Chapter 6. Ecological Resilience Indicators for Coral Ecosystems

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Ecosystem Description

Coral reefs are marine ecosystems found in oligotrophic waters composed largely of corals—large, limestone-building, colonial organisms in the phylum Cnidaria. The calcium carbonate skeletons secreted by the corals provide invaluable habitat for many other marine organisms, and coral reefs are often described as the “rainforests of the sea.” Although coral reefs cover less than 1% of the ocean floor, they support about a quarter of all known marine species for all or part of their life cycles (National Ocean Service, 2011).

Corals have a symbiotic relationship with a type of dinoflagellate algae called zooxanthellae, wherein corals provide the zooxanthellae shelter, and the zooxanthellae provide the corals energy from photosynthesis (e.g. Muscatine, 1958; Muscatine and Porter, 1977). Because of this important relationship with a photosynthetic organism, hermatypic corals (those associated with zooxanthellae) are mostly found in shallow waters within the photic zone. Temperature limitations also constrict corals to 30 degrees north and south of the equator; thus, they are generally warm, shallow-water ecosystems (Wells, 1957).

Typical tropical reef systems, with high topographic complexity, accretion, and diversity, are found elsewhere in the Caribbean and Western Atlantic but are rare in the Gulf of Mexico. The Gulf of Mexico is more temperate and eutrophic, and corals are at the northern limit of their range. Because abiotic aspects limit coral growth here, reefs in the Gulf of Mexico are composed of a mixture of scleractinian corals, sponges, octocorals, and hydrozoan corals. The distribution of corals in the Northern Gulf of Mexico (NGoM) is provided in Figure 6.1. Coral communities in this project include the Shallow and Mesophtic Reef Biota Subclass and the Attached Coral Biotic Group as described in CMECS (2012). In this study, we addressed the coral communities of the four major reef systems in the Gulf of Mexico based on geographic location and depth: shallow water West Florida Shelf reefs, Flower Garden Banks reefs, mesophotic reefs, and northwest Gulf of Mexico reefs.

Many stressors or drivers of change are widespread throughout the Gulf of Mexico. These include overfishing of grouper, snapper, shrimp, and sponges; red tides and harmful algal blooms; pollutant and nutrient loading from major US rivers; cold-water upwelling events; coastal development; climate change (including warming waters and increased frequency and intensity of storms and extreme weather events); invasion of lionfish, green mussels, and orange cup coral; and pollution from ocean dumping and oil and gas development (Puglise and Kelty, 2007).

Table 6.18. *Gulf of Mexico reef systems at a glance.* References used: Cairns, 1977; Cross et al., 2004; Cancelmo, 2008; Coleman et al., 2004; Coleman et al., 2005; Coleman et al., 2011 Continental Shelf Associates, 1992; Cross et al., 2005; David and Gledhil, 2010; Dennis and Bright, 1988 Department of the Interior, 2008; Dodge and Lang, 1983; Halley et al., 2003; Halley et al., 2005; Hickerson and Schmahl, 2007; Hickerson et al., 2008; Hine et al., 2004; Hine et al., 2008; Jaap et al., 1989; Jaap, 2015; Jaap et al., 2015; Jarrett et al., 2005; Nash, 2013; National Ocean Service, 2015; Parker et al., 1983; Reich et al., 2013; Rezak et al., 1990; Schmahl and Hickerson, 2006; Schmahl et al., 2008; Smith et al., 1975; Smith, 1976; Simmons et al., 2015; Turgeon et al., 2002; Weaver et al., 2002; Weaver et al., 2006.

