparrow Density*
		Decomposition	--
		Biogeochemical Cycling	--
Ecosystem Services	Supporting	Habitat	Specialist Birds/*Clapper Rail and Seaside Sparrow Density*
	Regulating	Coastal Protection	Wave Attenuation/*Percent Wave Height Reduction per Unit Distance*
		Water Quality	Nutrient Reduction/*Basin-wide Nutrient Load (Total Nitrogen, Total Phosphorus)*
		Carbon Sequestration	Soil Carbon Density/*Soil Carbon Density*
	Cultural	Aesthetics-Recreational Opportunities	Recreational Fishery/*Spotted Seatrout Density and Recreational Landings of Spotted Seatrout*

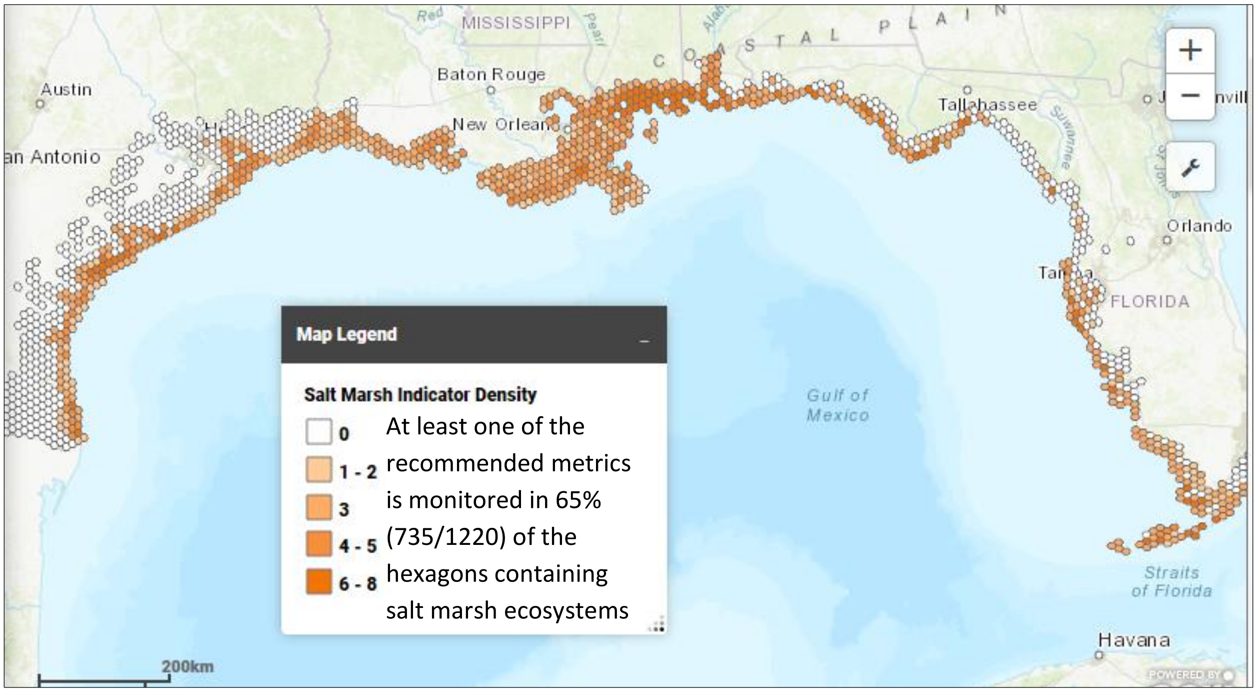


Figure 2.12. *Density of the recommended indicators being collected in salt marsh ecosystems in the NGoM. Shaded hexagons indicate the number of the recommended indicators that are collected by monitoring programs in each hexagon.*

Ecological Integrity Indicators

Indicator: Eutrophication

MEF: Abiotic Factors
KEA: Water Quality
Metric: Basin-wide Nutrient Load (Total Nitrogen [TN] and Total Phosphorus [TP])

Definition: An excess of mobilized nitrogen and phosphorus, measured in spatially explicit hydrologic units (following Hydrologic Unit Codes [HUCs] http://water.usgs.gov/nawqa/sparrow/) that encompass and contribute (downstream) to salt marshes.

Background: Eutrophication affects salt marsh vegetation structure and fisheries and aquatic communities. Perhaps the most notable effect of excess nutrient availability on vegetation is the decline of root-to-shoot ratios, which reflects decreasing belowground productivity and can lead to increased soil erosion and marsh collapse (Deegan et al., 2012). Additionally, eutrophication reduces dissolved oxygen concentrations and light transmission in surface water, with negative effects on competing aquatic biota.

Rationale for Selection of Variable: This metric was chosen because of the importance of nutrient availability to salt marsh ecosystem functioning and the prevalence of excess nutrients in the study region (Smith, 2003). TN and TP were selected because both nutrients are primary drivers of eutrophication and both have widely available data with existing assessment criteria.

Annual mean TN and TP concentrations are appropriate for assessment metrics, because nutrient fluxes vary at multiple spatial and temporal scales. Therefore, point measurements in space and time do not accurately represent the overall ecosystem condition with respect to nutrient cycling. Thus, a spatially and temporally aggregated metric is preferable for monitoring eutrophication. The HUC 8 scale is the most readily available aggregated measure available at spatial and temporal scales relevant to ecosystem condition trends.

Measures: Total phosphorus in mg L^{-1} and total nitrogen in mg L^{-1} (basin-wide)

Tier: 1 (remotely sensed and modeled)

Measurement: SPARROW (Spatially-Referenced Regression on Watershed Attributes) is a model that estimates basin-level long-term average fluxes of nutrients (Preston et al., 2011). The model integrates monitoring site data at high temporal resolution to develop site rating curves (integrating streamflow and water quality data) which are then extrapolated to individual basins with values scaled by land classifications within basins. The user-friendly online interface allows determination of both TN and TP loads for specific basins to identify relative water quality fluxes.

Metric Rating and Assessment Points:

Metric Rating	Basin-wide Nutrient Load (mg L^{-1})
Excellent	TP < 0.1 and TN < 1.0
Good	TP 0.1–0.2 and TN 1.0–2.0
Fair	TP 0.2–0.9 and TN 2.0–7.0
Poor	TP > 0.9 and TN > 7

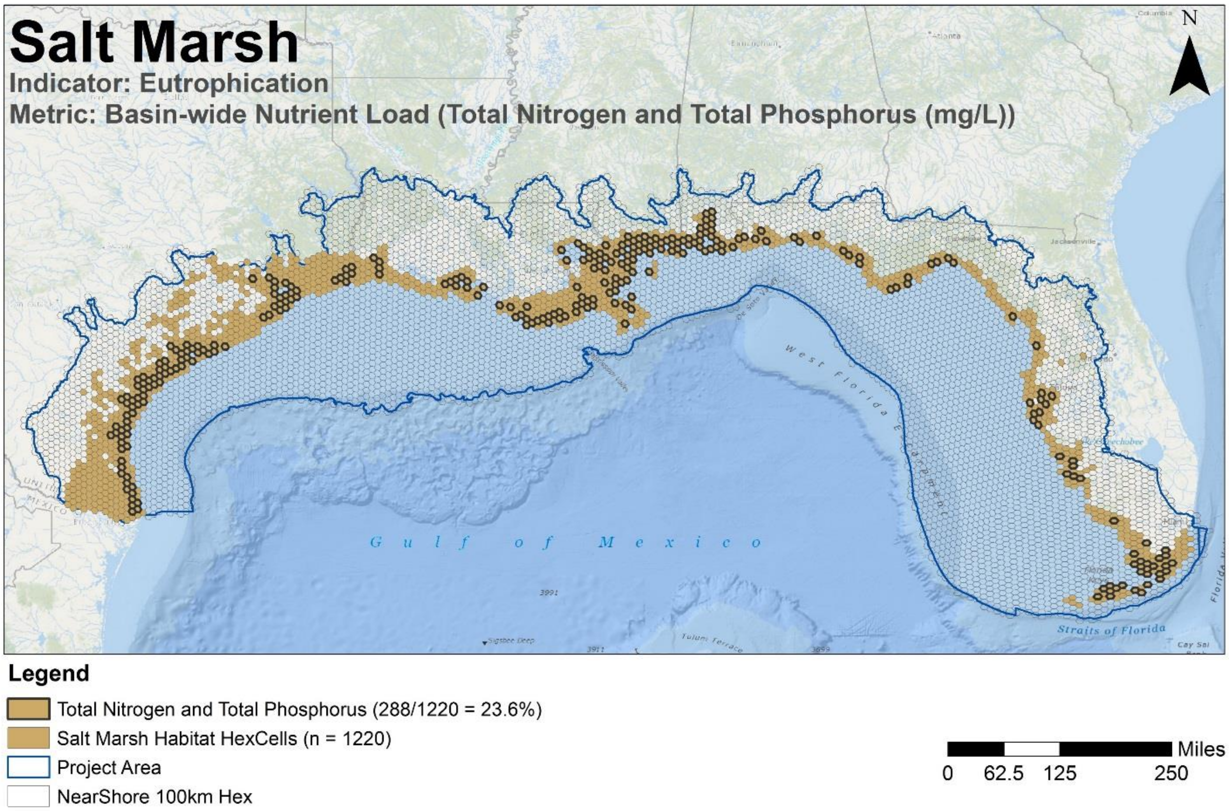
Scaling Rationale: SPARROW outputs for TN concentration range from near 0.05 to > 7 mg L^{-1} in coastal basins of the NGoM. TP concentrations range from near 0.00 to > 0.9 mg L^{-1} in coastal basins of the NGoM. While low nutrient concentrations do not necessarily indicate superior ecological function for all aspects of the ecosystem, the potential for eutrophication declines with lower nutrient concentration values. Assessment points were established in accordance with the SPARROW output breakpoints for mapping convenience; groupings were established to flag higher values as fair or poor. These higher values are in ranges generally associated with impaired water quality; of the NGoM states, only Florida has state-specific criteria (e.g., ~0.4 to 1 mg L^{-1} TN, depending on specific estuary; US EPA, 2016).

Analysis of Existing Monitoring Efforts:

<u>Geographic</u>: Basin-wide nutrient load is moderately well collected geographically in the NGoM, with 24% of habitat hexagons containing at least one monitoring site. Monitoring locations for this metric are relatively well distributed across the NGoM, with multiple monitoring sites in each state.

<u>Programmatic:</u> Data for this metric are collected by 5/49 (10%) of programs collecting relevant salt marsh data in the NGoM.

A list of the salt marsh monitoring programs included on the map and table below is provided in Appendix IV.



Metric	Number of Salt Marsh Monitoring Programs	Number of Programs Monitoring the Indicator	Percentage of Programs Monitoring the Indicator	Percent of Ecosystem Hexagons that Contain Monitoring Sites for the Indicator
Basin-wide Nutrient Load	49	5	10%	24%

Indicator: Land Aggregation

MEF: Ecosystem Structure
KEA: Marsh Morphology
Metric: Aggregation Index (AI)

Definition: The physical structure of the marsh, accounting for topography, spatial distribution and shape of land and water elements. This structure can partially be described quantitatively by the number of identical adjacent pixels of either water or land per pixel.

