Chapter 3. Ecological Resilience Indicators for Mangrove Ecosystems

Richard H. Day[1], Scott T. Allen[2], Jorge Brenner[3], Kathleen Goodin[4], Don Faber-Langendoen[4], Katherine Wirt Ames[5]

[1] U.S. Geological Survey, Wetland and Aquatic Research Center, Lafayette, LA, U.S.A.
[2] ETH Zurich, Department of Environmental Systems Science, Zurich, Switzerland
[3] The Nature Conservancy, Texas Chapter, Houston, TX, U.S.A.
[4] NatureServe, Arlington, VA, U.S.A.
[5] The Nature Conservancy, Gulf of Mexico Program, Punta Gorda, FL, U.S.A.

Ecosystem Description

Mangrove ecosystems are characterized by often flooded saline soil conditions. Three tree species are commonly found in the Northern Gulf of Mexico (NGoM) mangrove ecosystems: black mangrove (*Avicennia germinans*), white mangrove (*Laguncularia racemosa*), and red mangrove (*Rhizophora mangle*). While these species differ in growth form, there can also be substantial plasticity in individuals within a species, leading to a variety of different forest structures in different hydrogeomorphic environments. Mangrove ecosystems in the NGoM represent the majority of this ecosystem along the United States coastline. This is largely due to temperature sensitivity, which results in dramatic dieback of mangroves where freezing occurs, even periodically. Much of the NGoM is at the latitudinal limit for mangroves, and mangrove ecosystems in this region can be highly dynamic due to this driving disturbance regime. Figure 3.1 provides a general distribution of mangrove ecosystems in the NGoM.

Numerous independent or interacting factors control the condition, sustainability, and distribution of mangrove ecosystems. Like other coastal ecosystems, naturally dynamic conditions resulting from weather patterns drive riverine, estuarine, and coastal hydrogeomorphology and ultimately the spatial pattern of mangroves (Lugo and Snedaker, 1974). Precipitation gradients restrict the full development of mangrove ecosystems to relatively humid climates (Osland et al., 2016). Due to their sensitivity to freezing and regular damage/recovery cycles after freeze events (Osland et al., 2015), climate provides a major disturbance cycle at the northern limits. Heavily populated coastlines in the region also make mangroves vulnerable to anthropogenic disturbances such as those to the landscape (channelization, impoundment), those on soil or water properties (eutrophication, pollution), or those on species (vegetation planting/removal, burning, introduction of invasive species). People may actively manage to reduce mangroves where marsh ecosystems are preferred. Sea-level rise further limits their distribution.

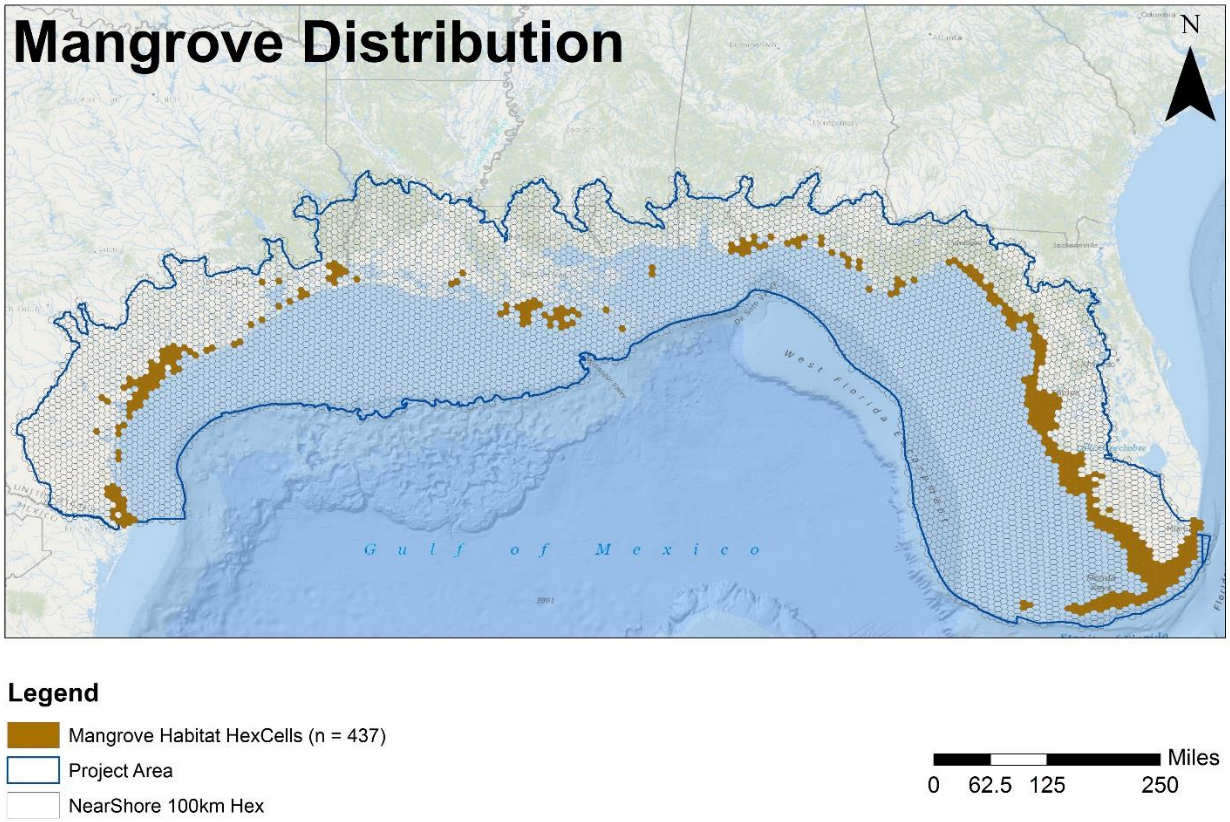


Figure 3.15. *Distribution of mangrove ecosytems in the Northern Gulf of Mexico. One of the sources of this mangrove distribution is the U.S. Fish and Wildlife Service National Wetlands Inventory (USFWS, 2016) using Estuarine Forested and Estuarine Scrub/Shrub classifications, which can include more than just mangrove species, causing an over-estimation of the distribution of mangroves in the northern Gulf of Mexico (NGoM), particularly near northern range limits in north Florida, Louisiana, and Texas. The hexagons depicted as mangrove habitat encompass the distribution of mangroves as of 2016, but some of the brown hexagons in north Florida, Louisiana, and Texas are known to not contain mangroves. We consider this map to be an appropriate representation of the distribution of mangroves in the NGoM using publicly available sources of data.*

To exist in a dynamic environment requires mechanisms for maintenance and responses to perturbations. These mechanisms aid in system resiliency against anthropogenic stressors. With rising sea levels, mangrove roots play an important role of gaining elevation by strengthening soil, contributing organic matter to the subsurface, and facilitating sediment deposition (Krauss et al., 2014; Woodroffe et al., 2016). Given their salinity tolerance, mangroves can continue to function when in a low position within the tidal prism. Mangroves readily grow from propagules so that they can become established in bare systems and newly aggraded land, prompting an elevation-maintaining feedback cycle.

To understand the ecological and human processes that affect the NGoM mangrove ecosystems, we developed a conceptual ecological model. We present the model as a diagram (Figure 3.2) that accompanies the following description of mangrove 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. Generally, the primary control over condition is the existence and development of the ecosystem, and secondarily the quality of ecosystem function; all indicators relate to one or more of these elements.

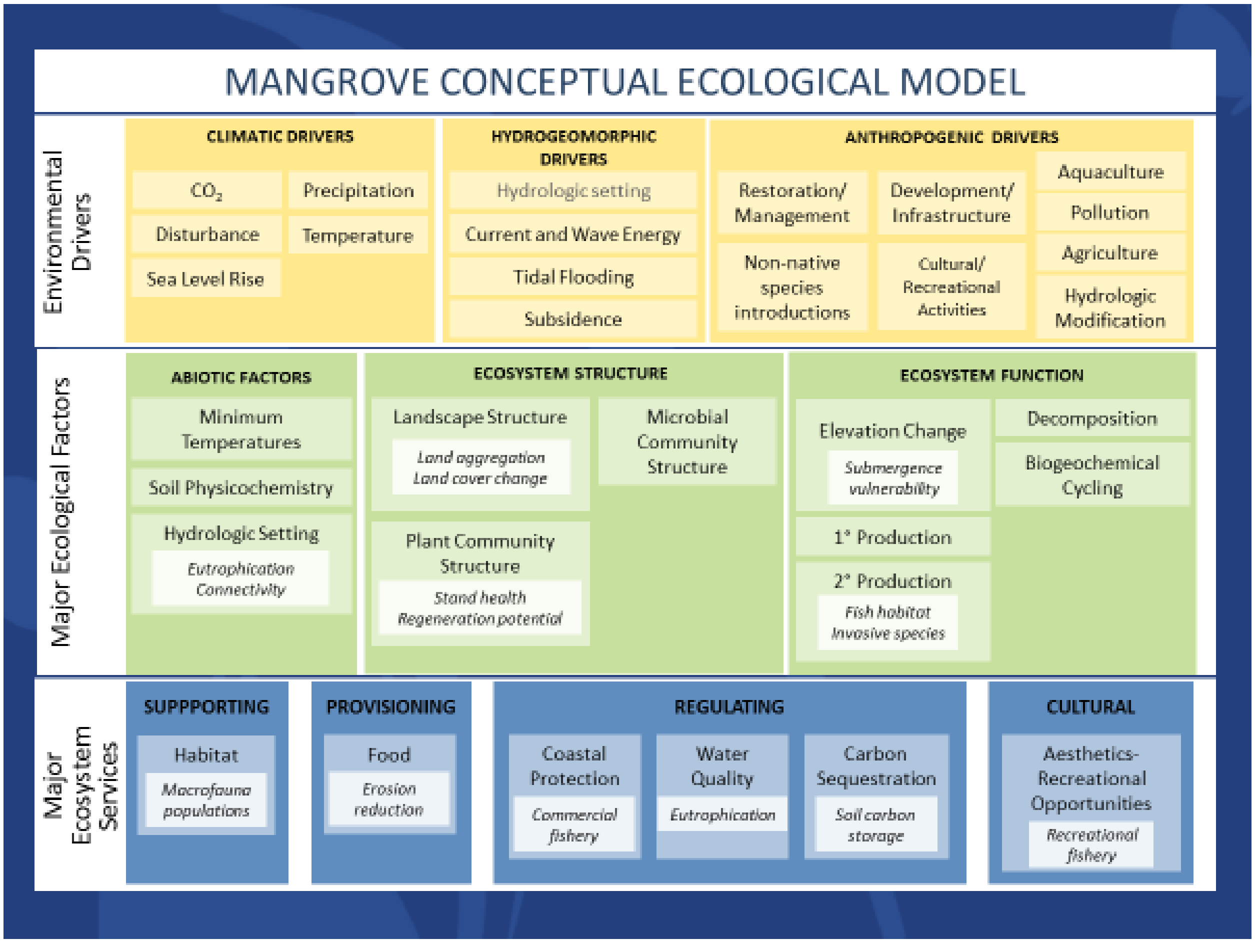


Figure 3.16. *Mangrove Conceptual Ecological Model*

Factors Involved in Ecological Integrity

Abiotic Factors

Minimum Temperatures

Mangrove forests are sensitive to low temperatures, with extended freeze events leading to partial or complete dieback. This freeze induced dieback, occurring with hydraulic failure and xylem cavitation, determines the physiological limits to mangrove range (Stuart et al., 2006). Given climate change effects on regionally increasing temperatures, freeze events are less common, enabling expansion of mangrove systems across the NGoM (Comeaux et al., 2012), including in Mississippi and Louisiana. However, across these regions freeze events still occur, resulting in dynamic ranges and general ecosystem transience. While air temperatures are important, other considerations such as tree size also affect resilience (Osland et al., 2015). Climate regime determines the permanence of the system, so more dynamic systems are expected at the latitudinal limits of mangroves (i.e., the northern edge of the NGoM—North Texas, Louisiana, Mississippi, Alabama, North Florida). Thus, a mangrove system near the latitudinal limit can still be behaving naturally with frequent mortality, albeit with reduced function (Cavanaugh et al., 2014; Osland et al., 2013; Saintilan et al., 2014). A similar effect occurs along the precipitation gradient on the Texas coast with less than optimum mangrove growing conditions along the arid coast nearing Mexico (Osland et al., 2014; Gabler et al., 2017; Feher et al., 2017).

Soil Physicochemistry

The physical and chemical properties of mangrove soils relate to the hydrologic and geomorphic setting. Topography and hydrologic regime (including water quality) determine deposition patterns, ultimately determining where and how much accretion occurs. Proximity to development also provides a major control on soil composition and how soils develop and change. Mangroves, like other wetlands, are characterized by soils with low oxygen levels due to frequent inundation.

Although hypoxia can generally inhibit primary production and soil microbial processes, mangroves are adapted to hypoxic conditions by being able to oxidize the rhizosphere. More importantly, frequent tidal flushing maintains higher dissolved oxygen concentrations than seen in impounded wetlands, which may have critically low oxygen concentrations (Mitsch and Gosselink, 2015). Decomposition of organic matter can and does also occur through anaerobic respiration pathways, facilitating energy flow through the detrital community. However, restrictions to tidal flushing result in dramatically reduced function due to limitations on dissolved oxygen (Lewis et al., 2016).

Salinity is a dominant feature of soil physicochemistry, excluding other species and thereby enabling the dominance of mangrove species. While mangroves tolerate high salinities, excess salinity can produce stressful conditions, particularly in basin mangrove systems where salinities can become hypersaline. Hypersalinity occurs in areas not connected to coastal fluxes, such that isolated areas become increasingly saline with evaporation. In contrast, isolated areas can also become increasingly fresh where and when precipitation is more frequent.

Mangrove ecosystems that are connected to estuaries and rivers generally have soils that have a higher nutrient and mineral content. Nutrient limitations can occur where there are only oceanic influences and terrigenous sediment inputs are minimal (e.g., biogenic wetlands on top of carbonate platforms as in South Florida) (Feller, 1995). The presence of mineral content shows an external deposition source that can aid in maintaining elevations and results in higher bulk density (Morris et al., 2016). Lower organic matter can indicate greater resistance to change because components are less likely to leave as dissolved lateral fluxes. Elevated nutrients, while potentially increasing plant production, are not necessarily optimal for system sustainability (Lovelock et al., 2009). Nutrient enrichment can increase aboveground production (leaves, stems) with simultaneous decreases to belowground production. A resulting lower root-to-shoot ratio can lead to mortality (Lovelock et al., 2009) and likely more erosion and elevation loss from reduced root strength.

Hydrologic Setting

Hydrologic setting incorporates precipitation patterns, connectivity to the ocean, connectivity to rivers, elevation, water table variability, sea level rise, water chemical composition, and many other factors. While all certainly have some effects on mangrove ecosystems, connectivity and hydrologic exchanges are prominently important. Mangroves exist in different geographic positions, which are associated with different hydrologic environments (Lugo and Snedaker, 1974; Mitsch and Gosselink, 2015). Fringe mangroves occupy coastal boundaries with frequent inundation, and water levels are almost exclusively driven by tide (most connected to ocean). Riverine mangroves occupy riparian zones along coastal channels and tidal creeks (less connected). Basin mangroves occupy inland depressions or impounded areas resulting in partially or fully stagnant water (least connected). Two other physiognomic settings of mangroves occur in overwash zones (high wave energy and/or tidal velocities) and dwarf or scrub forests (nutrient limited and/or hypersaline) (Lugo and Snedaker, 1974).