	West Florida Shelf		**Flower Garden Banks**		**West Florida Shelf Mesophotic Reefs**				
	Florida Middle Grounds	**Other Shelf Habitat**	**Coral Cap Zone (0-40m)**	**Mesophotic Zone**	**Pulley Ridge**	**West Florida Slope**	**Steamboat Lumps**	**The Edges**	**Madison-Swainson**
Area (km^2)	900-1,193	29-250	57.1/71.7 (East/West)		250	40-50,000	193	-	213
Depth range (m)	25-45	0-50	15-86		60-90	-	60-120	80	60-120
Vertical relief (m)	10-15	1-8	85		10-30	-	60	-	60
Coral species richness (per site)	6-21	14-21	23	5	7-10	7-43	-	-	-
Fish species richness (per site)	95-170	101	85	85	60	101	193	316	64

	Northwest Gulf of Mexico Reefs							
	Mid-shelf Banks		**Shelf-edge Banks**				**Relic Carbonate Bank**	**Other**
	Sonnier	**Stetson**	**Alderdice**	**McGrail**	**Bright**	**Geyer**	**South Texas Banks**	**The Pinnacles**
Area (km2)	0.4	1.1	7.6	2.5	13.8	17	16.22	-
Depth range (m)	18-50	17-62	55-84	32-11	37-110	37-190	55-90	73-101
Vertical relief (m)	30	45	29	78	73	153	10-35	9-15
Coral species richness (per site)	9	14	9	9	11	5	-	-
Fish species richness (per site)	77	76	95	78	95	95	66	159

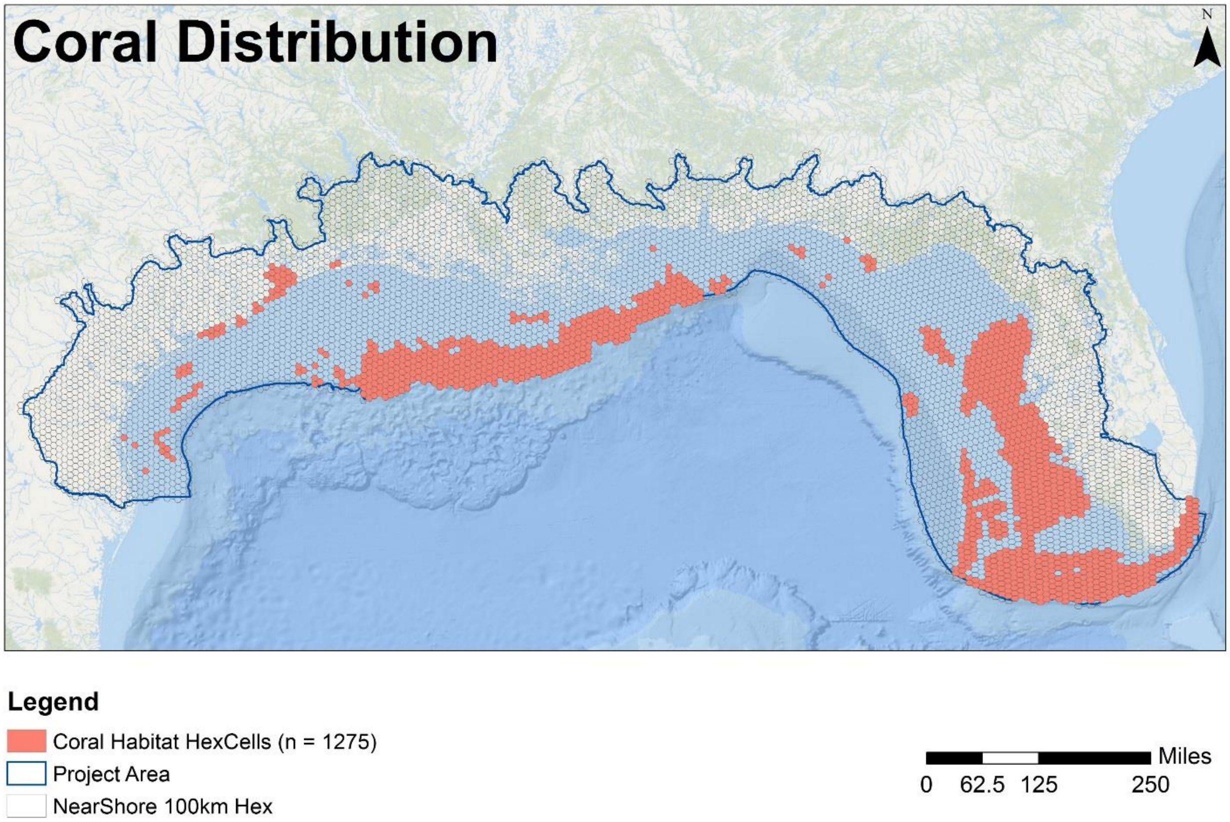


Figure 6.28. *Distribution of coral habitats in the study area. Data were assembled from various sources that are provided in Appendix III.*