Background: The lateral erosion and vertical subsidence of salt marshes are both related to the shape of the landscape. Subsidence generally occurs in interior marshes (Friedrichs and Perry, 2001), and thus the land form can suggest the relative degradation (Couvillion et al., 2016). The organization of the landscape structure is highly indicative of past changes and future trajectory (Kennish, 2001). Disaggregation also alters the flow of water into and out of the marsh and thus modifies where and whether deposition occurs (Bass and Turner, 1997).

Rationale for Selection of Variable: The organization of the landscape differs between healthy and degraded marsh, with a degraded or degrading marsh showing evidence of increased erosion, increased open water, and increased fragmentation of the landscape. In addition to indicating marsh loss, AI is important to quality of habitat.

Measure: Landsat 30 m pixels classified as either water or marsh

Tier: 1 (remotely sensed)

Measurement: Remote sensing (tier 1) techniques with Landsat data (30 m resolution) can provide the data needed to calculate the aggregation index, a metric quantifying the fraction of pixels with adjacent pixels of the same classification; precise methodological details are in Couvillion et al. (2016). This requires classifying the pixel as either water or marsh, and then applying the analysis directly to the raster of classified pixels. AI was calculated for a given area of interest (AOI):

$$\mathrm{AI} = \sum \frac{\text{Adjacencies per pixel}}{\text{Class Pixel Count } \times 8} \times \text{Percent AOI}$$

This yields values from zero to 100, with Adjacencies Per Pixel = the number of adjacencies of like class value per pixel, Class Pixel Count = the number of pixels of the class within the AOI, and Percent AOI = the percent area occupied by the class within the AOI. The aggregation index should be calculated as a moving average across 250 m square AOIs for a landscape-level assessment (integrating marsh and open water; Couvillion et al., 2016).

Metric Rating and Assessment Points:

Metric Rating	Aggregation Index (AI)
Good	Aggregation index is > 80%
Fair	Aggregation index is 50–80%
Poor	Aggregation index is < 50%
Severe	Aggregation index is < 20%

Scaling Rationale: Land aggregation scaling thresholds are defined with respect to Figure 2.4 in Couvillion et al. (2016). Nearly all sites with an aggregation index > 80% had 0–1% loss per year; few areas show 0% wetland loss. From 50% to 80% aggregated, losses increase. Below 50%, there are substantially higher loss rates, and below 20%, wetland loss rates are substantially higher and represent severe conditions.

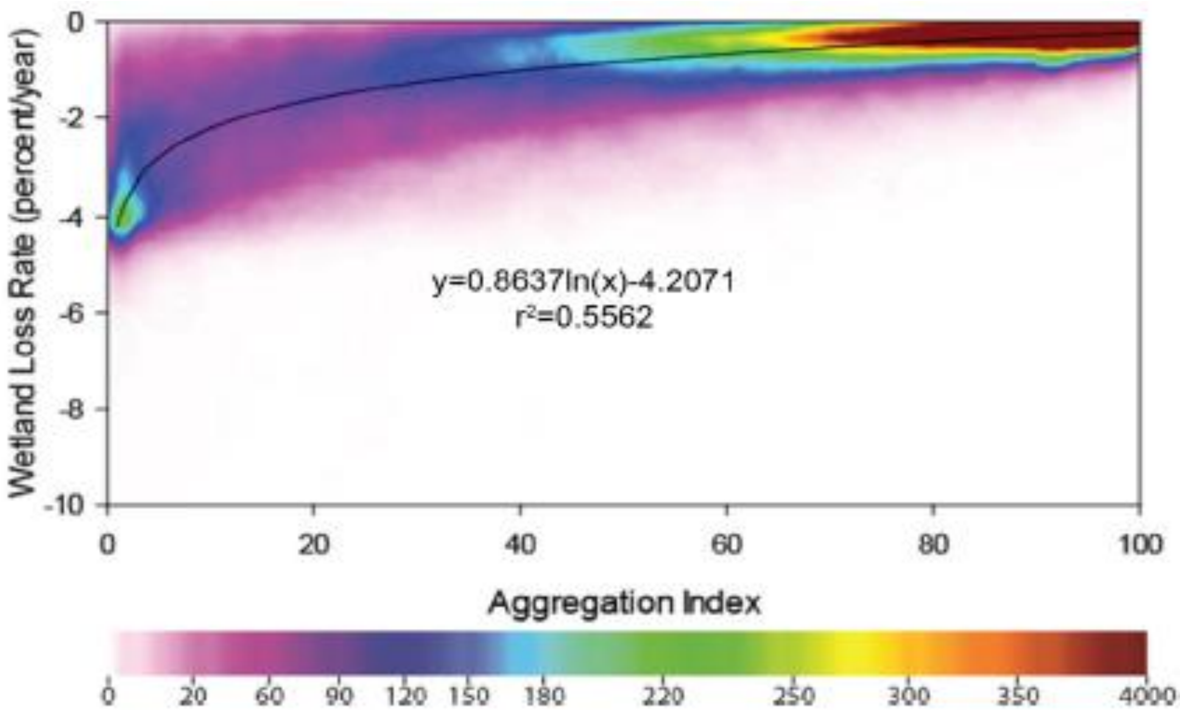


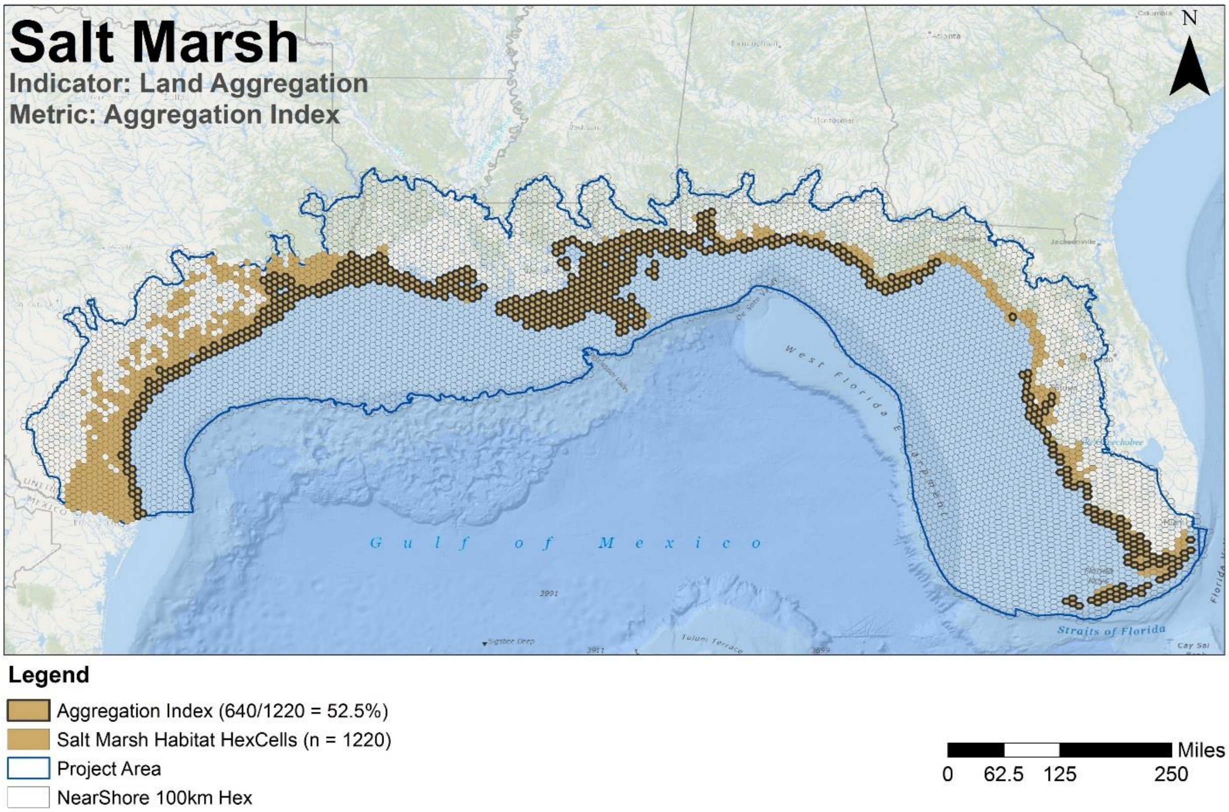
Figure 2.13. *Aggregation index versus change rate. From Couvillion et al., 2016.*

Analysis of Existing Monitoring Efforts:

<u>Geographic</u>: The data needed to calculate aggregation index are very well collected geographically in the NGoM, with 53% of habitat hexagons containing at least one monitoring site. Monitoring locations for this metric are relatively well distributed across the NGoM, with multiple monitoring sites in each state. Somewhat lower collection is evident along the Big Bend (and somewhat south) of Florida.

<u>Programmatic:</u> Data that allow for the calculation of this metric are collected by 23/49 (47%) of the programs collecting relevant salt marsh data in the NGoM.

A list of the salt marsh monitoring programs included on the map and table below is provided in Appendix IV.



Metric	Number of Salt Marsh Monitoring Programs	Number of Programs Monitoring the Indicator	Percentage of Programs Monitoring the Indicator	Percent of Ecosystem Hexagons that Contain Monitoring Sites for the Indicator
Aggregation Index	49	23	47%	53%

- Not all monitoring programs calculate aggregation index, but collect the data necessary to enable calculation. These programs were included in the map.
- Very large spatial footprints for two monitoring programs made assessment of sampling sites uncertain, and they were omitted from the map. Percent of hexagons containing monitoring sites may be an underestimate.

Indicator: Lateral Migration

MEF: Ecosystem Structure
KEA: Marsh Morphology
Metric: Shoreline Migration

Definition: The change in the location of the shore.

Background: Marsh loss can be monitored by measuring the location of the shoreline over time. At the local scale, the lateral retreat of the marsh can be seen by both a transition to open water and increased erosion at the water-marsh interface (Fagherazzi et al., 2013). This metric can be monitored by land use change via remote sensing or with field based measurements. Both measurement techniques are described below. The metric ratings and associated thresholds are the same for each measurement.

Rationale for Selection of Variable: Measuring the migration of the shoreline is a direct measurement of erosion and lateral marsh loss or gain.

Measure: Change in shoreline position

Tier: 1 (remotely sensed)

Measurement 1: Analysis of change in the shoreline position using remotely sensed land change data for the marsh edge. Remote-sensed data is valuable for analyzing trends in land change. However, in wetlands, it is critical to account for differences in fluvial and inundation differences when the images were captured. Multi-temporal data from the Landsat database (1983–current) can be used along with inundation data to estimate changes in the shoreline of a particular marsh. Multi-temporal analysis should be conducted according to Allen et al. (2011) to account for differences in inundation. When the required data is not available for a specific time period or location, use the Tier 3 field intensive approach.

Tier: 3 (intensive field measurement)

Measurement 2: Quantitative field survey of change in the shoreline position by GPS survey of marsh edge. Establish repeat measurement sites for which yearly GPS surveys of the marsh edge will be recorded. These may be co-located with vegetation assessment plots. Measurements after extreme events (e.g., hurricanes) are also warranted. Data should not be assessed until a several-year record is collected.