Often wetland water level variability is characterized by ‘hydroperiod’ incorporating flood depth, duration, and frequency, and the variability surrounding those parameters. However, the most important factor for mangroves is the degree of water exchange versus stagnancy. Lower elevation may be more vulnerable to submergence, and low elevation with exchange yields conditions that are more habitable than hypersaline disconnected areas. For low elevation to be sustainable and the hydrologic regime to be stationary (relative to elevation), sea-level rise must be matched by elevation gain.

Connectivity has many definitions, but here we use it to describe the ease of flow of matter. Low connectivity results in little water level variability, hypoxia, often hypersaline or fresh conditions (depending on climate), and accumulation of other chemicals. High connectivity areas have a chemical composition and water level pattern that mimics surrounding bodies of water, typically resulting in salinities and nutrient levels similar to adjacent aquatic environments. Altered connectivity (e.g., by construction of berms or diverted flows) can result in rapid decline and potentially complete mortality, because mangroves are stressed by anoxic and/or hypersaline conditions (Lewis et al., 2016). This can also result in degradation of associated communities (e.g., microbes and fish).

Water quality is affected by many of the factors that also influence hydrologic variability. The geomorphic setting determines water sources (Brinson, 1993) and ultimately the constituents within that water. Important components of water quality in mangroves are salinity, total suspended solids (TSS), and nutrient load—particularly those nutrients contributing to eutrophication. These same three factors are necessary elements of mangrove ecological function, but can become stressors to the system at higher concentrations. Human activity can directly and indirectly influence quality through system modifications. For example, dams and levees alter flow velocity and therefore how much sediment exits a river system (Tockner et al., 1999). Agricultural activity generally increases nutrients loads, increasing the likelihood of eutrophication.

Ecosystem Structure

Plant Community Structure

Mangrove ecosystems exist with a diversity of structures that arise from land history, abiotic conditions, and the species present. Prominent physical characteristics defining mangrove systems are a dense canopy with highly intertwined crowns, frequently an understory dominated by prop roots, and a ground surface that is regularly flooded, with microbial mats, pneumatophores (extending from mangrove roots), or salt marsh grasses and forbs. Otherwise the understory can be remarkably bare (Mitsch and Gosselink, 2015).

Tree growth forms vary both within and across species, generally ranging from low shrubs to tall trees. Fringe and overwash systems tend to have mostly red mangroves; basin mangrove forests are dominated by black mangroves and white mangroves; and riverine and dwarf/scrub forests have mixtures of all three species. Riverine forests have generally taller and larger trees compared to basin and scrub mangroves, which are dominated by smaller and less dense individuals (Lugo and Snedaker, 1974; Day et al., 1989; Mitsch and Gosselink, 2015). All of these physiognomic patterns are mediated by the climate of the geographic location within the NGoM; freezing winter temperatures will have species specific effects of dieback, which can result in a scrub form (McMillan and Sherrod, 1986; Day et al., 2013). Black mangroves are the most freeze-tolerant and thus dominate the extreme northern latitudes of the NGoM, regardless of hydrologic setting (Day et al., 2013). Given that these trees are long-lived, these size relationships are also a function of site permanence as opposed to just growth and production rates; for large trees to occur, the ecosystem must be stable enough to maintain adequate growing conditions over a long duration.

Viability of propagules and saplings vary by site biotic and abiotic conditions. Optimal conditions for sapling growth are generally below ocean salinities (3–27 PSU), temperatures well below physiological limits, with gaps and thus available light; however, results are variable among studies (Krauss et al., 2008). It is likely that, like most plant ecosystems, establishment relies upon the availability of propagules, availability of growing space, and appropriate conditions that do not appear particularly distinct from those where overstory mangroves exist. The ability to successfully establish from propagule (Delgado et al., 2001) does enable development of new mangrove systems.

Landscape Structure

Despite low species diversity, morphology of the mangrove landscape 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 ecological and anthropogenic factors. Mangroves expand through dispersal of floating propagules, and hydrology plays a key role in the rate of expansion as well as the relation of hydrologic barriers to landscape structure. Mangroves can expand into systems other than mudflats if conditions change to favor mangroves or if mangroves simply outcompete marsh vegetation.

Like marshes, landscape change in mangrove ecosystems 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; Smith et al., 2009). While mangroves can exist in large expansive areas, internal basins receive increasingly less exchange, which ultimately leads to dieback of internal areas (Lewis et al., 2016). Internal die back leads to a more disaggregated landscape (i.e., greater edge-to-area ratio).

Human effects on landscape structure are prominent. Indirect anthropogenic effects on landscape patterns include upstream control over the transport of sediment and nutrients (Kennish, 2001). Even if infrastructure development does not directly remove mangroves, modifications to the environment can have significant effects on 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 mangrove forests, as well as alter species corridors (Turner, 2010). Oil removal can directly drive subsidence (Kennish, 2001), and unintentional releases of petrochemicals can alter geomorphic stability (DeLaune et al., 1979). Reduced or absent vegetation, whether impaired by petrochemicals (Culbertson et al., 2008) or other processes, results in less protection of surface sediments from erosive forces (Kadlec, 1990).

Microbial Community Structure

Mangrove microorganisms include fungi, bacteria, and other species that occupy the rhizosphere and litter layers. Microbial mats on the soil surface can be particularly high in productivity (Zedler, 1981) and play an important role in total ecosystem function. Subsurface processes maintain elevation and provide the organic effluxes that provide an energy source for landscape-level productivity. Studies have shown that coastal soil microbial communities, or at least the fluxes they control, can be fairly resilient against pollution effects (DeLaune et al., 1979; Li et al., 1990), although changes may alter respiration and other processes (Chambers et al., 2013).

Ecosystem Function

Elevation Change

Elevation change is an essential function for the sustainability of mangrove ecosystems because sea levels change and land subsides. Interpretation of elevation change should be placed in the context of initial elevation relative to sea level, sea-level change, and tidal range. Decreases in elevation relative to sea level occur with sea-level rise and surface erosion and subsidence, which is influenced by erosion, decomposition, and compaction of sediments (Cahoon and Turner, 1989), subsurface withdrawals (e.g., water, oil, gas) and geologic activity (Kennish, 2001). Elevation gains occur by sediment deposition and in situ biomass production contributing to organic accretion (from leaves, roots, exudates, and soil biota). Slow decomposition rates associated with mangrove biomass can be important to maintaining peat accumulation that contributes to elevation capital (McKee et al., 2007).

Elevation and sea level change have feedback because 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. While this concept has mostly been explored in salt marshes (e.g., Kirwan and Megonigal, 2013), the same processes occur in mangroves. Spring tidal ranges in the Gulf 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 the small tidal range and small allochthonous sediment supply.

Primary Production

Primary production varies by system type, with higher productivity in fringe and riverine systems (Mitsch and Gosselink, 2015). Overall, mangroves are high productivity systems (10–30 Mg ha^{-1} yr^{-1} (Bouillon et al., 2008), comparable to other forest systems in tropical regions (e.g., biome mean of tropical rain forest aboveground net primary productivity = 1.4 Mg ha^{-1} yr^{-1}; Chapin et al., 2002). While these values are not well constrained and are considerably uncertain, the potentially high production is noteworthy because of its contribution towards elevation gains.

Controls over productivity are not well understood, but salinity, phosphorus, nitrogen, and hydroperiod appear to have important effects (Feller et al., 2003; Feller et al., 2007; Krauss et al., 2006; Scharler et al., 2015), but with optimal conditions being more intermediate. In general, phosphorus is limiting on carbonate substrates, and nitrogen is limiting in areas that receive high sediment inputs (Feller et al., 2007; McKee et al., 2002). Climate is an important control, with lower latitudes having higher productivity. Understanding of productivity is limited by very few measurements of wood production and even fewer estimates of root production (Bouillon et al., 2008). However, impeded connectivity is a stressor (Lewis et al., 2016) and associated conditions (low dissolved oxygen, low matter exchange, and high salinity) reduce productivity (Gilman et al., 2008). These effects are exacerbated by lower precipitation amounts that can further increase salinity and force early senescence (e.g., Day et al., 1996).

Decomposition

Besides the importance of decomposition to elevation changes, secondary production largely relies on decomposition (herbivores use a small fraction of live biomass) and the organic exports, which can be particularly high in mangroves (Maher et al., 2013). However, the high tannin content of partially decomposed mangrove materials may be less ideal for macrofaunal consumption (Lee, 1985). This is a primary difference from marsh ecosystems, where decomposition largely takes place in the marsh and is thus exported as more readily consumable products (Lee, 1985). Decomposition rates vary tremendously by species, plant component, and ecosystem, with more impounded areas generally having slower decay rates (and, therefore lower DOC and DIC exchange rates).

Secondary Production

Secondary production in mangroves is mostly composed of soil microbial processes, with their biological activity most easily monitored through soil respiration measurements, which are largely driven by soil temperatures (e.g., Lovelock, 2008). Besides the microbial community, crabs are abundant; however, they do not necessarily play an important role in leaf decomposition as observed elsewhere (McIvor and Smith, 1995).

Bird and fish communities are apparent. The dense ecosystem structure provides important nursery habitat for many species. Due to the southern extent of mangroves into tropical Florida, several species that are rare or absent from the rest of the United States are found in mangrove ecosystems (mangrove cuckoo, white crowned pigeon) (Bird Watcher’s Digest, 2017). Likewise, southern mangrove systems are vulnerable to species invasion by tropical species—an abundance of invasive species are currently in mangroves in southern Florida (Fourqurean et al., 2010; Ward et al., 2016).

Management considerations that negatively affect the trees and their production have cascading effects on the heterotrophic communities. Conditions that lower tree productivity also alter the availability of energy sources to other trophic levels. Furthermore, the physical impediments to connectivity that stress trees also limit the exchange of matter and biota between mangrove forests and the surrounding aquatic environment (Lewis and Gilmore, 2007).

Biogeochemical Cycling

Biogeochemical cycles are inexorably involved in all factors discussed above because of the chemical transformations and exchanges that occur. Nitrogen cycles are especially distinct in wetlands because of the presence of both oxic and anoxic conditions, enabling nitrification and subsequent denitrification. In areas where nitrogen is unnaturally elevated, nitrogen cycling in wetlands can play an important role in reducing eutrophication (Mitsch and Gosselink, 2015).

The accretion of nutrient-rich sediments in wetlands can allow for storage of nutrients, removing a portion from circulation. Accordingly, the conditions that allow these long-term capture, storage, or transformation are essential to elevation 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.

Mangroves play an atypical role in the greenhouse gas budget where salinity and water level variations can occur such that they can act as a carbon sink (through production and storage) or as a carbon source, due to effluxes of CO_2, CH_4, and nitrous oxide (e.g., Chen et al., 2016), which alter atmospheric chemistry and radiative forcing. In general, healthy mangrove ecosystems in a stable tidal regime can sequester carbon, but factors which degrade or cause mortality of mangroves can lead to carbon release.

Factors Involved in Ecosystem Service Provision

Mangrove forests constitute one of the most productive ecosystems in the world, providing a diverse suite of ecosystems services upon which human well-being depends. These unique forests exist both above and below the waterline, providing habitat for an exceptional suite of biodiversity, including many threatened species. They provide fish habitat and nursery areas which support subsistence and commercial production while also providing timber, wood and medicinal plants. The physical structure of mangrove ecosystems acts to stabilize shorelines and protect vulnerable coasts from wind and wave erosion. Several studies have analyzed the value of mangroves and other habitats for protection of coastal communities from storm surge (e.g., Barbier et al., 2008; Costanza et al., 2008; Das and Vincent, 2009). It is often difficult to be precise about how much protection ecosystems are likely to provide given the variability of storms, including wind speed and direction, duration, and arrival of the storm relative to high tides (Koch et al., 2009), but there can be little doubt that their contributions can be significant. These protection benefits reduce the risk of human and material losses, thus enhancing economic benefits by upholding the diverse functions and uses of mangrove ecosystems, including potential biodiversity-related tourism (UNEP, 2014; Danielsen et al., 2005).

Globally, mangrove forests and estuaries provide environmental services that mitigate and facilitate adaption to climate change, as they not only reduce the risks of extreme weather events, but also have great potential to sequester and store carbon (Twilley et al., 1992; Donato et al., 2011; Coastal Blue Carbon, 2015; Barbier et al., 2011). A complete list of the services provided by mangroves in the NGoM is provided by Yoskowitz et al. (2010); below we provide an overview of the most important Key Ecosystem Services that we included in the conceptual ecological model.

Supporting

Habitat

Mangrove vegetation provides habitat to support the diversity of terrestrial and marine invertebrates and vertebrates. The mangrove forest provides habitat characteristics that many species depend on, including good water quality, moderate slope in banks, slow currents, overhanging vegetation that provides shade, and the structure and protection that is provided by the mangrove shoot and root systems (Seaman and Collins, 1983). The ability of the mangrove to provide habitat for commercially important species depends on the factors described for the "Secondary Production" Key Ecological Attribute above.

Provisioning

Food

Mangroves are the breeding and nursery grounds for many fish species. Ninety percent of the commercial species in South Florida are dependent on mangrove ecosystems (Law and Pywell, 1988).

Regulating

Coastal Protection

Mangroves provide ecosystem benefits that reduce coastal risks, such as coastal erosion, wave energy reduction, and storm surge reduction (McIvor et al., 2012). Mangroves help stabilize the shoreline by reducing the erosion and therefore making the shoreline less vulnerable to other natural hazards (The Nature Conservancy, 2017). 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). The protection benefit of any mangrove vegetation will depend on many factors, such as exposure, intensity, and local conditions.

Reduction of wave energy depends on the structure of the plant canopy, its height and density, and the cross-shore and along-shore extent of the wetland (Koch et al., 2009; Krauss et al., 2009; Massel et al., 1999; Narayan and Kumar, 2006; Shepard et al., 2011; Vosse, 2008). The velocity of water traveling within a plant canopy is relatively lower than above the canopy. Canopy height in relation to water depth is relevant because water flowing through the vegetation encounters a higher friction than does the water above the vegetation. Therefore, the total friction in the water column will change with the depth of vegetated and non-vegetated areas. Because a mangrove canopy is taller and exerts more drag than a salt marsh community, mangroves are more effective at reducing water inflow and waves than are salt marshes. Quartel et al. (2007) suggested that the drag force exerted by a mangrove forest can be approximated by the function CD = 0.6e0.15A, where CD is the coefficient of drag and A is the projected cross-sectional area of the submerged canopy. For the same muddy surface without mangroves, the drag is a constant 0.6. Mazda et al. (1997) observed that a 100-m-wide strip of mangrove forest was capable of reducing wave energy by 20 percent. Reduction in water levels across a mangrove area in Florida was 9.4 cm/km (Krauss et al., 2009).