Shallow-Water West Florida Shelf Reefs

Shallow-water Florida Shelf reefs are here defined as reef systems on the West Florida Shelf shallower than 40 m depth. They are generally relic shorelines of limestone hardbottom with low to moderate relief, with sediments composed predominately of carbonate materials (Phillips et al., 1990). The West Florida Shelf is a distally steepened carbonate ramp that terminates on the West Florida Escarpment, an underwater cliff dropping to 3,200 m (Hine et al., 2008). It is one of the largest continental shelf/slope systems in the world, extending 900 km along the 75-m bathymetric line and is 250 km wide (Hine et al., 2008). The Florida Middle Grounds are the only major reef area on the West Florida Shelf, but live bottom communities are present throughout the area. Most of the shelf is a mosaic of sandy bottom and hard bottom covered with a thin sand veneer, with occasional rock outcrops and generally less than 1 m relief (Phillips et al., 1990). Live bottom above 50 m is most common in 10–20m of water (Phillips et al., 1990), where the sand veneer over the limestone bedrock is thin enough to allow for benthic faunal settlement. Coral abundance and diversity on the hard bottom habitat throughout the region is higher on structures like ledges and rocky outcrops and lower near outflows of rivers (Jaap et al., 2015).

Florida Middle Grounds

The Florida Middle Grounds are a 1,200 sq km area in the northeastern Gulf of Mexico (see Figure 6.2) composed of two parallel ridges running north to northwest, separated by a valley with depth ranges of 25–45 m. They were likely formed by shore-paralleling sediment bars preserved by vermetid gastropods 10,000 years ago (Reich et al., 2013). They are mainly composed of a limestone platform, with carbonate mud, sand, and mangrove peat also present (Reich et al., 2013). The Loop Current supplies nutrients and warmer waters, and, when combined with topography of overhangs and caverns, allows for a diverse assemblage of fish, invertebrates, and algae (Phillips et al., 1990). However, diversity is reduced by winter water temperatures that exclude most tropical marine species. It is the northernmost hermatypic coral reef in the Gulf of Mexico (GMFMC and SAFMC, 1982; Simmons et al., 2015).

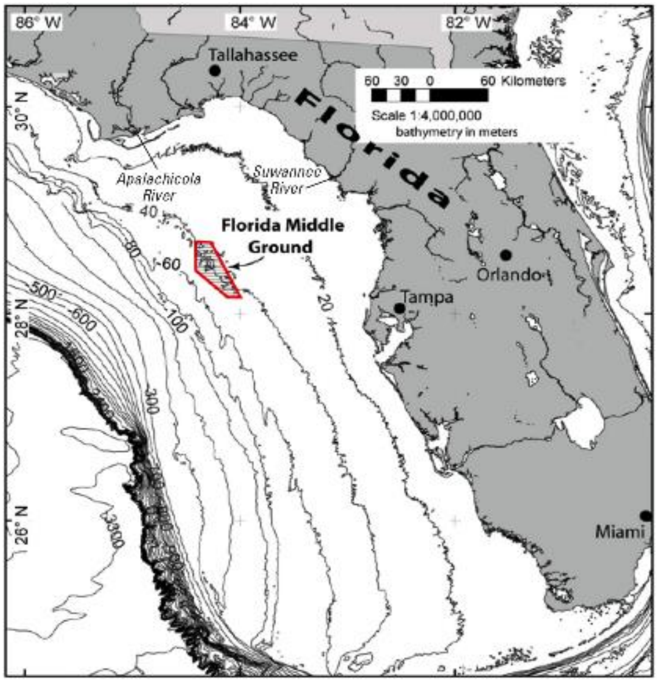


Figure 6.29. *Location of the Florida Middle Grounds on the West Florida Shelf. Credit: Reich et al., 2013.*