Metric Rating and Assessment Points:

Metric Rating	Shoreline Migration
Good	Net gains (significantly > 0 m over 5 years)
Fair	No change (0 m over 5 years)
Poor	Net losses (significantly > 0 m over 5 years)

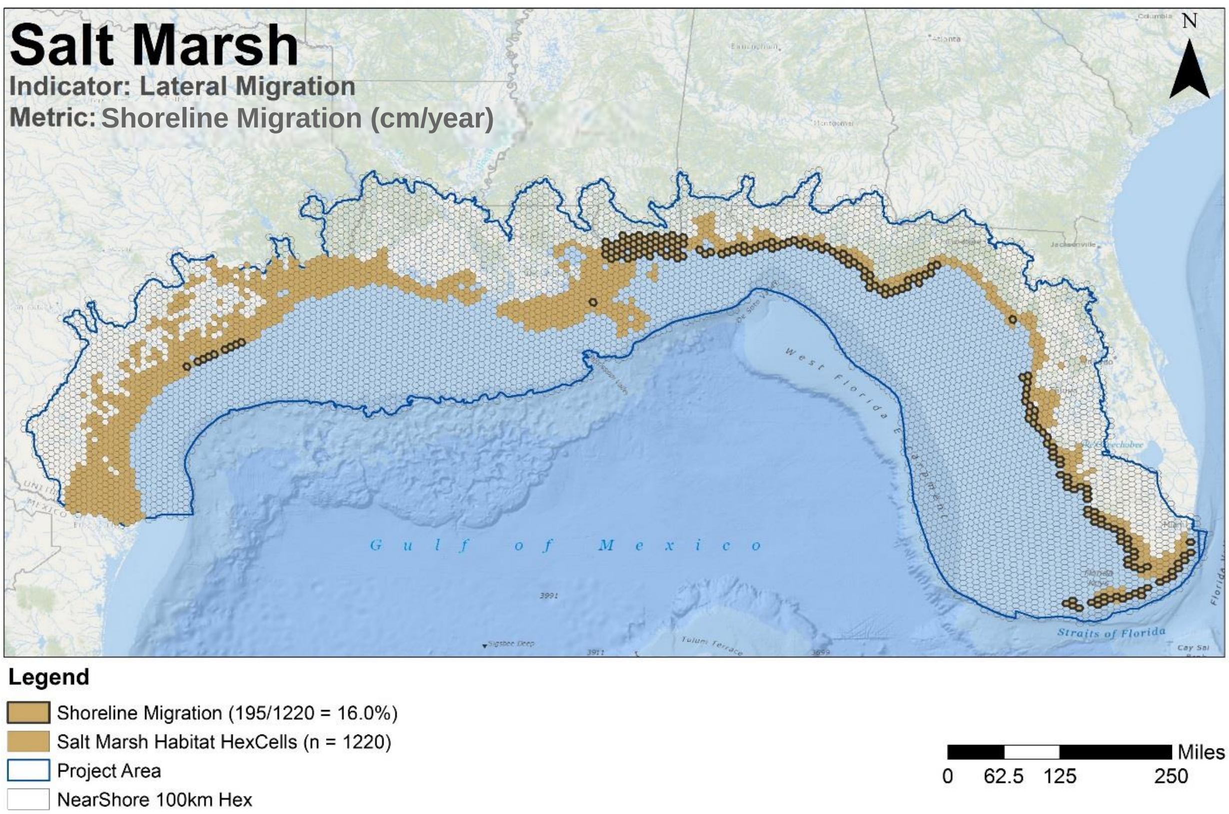
Scaling Rationale: While channel and marsh morphology are temporally dynamic and a natural element of variation, a net lateral loss (e.g., channel widening or submergence) is a negative effect. Thus, thresholds are simply statistically significant gain, no change, or significant loss. For context, Louisiana marsh erosion rates average -8.2 m y^{-1}, which we know to be a "poor" condition system (Morton et al., 2005). Statistical significance can be evaluated by t-test test of H_0 = no change.

Analysis of Existing Monitoring Efforts:

Geographic: Lateral Shoreline Migration is less well collected geographically in the NGoM, with 16% of habitat hexagons containing at least one monitoring site. Monitoring locations for this metric are skewed towards Mississippi, Alabama, and Florida (except the Big Bend and somewhat south), with very few collections in Louisiana and Texas.

Programmatic: Data for this metric are collected by 8/49 (16%) of the programs collecting relevant salt marsh data in the NGoM.

A list of the salt marsh monitoring programs included on the map and table below is provided in Appendix IV.



Metric	Number of Salt Marsh Monitoring Programs	Number of Programs Monitoring the Indicator	Percentage of Programs Monitoring the Indicator	Percent of Ecosystem Hexagons that Contain Monitoring Sites for the Indicator
Shoreline Migration	49	8	16%	16%

Indicator: Submergence Vulnerability

MEF: Ecosystem Function
KEA: Elevation Change
Metric: Wetland Relative Sea Level Rise ($RSLR_{wet}$) and Submergence Vulnerability Index (SVI)

Definition: The rate of change in marsh surface elevation with respect to a hydrologic datum.

Background: Marsh elevation increases with organic and mineral accretion. Accretionary processes feedback with elevation, such that sediment deposition rate (i.e., mineral accretion) is higher at lower elevation (with greater flood depth); conversely, accretion rates decline as elevation increases (lower flood depth). Productivity (and thus organic accretion) is maximized in intermediate conditions, but decreases at both extreme high and low elevation (Morris et al., 2002). The ability of the marsh to maintain its intertidal position during periods of sea-level rise, in spite of other negative forces, is an example of an emergent ecosystem property of resilience (*sensu* Holling, 1973), and thus elevation change can be used as a measure of resilience to sea-level rise. However, with this feedback, sites with a smaller tidal range, such as those in the NGoM, are more vulnerable to sea-level rise (Kirwan and Megonigal, 2013).

Rationale for Selection of Variable: Elevation change is a key indicator of marsh vulnerability, because elevation change (1) integrates ecologically relevant biogeochemical, hydrogeomorphic, and biologic processes (Kirwan and Megonigal, 2013), and (2) it indicates vulnerability to submergence when compared with sea-level rise (Cahoon, 2015). Wetland elevation should be measured alongside water level to quantify wetland relative sea-level rise ($RSLR_{wet}$), which is the difference between tide gauge RSLR and wetland surface elevation (Cahoon et al., 2015). An elevation rate deficit (sea level rising compared to wetland elevation) indicates vulnerability, whereas an elevation rate surplus (sea level falling compared to wetland elevation) indicates stability. However, because this assessment only considers differences between the water and wetland trajectories, a wetland that is situated high in the tidal frame with an elevation rate deficit may be considered vulnerable, when in fact it is not excessively flooded and has high rates of production (Morris et al., 2002). Therefore, when possible, an index of relative elevation within the tidal frame must also be used (submergence vulnerability index, SVI; Stagg et al., 2013) in complement to $RSLR_{wet}$.

Measure: The rate of change in marsh surface elevation, based on rod surface elevation tables (RSET) with respect to a hydrologic datum

Tier: 3 (intensive field measurement)

Measurement: Elevation change is measured using rod surface elevation tables (RSET; Cahoon et al., 2002a, 2002b). The elevation of the marsh surface relative to a fixed datum, established by a rod driven into the substrate until refusal, is measured periodically. Surface elevation change is quantified by estimating the change in marsh surface elevation over time using linear regression. Surface elevation change represents surface and subsurface processes occurring between the marsh surface and the bottom of the rod benchmark (Cahoon et al., 2002a). RSET stations are currently installed in many locations across NGoM states. SETs are generally measured at six-month intervals, with data quality improving over length of measurement. Further details are available at http://www.pwrc.usgs.gov/set/.

RSET measurements should be paired with water level measurements and sea-level rise rates (NGoM sea-level rise rates range from 1.38 mm yr^{-1} to 9.65 mm yr^{-1}, with highest values from east Texas through Mississippi and with lower values on the Alabama and Florida coasts [Pendleton et al., 2010]).

The calculation of SVI is a comparison of projected elevation to projected tidal range to assess not only the differences in trajectories, but also the relative position of the wetland within that tidal range. The SVI is a projection of wetland flooding frequency five years into future, accounting for tidal amplitude, periodicity, and projected site-relative elevation. In addition to long-term RSET and hydrologic data, wetland and water elevation must be referenced to a common datum (NAVD 88) to calculate the SVI (Stagg et al., 2013).

Metric Rating and Assessment Points:

Metric Rating	$RSLR_{wet}$ and SVI
Good	$RSLR_{wet}$ is negative or stationary (sea level falling relative to wetland), or $RSLR_{wet}$ is positive and SVI > 50
Poor	$RSLR_{wet}$ is positive (sea level rising relative to wetland) and SVI < 50

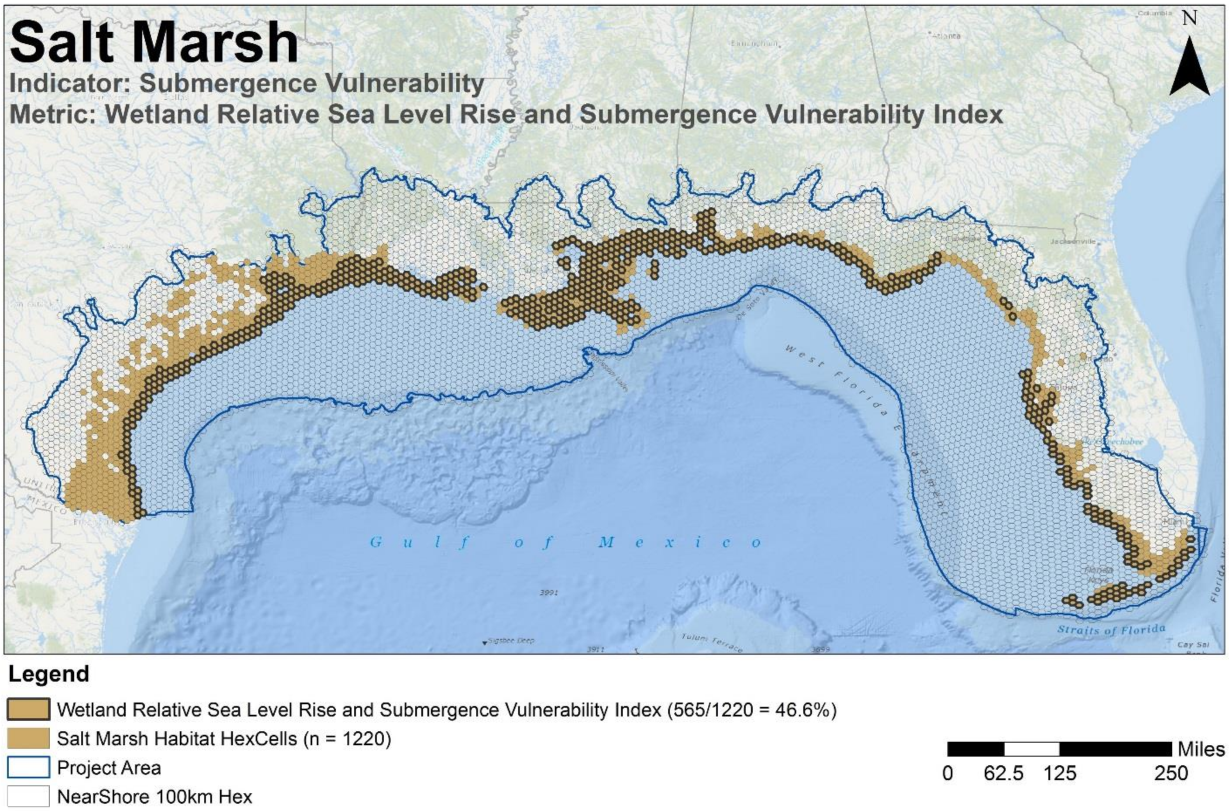
Scaling Rationale: Good conditions are met when the wetland elevation is either matching or exceeding sea-level rise. Poor conditions occur when the wetland elevation is declining relative to sea level, which indicates that marsh is submerging. When $RSLR_{wet}$ is positive but the salt marsh elevation is high (SVI > 50), the wetland cannot be considered unstable. Although wetlands situated higher in the tidal frame may have a negative elevation trajectory due to low rates of accretion associated with shallow flood depth (Morris et al., 2002), the wetland is not excessively flooded or at risk of submergence.