Water Quality

Mangroves improve water quality by retaining sediment particles and pollutants. Mineral accretion is important to long-term mangrove sustainability and is dependent on flood regime and the availability of mineral sediments in the water column (Childers and Day, 1990). While soil organic matter content reflects some aspects of total suspended solids, it is not directly related due to variations in hydrogeomorphic position (Hatton et al., 1983). Sediment sources are highly correlated to river delta morphology and river discharge, but these sources are altered by anthropogenic activity (e.g., levees and dams; Kennish, 2001).

Carbon Sequestration

Due to high above- and belowground productivity and minimal decomposition, mangroves are capable of storing large amounts of organic carbon. As such, they play an important role in mitigating climate change despite their relatively small footprint.

Cultural

Aesthetics-Recreational Opportunities

As nursery grounds for important game fish, mangroves provide opportunities for recreational fishing.

Indicators, Metrics, and Assessment Points

Using the conceptual model described above, we identified a set of indicators and metrics that we recommend be used for monitoring mangrove ecosystems across the NGoM. Table 3.1 provides a summary of the indicators and metrics proposed for assessing ecological integrity and ecosystem services of mangrove 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 an indicator that was practical to apply based on our selection criteria. Below we provide a detailed description of each recommended indicator and metric(s), including 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 mangrove ecosystems. Figure 3.3 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 3.15. *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/*Basin-wide Nutrient Load (Total Nitrogen, Total Phosphorus)*
			Connectivity/*Multi-metric*
	Ecosystem Structure	Plant Community Structure	Stand Health/*Foliage Transparency*
			Regeneration Potential/*Propagule, Seedling, Sapling Presence*
		Landscape Structure	Land Aggregation/*Aggregation Index (AI)*
			Land Cover Change/*Land Cover Change Rate*
		Microbial Community Structure	--
	Ecosystem Function	Elevation Change	Submergence Vulnerability/*Wetland Relative Sea Level Rise (*$RSLR_{wet}$*) and Submergence Vulnerability Index (SVI)*
		Primary Production	--
		Decomposition	--
		Secondary Production	Fish Habitat/*Killifish Species Diversity*
			Invasive Species/*Presence (Multiple Species)*
		Biogeochemical Cycling	--
Ecosystem Services	Supporting	Habitat	Status of Macrofauna Populations/*Density of Juvenile Common Snook*
	Provisioning	Food	Status of Snapper-Grouper Complex Commercial Fishery/*Density of Gray Snapper* and *Annual Commercially Landed Weight of Gray Snapper (*Lutjanus griseus*) in the Gulf of Mexico States and/or Federal Waters*
	Regulating	Coastal Protection	Erosion Reduction/*Shoreline Change*
		Water Quality	Nutrient Reduction/*Basin-wide Nutrient Load (Total Nitrogen, Total Phosphorus)*
		Carbon Sequestration	Soil Carbon Storage/*Mangrove Height*
	Cultural	Aesthetics-Recreational Opportunities	Recreational Fishery/*Density of Juvenile Common Snook*

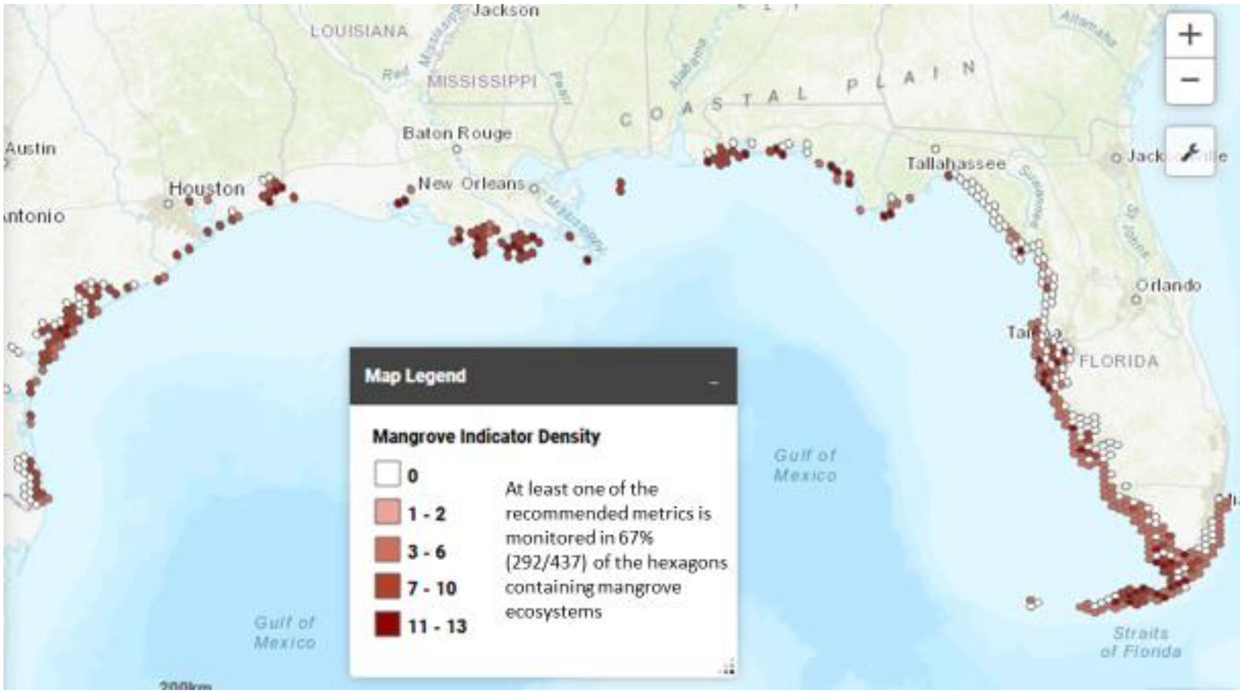


Figure 3.17. *Density of the recommended indicators being collected in mangrove ecosystems in the NGoM. Shaded hexagons indicate the number of the recommended indicators that are collected by monitoring programs in each hexagon.*

Ecological Integrity Indicators

Indicator: Eutrophication

MEF: Abiotic Factors
KEA: Hydrologic Setting
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 mangrove waters.

Background: Eutrophication affects root and production patterns (Krauss et al., 2008; Feller et al., 2007) 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, which, in turn, can lead to increased soil erosion and soil collapse (Deegan et al., 2012; Lovelock et al., 2009). 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 ecosystem functioning, and prevalence of excess nutrients in the NGoM 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 regard to nutrient cycling. Thus, a spatially and temporally aggregated metric is preferable for monitoring eutrophication. The HUC 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 (remote sensing and modeling)

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 mg
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

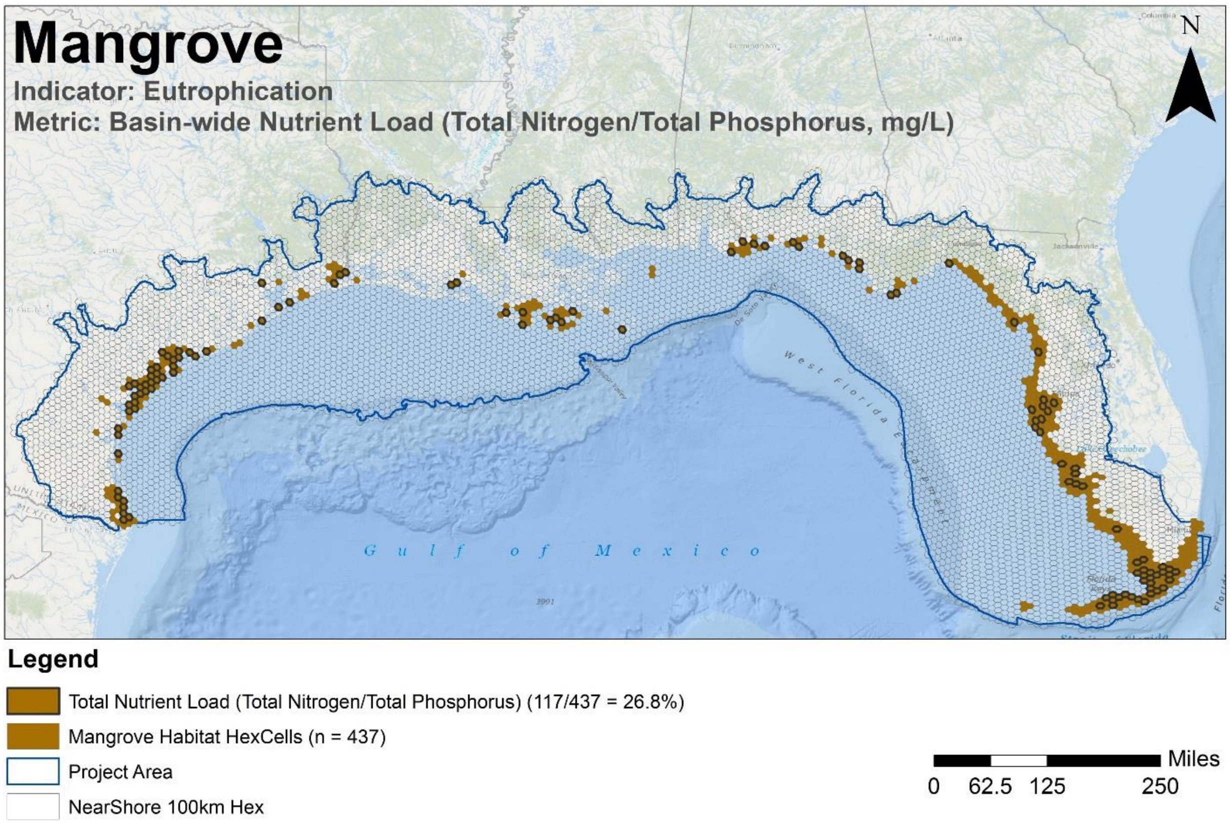
Scaling Rationale: SPARROW outputs for TN concentration range from near 0.05 to > 7 mg L^{-1} in coastal basins of the NGoM. TP concentrations range from near 0.00 to > 0.9 mg L^{-1} in coastal basins of the NGoM. Applying these criteria to mangrove ecosystems necessarily takes into account that mangroves grow in varying steady-state morphological forms (gallery forests in riverine areas to dwarf forests on carbonate substrates in the Florida Keys). While low nutrient concentrations do not necessarily indicate superior ecological function for all aspects of the ecosystem, the potential for eutrophication in soils and within the water column 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 27% of habitat hexagons containing at least one monitoring site. Monitoring locations for this metric are relatively well distributed across the NGoM where mangroves occur.

<u>Programmatic:</u> Data for this metric are collected by 2/42 (5%) of the programs collecting relevant mangrove data in the NGoM.

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



Metric	Total Relevant Mangrove 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	42	2	5%	27%

Indicator: Connectivity

MEF: Abiotic Factors
KEA: Hydrologic Setting
Metric: Multi-metric

Definition: The ease of water flow into and out of a site.

Background: Where connectivity is impaired, issues such as hypoxia and hyper-salinity affect forest health. These impacts are arguably more prevalent to aquatic communities affected by changing water quality. Connectivity impairment manifests in quantitative and qualitative changes to hydrologic variability and water chemistry that can be detected. As mangrove stands lose hydrologic connectivity and become more stagnant, dissolved oxygen levels decrease, salinity increases, standing water in the stand builds up tannins, and sulfate-reducing bacteria become visibly apparent (anaerobic bacteria indicative of anoxic conditions [Day et al., 1989]). Because connectivity impairment is not likely in a fringe mangrove system, this assessment only applies to basin mangroves.

Rational for Selection of Variable: In the absence of hydrologic connectivity, there are rapid consequences that alter the biogeochemical and physiological processes that can lead to mortality and change of the ecosystem entirely.

Measure: (a) relative tidal signature | (b) water color | (c) dissolved oxygen (DO) level | (d) sulfate-reducing bacteria | (e) salinity | (f) observable presence of flow barriers

Tier: 2 (rapid field measurement) and 3 (intensive field measurement)

Measurement: Multiple assessment approaches are offered because sites differ in logistical ease of access. With proper equipment, salinity, dissolved oxygen, and water level variability are all easily measured. With experience, connectivity may be assessed by simple observations of water color, presence of bacterial films, or presence of obvious flow barriers. Although six metrics are described (a–f), one metric should be chosen due to ease of measurement, or observer expertise, and followed through all three ratings, rather than using a different metric for each rating.

Metric Rating and Assessment Points:

Metric Rating	Connectivity Multi-metric
Excellent–Good	(a) sinusoidal tidal signature mirroring connected body of water, (b) water has color expected based on nearby water bodies, (c) DO varies with tide, (d) bacterial films are not apparent, (e) salinity >10 PSU and < 45 PSU, depending on location of mangroves with relation to freshwater input (f) no apparent obstructions to flow
Fair	(a) some tidal variability apparent, but not following reference pattern, (b) reddish brown colored water (c) DO < 2 mg/L (hypoxic) under restricted flow condition, (d) sulfate reducing bacterial films may be present in small non-draining pools, (e) PSU > 45 or PSU < 90 (f) flow barriers restricting flow (e.g., road with undersized culvert)
Poor	(a) no tidal signature, (b) dark brown to black colored water, (c) DO near 0 mg/L (anoxic) under chronic stagnant condition, (d) bacterial films are widespread (e) PSU > 90 (f) berm around site or tidal channel filled, cutting off all flow

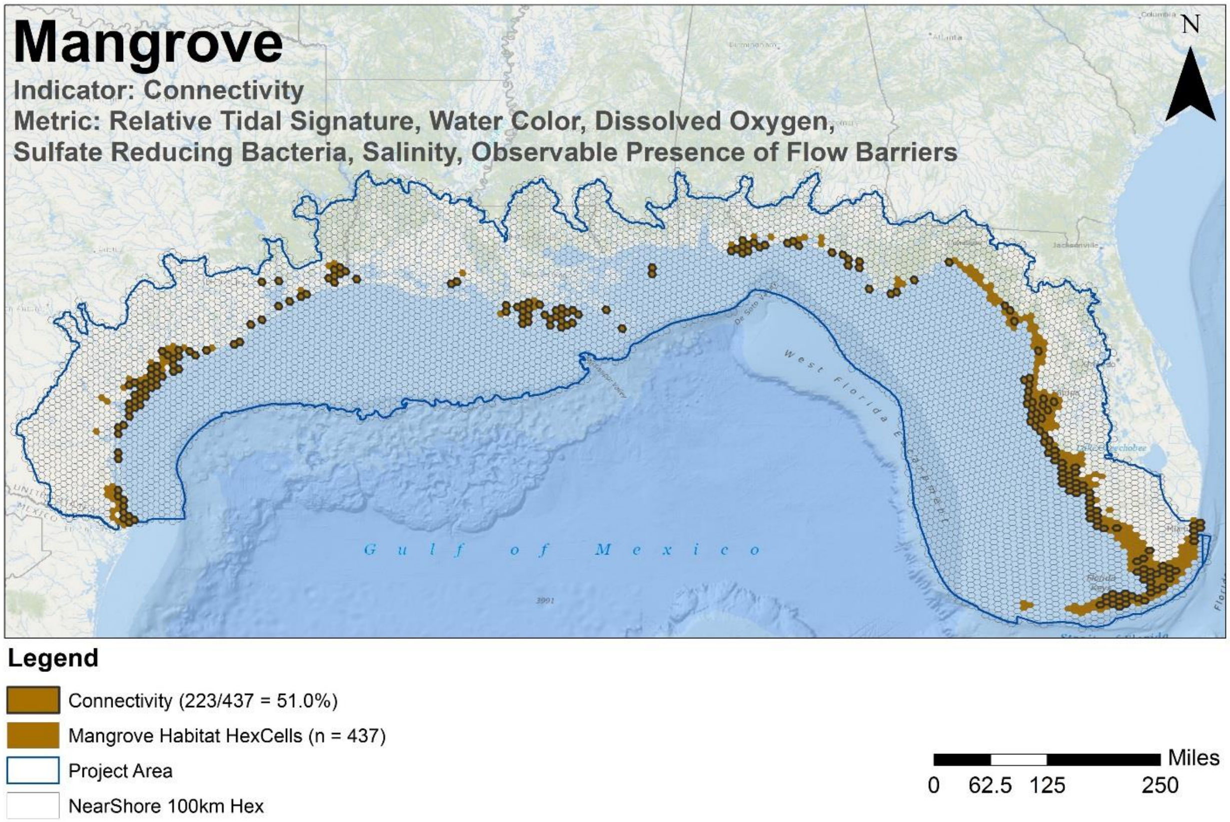
Scaling Rationale: Measurement of a tidal signature within a mangrove stand that is similar to the connecting body of water outside the stand is direct evidence of water flow in and out of the stand. Attenuation to absence of the tidal signature (caused by berms or tidal channel filling) indicates restricted to no flow, respectively. With restricted or absence of flow, water color becomes more tannic as stagnation ensues. Flow from a connecting body of water imparts oxygenated water to a mangrove stand. NOAA has defined hypoxia in the NGoM as water where the DO concentration is less than 2 mg/L (https://www.ncddc.noaa.gov/hypoxia/). While mangroves are adapted to survive in hypoxic and hypersaline conditions (Mitsch and Gosselink, 2015), it is not the optimum for highest mangrove growth and productivity. While mangroves may survive in conditions of PSU > 90, optimum growth of some species is about half of seawater (Tomlinson, 1986). Seawater averages about PSU 35 (http://oceanservice.noaa.gov/facts/whysalty.html). Sulfate-reducing bacterial films indicating anoxic conditions are easily visible to a trained eye.