Flower Garden Banks Reefs

The East and West Flower Garden Banks are located in the Flower Garden Banks National Marine Sanctuary (FGBNMS). They are the only true massive-growth coral reef communities in the northern Gulf of Mexico (Dodge and Lang, 1983). The banks are salt domes, formed by salt layers sandwiched between ancient riverine sediments expanding and pushing upward (Simmons et al., 2015). Coral reefs started to form on these domes between 10–15,000 years ago (Bright et al., 1985; Rezak et al., 1990; Cancelmo ,2008), when coral larvae were likely transported here on now defunct currents moving northward from Mexico (National Ocean Service, 2015). These reefs are unique from other Gulf of Mexico reefs and are more similar to oligotrophic Caribbean reefs because of their distance from shore (largely outside of the zone of influence from major freshwater rivers entering the Gulf), allowing for the clearer, nutrient poor water in which hermatypic corals thrive (Simmons et al., 2015; Rezak et al., 1990). In fact, reef assemblages are more similar to Bermudan reefs than other Gulf of Mexico reefs due to their northerly location and distance from source populations, leading to lower diversity than other south Atlantic reefs (Simmons et al., 2015).

The designation of the Flower Garden Banks as a National Marine Sanctuary alleviated some stressors common to the Gulf, including fishery-associated stressors, point sources of pollution, and physical degradation. Most significantly, no oil and gas exploration activity is allowed within a four-mile buffer zone around the FGBNMS, reducing potential for sedimentation onto the reefs and pollution (Schmahl et al., 2008). No vessels of any length are allowed to anchor within the preserve, eliminating physical damage to the reef from anchoring. Harvesting of any marine life (coral, crustacean, or fish) is prohibited. These protections, along with their distance from shore and many human impacts, may explain why coral reefs of the Flower Garden Banks have not shown as severe declines as the Caribbean and western Atlantic reefs in the last 30 years (Deslarzes and Lugo-Fernandez, 2007; Gardner et al., 2003).

Mesophotic Reefs

Mesophotic reefs are reefs located in the "twilight zone" between 40–150 m (Kahng et al., 2010). Beyond 150 m, no photosynthesis can occur and hermatypic, *Symbiodinium*–bearing corals cannot survive. The reduced light availability leads to changes in both species assemblage and growth forms (i.e., platy growth forms), but there are some overlaps between mesophotic reefs and typical shallow water reefs, which extend to the 50 m depth batholine. Numerous areas of live bottom habitat on the West Florida Shelf exist throughout the mesophotic depth range, especially between 70–90 m and 120–160 m (Phillips et al., 1990). The higher abundance of benthic organisms at 70 m on the southern part of the shelf is due to Pulley Ridge, which acts like a giant berm and blocks large amounts of sand from accumulating and forming thick sand veneer over the limestone bedrock here (Phillips et al., 1990).

Major mesophotic reefs in the eastern Gulf of Mexico include (from south to north) Pulley Ridge, Steamboat Lumps, the Edges, Madison-Swainson, and the Pinnacles.

Pulley Ridge

Pulley Ridge is the deepest known hermatypic coral reef in the United States (Hine et al., 2008; Halley et al., 2004). It is a North-South trending drowned paleo-barrier island that is 5 km across with up to 10 m of relief, shallowing up to 60 m (see Figure 6.3). Benthic productivity is moderate to high on parts of Pulley Ridge, unusual at this depth in the Gulf of Mexico and the Caribbean. This is due to the topography of the bottom, the Loop Current bringing in clear and warm water over the area, and upwelling nutrients within a thermocline (Jarrett et al., 2005). The system is thriving at 1–2% of PAR (available surface light) and about 5% of the light typically available to shallow water reefs (Jarrett et al., 2005), indicating it is adapted to low light conditions. Reef accretion likely started in the last 6,000 years, is very slow growing, and is forming as a biostrome (laterally extensive instead of vertical framework constructed) reef (Hine et al., 2008; Jarrett et al., 2005). Coral growth here often takes on platy forms as a response to low light conditions.