Analysis of Existing Monitoring Efforts:

<u>Geographic</u>: Wetland relative sea-level rise ($RSLR_{wet}$) and submergence vulnerability index (SVI) are moderately well collected geographically in the NGoM, with 47% of habitat hexagons containing at least one monitoring site. Monitoring locations for this metric are relatively well distributed across the NGoM, with multiple monitoring sites in each state.

<u>Programmatic:</u> Data for this metric are collected by 17/49 (35%) of the programs collecting relevant salt marsh data in the NGoM.

A list of the salt marsh monitoring programs included on the map and table below is provided in Appendix IV.



Metric	Number of Salt Marsh Monitoring Programs	Number of Programs Monitoring the Indicator	Percentage of Programs Monitoring the Indicator	Percent of Ecosystem Hexagons that Contain Monitoring Sites for the Indicator
Wetland Relative Sea Level Rise ($RSLR_{wet}$) and Submergence Vulnerability Index (SVI)	49	17	35%	47%
• Spatial footprint for one monitoring program was not available and not included on the map. Percent of hexagons containing monitoring sites may be an underestimate.				

Indicator: Aboveground Primary Production

MEF: Ecosystem Function
KEA: Primary Production
Metric: Aboveground Live Biomass Stock

Definition: Aboveground primary production of vegetation is the annual biomass growth per area. For *S. alterniflora*, aboveground standing live biomass calculated from stem height can be used as a proxy for aboveground production. Other species, when significantly present, should be sampled to assess aboveground production.

Background: Salt marshes are one of the most productive ecosystems globally (Mitsch and Gosselink, 2007), and salt marshes in the NGoM are among the most productive (Kirwan et al., 2009). At a system level, this high biomass is important because it not only reflects the overall productivity of the system, but also drives accretion that is necessary for the sustainability of the marshes (Morris et al., 2002; Neubauer, 2008). There are natural variations in production related to hydrogeomorphic position on the landscape, where intermediate elevations have the greatest production. Accordingly, unstable water-level fluctuations (especially with relative sea-level rise) can also affect production (Gedan et al., 2010).

Rationale for Selection of Variable: Aboveground net primary production is a challenge to measure because of complexities of carbon allocation (Chapin et al., 2002) and high turnover within growing seasons (e.g., Kirby and Gosselink, 1976). For measurement efficiency, we instead recommend aboveground standing live biomass as a proxy. Biomass has important limitations (Linthurst and Reimold, 1978), but is a better metric than aboveground net primary production for rapid assessment.

Measure: Height of the five tallest plants (mm)

Tier: 2 (rapid field measurement)

Measurement: Randomly establish a 0.1 m^2 quadrat in at least 10 sampling points within the site.

For *S. alterniflora* marshes, within the quadrat, measure and average the height of the five tallest plants. Aboveground standing (live) biomass of a *S. alterniflora*–dominated marsh is estimated non-destructively using the culm height of *S. alterniflora*, in the following equation:

$$b = 0.074 \times h \times c + 15.973$$

where b is standing live biomass (dried) in g m^{-2}, h is the height in mm, and c is a scaling coefficient with value of 10 (Valiela et al., 1976). Measurements should be taken at the end of the growing season for comparison to assessment points.

For other species, scaling relationships have not been established, so individuals should be destructively harvested (cut the soil surface within quadrats), brought back to lab, and dried to a constant mass. Dry mass per m^2 is the sum of all ten 0.1 m^2 quadrats.

Metric Rating and Assessment Points:

Metric Rating	Aboveground Live Biomass Stock
Good/Excellent	Standing biomass > 600 g m^{-2}
Fair	Standing biomass 300–600 g m^{-2}
Poor	Standing biomass < 300 g m^{-2}

Scaling Rationale: The linkage between biomass and aboveground productivity was derived by comparing the biomass values compiled in Kirwan et al. (2009) versus productivity values described in other *S. alterniflora* studies in the southeastern US (Bellis and Gaither, 1985; Kirby and Gosselink, 1976; Morris and Haskin, 1990; Visser et al., 2006; White et al., 1978). Generally, aboveground primary productivity is one to two times higher than end of season biomass. While substantially higher values are reported (e.g., Darby and Turner, 2008, and others cited in Mitsch and Gosselink, 2007), they often are a function of assumed high turnover rates. Typical values of standing biomass for *Distichlis spicata* (Bellis and Gaither, 1985), *Juncus roemerianus* (Bellis and Gaither, 1985), and *Spartina patens* marshes (Ruber et al., 1981; White et al., 1978; Linthurst and Reimold, 1978) are similar; biomass for succulents (e.g., *Salicornia spp*.) are lower, but still within the ranges presented here (Zedler et al., 1980; Rey et al., 1990), particularly if the algal mat is also sampled (Zedler, 1980).

For the combined good/excellent rating, assessment point values were not set extremely high so that they encompass the majority of records typical across a marsh gradient. This range represents the values seen for most NGoM and southeastern Atlantic coast studies (Kirwan et al., 2009). Very high values are not needed for marsh resilience (Kirwan et al., 2016). The values for the fair rating are derived from the same meta-analysis, but with values accounting for aboveground net primary production up to 600 g m^{-2}, which encompasses the lower third of studies.

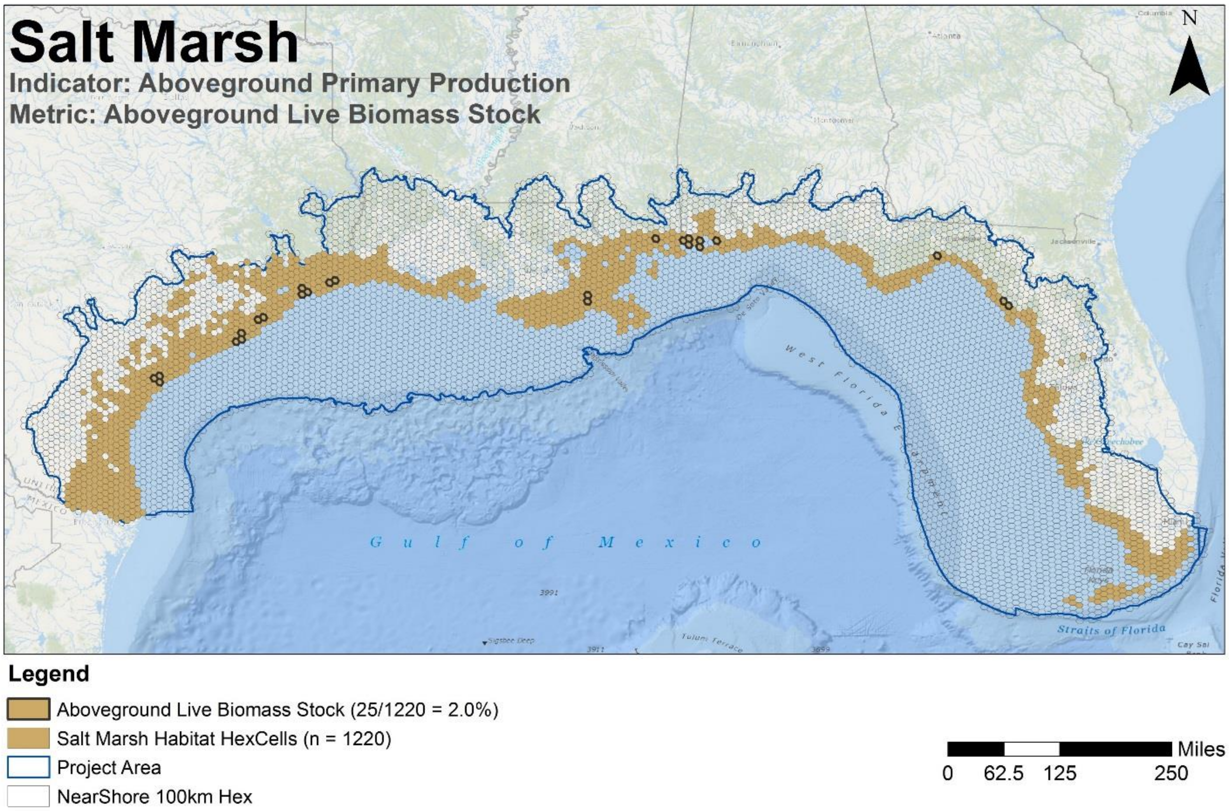
The poor rating was based on values from known degraded sites (Stagg and Mendelssohn, 2010; Stroud, 1976). Although the measurements from these studies were of productivity (i.e., accounting for intra-season turnover), observations of these studies were still substantially lower than biomass values cited above.

Analysis of Existing Monitoring Efforts:

<u>Geographic</u>: Aboveground Live Biomass Stock is little-collected geographically in the NGoM, with 2% of habitat hexagons containing at least one monitoring site. Monitoring locations for this metric are sparsely but evenly distributed across the NGoM, with samples collected in every state.

<u>Programmatic:</u> Data for this metric are collected by 6/49 (12%) of the programs collecting relevant salt marsh data in the NGoM.

A list of the salt marsh monitoring programs included on the map and table below is provided in Appendix IV.



Metric	Number of Salt Marsh Monitoring Programs	Number of Programs Monitoring the Indicator	Percentage of Programs Monitoring the Indicator	Percent of Ecosystem Hexagons that Contain Monitoring Sites for the Indicator
Aboveground Live Biomass Stock	49	6	12%	2%

Indicator: Belowground Primary Production

MEF: Ecosystem Function
KEA: Primary Production
Metric: Soil Shear Stress

Definition: Belowground primary production of vegetation is the annual belowground biomass growth per area. Soil shear stress, a proxy for belowground biomass production, is a common geotechnical measurement that is strongly related to root occupation of the soil (Tobias, 1995).

Background: Although not as commonly measured as aboveground biomass production, belowground biomass is possibly more important to the function and resilience of marshes (Turner et al., 2004; Turner, 2010), and is not necessarily correlated to aboveground biomass (Darby and Turner, 2008; Deegan et al., 2012; Stroud, 1976; Valiela et al., 1976). Roots provide strength to the soil (enabling shear stress to be a useful proxy), mitigating lateral erosive forces. Roots also contribute to vertical accretion of organic matter. Belowground biomass is responsive to environmental conditions, and the ratio of belowground to aboveground vegetation is also strongly affected by nutrient availability and soil redox condition (Stagg and Mendelssohn, 2010).

Rationale for Selection of Variable: Belowground net primary production is a challenge to measure because of turnover within growing seasons (e.g., Kirby and Gosselink, 1976), the small spatial scale of cores, and the time-intensive labor of processing roots from cores. For measurement efficiency, we instead use shear stress as a metric to indicate belowground production, which correlates with the strength of the existing root biomass (Tobias, 1995). Shear stress can be rapidly calculated using a shear vane (Swarzenski et al., 2008; Turner et al., 2009).