Analysis of Existing Monitoring Efforts:

Geographic*:* The metrics that are used to assess connectivity are collectively well collected geographically in the NGoM, with 51% of habitat hexagons containing at least one monitoring site for at least one of the metrics. Monitoring locations for these metrics are well distributed across the NGoM where mangroves occur.

Programmatic: Data for this metric are collected by 9/42 (21%) of the programs collecting relevant mangrove data in the NGoM.

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



Metric	Total Relevant Mangrove 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
Connectivity Multi-metric	42	9	21%	51%

Indicator: Stand Health

MEF: Ecosystem Structure
KEA: Plant Community Structure
Metric: Foliage Transparency

Definition: Relative assessment of the amount of light penetrating the tree canopy.

Background: A mangrove forest stand losing foliage cover is a sign of unhealthy conditions because mangroves are evergreen, and healthy mangroves have a cover of green leaves all year round, initiating new leaves as older leaves senesce to maintain constant leaf coverage (Tomlinson, 1986). Light penetration through the canopy is an indirect measure of the cover of leaves in the canopy. A distinction must be made between the loss of leaf cover from chronic health issues vs. the sudden defoliation caused by storms, especially hurricanes (wind and/or wave action) or acute freeze damage. Prior knowledge of these sudden events is essential before making an assessment of site health using leaf cover as an indicator.

Rational for Selection of Variable: Light penetration measurement gives a very quick estimation of leaf cover and can be measured quantitatively with light detecting instruments or qualitatively by visual observation.

Measure: Measures were adapted from the US Forest Service Forest Inventory and Analysis (USFS FIA) protocol, with adjustments necessary for mangrove forest structure; specifically, we assess the "foliage transparency." Only canopy trees (i.e., dominant/codominant) should be selected for analysis.

Tier: 2 (rapid field measurement)

Measurement: Foliage transparency is assessed by examining the crown of a tree, identifying where branches support foliage, and then assessing the amount of light transmission through that foliage. Figure 3.4 provides guidance on assessment of potential foliated outline, and Figure 3.5 on the relative transmission through. Note that epicormic branches—shoots directly from dormant buds in a main branch or stem—do not count as crown and thus receive a rating of 100% transparency. Likewise, branches without foliage may still intercept light but should not be included in the rating (i.e., a fully defoliated tree has a 100% transparency). Branches that are shaded and have apparently died because of light competition and subsequent self-pruning (i.e., in deep shade) should not be treated as capable of maintaining foliage. Foliage transparency should be assessed at 10 randomly selected points within each monitoring plot. Due to differences between mangroves and other forests, we assess transparency vertically and for a single field of view at 45 degrees from vertical.

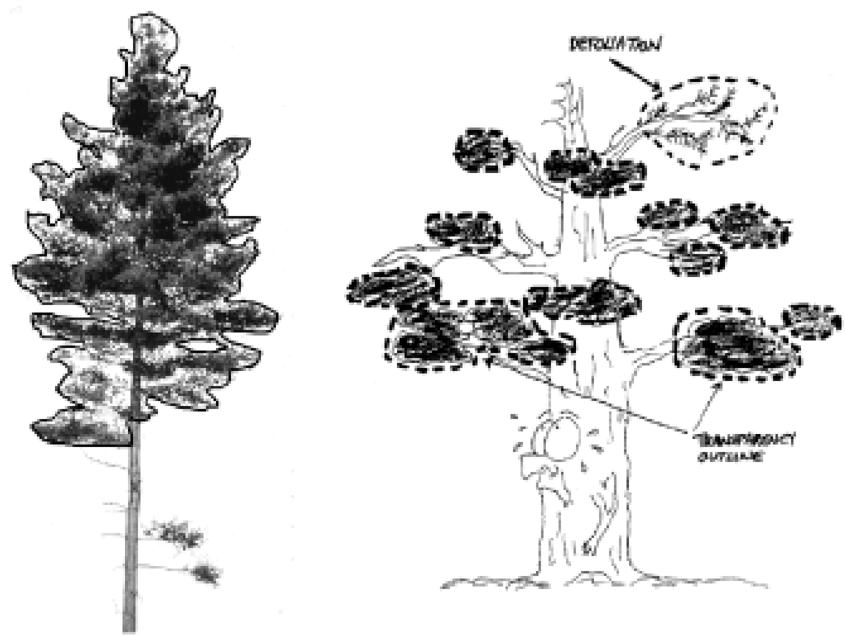


Figure 3.19. Diagram showing how to assess the foliar outline over which areas foliage density should be assessed (from USFS FIA)

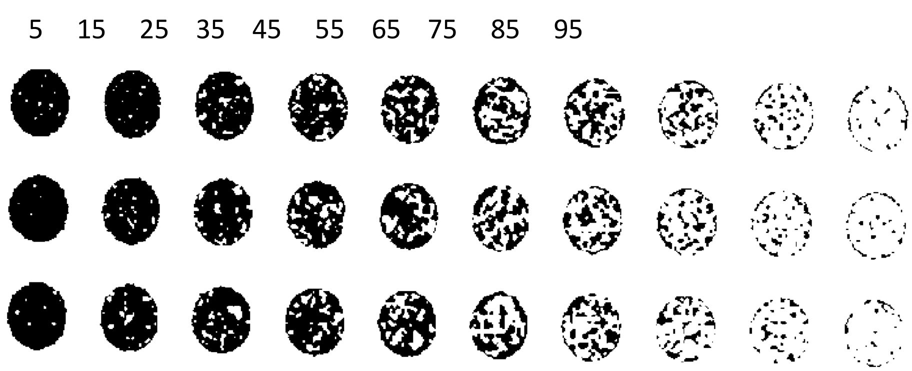


Figure 3.18. Diagram to aid in determining the relative transparency of

Metric Rating and Assessment Points:

Metric Rating	Foliage Transparency
Good	Transparency < 25%
Fair	25 % < Transparency < 50%
Poor	Transparency > 50%

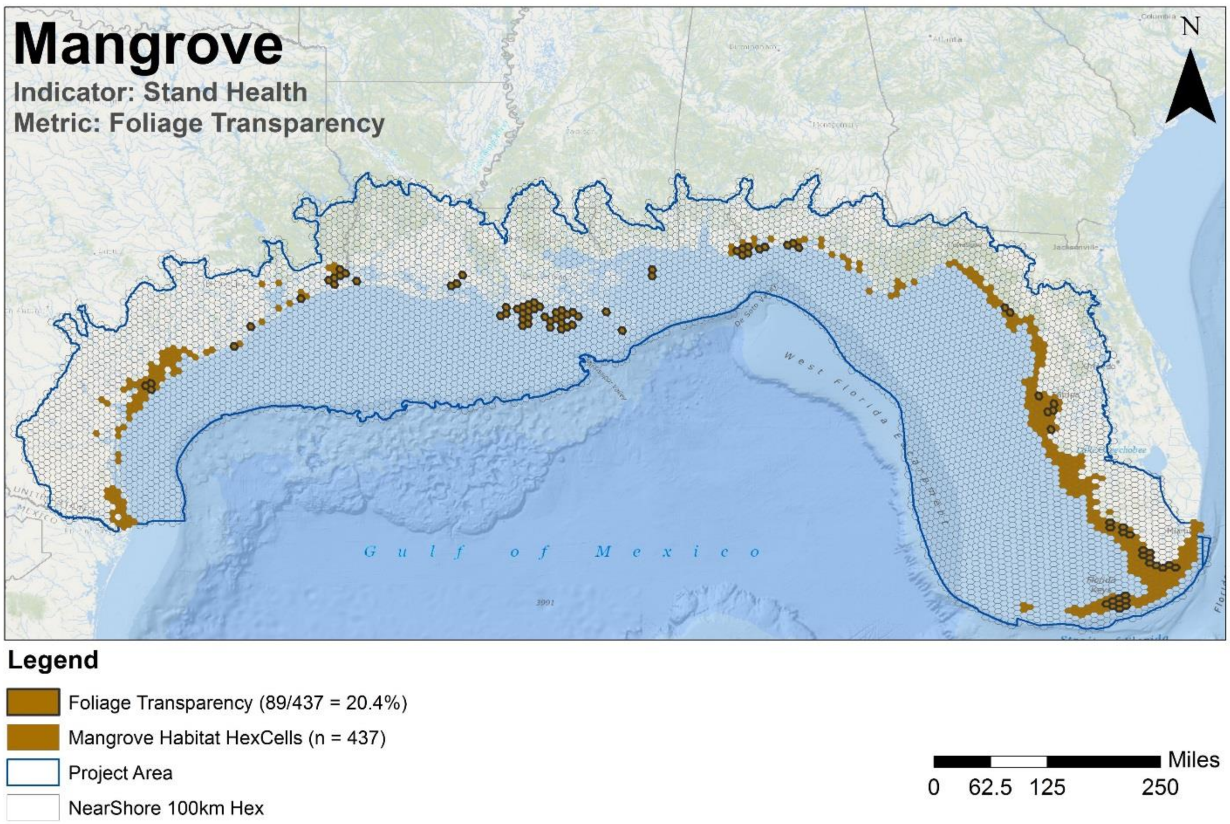
Scaling Rationale: Lewis et al. (2016) provide an in-depth discussion of detecting mangrove degradation and observations of stressed mangrove stands, including photographs. Given the absence of sudden defoliation caused by severe storms or freezes, percentages of 25% and 50% transparency are considered appropriate measures of mangrove stands in good and poor health condition, respectively.

Analysis of Existing Monitoring Efforts:

Geographic*:* Foliage transparency is less collected geographically in the NGoM, with 20% of habitat hexagons containing at least one monitoring site. Monitoring locations for this metric are distributed across the NGoM where mangroves occur.

Programmatic: Data for this metric are collected by 15/42 (36%) of the programs collecting relevant mangrove data in the NGoM.

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



Metric	Total Relevant Mangrove 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
Foliage Transparency	42	15	36%	20%

- 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: Regeneration Potential

MEF: Ecosystem Structure
KEA: Plant Community Structure
Metric: Propagule, Seedling, Sapling Presence

Definition: The density of mangrove species (*R. mangle, A. germinans, L. racemosa*) seedlings (< 1 m tall) and saplings (< 2.5 cm diameter) (Baldwin et al., 2001) and seed propagules over a given area.

Background: The condition of a stand goes well beyond simply examining canopy structure because the regeneration potential indicates the system's long-term viability. In the absence of regeneration potential, a disturbance event can trigger a direction state change away from the target system. Mature trees generally better tolerate stress, which means that conditions that alter stand condition may be seen more readily in saplings and seedlings.

Rational for Selection of Variable: All metrics are indicators of the ability for gaps to be filled, recover from disturbance, and general suitability of mangroves for the present abiotic conditions.

Measure: Mean density of seedlings, saplings, and viable propagules across 10 plots

Tier: 3 (intensive field measurement)

Measurement: For a given assessment site, establish 10 randomly placed 5 × 5 m plots. Within each plot, count number of seedlings, saplings, and viable propagules. Calculate mean of the 10 plots.

Metric Rating and Assessment Points:

Metric Rating	Propagule, Seedling, Sapling Presence
Good	> 1 seedling or sapling per plot
Fair	< 1 seedling or sapling per plot and propagules are present
Poor	< 1 seedling per plot and propagules are absent

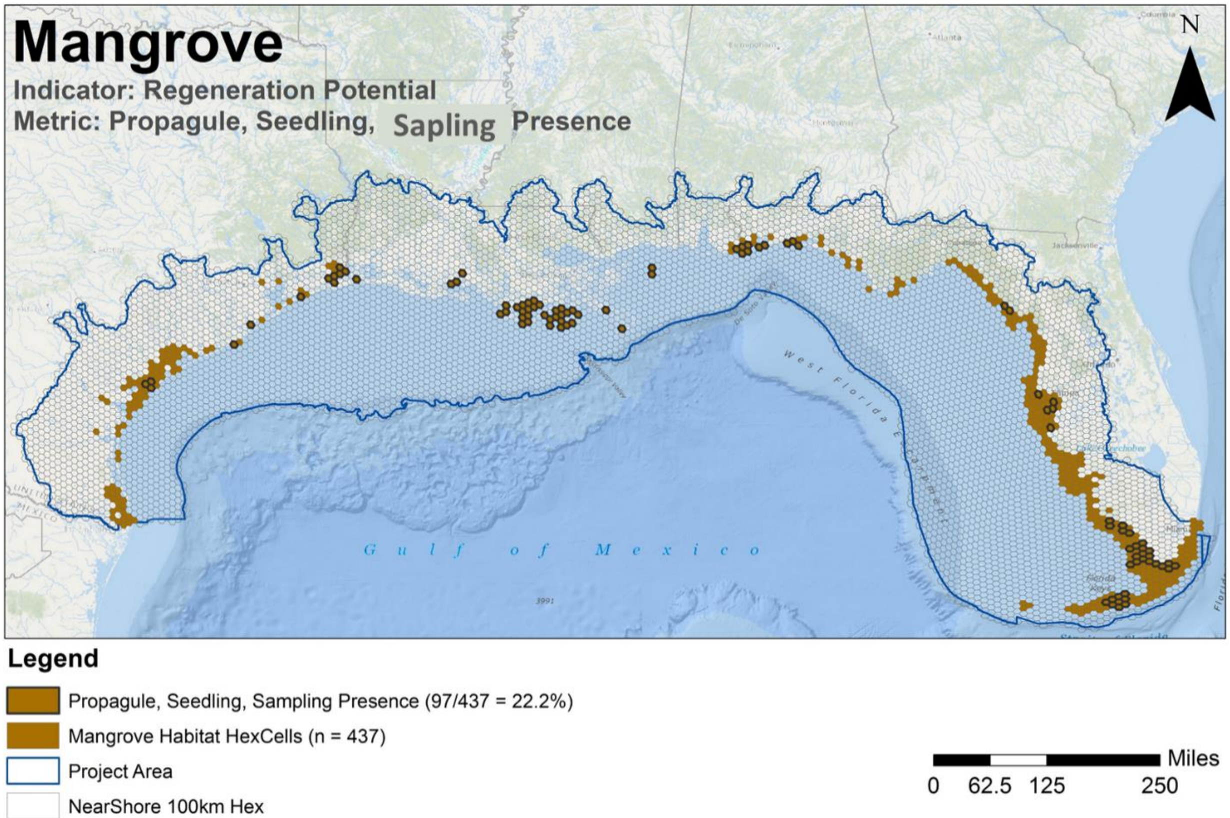
Scaling Rationale: While more seedlings and saplings would be ideal, it is reasonable for them to be absent under dense canopies because of light competition. However, if suitable establishment conditions exist, there will always be some seedlings and/or saplings because of natural heterogeneities in the light environment. Thus, the average over 10 plots is used. Presence of propagules is considered sufficient to indicate the potential for a sustainable stand, so a fair rating is assigned.