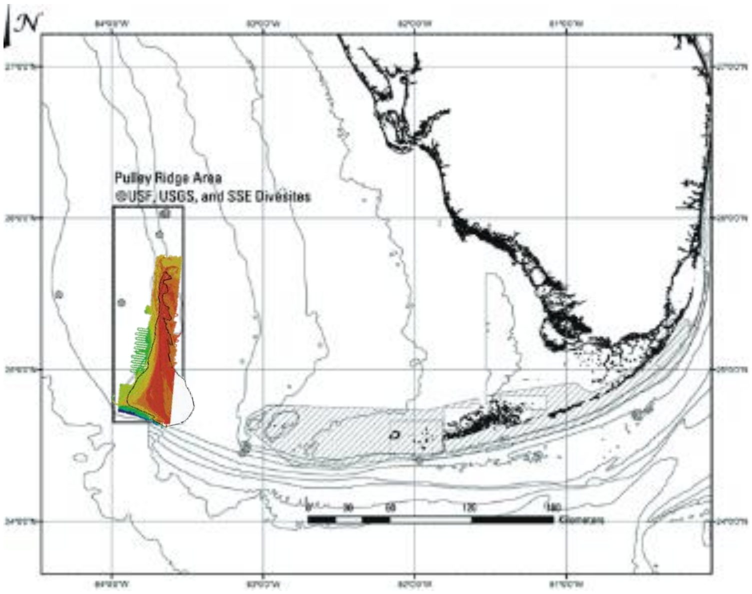


Figure 6.30. *Location of the Pulley Ridge on the West Florida Shelf. Credit: USGS.*

West Florida Slope

Rocky outcrops are less common below 50 m than they are on the shallower parts of the West Florida Shelf, and therefore corals are less common. The coral communities here are dominated by small, solitary, non-reef building azooxanthellate corals. Benthic communities are composed of algae, sponges, octocorals, and scleractinian corals (Jaap et al., 2015).

Steamboat Lumps, The Edges, and Madison Swanson

These reef habitats off the Big Bend region of Florida are composed of drowned fossil reefs on the edge of the West Florida Shelf, providing hard substrate for benthic fauna to grow on. Rugosity is higher at Madison-Swainson, with sandy plains surrounded by rocky ridges, pinnacles, boulders, and caves (Jaap et al., 2015). Steamboat Lumps is made up of a series of low-relief terraces composed of carbonate rocks. Dense invertebrate communities are found here, with sponges, octocorals, coralline algae, and occasional *Oculina* colonies. They are documented spawning site for gag, scamp, red grouper, and red snapper (Simmons et al., 2015).

Northwest Gulf of Mexico Reefs

Unlike the carbonate system of the West Florida shelf, the substrate of the northwestern Gulf of Mexico is largely made up of riverine sediments (Schmahl et al., 2008). The continental shelf slopes gradually from shore to depths of 100–200m, with scattered banks rising out of the soft sediments paralleling the edge of the shelf. Many of these are salt diapirs, like the East and West Flower Garden Banks.

Major and studied reef systems in this region include The Pinnacles and McGrail, Alderdice, Sonnier, Bright, and Stetson Banks. They can largely be divided into three main types: mid-shelf banks with carbonate reef caps, shelf-edge or outer-shelf banks with carbonate reef caps, and reefs growing on relic carbonate shelf.

Mid-shelf bank reefs include Claypile, Sonnier, Stetson, Fishnet, Coffee Lump, and 32 Fathom Banks. The two most studied of these are Stetson and Sonnier Banks. Mid-shelf banks have a diverse fish assemblage with many important commercial and recreational fish (Dennis and Bright, 1988; Weaver et al., 2006).

Many of the reef areas in the northern Gulf were protected under the designation as a Habitat Area of Particular Concern (HAPC) in 2006, including Alderdice, Geyer, McGrail, Stetson, and Sonnier Banks (Simmons et al., 2015). Of these, Stetson was included within the Flower Garden Banks Marine Sanctuary in 1996, and Stetson and McGrail have fishing regulations and restrictions that alleviate stresses due to overfishing or poor fishing practices.