Measure: Shear stress recorded by a shear vane at 5 cm depth increments

Tier: 3 (intensive field measurement)

Measurement: Within the site, randomly selected locations (> 10, paired with aboveground biomass measurement locations) are used for soil shear stress measurement. Measurements are made using a shear vane (e.g., 16-T0174, Controls Group Inc., Milan, Italy) following standard methods (ASTM D2573/D2573M - 15e1), which yields a quantitative measurement of soil shear stress. Measurements should be taken annually during peak growing season at 5 cm depth increments from the surface down to 50 cm deep (adapted from Turner [2010]). Measurements are averaged across the 10 increments and across the > 10 locations. Strength is a function of wetness, so repeat measurements should be taken during similar flooding conditions (e.g., low tide of a neap period).

Metric Rating and Assessment Points:

Metric Rating	Soil Shear Stress
Good	Shear strength values remain constant or increasing over time
Poor	Shear strength declines over time

Scaling Rationale: While the shear vane test is a commonly used method for many applications (e.g., geotechnical surveys) and has been used in marshes to assess belowground biomass (Swarzenski et al., 2008; Turner et al., 2009), critical values to define assessment points cannot be extracted, because values are dependent on moisture content and species and soil properties, among other factors (Tobias, 1995). Thus, metric ratings are written in comparison to values taken at the same locations over time; this requires that several years of data are collected. Good is defined as conditions that are self-sustaining (i.e., stable or increasing strength). Poor conditions are those of declining strength.

Analysis of Existing Monitoring Efforts:

No programs in the monitoring program inventory specifically noted collection of soil shear stress. This method of data collection is relatively new and has not been widely implemented yet, though it has great promise for assessing belowground biomass.

Indicator: Specialist Birds

MEF: Ecosystem Function
KEA: Secondary Production
Metric: Clapper Rail and Seaside Sparrow Density

Definition: Density, the abundance per unit area, of two salt marsh specialist species: clapper rail (*Rallus crepitans*) and seaside sparrow (*Ammodramus maritimus*).

Background: These two species are highly dependent on the salt marsh habitat and are responsive to its perturbation (Stouffer et al., 2013); these characteristics make for useful indicators of the habitat quality. Both are permanent residents of the coastal marshes, relying on the marsh for both foraging and nesting habitat. Clapper rails forage for seeds and invertebrates, including crabs, along the marsh edges and along tidal channels. Seaside sparrows prefer to perch on tidal and salt marsh, favoring taller grass patches. Therefore, they require the physical structure of healthy marsh vegetation and productive soil and aquatic biota (small fish and invertebrates) that are a food source (Leggett, 2014; Mitchell et al., 2006).

Rationale for Selection of Variable: Given clapper rail and seaside sparrow specificity to and dependence on the salt marsh environment (including landscape, vegetation, and trophic structure), their presence and density are instructive as an integrative ecological indicator.

Measure: Density (birds ha^{-1}) of individuals of clapper rail (*R. crepitans*) and of male seaside sparrow (*A. maritimus*)

Tier: 3 (intensive field measurement)

Measurement: The survey route method described in Conway (2011) for secretive marsh birds, with call back surveys using recordings to correlate to density, should be used. These specific routines should be used due to the spatiotemporal variability in a tidal marsh landscape and the inconspicuous nature of these species, which must be accounted for in detection probability. Values should be reported in density with units of individual per hectare; for clapper rails, assessment points are defined for individuals of either sex while seaside sparrows are just males.

Metric Rating and Assessment Points:

Metric Rating	Clapper Rail and Seaside Sparrow Density
Good	Seaside sparrow population of > 1 male ha^{-1} and clapper rail population > 1 individual ha^{-1}
Fair	Seaside sparrow population of > 1 male ha^{-1} or clapper rail population > 1 individual ha^{-1}
Poor	Seaside sparrow population of < 1 male ha^{-1} and clapper rail population < 1 individual ha^{-1}

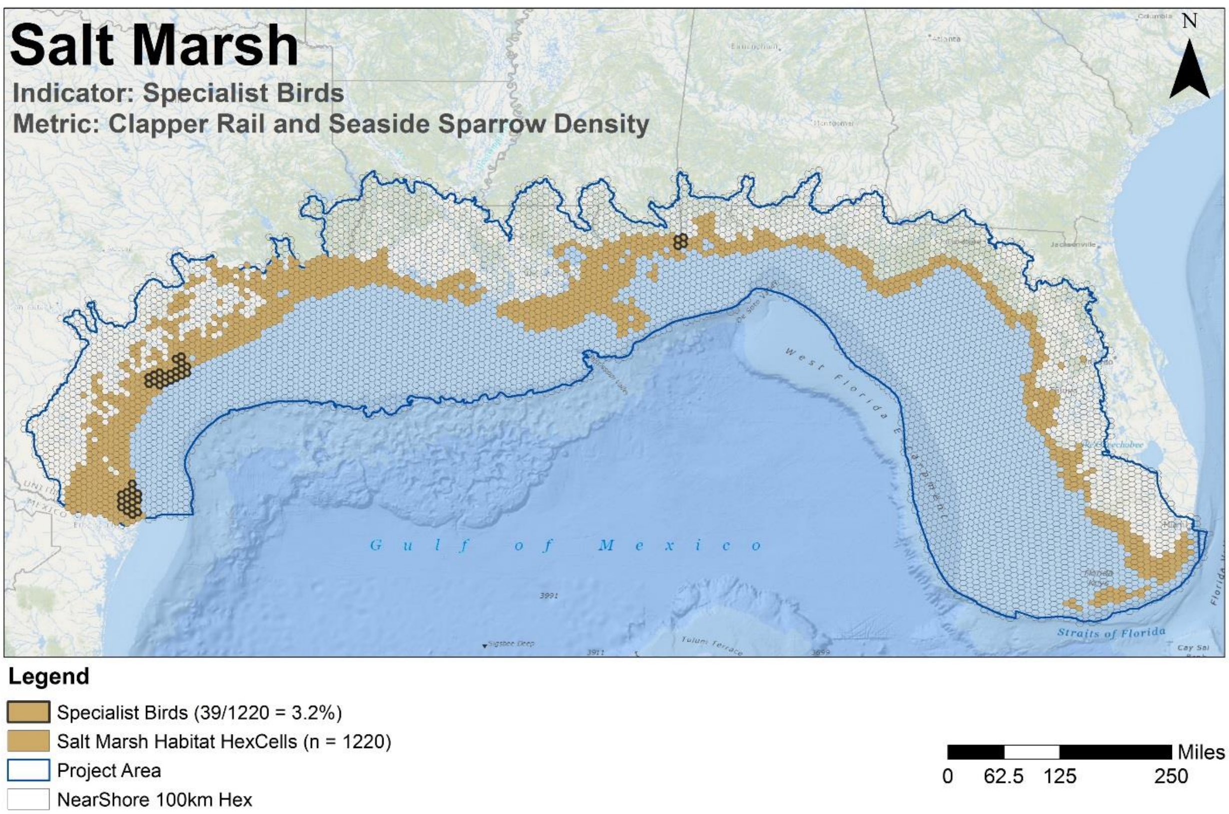
Scaling Rationale: The scaling rationale was derived from analysis of densities across several studies for both clapper rails and seaside sparrows. In good condition sites, clapper rail densities tend to be greater than one individual ha^{-1} although rarely greater than 2–4 individuals ha^{-1} (Rush et al., 2012). Likewise, seaside sparrows can have considerably higher population densities (up to 20 males ha^{-1}), but degraded marshes have been observed to have < 1 males ha^{-1} (Post and Greenlaw, 2009). While narrow, these rating points are conservative (likely densities are higher) to account for variability.

Analysis of Existing Monitoring Efforts:

Geographic: Monitoring data collected specifically on clapper rails and seaside sparrows are not widely collected geographically in the NGoM, with 3% of habitat hexagons containing at least one monitoring site. Monitoring locations for this metric are clustered in Texas and Mississippi.

Programmatic: Data for this metric are collected by 4/49 (8%) of the programs collecting relevant salt marsh data in the NGoM.

A list of the salt marsh monitoring programs included on the map and table below is provided in Appendix IV.



<table>
<tr><th>Metric</th><th>Number of Salt Marsh Monitoring Programs</th><th>Number of Programs Monitoring the Indicator</th><th>Percentage of Programs Monitoring the Indicator</th><th>Percent of Ecosystem Hexagons that Contain Monitoring Sites for the Indicator</th></tr>
<tr><td>Clapper Rail and Seaside Sparrow Density</td><td>49</td><td>4</td><td>8%</td><td>3%</td></tr>
<tr><td colspan="5">• Spatial footprint for one monitoring program was not available and not included on the map. Percent of hexagons containing monitoring sites may be an underestimate.
• We included only studies that were specifically monitoring either of these species. We did not include wider multi-species bird counts in our assessment since methods may not be appropriate for documenting species that occur at such low densities.</td></tr>
</table>

Ecosystem Service Indicators

Indicator: Specialist Birds

MES: Supporting
KES: Habitat
Metric: Clapper Rail and Seaside Sparrow Density

Secondary Production is used here as a proxy for the Habitat Provision ecosystem service and the indicator is the same as the Specialist Birds indicator above.

Definition: Density, the abundance per unit area, of two salt marsh specialist species: clapper rail (*Rallus crepitans*) and seaside sparrow (*Ammodramus maritimus*).

Background: These two species are highly dependent on the salt marsh habitat and are responsive to its perturbation (Stouffer et al., 2013); these characteristics make for useful indicators of the habitat quality. Both are permanent residents of the coastal marshes, relying on the marsh for both foraging and nesting habitat. Clapper rails forage for seeds and invertebrates, including crabs, along the marsh edges and along tidal channels. Seaside sparrows prefer to perch on tidal and salt marsh, favoring taller grass patches. Therefore, they require the physical structure of healthy marsh vegetation and productive soil and aquatic biota (small fish and invertebrates) that are a food source (Leggett, 2014; Mitchell et al., 2006).

Rationale for Selection of Variable: Given clapper rail and seaside sparrow specificity to and dependence on the salt marsh environment (including landscape, vegetation, and trophic structure), their presence and density is instructive as an indicator of habitat provision.

Measure: Density (birds ha^{-1}) of individuals of clapper rail (*R. crepitans*) and of male seaside sparrow (*A. maritimus*)

Tier: 3 (intensive field measurement)

Measurement: The survey route method described in Conway (2011) for secretive marsh birds, with call back surveys using recordings to correlate to density, should be used. These specific routines should be used due to the spatiotemporal variability in a tidal marsh landscape and the inconspicuous nature of these species, which must be accounted for in detection probability. Values should be reported in density with units of individual per hectare; for clapper rails, assessment points are defined for individuals of either sex while seaside sparrows are just males.