Analysis of Existing Monitoring Efforts:

Geographic*:* Propagule, seedling, or sapling presence is less collected geographically in the NGoM, with 22% of habitat hexagons containing at least one monitoring site. Monitoring locations for this metric are relatively well distributed across the NGoM where mangroves occur.

Programmatic: Data for this metric are collected by 13/42 (31%) of the programs collecting relevant mangrove data in the NGoM.

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



Metric	Total Relevant Mangrove 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
Propagule, Seedling, Sapling Presence	42	13	31%	22%

- Very large spatial footprints for one monitoring programs made assessment of sampling sites uncertain, and they were omitted from the map.
- Spatial footprint for one monitoring program not available.
- Percent of hexagons containing monitoring sites may be an underestimate.

Indicator: Land Aggregation

MEF: Ecosystem Structure
KEA: Landscape Structure
Metric: Aggregation Index (AI)

Definition: The physical structure of the landscape, 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 coastal ecosystems are both related to the shape of the landscape. Subsidence generally occurs in interior areas (Lewis et al., 2016), 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).

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

Measure: Landsat 30 m pixels classified as water, unvegetated mudflats, marsh, or mangrove

Tier: 1 (remotely sensed)

Measurement: Remote sensing (tier 1) techniques with Landsat data (30 m resolution) will provide the data needed to calculate AI, a metric quantifying the fraction of pixels with adjacent pixels of the same classification. Winter images should be used because of the distinction between senescent marsh and evergreen mangroves during the winter. Precise methodological details are in Couvillion et al. (2016). This requires classifying the pixel as either water, marsh, or mangrove, and then applying the analysis directly to the raster of classified pixels. AI was calculated for a given area of interest (AOI):

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

yielding 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 mangrove, marsh, and open water; Couvillion et al. 2016).

Metric Ratings and Assessment Points:

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

Scaling Rationale: Land aggregation scaling assessment points are defined with respect to Figure 9 in Couvillion *et al*. (2016). While these metrics were developed for assessing salt marshes, we assume these same values apply to mangroves. 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. Note that below 20%, wetland loss rates are substantially higher and represent severe conditions.

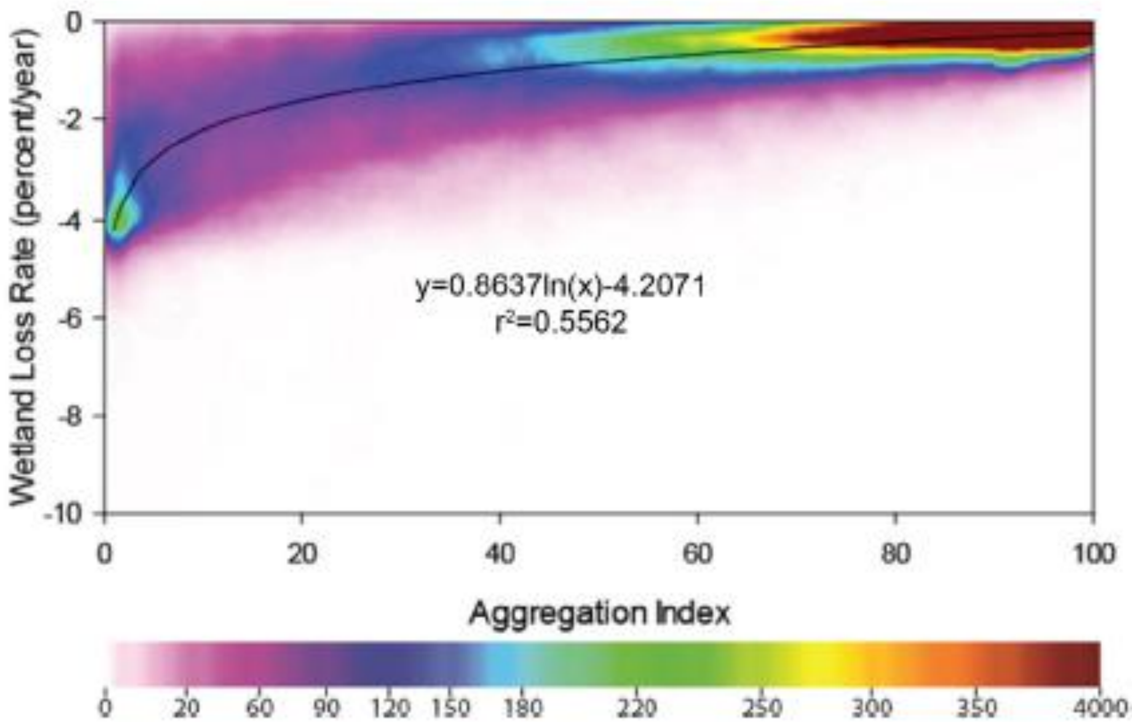


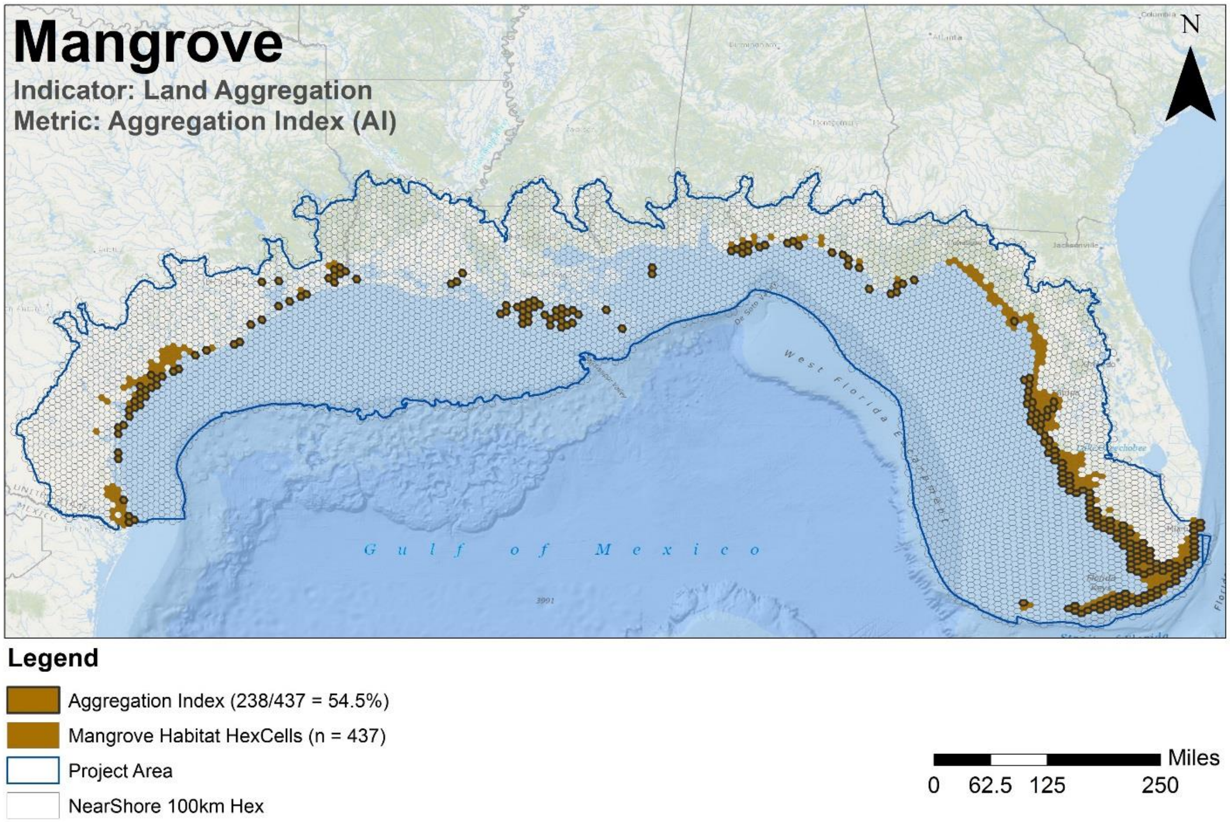
Figure 4.20. *Aggregation index versus change rate. From Couvillion et al, 2016.*

Analysis of Existing Monitoring Efforts:

<u>Geographic</u>*:* The measurements needed to calculate the Aggregation Index are well collected geographically in the NGoM, with 55% of habitat hexagons containing at least one monitoring site. Monitoring locations for this metric are relatively well distributed across the NGoM where mangroves occur, with perhaps the exception of the Big Bend of Florida where the measurements appear under-collected.

<u>Programmatic:</u> Data for this metric are collected by 23/42 (55%) of the programs collecting relevant mangrove data in the NGoM.

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



Metric	Total Relevant Mangrove 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	42	23	55%	55%

- 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: Land Cover Change

MEF: Ecosystem Structure
KEA: Landscape Structure
Metric: Land Cover Change Rate

Definition: Rate of expansion or contraction of vegetative cover over a five-year period.

Background: Mangrove areal coverage within a landscape may contract or expand due to a variety of factors. Contraction is cause by lateral erosion, dieback within stagnated basin stands, or freeze dieback at the northern fringe of each mangrove species' distribution in the NGoM. Expansion may occur onto newly formed mudflats after deposition events, ingrowth into basin mangrove stands after hydrology is restored, or poleward expansion during warm years lacking freeze mortality events (Diop et al., 1997; Eslami-Andargoli et al., 2009).

Rational for Selection of Variable: Physical loss of mangroves due to dieback or erosion is unhealthy for ecosystem sustainability. Likewise, expansion of mangrove habitat indicates conditions favorable for growth.

Measure: Landsat 30 m pixels classified as mangrove in a series of images spanning a five-year period

Tier: 1 (remotely sensed)

Measurement: Remote sensing (tier 1) techniques with Landsat data (30 m resolution) will provide the data needed to calculate the areal extent of mangroves in the landscape. Winter images should be used because of the distinction between senescent marsh and evergreen mangroves during the winter. Pixels covering a chosen area are classified as mangrove or non-mangrove in least one image per year for five years. The rate of change is calculated from the difference in mangrove pixel count between years divided by the number of years.

Metric Rating and Assessment Points:

Metric Rating	Land Cover Change Rate
Excellent	Mangrove areal cover expands at a rate detectable by remote sensing
Good	Mangrove areal cover stable
Fair	Mangrove areal cover contracts at a slow rate (< 10%) detectable by remote sensing
Poor	Mangrove areal cover contracts at a rapid rate (> 10%) detectable by remote sensing

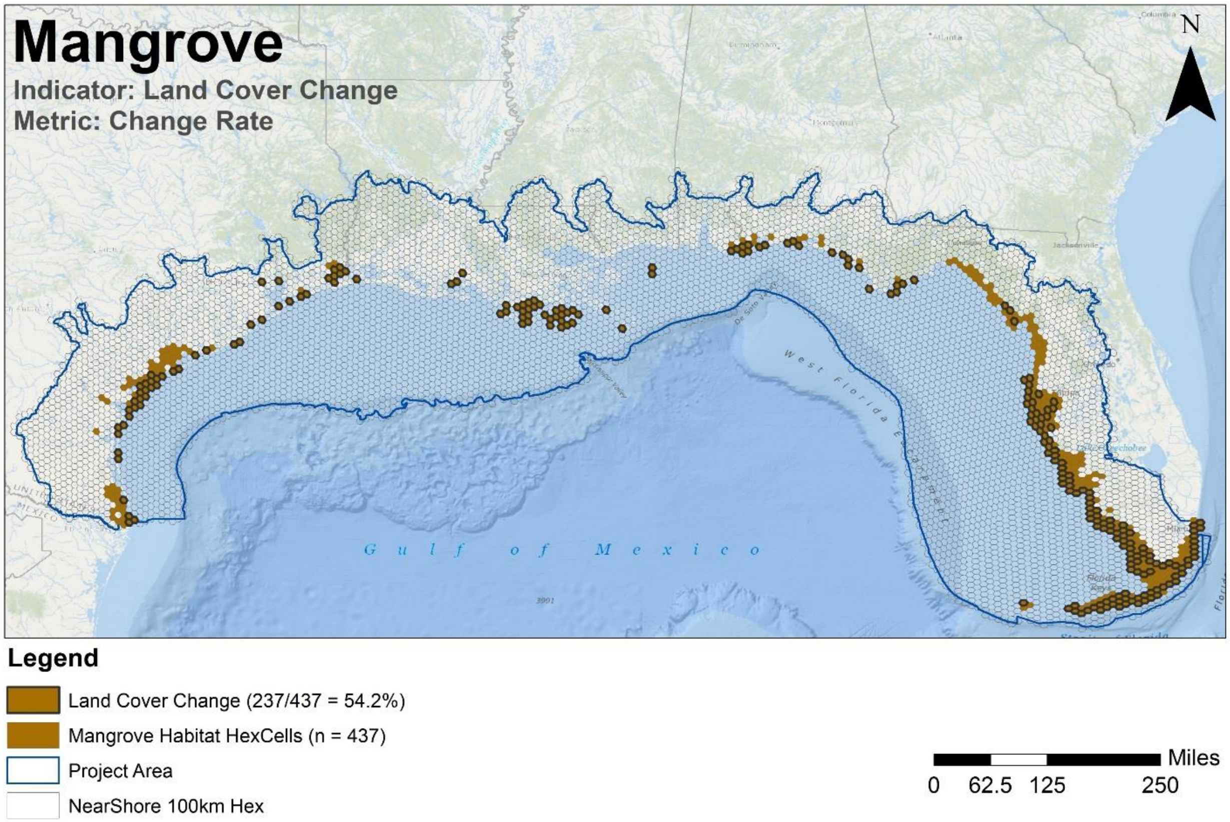
Scaling Rationale: Mangrove expansion indicates conditions favorable to growth, while mangrove contraction indicates a condition (acute or chronic) causing loss of vegetative cover.