Sonnier Bank

Sonnier Bank is composed of eight separate banks associated with the same salt dome. It is within the *Millepora*-Sponge zone described by Rezak et al. (1990) with three primary genera of coral—*Stephanocoenia* sp., *Millepora* spp., and *Agarcia* spp.—abundant sponges, and uncommon isolated stony coral heads and coralline algae. The benthic community here is described as a “coral community” (Geister, 1983) with other organisms besides corals dominating the benthos (Schmahl et al., 2008).

Stetson Bank

Stetson Bank is 48 km northwest of the West Flower Garden Banks. The benthic community here is similar to Sonnier and is a “coral community” (Geister, 1983) further characterized as *Millepora*-Sponge zone (Rezak et al., 1990). *Millepora alcicornis* can make up 30% of the benthic cover in some areas of Stetson, with sponges composing another 30% and limited abundance of isolated stony coral heads and coralline algae (Schmahl et al., 2008; Rezak et al., 1990).

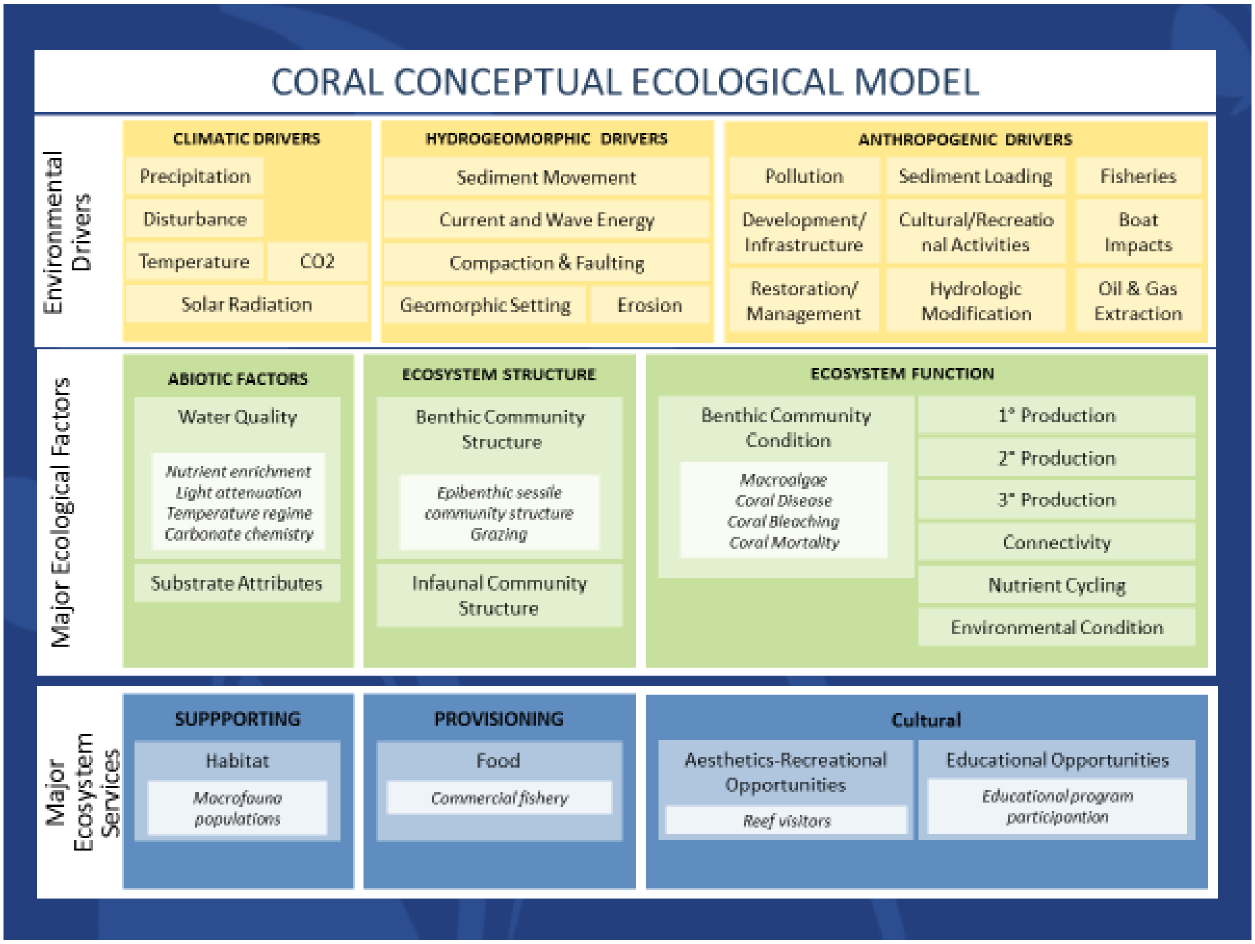


Figure 6.31. *Coral Conceptual Ecological Model*

Factors Involved in Ecological Integrity

Abiotic Factors

Water Quality

Abiotic factors associated with the water column strongly control the distribution of coral reefs around the world. The “first-order determinants of reef distribution at the global scale” are light attenuation, temperature, salinity, nutrients, and aragonite saturation state (Kleypas et al., 1999). Changes in water quality can affect many of these determinants—an increase in nutrients can be detrimental to coral both for the reduction in available light and from increases in macroalgae and other eutrophication impacts, for example. Corals can be extremely sensitive to change in any of these five factors, especially extreme fluctuations in short time periods. Therefore, the duration of stressful events can be just as important as the intensity of the event. There is some evidence of corals adapting to subpar conditions in the face of gradual change or more minor fluctuations over the long-term by morphological variation or altering zooxanthellae density (e.g. Kleypas et al., 1999; Chalker, 1981; Mass et al., 2007; Lesser et al., 2009). Light, temperature, and aragonite saturation state are the factors accounting for most of the variance in coral distribution data around the world (Kleypas et al., 1999). Excess nutrient input can indirectly affect reefs by increasing macroalgal populations.