Metric Rating and Assessment Points:

Metric Rating	Clapper Rail and Seaside Sparrow Density
Good	Seaside sparrow population of > 1 male ha^{-1} and clapper rail population > 1 individual ha^{-1}
Fair	Seaside sparrow population of > 1 male ha^{-1} or clapper rail population > 1 individual ha^{-1}
Poor	Seaside sparrow population of < 1 male ha^{-1} and clapper rail population < 1 individual ha^{-1}

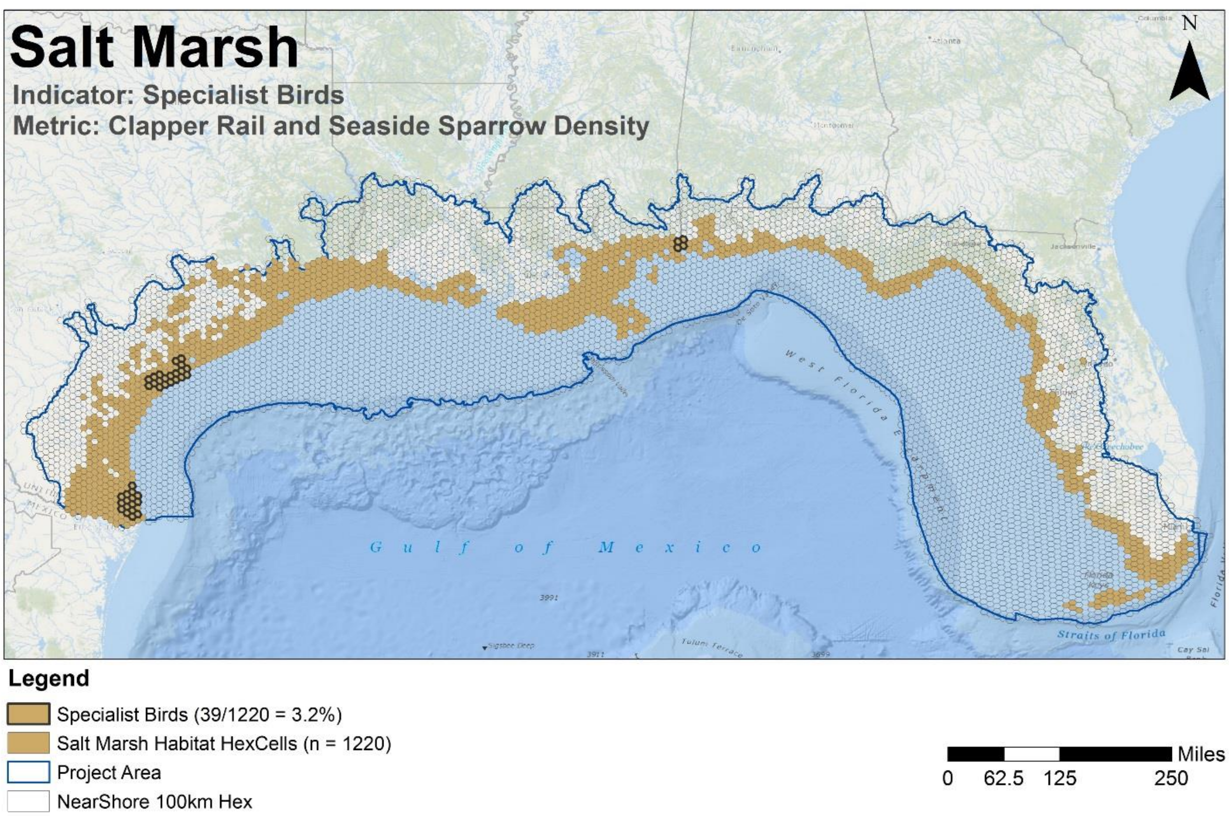
Scaling Rationale: The scaling rationale was derived from analysis of densities across several studies for both clapper rails and seaside sparrows. In good condition sites, clapper rail densities tend to be greater than one individual ha^{-1} although rarely greater than 2–4 individuals ha^{-1} (Rush et al., 2012). Likewise, seaside sparrows can have considerably higher population densities (up to 20 males ha^{-1}), but degraded marshes have been observed to have < 1 males ha^{-1} (Post and Greenlaw, 2009). While narrow, these rating points are conservative (likely densities are higher) to account for variability.

Analysis of Existing Monitoring Efforts:

<u>Geographic</u>: Monitoring data collected specifically on clapper rails and seaside sparrows are not widely collected geographically in the NGoM, with 3% of habitat hexagons containing at least one monitoring site. Monitoring locations for this metric are clustered in Texas and Mississippi.

<u>Programmatic:</u> Data for this metric are collected by 4/49 (8%) of the programs collecting relevant salt marsh data in the NGoM.

A list of the salt marsh monitoring programs included on the map and table below is provided in Appendix IV.



<table>
<tr><th>Metric</th><th>Number of Salt Marsh Monitoring Programs</th><th>Number of Programs Monitoring the Indicator</th><th>Percentage of Programs Monitoring the Indicator</th><th>Percent of Ecosystem Hexagons that Contain Monitoring Sites for the Indicator</th></tr>
<tr><td>Clapper Rail and Seaside Sparrow Density</td><td>49</td><td>4</td><td>8%</td><td>3%</td></tr>
<tr><td colspan="5">Spatial footprint for one monitoring program was not available and not included on the map. Percent of hexagons containing monitoring sites may be an underestimate.
We included only studies that were specifically monitoring either of these species. We did not include wider multi-species bird counts in our assessment since methods may not be appropriate for documenting species that occur at such low densities.</td></tr>
</table>

Indicator: Wave Attenuation

MES: Regulating
KES: Coastal Protection
Metric: Percent Wave Height Reduction per Unit Distance Across Marsh Vegetation

Definition: Wave attenuation is the reduction in wave height that occurs when a water wave passes through vegetated salt marsh. Shoreline width can be used as a proxy for wave attenuation.

Background: Salt marshes are frequently exposed to tide and wave influence. By absorbing wave energy, salt marshes provide a natural buffer to regular wave action and can help protect adjacent lands from storm surge impacts (Pinksy et al., 2013). While marshes cannot prevent significant damage from major hurricanes, these wetland habitats are known to significantly reduce wave energy and storm surges associated with frequently occurring storm disturbances (Shepard et al., 2011). In their meta-analysis of wave attenuation studies, Shepard et al. (2011) found that attenuation rates increased with marsh transect length, or shoreline width. Wave attenuation and shoreline stabilization were also positively correlated to vegetation density, biomass production, and marsh size.

Shoreline width can be modeled using remote sensing data or field measurements. We provide both measurements below.

Rationale for Selection of Variable: Salt marsh vegetation has the potential to reduce the energy of frequent waves and stabilize shorelines by promoting sediment deposition and reducing shoreline erosion (Shepard et al., 2011). Wave energy reduction can be assessed by using a metric based on the relationship between wave attenuation and area of vegetated marsh. NAS (2013) suggest that the value of ecosystem services for NGoM storm protection is directly related to the total area of wetlands and to plant community composition.

Measure: Salt marsh shoreline width in meters

Tier: 1 (model using remotely sensed data)

Measurement 1: From Shepard et al. (2011): For wave attenuation, percent wave height reduction per unit distance is designated as the response variable. To measure shoreline width, remote sensed data from the Landsat dataset can be used if there is sufficient imagery within the appropriate time period (<1 year from assessment date, or after most recent major storm event, whichever is more recent). For each site, the average width of the shoreline (up to 1000 m) is measured. The shoreline width will be used to predict the percent wave attenuation using the relationship established in Shepard et al. (2011).

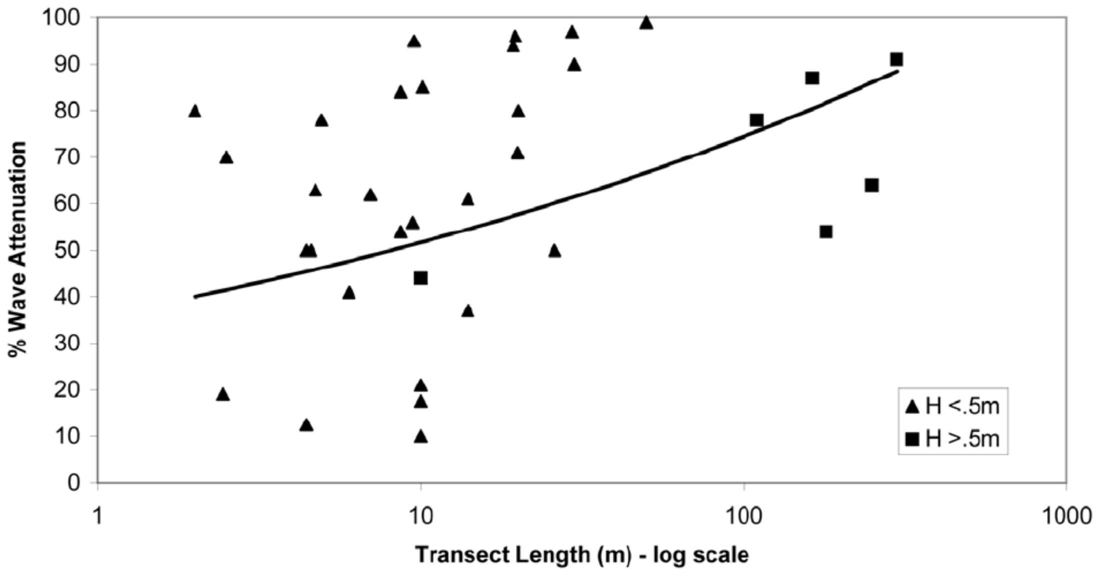


Figure 2.14. *Wave attenuation rates versus salt marsh transect length. From Shepard et al., 2011.*

Tier: 2 (model using rapid field measurement)

Measurement 2: From Shepard et al. (2011): For wave attenuation, percent wave height reduction per unit distance is designated as the response variable. To measure shoreline width, at least 10 transects will be established perpendicular to the shoreline. The distance of vegetated marsh from the shoreline up to 1000 m inland will be measured along the transect. For each site, the average width of the shoreline (up to 1000 m) is calculated from the 10 transect distances. The shoreline width will be used to predict the percent wave attenuation using the relationship established in Shepard et al. (2011, Fig. 2.5).