Analysis of Existing Monitoring Efforts:

<u>Geographic</u>*:* Land cover change rate is well collected geographically in the NGoM, with 54% of habitat hexagons containing at least one monitoring site. Monitoring locations for this metric are relatively well distributed across the NGoM where mangroves occur, with perhaps the exception of the Big Bend area of Florida, where the metric seems under-collected.

Programmatic: Data for this metric are collected by 30/38 (79%) of programs collecting relevant seagrass bed data in the NGoM.

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



Metric	Total Relevant Mangrove 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
Land Cover Change Rate	42	23	55%	54%
• Very large spatial footprints for three 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: 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: Mangrove elevation increases with organic and mineral accretion, largely related to root growth (McKee, 2011; McKee et al., 2007). Elevation change can be used as a measure of resilience to sea-level rise. Low tidal ranges result in greater vulnerability because of lower accretion rates (Cahoon et al., 2006). Due to the importance of root growth, any alteration to root-to-shoot ratios or overall reduction in production could limit ability to maintain elevation.

Rational for Selection of Variable: Elevation change 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 $RSLR_{wet}$ only considers differences between the water and wetland trajectories, this would mischaracterize the vulnerability of a wetland that is situated high in the tidal frame that will likely change types (depending on climate) as sea level rises (e.g., Osland et al., 2014). 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 wetland 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 wetland 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 wetland surface elevation over time using linear regression. Surface elevation change represents surface and subsurface processes occurring between the wetland surface and the bottom of the rod benchmark (Cahoon et al., 2002a). RSET locations 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/. SET measurements should be paired with water level measurements and sea level rise rates. NGoM sea level rise rates ranges from 1.38 mm yr^{-1} to 9.65 mm yr^{-1}, with highest values from Mississippi through east Texas, and with lower values on the Florida and Alabama 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

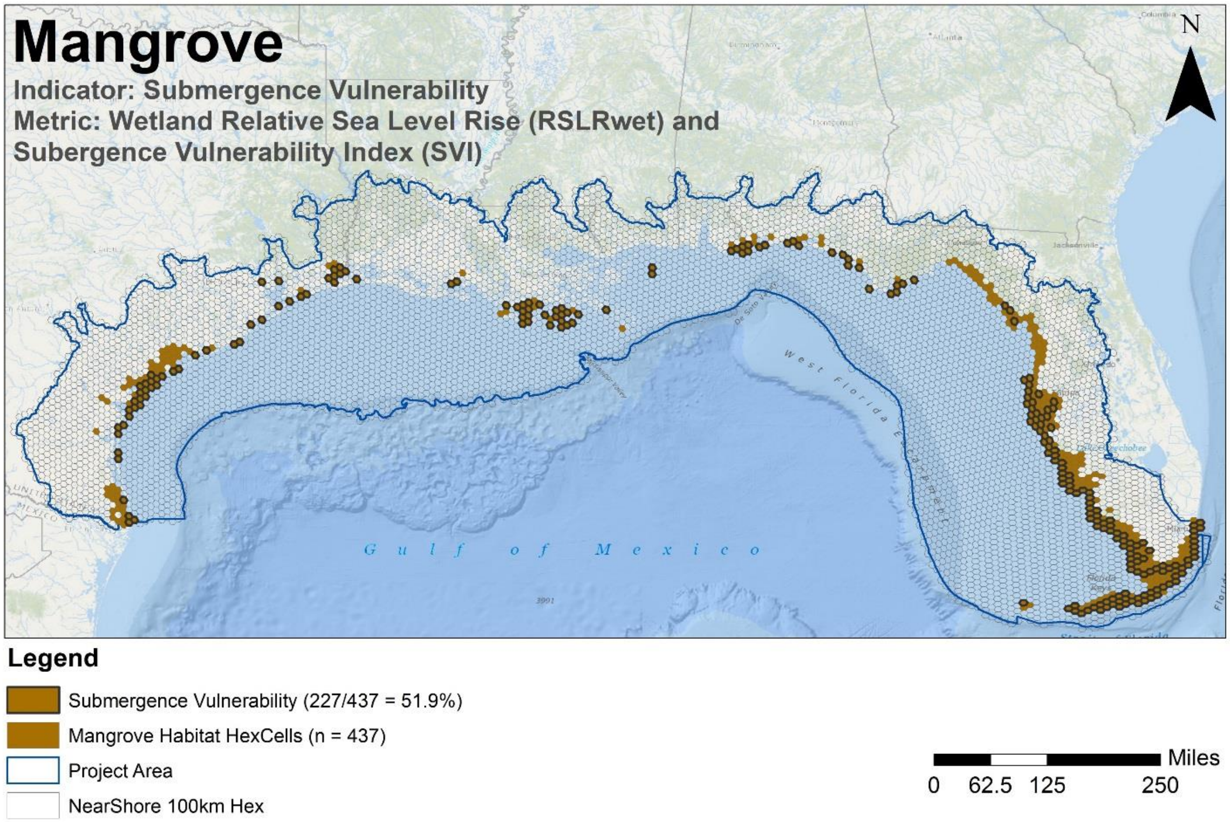
Scaling Rationale: Good conditions are met when the wetland elevation is either matching or exceeding sea level rise. Poor conditions occur when the wetland elevation is declining relative to sea level, which indicates that wetland is submerging. When $RSLR_{wet}$ is positive but the salt wetland elevation 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 production associated with little flooding, the wetland is not excessively flooded or at risk of submergence.

Analysis of Existing Monitoring Efforts:

Geographic*:* Wetland relative sea level rise ($RSLR_{wet}$) and submergence vulnerability index (SVI) are well collected geographically in the NGoM, with 52% of habitat hexagons containing at least one monitoring site. Monitoring locations for this metric are relatively well distributed across the NGoM where mangroves occur.

Programmatic: Data for this metric are collected by 19/42 (45%) of the programs collecting relevant mangrove data in the NGoM.

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



Metric	Total Relevant Mangrove 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)	42	19	45%	52%
• 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: Fish Habitat

MEF: Ecosystem Function
KEA: Secondary Production
Metric: Killifish Species Diversity

Definition: Fish habitat is assessed by diversity of killifish, which includes any egg-laying cyprinodontiform fish, spanning across several families.

Background: Killifish are generally small (1–2 inches) and feed on insects, crustaceans, algae, or worms. As abundant small fish, they constitute an important energy source to high trophic level organisms.

Rational for Selection of Variable: Given their importance to higher trophic levels and their advantage associated with mangrove forest structure (Laegdsgaard and Johnson, 2001), presence of killifish indicates system health. Diversity specifically is assessed because while some species are common generalists and widespread (e.g., mosquitofish), others (e.g., mangrove rivulus) are mangrove specialists (Davis et al., 1995).

Measure: Number of killifish species

Tier: 3 (intensive field measurement)

Measurement: Standard fish collection methods may be used which are suitable for mangrove habitats such as throw traps, pull traps, drop nets, or minnow traps (Trexler et al., 2000), and adapted to maximize the catch of small fish.

Metric Rating and Assessment Points:

Metric Rating	Killifish Species Diversity
Good	More than one killifish species present
Fair	One killifish species present
Poor	No killifish present

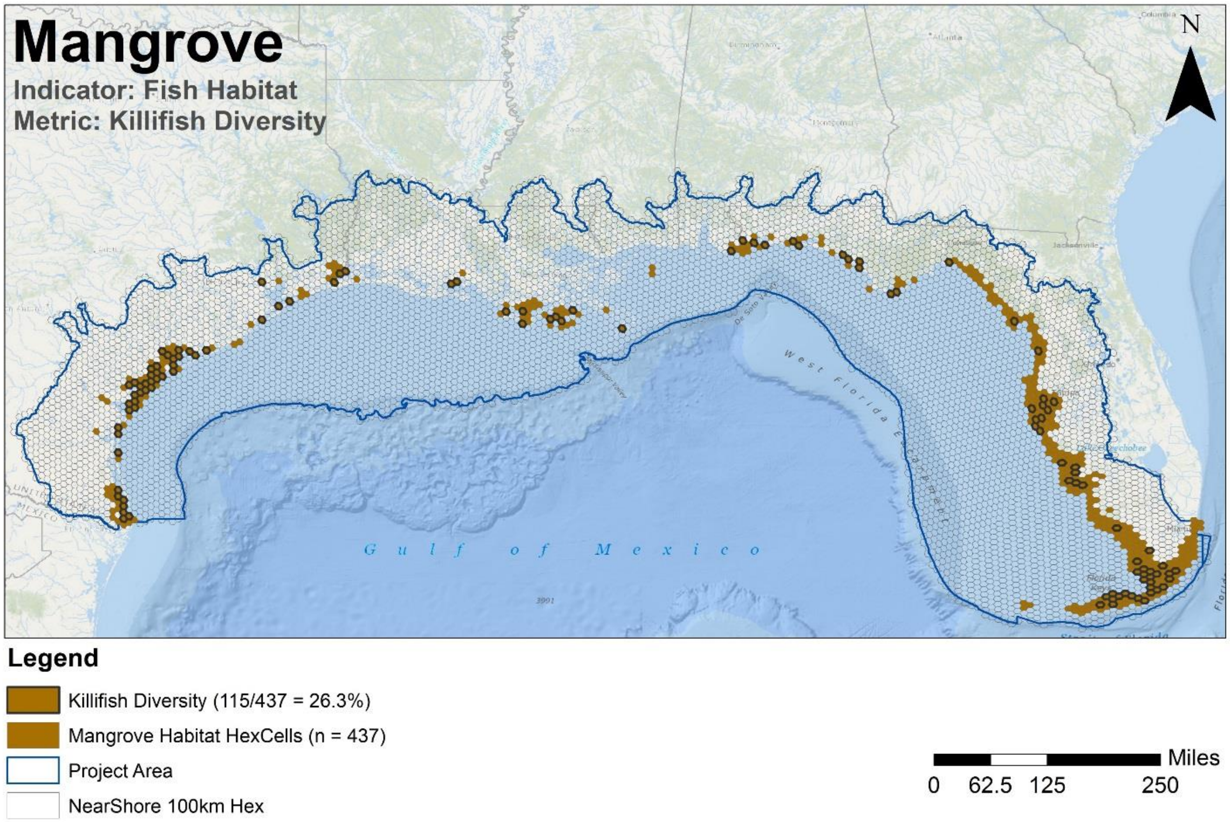
Scaling Rationale: Presence of more than one killifish species indicates mangrove ecosystem conditions are diverse enough to include killifish species with differing requirements. Presence of only one killifish species may indicate a condition very specific for the survival of that species although deleterious to other species. No killifish present in a mangrove stand is indicative of a system that has a poor food web structure, since killifish are near the base of the secondary producer food chain and are fed upon by fish as well as wading birds (Day et al., 1989).

Analysis of Existing Monitoring Efforts:

<u>Geographic</u>*:* Killifish diversity is moderately well collected geographically in the NGoM, with 26% of habitat hexagons containing at least one monitoring site. Monitoring locations for this metric are relatively well distributed across the NGoM where mangroves occur.

<u>Programmatic:</u> Data for this metric are collected by 6/42 (14%) of the programs collecting relevant mangrove data in the NGoM.

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



Metric	Total Relevant Mangrove 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
Killifish Diversity	42	6	14%	26%
• Very large spatial footprints for one 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: Invasive Species

MEF: Ecosystem Function
KEA: Secondary Production
Metric: Presence (Multiple Species)

Definition: Presence of invasive species that have a detrimental effect on the ecosystem function, including: Nilgai (*Boselaphus tragocamelus*), lionfish (*Pterois miles* and *Pterois volitans*), feral pig (*Sus scrofa*), and python (*Python bivittatus*).

Background: Various invasive species have become common within the mangrove ecosystems, but with varying detrimental effects. Nilgai (an antelope introduced from India to Texas hunting ranches) and feral pigs are large mammals which directly disturb vegetation through trampling and/or feeding on vegetation (Leslie, 2016). The *Rhizophora* borer (*Coccotrypes rhizophorae*) can destroy propagules and also directly invade trees. The lionfish and pythons are both invasive predators that can substantially alter the trophic dynamics (Barbour et al., 2010). Other species may be present (e.g., iguana, monitor lizard, cichlids), although they are less likely to have large systemic impacts. Others have substantial impacts but are not easily detectable and thus are not useful as an indicator (e.g., *Rhizophora* borer). Two species of non-native mangroves were introduced into south Florida (*Bruguiera gymnorrhiza* and *Lumnitzera racemosa*), which were competing directly for space with native mangroves (Fourqurean et al., 2010). Efforts to eradicate mature individuals of these invasive mangroves have been successful thus far, but saplings continue to reappear, possibly posing a threat in the future if control is relaxed.

Rational for Selection of Variable: The presence of these species necessarily involves an alteration to the ecosystem function at the specific site observed, constituting an important variable to measure.

Measures/Measurement:

<u>Nilgai evidence:</u> Nilgai leave widespread evidence of browsing and tracks (detectable by aerial image). Currently, this is only relevant to Texas ecosystems.

<u>Feral pig evidence:</u> Similarly, feral pig presence can be identified by the presence of tracks, root foraging, or wallows.

<u>Lionfish evidence:</u> Use of citizen science observations presents an effective solution for monitoring lionfish presence (Scyphers et al., 2014). In sites that have tourism, recreation, and fishery uses, establishing a system for reporting observations can identify where lionfish are.

<u>Python evidence:</u> Currently pythons are only known to exist in south Florida ecosystems where extensive detection, monitoring, and eradication programs are already in progress, using multiple methods (e.g., eDNA and dogs; Avery, 2014; Hunter, 2015). While they are elusive, monitoring agencies should contact local wildlife management agencies for further information.