Substrate Attributes

Substrate is often regarded as the single most important factor in benthic invertebrate distribution (Collard and D'Asaro, 1973). Corals require hard, stable substrate to attach to, such as limestone or artificial reef habitats. Suitable substrate must occur in areas which do not receive large amounts of allochthonous terrigenous inputs, which can preclude corals from living there due to eutrophication, sedimentation, and light limitations. The hard substrate needs to be stable—corals cannot attach or will soon die if they settle on substrate that has too thick a veneer of sand on top of it, or is comprised of loose rubble. Additionally, suitable substrate must be located at or above the depth at which hermatypic corals can thrive. Relief or substrate angle may also be important—some coral species prefer vertical or horizontal substratum (Bak and Engel, 1979).

Coral planulae larvae are planktonic and swim in the water column until they find suitable substrate to attach to using chemical signals. The presence of crustose corraline algae is highly attractive for many coral species (Vermiej, 2005). However, certain species of macroalgae emit chemical signals that can negatively impact coral larval settlement via modifying the pH of the water (McConnaughey et al., 2000), altering dissolved nutrient concentrations (Carpenter et al., 1991; Larkum et al., 2003), or by emitting secondary metabolites that effect the larvae itself (Steinberg and de Nys, 2002; Gross, 2003; Walter et al., 2003; Harrison and Wallace, 1990; Pawlik, 1992; Birrell et al., 2008). Many rivers that run through major agricultural areas in the United States flow into the Gulf of Mexico, making it a more eutrophic system than the rest of the Caribbean. This shrinks the amount of substrate available to corals and precludes them from settling in nearshore areas that are within the riverine plumes entering the Gulf. The advent of oil and gas exploration in the Gulf and the subsequent construction of oil platforms have served as new substrate for corals in the northern Gulf since the 1940s (Atchison et al., 2008).