Metric Rating and Assessment Points:

Metric Rating	Percent Wave Height Reduction
Excellent	> 1000 m, shoreline width associated with > 75% wave attenuation
Good	100–1000 m, shoreline width associated with > 50% wave attenuation
Fair	10–100 m, shoreline width associated with 40–50% wave attenuation
Poor	< 10 m, shoreline width associated with < 40% wave attenuation

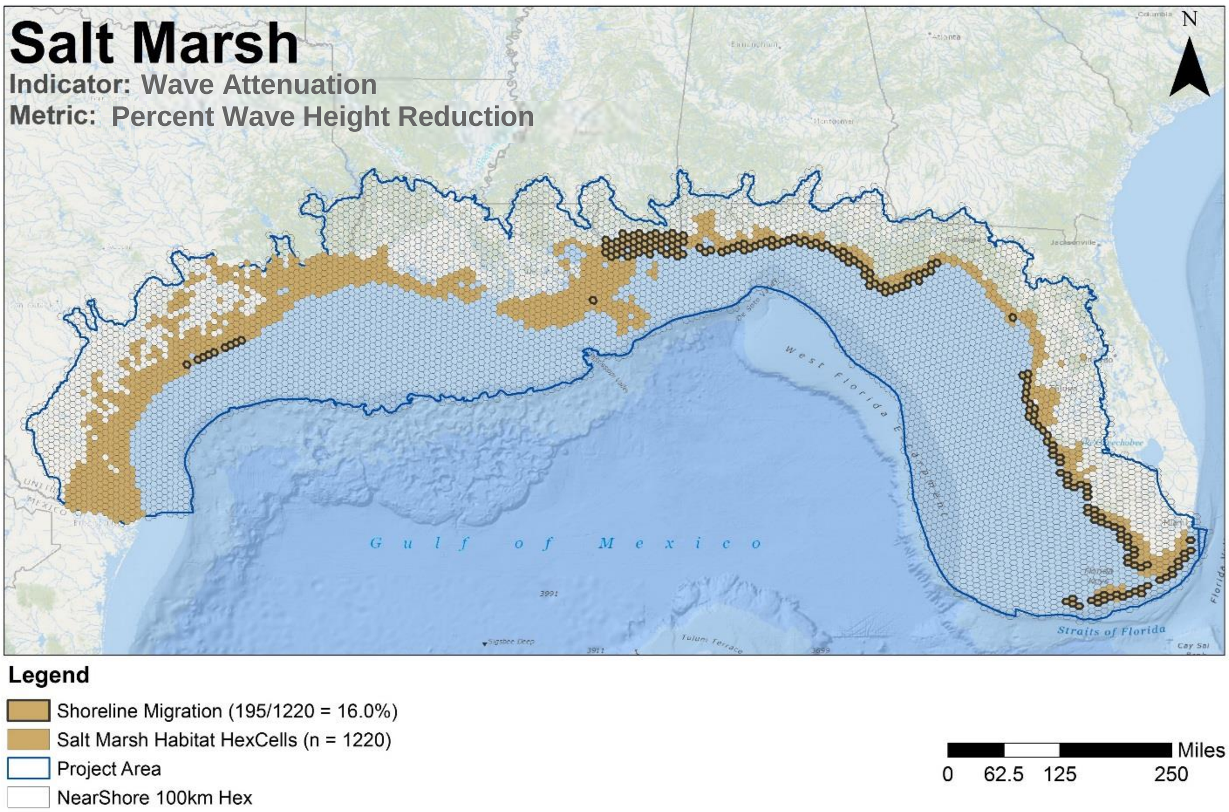
Scaling Rationale: Ratings for indicator values constitute the average percent wave attenuation derived from a meta-analysis conducted by Shepard et al. (2011) using seven studies with sufficient detail to assess a significant positive effect of vegetation on wave attenuation by a 0.5 m high wave. Thresholds used a 0.5 m high incoming wave across different transect lengths over salt marsh (perpendicular to shoreline).

Analysis of Existing Monitoring Efforts:

Geographic: Shoreline width is less well collected geographically in the NGoM, with 16% of habitat hexagons containing at least one monitoring site. Monitoring locations for this metric are skewed towards Mississippi, Alabama, and Florida (except the Big Bend and somewhat south), with very few collections in Louisiana and Texas.

<u>Programmatic:</u> Data for this metric are collected by 8/49 (16%) of the programs collecting relevant salt marsh data in the NGoM.

A list of the salt marsh monitoring programs included on the map and table below is provided in Appendix IV.



Metric	Number of Salt Marsh Monitoring Programs	Number of Programs Monitoring the Indicator	Percentage of Programs Monitoring the Indicator	Percent of Ecosystem Hexagons that Contain Monitoring Sites for the Indicator
Percent Wave Height Reduction	49	8	16%	16%

Indicator: Nutrient Reduction

MES: Regulating
KES: Water Quality
Metric**:** Basin-wide Nutrient Load (Total Nitrogen [TN] and Total Phosphorus [TP])

The indicator, metrics, and measurement techniques for assessing the Water Quality KES are the same as for the Water Quality KEA described above.

Definition: A reduction of mobilized nitrogen and phosphorus, measured in spatially explicit hydrologic units (following Hydrologic Unit Codes [HUCs] http://water.usgs.gov/nawqa/sparrow/) that encompass and contribute (downstream) to salt marshes.

Background: Salt marshes protect water quality by filtering runoff. Salt marsh vegetation enhances sediment deposition, thereby removing suspended solids from the water column (Leonard and Luther, 1995). Additionally, salt marsh vegetation reduces the nutrient load in the water column through uptake and metabolism of excess nutrients in estuarine systems (Mitsch and Gosselink, 2008).

Rationale for Selection of Variable: This metric was chosen because of the prevalence of excess nutrients in the study region (Smith, 2003) that impact water quality. TN and TP were selected because both nutrients are primary drivers of eutrophication and both have widely available data with existing assessment criteria.

Annual mean TN and TP concentrations are appropriate for assessment metrics, because nutrient fluxes vary at multiple spatial and temporal scales. Therefore, point measurements in space and time do not accurately represent the overall ecosystem condition with respect to nutrient cycling. Thus, a spatially and temporally aggregated metric is preferable for monitoring eutrophication. The HUC 8 scale is the most readily available aggregated measure available at spatial and temporal scales relevant to ecosystem condition trends.

Measures: Total phosphorus in mg L^{-1} and total nitrogen in mg L^{-1} (basin-wide)

*Tier***:** 1 (remotely sensed and modeled)

Measurement: SPARROW (Spatially-Referenced Regression on Watershed Attributes) is a model that estimates basin-level long-term average fluxes of nutrients (Preston et al., 2011). The model integrates monitoring site data at high temporal resolution to develop site rating curves (integrating streamflow and water quality data), which are then extrapolated to individual basins with values scaled by land classifications within basins. The user-friendly online interface allows determination of both TN and TP loads for specific basins to identify relative water quality fluxes.

Metric Rating and Assessment Points:

Metric Rating	Basin-wide Nutrient Load (mg L^{-1})
Excellent	TP < 0.1 and TN < 1.0
Good	TP 0.1–0.2 and TN 1.0–2.0
Fair	TP 0.2–0.9 and TN 2.0–7.0
Poor	TP > 0.9 and TN > 7

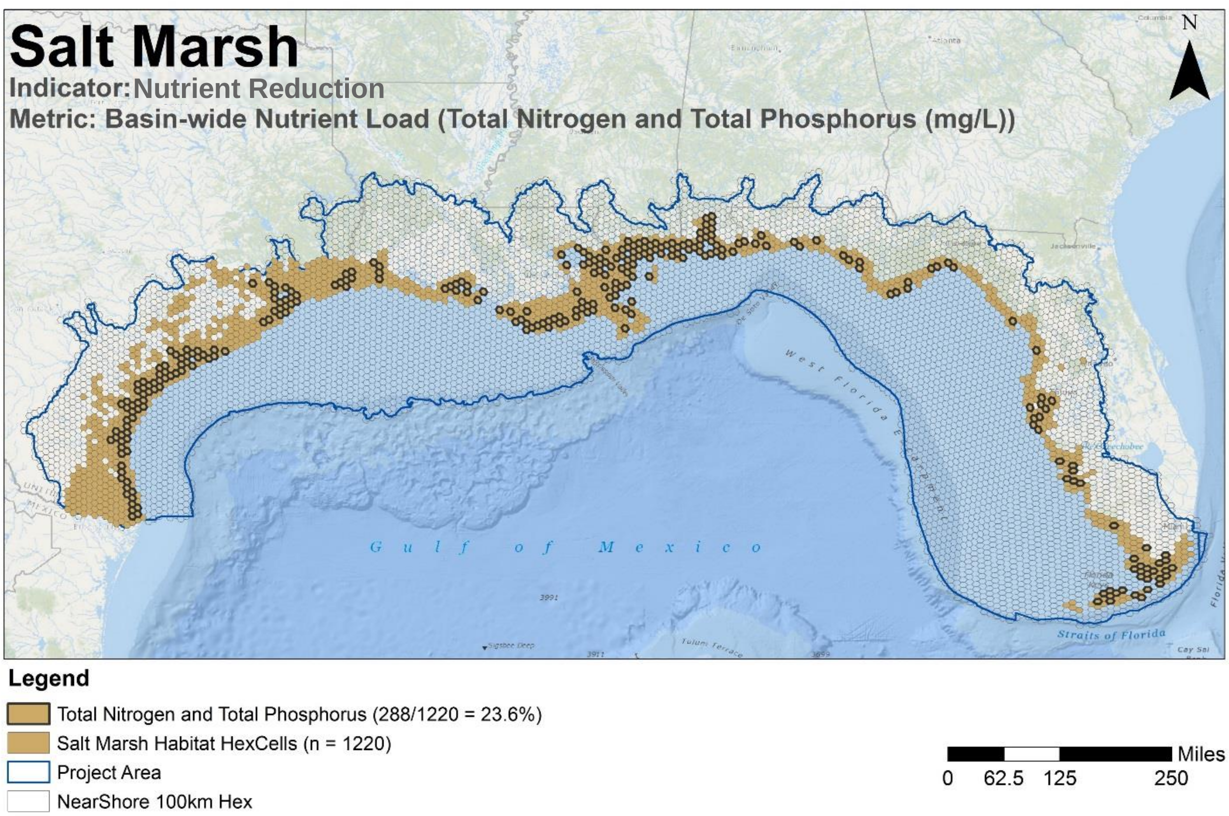
Scaling Rationale: SPARROW outputs for TN concentration range from near 0.05 to > 7 mg L^{-1} in coastal basins of the NGoM. TP concentrations range from near 0.00 to > 0.9 mg L^{-1} in coastal basins of the NGoM. While low nutrient concentrations do not necessarily indicate superior ecological function for all aspects of the ecosystem, the potential for eutrophication declines with lower nutrient concentration values. Assessment points were established in accordance with the SPARROW output breakpoints; groupings were established to flag higher values as fair or poor. These higher values are in ranges generally associated with impaired water quality. Of the NGoM states, only Florida has state-specific criteria (e.g., ~0.4 to 1 mg L^{-1} TN, depending on specific estuary; US EPA, 2016).

Analysis of Existing Monitoring Efforts:

<u>Geographic</u>: Basin-wide Nutrient Load is moderately well collected geographically in the NGoM, with 24% of habitat hexagons containing at least one monitoring site. Monitoring locations for this metric are relatively well distributed across the NGoM, with multiple monitoring sites in each state.

<u>Programmatic:</u> Data for this metric are collected by 5/49 (10%) of programs collecting relevant salt marsh data in the NGoM.

A list of the salt marsh monitoring programs included on the map and table below is provided in Appendix IV.



Metric	Number of Salt Marsh Monitoring Programs	Number of Programs Monitoring the Indicator	Percentage of Programs Monitoring the Indicator	Percent of Ecosystem Hexagons that Contain Monitoring Sites for the Indicator
Basin-wide Nutrient Load	49	5	10%	24%

Indicator: Soil Carbon Density

MES: Regulating
KES: Carbon Sequestration
Metric: Soil Carbon Density

Definition: Soil carbon density is the quantity of carbon in the soil, which is a product of percent soil carbon and soil bulk density (Chmura, 2013).

Background: Salt marshes can store large quantities of carbon in the soil because of high rates of belowground primary production (carbon input) and relatively low rates of decomposition (carbon export). Salt marsh plants fix (or sequester) large amounts of carbon dioxide (CO_2) in belowground biomass, which is ultimately incorporated into the soil. Soil carbon in flooded anaerobic wetland soils decomposes more slowly, because anaerobic respiration is less efficient than aerobic respiration. Therefore, the potential for long-term storage of carbon in wetland soils is significant, and salt marsh soils store more carbon than any other ecosystem globally (Mcleod et al., 2011). Salt marshes constitute approximately 25% of the global soil carbon storage (Chmura et al., 2003), and rates of atmospheric carbon sequestration in salt marshes are likely an order of magnitude higher than that of temperate and tropical forests (Nellemann et al., 2009).