Tier: 2 (rapid field measurement)

Metric Rating and Assessment Points:

Metric Rating	Presence (Multiple Species)
Good	No evidence of invasive species
Fair	Evidence of invasive species, but not affecting vegetation structure
Poor	Evidence of invasive species altering vegetation structure

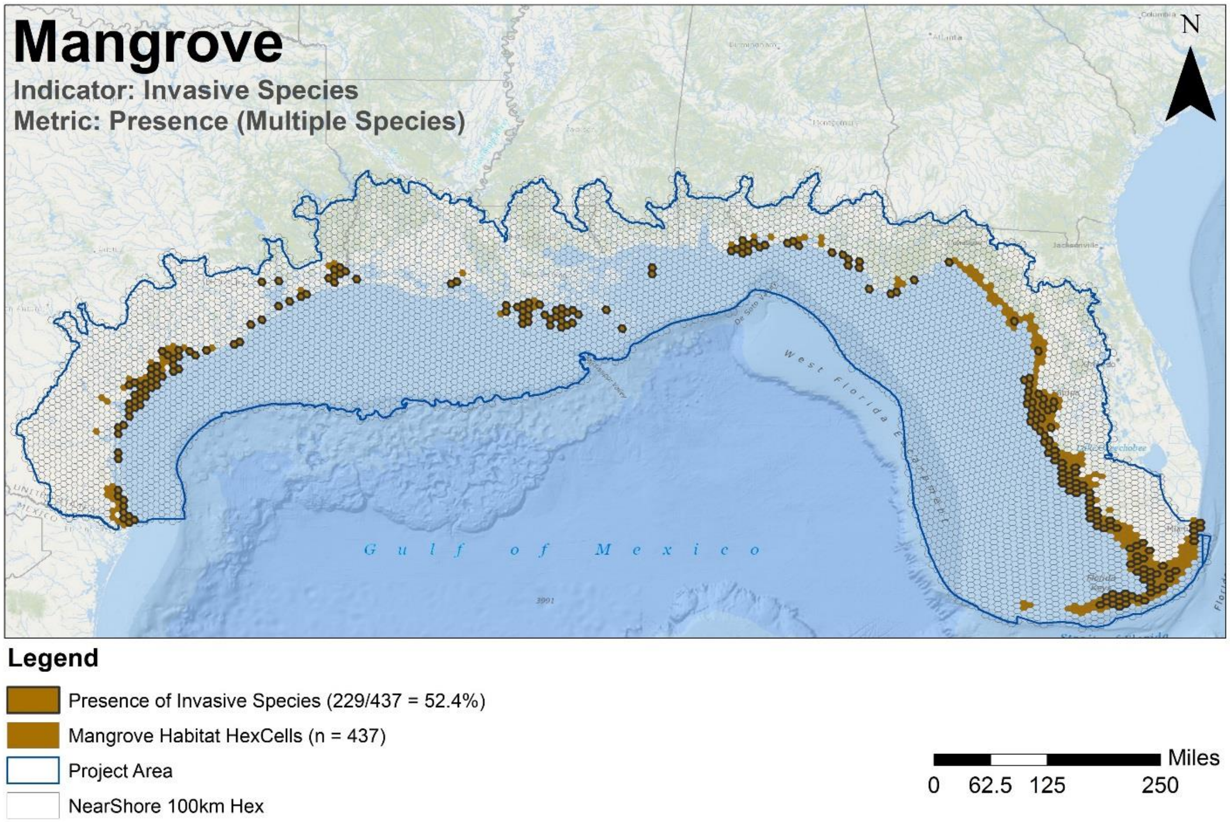
Scaling Rationale: If invasive species alter the vegetation structure, this receives a poor rating because structural alterations affect related functions (e.g., elevation maintenance, habitat, production, regeneration potential) and many ecological services (e.g., aesthetics, habitat values). In contrast, invasives that do not directly affect structure (e.g., lionfish) will likely only directly affect the secondary producers and not affect other important functions.

Analysis of Existing Monitoring Efforts:

Geographic*:* Invasive species presence is well collected geographically in the NGoM, with 52% of habitat hexagons containing at least one monitoring site. Monitoring locations for this metric are relatively well distributed across the NGoM where mangroves occur, with lower collection rates in the Big Bend area of Florida.

Programmatic: Data for this metric are collected by 15/42 (36%) of the programs collecting relevant mangrove data in the NGoM.

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



Metric	Total Relevant Mangrove 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
Presence (Multiple Species)	42	15	36%	52%

- Very large spatial footprints for one 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.

Ecosystem Service Indicators

Indicator: Status of Macrofauna Population

MES: Supporting and Provisioning
KES: Habitat
Metric: Density of Juvenile Common Snook

Definition: Number of individuals of juvenile (standard length [SL] <= 25.4 cm [10 in]) common snook (*Centropomus undecimalis*), per unit area.

Background: Snook are subtropical euryhaline fishes with a strong preference for mangrove estuarine habitats. Of the five species that occur in Florida, common snook (*Centropomus undecimalis*) is the most common and popular inshore game fish in Florida (other snook species: http://myfwc.com/research/saltwater/fish/snook/sketch-common-snook/). Juvenile snook are found between freshwater rivers to mangrove-fringed estuarine coast until they reach about 10 to 14 inches long. After this they reach sexual maturity and move to higher-salinity areas of the estuaries. Their habitat preference lies in the common characteristics of mangrove forest habitat of good water quality, moderate slope in banks, slow currents, overhanging vegetation that provides shade, and the structure that is provided by the mangrove root system (Seaman and Collins, 1983).

Rationale for Selection of Variable: The fish densities used were estimated by Brame (2012) in the study of juvenile common snook along mangrove shoreline in Frog Creek, a tidal tributary of Tampa Bay, Florida. Density constitutes an important statistic to describe and understand wild populations. It allows for the assessment of population resource utilization at a specific habitat. The measurement of density is relevant when dealing with resident small fish and invertebrates when the goal is to assess complex areas (Beck et al., 2001) and where visual census is not suitable.

Measure: Individuals per square meter. Field-collected organisms should be identified and enumerated.

Tier: 3 (intensive field measurement)

Measurement: Standard fish collection methods may be used which are suitable for mangrove habitats such as throw traps, pull traps, drop nets, or minnow traps (Trexler et al., 2000). Record all organisms, and data should be presented on individuals/m^2. Conduct field measures at different areas of the estuaries such as upstream and downstream where the salinity gradient is different.

Metric Rating and Assessment Points:

Metric Rating	Density of Juvenile* Common Snook (*Centropomus undecimalis*)	
	Upstream (ponds and creeks mean)	Downstream (ponds and creeks mean)
Good–Excellent	>= 7.0 fish/100m^2 or stable/increasing	>= 2.6 fish/100m^2 or stable/increasing
Poor	< 7.0 fish/100m^2 or decreasing	< 2.6 fish/100m^2 or decreasing

*Ratings here are provided for young of the year fish < 150 mm SL.

Scaling Rationale: The fish densities used were estimated by Brame (2012) in the study of juvenile common snook along mangrove shoreline in Frog Creek, a tidal tributary of Tampa Bay, Florida. Density values above the published mean from Brame (2012) are considered good to excellent population health. Fish densities below are considered poor. Densities at different salinity gradients—i.e., upstream and downstream estuarine areas—are presented. Since the available assessment points are available from only one study, if densities vary significantly from the suggested values, employ the stable/increasing/decreasing metric ratings instead.

Analysis of Existing Monitoring Efforts:

No programs in the monitoring program inventory specifically noted collection of data on snook densities.

Indicator: Status of Snapper-Grouper Complex Commercial Fishery

MES: Provisioning
KES: Food
Metric 1: Gray Snapper Density
Metric 2: Commercial Landings of Gray Snapper

Metric 1: Gray Snapper Density

Definition: Number of individuals of gray snapper per unit area.

Background: Gray snapper (also known as gray mangrove snapper or mangrove snapper) is a shallow species common to mangroves. Adults seek shelter in warm temperate reefs, mangroves, and seagrass habitats throughout the entire Gulf of Mexico. Juveniles typically settle in suitable estuarine habitat such as mangroves. Spatial and temporal dynamic analysis of their diel migratory movements using acoustic tagging and video show that shallow seagrass beds are frequented nocturnally and mangroves are occupied diurnally (Luo et al., 2009).

Gray snapper constitutes an important commercial fishery species that has been monitored nearly continuously since 1958 in Florida and along the southeast U.S. coast (Rutherford et al., 1989). The species is sought largely as a seasonal supplement to other fisheries. Gray snapper fisheries are managed by federal and state agencies using common regulations, and commercial and recreational annual catch limits are set every year in the NGoM. Although its abundance on the Atlantic and Gulf coasts is unknown, it appears to have remained mostly stable over the last few decades. However, in the south Florida region, it is likely that gray snapper is overfished (Burton, 2001; http://safinacenter.org/documents/2014/08/mangrove-snapper-u-s-full-species-report.pdf). In the NGoM, a combined commercial and recreational annual catch limit (ACL) has been set at 1,097 metric tons (GMFMC, 2011).

Rationale for Selection of Variable: Density allows for the assessment of population resource utilization at a specific site and provides an indication of the potential for a site to contribute to commercial fishing. It is not a direct measure of the ecosystem service because little is known about population dynamics and fisheries impacts. This metric is best used when it is important to tie the ecosystem service to a specific site.

Measure: Number individuals m^{-2}

Tier: 3 (intensive field measurement)

Measurement: Standard fish collection methods may be used which are suitable for mangrove habitats such as throw traps, pull traps, drop nets, and/or minnow traps (Trexler et al., 2000). Record all organisms, and data should be presented on individuals/m^2. Field-collected organisms should be identified and enumerated by age/size class. Conduct annual field measurements.

Metric Rating and Assessment Points:

Metric Rating	Density of Gray Snapper (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 gray snapper density would indicate a decrease in a site's capacity to provide fish for commercial 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.

Analysis of Existing Monitoring Efforts:

No programs in the monitoring program inventory specifically noted collection of gray snapper data. Data for this resource 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. No map or hexagon distribution statistics were calculated.

Metric 2: Commercial Landings of Gray Snapper

Definition: Annual commercially landed weight of gray snapper *(Lutjanus griseus*).

Background: Gray snapper (also known as gray mangrove snapper or mangrove snapper) is a shallow species common to mangroves. Adults seek shelter in warm temperate reefs, mangroves, and seagrass habitats throughout the entire Gulf of Mexico. Juveniles typically settle in suitable estuarine habitat such as mangroves. Spatial and temporal dynamic analysis of their diel migratory movements using acoustic tagging and video show that shallow seagrass beds are frequented nocturnally and mangroves are occupied diurnally (Luo et al., 2009).

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Rationale for Selection of Variable: Commercial fishery landing statistics provide direct measure of the degree of service enjoyed by humans. At best, current statistics are available annually at the state level (but only for some states) and cannot assess the contribution of a given site to the ecosystem service. This metric is best used to assess the potential contribution of mangroves to commercial fisheries at the state or regional level on an annual basis. Note that this is somewhat confounded by the fact that gray snapper use other estuarine habitats as well (such as seagrass and coral reefs).

Measure: Metric tons (t) of gray snapper landed per year

Tier: 3 (intensive field measurement)

Measurement: Assess the total weight of gray snapper annually using recreational fishery statistics reported by the National Marine Fishery Service (NMFS). Federal and state data are available at the Annual Commercial Landings Statistics site of the NMFS at http://www.st.nmfs.noaa.gov/st1/commercial/landings/annual_landings.html. Statistics for each state or area (e.g., NGoM), represent a census of the volume and value of finfish and shellfish landed and sold at the dock, rather than an expanded estimate of landings based on sampling data. Principal landing statistics that are collected consist of the pounds of landings identified by species, year, month, state, county, port, water, and fishing gear.

Metric Rating and Assessment Points:

Metric Rating	Commercial Landings of Gray Snapper (Metric Tons Landed/Year)		
	Florida West Coast	Texas*	Gulf (northern)
Good–Excellent	> 135.4 t	> 0.6 t	> 151.8 t
Fair	119.6–135.4 t	0.4–0.6 t	135.6–151.8 t
Poor	< 119.6 t	< 0.4 t	< 135.6 t

*Data for Texas is only available for the period 2006–2009.

Scaling Rationale: Metric ratings and assessment points are based on the average weight (metric tons) of total gray snapper caught in the Gulf (for Texas and Florida) over the last two decades (1995–2015). The range between the second and third quartile of commercial landing statistics reported by the NMFS (http://www.st.nmfs.noaa.gov/st1/commercial/landings/annual_landings.html) was used to define the fair rating level for each geography: Florida west coast, Texas, and the entire northern Gulf. Landings above and below that range were rated as good to excellent, and poor, respectively.

Analysis of Existing Monitoring Efforts:

No programs in the monitoring program inventory specifically noted collection of gray snapper data. Data for this resource 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. No map or hexagon distribution statistics were calculated.

Indicator: Erosion Reduction

MES: Regulating
KES: Coastal Protection
Metric: Shoreline Change

Definition: The statistically significant gain or loss in shoreline positions over a length of time.

Background: Shoreline protection capacity is provided by the relative inflexible plants that dissipate the incoming wave energy due to their height and width, and dense structure along the shoreline (Betts, 2006; Marois and Mitsch, 2015). Suzuki et al. (2012) also provide various examples of wave attenuation by mangroves.

Rationale for Selection of Variable: Shoreline stabilization constitutes an important measure of the risk reduction benefits provided by mangroves. Mangrove vegetation absorbs wave energy that otherwise would put at risk people, property, or landscapes (The Nature Conservancy, 2017).

Measure: Mangrove shoreline change in meters per year across permanent transects, and length of affected shoreline

Tier: 1 (remotely sensed and modeled)

Measurement: To measure mangrove 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). Repeat over a time period of interest, such as a number of years in the past up to the present, or before and after storm.

Tier: 3 (intensive field measurement)

Measurement: Field measurements should be performed on the shoreline of the area adjacent to the mangrove, and at a control site with similar current and wave conditions in the region. Repeat over a time period of interest, such as a number of years in the past up to the present, or before and after a storm. For a complete description of the methods, see The Nature Conservancy (2017).

Metric Rating and Assessment Points:

Metric Rating	Shoreline Change (meters per/year and length of affected shoreline)
Good–Excellent	No change, gain (accretion)
Poor	Loss (erosion)

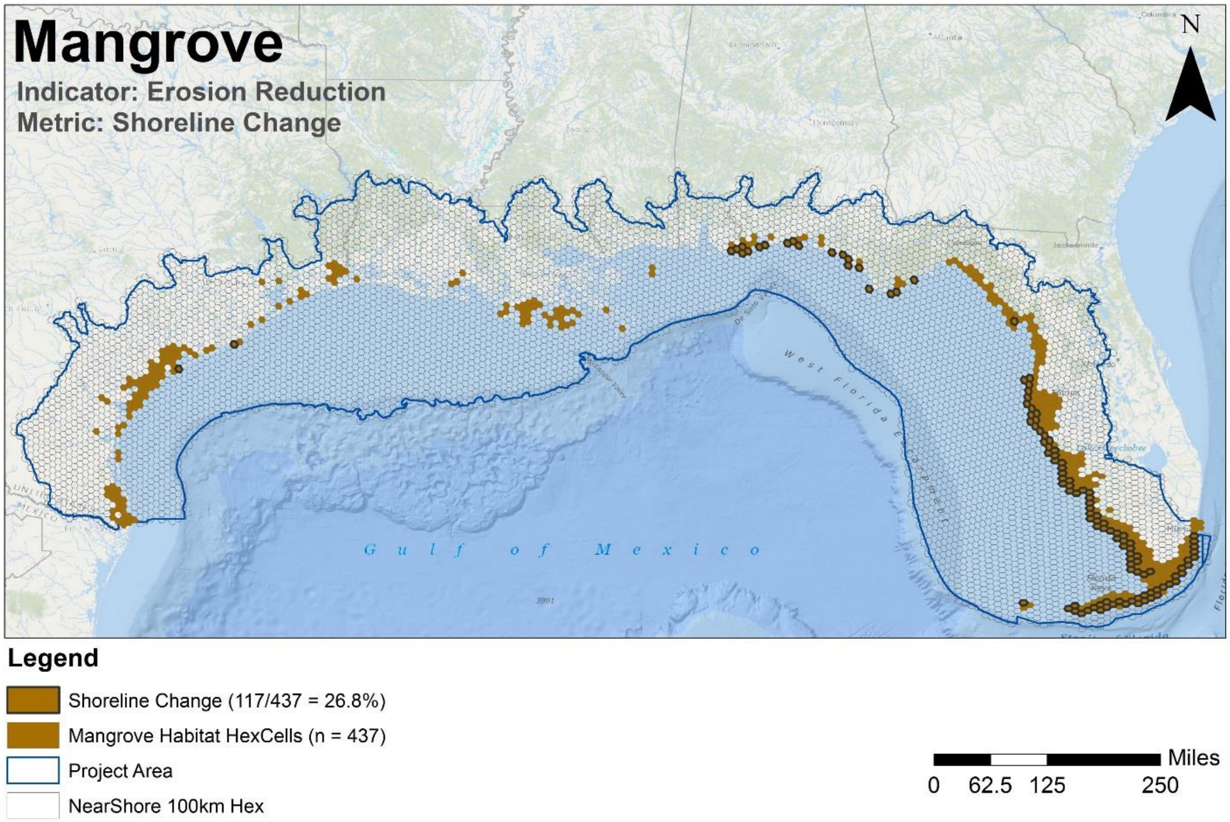
Scaling Rationale: Assessment points for indicator values constitute no change or positive (accretion) and negative (erosion) changes in shoreline areas adjacent to the mangrove.