Rationale for Selection of Variable: In salt marshes, soil carbon stocks are more stable than above- or belowground biomass or litter stock pools. Therefore, to assess carbon sequestration, or long-term carbon storage, it is most appropriate to measure soil carbon stocks. Soil carbon density is a measure of carbon quantity in the soil. Soil carbon density incorporates both percent carbon measurements and bulk density measurements to provide soil carbon concentration. When bulk density data are not considered in soil carbon measurements, relative carbon content measures alone will underestimate carbon quantity in soils with high bulk densities (Chmura, 2013).

Measure: Density of carbon (g cm^{-3})

Tier: 3 (intensive field measurement)

Measurement: Soil carbon density is calculated as the product of soil carbon content (gC $gsoil^{-1}$) and soil bulk density (g cm^{-3}). Soil carbon content can either be measured directly using total carbon analysis of the soil, or indirectly using a habitat-specific conversion factor to derive soil carbon from soil organic matter (Wang et al., 2016). Soil organic matter is measured using loss on ignition (LOI) methodology (Wang et al., 2011). At least six soil cores (three near shoreline and three inland) will be collected to a depth of 1 m, and the core will be divided into 10 cm intervals. Each interval will be analyzed for bulk density, soil carbon content will be determined (directly measured or converted from soil organic matter), and the carbon density will be calculated. Interval estimates will be averaged at the core and site level, and site-level carbon density values will be used in the assessment based on Chmura et al. (2003).

Metric Rating and Assessment Points:

Metric Rating	Soil Carbon Density
Good	> 0.101 g/cm^3
Fair	0.027–0.101 g/cm^3
Poor	< 0.027 g/cm^3

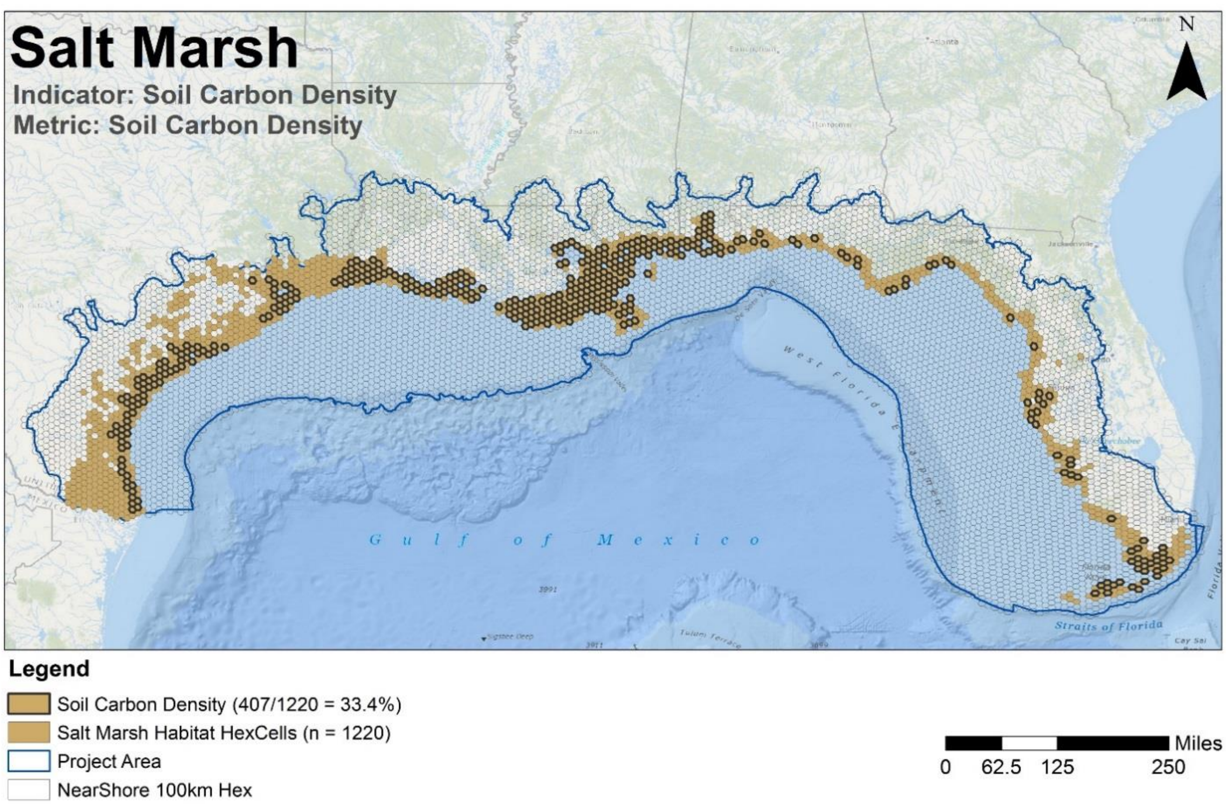
Scaling Rationale: Soil carbon density estimates were obtained from 27 salt marsh sites in the NGoM in a field study by Chmura et al. (2003). The medium range (second and third quartile) of belowground carbon empirical values assessed in the NGoM sites represent the fair condition. Carbon values above and below the range and assessed in the region represent the good and poor conditions, respectively.

Analysis of Existing Monitoring Efforts:

Geographic: Soil carbon density is moderately well collected geographically in the NGoM, with 33% of habitat hexagons containing at least one monitoring site. Monitoring locations for this metric are relatively well distributed across the NGoM, with samples collected in every state.

Programmatic: Data for this metric are collected by 4/49 (8%) of the programs collecting relevant salt marsh data in the NGoM.

A list of the salt marsh monitoring programs included on the map and table below is provided in Appendix IV.



Metric	Number of Salt Marsh Monitoring Programs	Number of Programs Monitoring the Indicator	Percentage of Programs Monitoring the Indicator	Percent of Ecosystem Hexagons that Contain Monitoring Sites for the Indicator
Soil Carbon Density	49	4	8%	33%

Indicator: Recreational Fishery

MES: Cultural
KES: Aesthetics-Recreational Opportunities
Metric 1: Spotted Seatrout Density
Metric 2: Recreational Landings of Spotted Seatrout

Metric 1: Density of spotted seatrout (all size/age classes)

Definition: Number of individuals of spotted seatrout (*Cynoscion nebulosus*) per unit area.

Background: Spotted seatrout (*C. nebulosus*), also known as speckled trout**,** is a common estuarine fish found along the entire NGoM coast. The spotted seatrout is a euryhaline fish with a large range of salinity tolerance (0.2–75 ppt). Although adult spotted seatrout are typically associated with salt marsh and seagrass habitats in the warmer months and deeper open water areas within the estuaries during colder periods, habitat utilization varies by geographic location within the NGoM based on the habitat types available and life history stage. Spotted seatrout constitutes one of the most important recreational and commercial components of the total NGoM fin-fishery (VanderKooy, 2001). The spotted seatrout is caught almost exclusively within state waters jurisdiction, due to its close association with salt marsh and seagrass habitats. Spotted seatrout have been declared gamefish in Texas and Alabama, and only limited commercial fisheries exist in Louisiana, Mississippi, and Florida (VanderKooy, 2001). Spotted seatrout constitutes the largest recreational fishery in the NGoM region, with 36 million fish caught in 2006 (66% in Louisiana; NMFS 2007).

Rationale for Selection of Variable: Spotted seatrout density measurements allow for the assessment of population resource utilization at a specific site and provide an indication of the potential for a site to contribute to recreational fishing. This metric is best used to assess ecosystem service of a specific site.

Measure: Number of individuals m^{-1}

Tier: 3 (intensive field measurement)

Measurement: Field-collected organisms should be identified and enumerated by age/size class. Conduct annual field measures during warmer months, post-spawning, when populations are expected to be the highest. Data should be presented on individuals/m^2.

Metric Rating and Assessment Points:

Metric Rating	Density of Spotted Seatrout (or Significant Change in Age/Size Class Distribution)
Good	Increasing/stable
Poor	Decreasing

Scaling Rationale: Specific expected densities at given sites are not available to establish assessment points. Decreases in spotted seatrout density would indicate a decrease in a site's capacity to provide fish for recreational fisheries. Changes in age/size class distribution (e.g., a decline in juveniles over time) may also indicate potential for declining contribution to recreational fisheries.

Metric 2: Recreational landings of spotted seatrout

Definition: Annual recreationally landed weight of spotted seatrout (*C. nebulosus*). Fishing can be conducted using different gear types as defined and allowed by state regulations.

Background: Spotted seatrout (*C. nebulosus*), also known as speckled trout**,** is a common estuarine fish found along the entire NGoM coast. The spotted seatrout is a euryhaline fish with a large range of salinity tolerance (0.2–75 ppt). Although adult spotted seatrout are typically associated with salt marsh and seagrass habitats in the warmer months and deeper open water areas within the estuaries during colder periods, habitat utilization varies by geographic location within the NGoM based on the habitat types available and life history stage. Spotted seatrout constitutes one of the most important recreational and commercial components of the total NGoM fin-fishery (VanderKooy, 2001). The spotted seatrout is caught almost exclusively within state waters jurisdiction, due to its close association with salt marsh and seagrass habitats. Spotted seatrout have been declared gamefish in Texas and Alabama, and only limited commercial fisheries exist in Louisiana, Mississippi, and Florida (VanderKooy, 2001). Spotted seatrout constitutes the largest recreational fishery in the NGoM region, with 36 million fish caught in 2006 (66% in Louisiana; NMFS 2007).

Rationale for Selection of Variable: Recreational fishery landing statistics for spotted seatrout provide a direct measure of ecosystem service. Current statistics are available annually at the state level. The recreational fishery landing statistic metric is best used to assess the potential contrition of salt marshes to recreational fisheries at the state level on an annual basis. Because this metric has application at a broad spatial scale (state-level), it can be used to assess other spotted seatrout habitats, such as seagrasses.

Measure: Total spotted seatrout weight caught per year in metric tons

Tier: 3 (intensive field measurement)

Measurement: Assess the total weight of spotted seatrout annually using recreational fishery statistics reported by the National Marine Fishery Service. Data for this database is gathered by the Marine Recreational Information Program (MRIP) and can be accessed at https://www.st.nmfs.noaa.gov/recreational-fisheries/data-and-documentation/queries/index.

Metric Rating and Assessment Points:

Metric Rating	Total Spotted Seatrout Weight (Tons)				
	NGoM	Louisiana	Mississippi	Alabama	Florida (west coast)
Good	> 6,568 t	> 4,970 t	> 401 t	> 309 t	> 1,130 t
Fair	5,508–6,568 t	3,812–4,970 t	251–401 t	228–309 t	1,075–1,130 t
Poor	< 5,508 t	< 3,812 t	< 251 t	< 228 t	< 1,075 t

Scaling Rationale: The assessment scale is based on the average weight (metric tons) of total spotted seatrout caught between 1995 and 2015 in state waters in the NGoM (MRIP). The range between the second and third quartile of commercial landing statistics, reported by the NMFS (https://www.st.nmfs.noaa.gov/recreational-fisheries/data-and-documentation/queries/index), was used to define the medium rating level. Data for Texas is not available in the MRIP database.

Analysis of Existing Monitoring Efforts:

No programs in the monitoring program inventory specifically noted collection of spotted seatrout data, so no geographic or programmatic statistics were calculated for this indicator.

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