Analysis of Existing Monitoring Efforts:

<u>Geographic</u>*:* Shoreline change is moderately well collected geographically in the NGoM, with 27% of habitat hexagons containing at least one monitoring site. Monitoring locations for this metric are mostly collected in Florida, with a few monitoring sites in Texas.

<u>Programmatic:</u> Data for this metric are collected by 2/42 (5%) of the programs collecting relevant mangrove data in the NGoM.

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



Metric	Total Relevant Mangrove 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 Change	42	2	5%	27%

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: 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 mangrove waters.

Background: Mangroves improve water quality by retaining sediment particles, nutrients, and pollutants. Mineral accretion is important to long-term mangrove sustainability and is dependent on flood regime and the availability of mineral sediments in the water column (Childers and Day, 1990).

Rationale for Selection of Variable: This metric was chosen because of the importance of the prevalence of excess nutrients in the NGoM 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 water quality with regard to nutrient cycling. Thus, a spatially and temporally aggregated metric is preferable for monitoring eutrophication. The HUC scale is the most readily available aggregated measure available at spatial and temporal scales relevant to water quality 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 mg
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

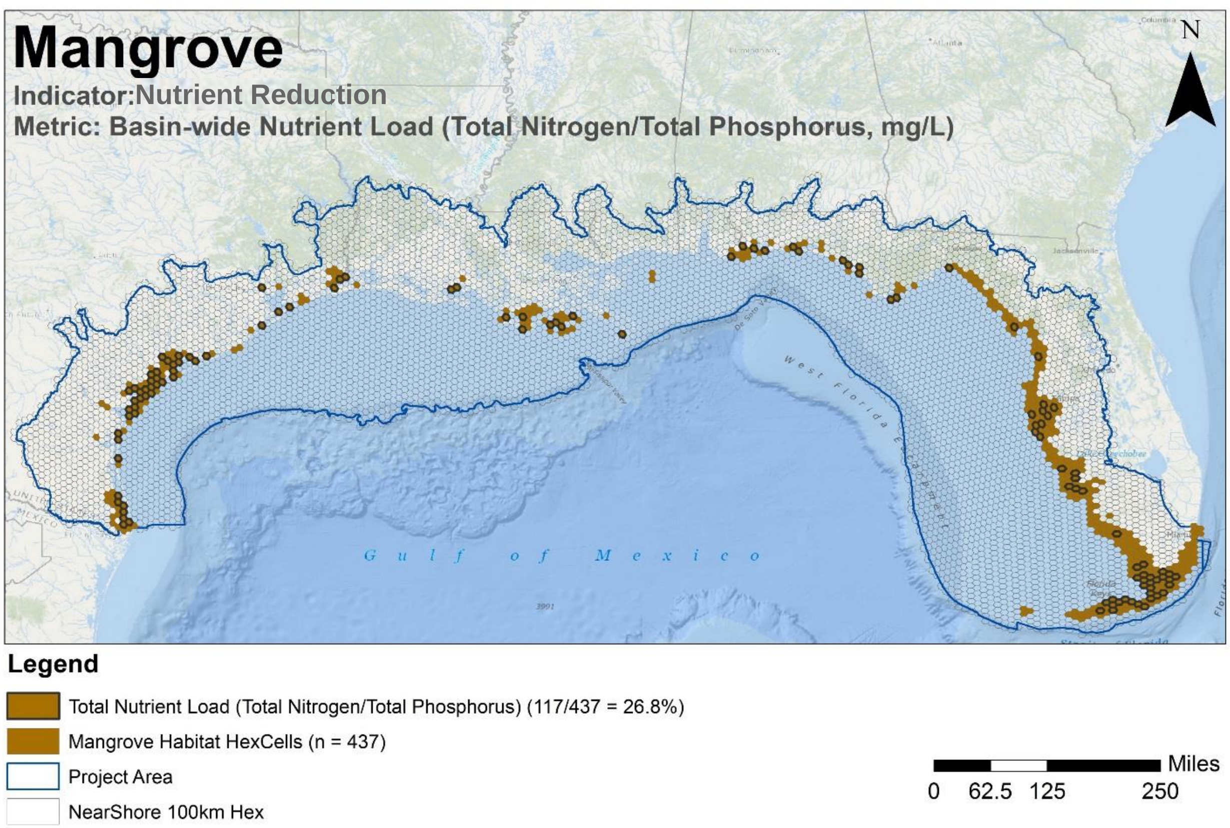
Scaling Rationale: SPARROW outputs for TN concentration range from near 0.05 to > 7 mg L^{-1} in coastal basins of the NGoM. TP concentrations range from near 0.00 to > 0.9 mg L^{-1} in coastal basins of the NGoM. Applying these criteria to mangrove ecosystems necessarily takes into account that mangroves grow in varying steady-state morphological forms (gallery forests in riverine areas to dwarf forests on carbonate substrates in the Florida Keys). While low nutrient concentrations do not necessarily indicate superior ecological function for all aspects of the ecosystem, the potential for eutrophication in soils and within the water column 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:

Geographic*:* Basin-wide nutrient oad is moderately well collected geographically in the NGoM, with 27% of habitat hexagons containing at least one monitoring site. Monitoring locations for this metric are relatively well distributed across the NGoM where mangroves occur.

Programmatic: Data for this metric are collected by 2/42 (5%) of the programs collecting relevant mangrove data in the NGoM.

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



Metric	Total Relevant Mangrove 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	42	2	5%	27%

Indicator: Soil Carbon Storage

MES: Regulating
KES: Carbon Sequestration
Metric: Mangrove Height

Definition: Soil carbon storage is the quantity of carbon stored in the soil. Mangrove height is a good indicator of ecosystem productivity and soil carbon storage.

Background: Coastal wetland ecosystems (i.e., salt marshes, mangroves, and seagrass beds) can store large quantities of carbon in the soil because of high rates of above- and belowground primary production (carbon input), relatively low rates of decomposition (carbon export), and accretionary (i.e., soil burial) processes due to rising sea levels (Chmura et al., 2003; Donato et al., 2011; Mcleod et al., 2011). Mangrove ecosystems fix (or sequester) large amounts of carbon dioxide (CO_2) in the soil. Soil carbon in flooded and anaerobic wetland soils decompose 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 much greater than most terrestrial ecosystems.

Rationale for Selection of Variable: In mangrove ecosystems, there is often a positive relationship between plant height and plant productivity (Komiyama et al., 2008; Castañeda-Moya et al., 2011; Castañeda-Moya et al., 2013). At the scale of the Gulf of Mexico, which spans many environmental gradients that affect carbon storage, plant height can serve as a proxy for productivity and soil carbon accumulation. Since data for these latter two rates (i.e., carbon accumulation and productivity) are often not readily available, plant height is a valuable indicator that can be used to coarsely characterize and quickly assess the potential for carbon storage in mangrove ecosystems.

Measure: Mangrove plant height (m)

Tier: 3 (intensive field measurement)

Measurement: There are many approaches for measuring height. Height measurements could be conducted in the field and/or via remotely-sensed approaches.

Metric Rating and Assessment Points:

Metric Rating	Mangrove Height
Excellent	> 2 m
Good	1–2 m
Fair	< 1 m

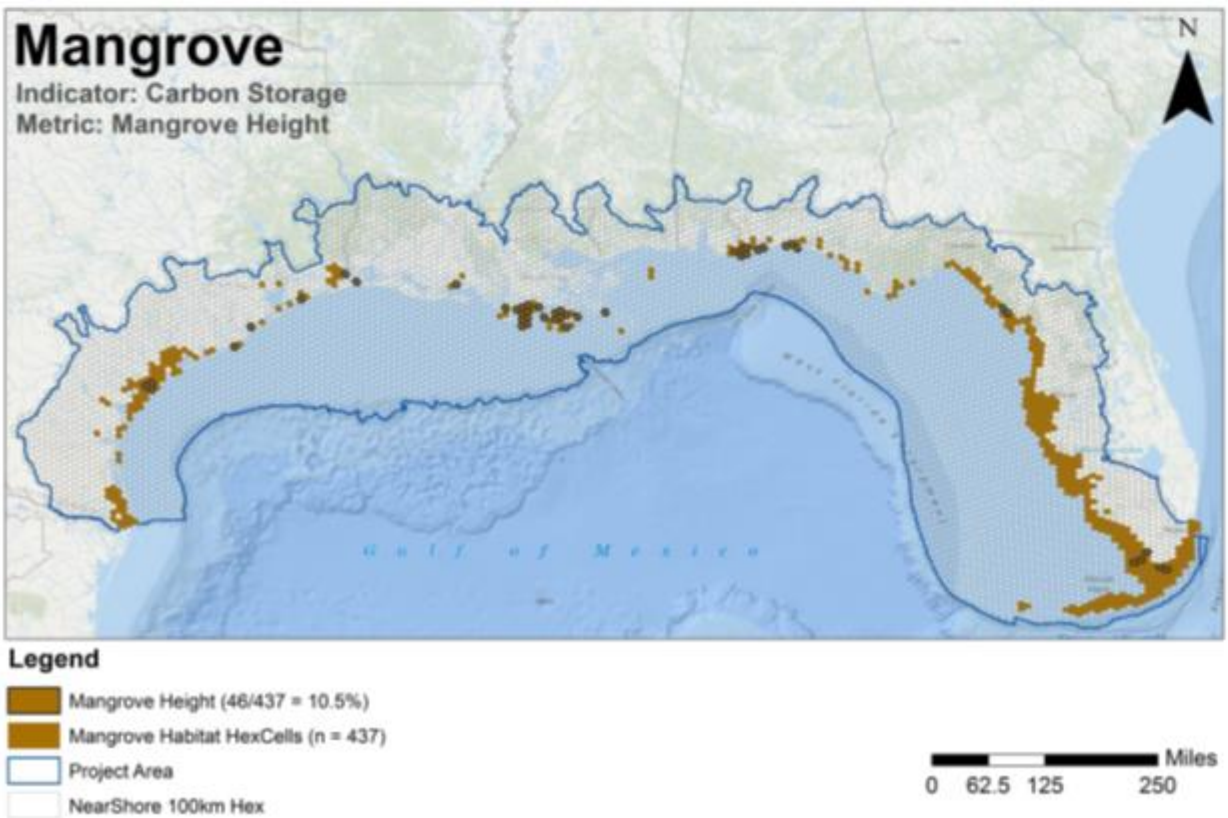
Scaling Rationale: Carbon storage potential is high in almost all mangroves. Hence, the excellent rating in the greater than 2 m height category and the good rating in the 1 to 2 m height category. Carbon storage is only likely to be low in ecosystems where an abiotic factor (e.g., hypersalinity, oligotrophic conditions, excessive inundation) limits mangrove development and productivity. In these systems, mangroves are likely to be short (i.e., less than 1 m in height).

Analysis of Existing Monitoring Efforts:

<u>Geographic</u>*:* Soil carbon storage is less well collected geographically in the NGoM, with 11% of habitat hexagons containing at least one monitoring site. Monitoring locations for this metric are collected in Florida, Louisiana, and Texas.

<u>Programmatic:</u> Data for this metric are collected by 6/42 (14%) of the programs collecting relevant mangrove data in the NGoM.

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



Metric	Total Relevant Mangrove 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
Mangrove Height	42	6	14%	11%

Indicator: Recreational Fishery

MES: Cultural
KES: Aesthetics-Recreational Opportunities
Metric: Density of Juvenile Common Snook

This metric is the same as used for the Status of Macrofauna Population indicator above.

Definition: Number of individuals of juvenile (standard length [SL] <= 10 in) common snook (*Centropomus undecimalis*), per unit area.

Background: Snook are subtropical euryhaline fishes with a strong preference for mangrove estuarine habitats. Of the five species that occur in Florida, common snook (*Centropomus undecimalis*) is the most common and popular inshore game fish in Florida (see other species: http://myfwc.com/research/saltwater/fish/snook/sketch-common-snook/). In the NGoM, they occur just north of Tampa Bay, covering the densely mangrove-populated coast line. Juvenile snook are found between freshwater rivers to mangrove-fringed estuarine coast until they reach about 10 to 14 inches long. After this, they reach sexual maturity and move to higher-salinity areas of the estuaries. Their habitat preference lies in the common characteristics of mangrove forest habitat of good water quality, moderate slope in banks, slow currents, overhanging vegetation that provides shade, and the structure that is provided by the mangrove root system (Seaman and Collins, 1983). Snook are fished year-round in Florida, and its recreational fishery is regulated in state and federal waters. No commercial harvest or sale of snook is permitted at this point.

Rationale for Selection of Variable: Density constitutes an important statistic to describe and understand wild populations. It allows for the assessment of population resource utilization at a specific habitat. The measurement of density is relevant when dealing with resident small fish and invertebrates when the goal is to assess complex areas (Beck et al., 2001) and where visual census is not suitable.

Measure: Individuals per square meter. Field-collected organisms should be identified and enumerated.

Tier: 3 (intensive field measurement)

Measurement: Use standard methods for fish census. Record all organisms and data should be presented on individuals/m^2. Conduct field measures at different areas of the estuaries such as upstream and downstream where the salinity gradient is different.

Metric Rating and Assessment Points:

Metric Rating	Density of Juvenile* Common Snook (*Centropomus undecimalis*)	
	Upstream (ponds and creeks mean)	Downstream (ponds and creeks mean)
Good–Excellent	>= 7.0 fish/100m^2 or stable/increasing	>= 2.6 fish/100m^2 or stable/increasing
Poor	< 7.0 fish/100m^2 or decreasing	< 2.6 fish/100m^2 or decreasing

*Ratings here are provided for young of the year fish < 150 mm SL.

Scaling Rationale: The fish densities used were estimated by Brame (2012) in the study of juvenile common snook along mangrove shoreline in Frog Creek, a tidal tributary of Tampa Bay, Florida. Density values above the published mean from Brame (2012) are considered good to excellent population health. Fish densities below are considered poor. Densities at different salinity gradients—i.e., upstream and downstream estuarine areas—are presented. Since the available assessment points are available from only one study, if densities vary significantly from the suggested values, employ the stable/increasing/decreasing metric ratings instead.

Analysis of Existing Monitoring Efforts:

No programs in the monitoring program inventory specifically noted collection of common snook. Spatial data from Frog Creek study were not available.

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