Ecosystem Structure

Benthic Community Structure

Monitoring the structure and composition of the principal components of the ecosystem (scleractinian corals, hydrozoan corals, octocorals, and/or sponges) is important to determine if changes are happening in the reef system. Changes in the environment will be reflected by changes in species composition and the evenness or abundance of certain species. In particular, percent cover is a commonly used metric for assessing the status of reefs (i.e., Jokiel et al., 2005). A healthy ecosystem is stable and can maintain its organization and structure over time, as well as being resilient (able to bounce back to its previous state) to stressors (Rapport et al., 1998). When a system's resilience is exceeded, its structure and organization will change to an alternate state.

Infaunal Community Structure

Infaunal organism are benthic animals that live in and burrow into the bottom. Benthic invertebrate communities of reef systems are controlled by temperature, salinity, turbidity, and substrate (Collard and D'Asaro, 1973). Infaunal invertebrate community assemblages will differ based on characteristics of those four controls and on the quality of the habitat. Changes in community assemblages will reflect changes in habitat quality. In coral reefs, infaunal communities are comprised of polychaete worms, mollusks (bivalves and gastropods), echinoderms (crinoids, asteroids, ophiruoids, echinoids, holothurians, and concentricycloids), and crustaceans (decopods, amphipods, isopods, cumaceans, and tanaids). Boring organisms in these groups excavate the limestone structure left from dead coral colonies and fossil reefs, creating a network of cavities within the reef framework and increasing habitat complexity.

Besides composition changes to the infaunal assemblage, certain species or groups can act as indicators for the overall system. Good biological indicators must be vital to the ecology and trophic structure of the community, be numerically important, show high niche specificity, be sensitive to disturbances, and have limited mobility and dispersion patterns. As such, benthic invertebrates are often good biological indicators because they are more likely to meet these requirements, unlike more motile fish (Levy et al., 1996). Amphipods are particularly suitable for reef indicators. They are a large, diverse, and abundant group with a variety of niche partitions. A change in the assemblage of amphipods could indicate a change in habitat structure, availability, and/or quality.

Ecosystem Function

Benthic Community Condition

The condition, or health, of the principal components of the ecosystem (scleractinian corals, hydrozoan corals, octocorals, and/or sponges) is critical in determining the integrity of the reef system. Widespread disease and illness is indicative of stress and may eventually lead to mortality of key species and degraded ecosystem state and function. Under this MEF, we assess macroalgal cover, disease, bleaching, and mortality as reflecting changes in ecosystem function. Reefs in decline often have high fleshy macroalgae biomass that inversely correlates with coral cover, providing a good indicator of ecosystem degradation (Hughes, 1994; Adey, 1998; McCook et al., 2001; Bruno et al., 2009; Barott and Rohwer, 2012; Jackson et al., 2014). Estimates of the partial morality of coral colonies can be used to determine if there are changes in the ecosystem leading to large amounts of recent coral mortality, or if most of the mortality is “old” and cumulative over many years (Kramer, 2003).

Connectivity

Connectivity between reefs is important when considering genetic diversity and the ability of reefs to recover after disturbance events (Roberts, 1997). Gulf of Mexico reef systems are susceptible to issues caused by low genetic diversity because of the distance between reef systems. The Flower Garden Banks, for example, are 650 km of the next major “upstream” reef—the Lobos-Tuxpan Reef System off of Cabo Rojo, Mexico (Atchison et al., 2008). West Florida shelf reefs are even further from potential source reefs—between the diverse Flower Garden Banks and generally depauperate West Florida Shelf is a hydrologic barrier created by the riverine plume from the Atchalafaya and Mississippi Rivers.

Corals can reproduce via broadcast spawning, brooding, or clonal fragmentation. Most coral larvae can survive for 1–2 months (Roberts, 1997). Brooding corals are sexually mature at 1–2 years and can release larvae up to 10 times a year. Their planulae are fully developed and ready to settle onto substrate in under four hours (Harrison and Wallace, 1990). Broadcast spawners reproduce only once a year, become sexually mature at four years or more, and their embryos can take up to a week to fully develop (Atchison et al., 2008). Before the fertilized embryos fully develop into competent planular larvae, they have no motile capabilities and are at the whim of currents. Because of these differences, brooding corals are more effective at short-distance dispersal, while broadcast spawners can disperse longer distances. Brooding corals have an advantage over broadcasters because their larvae are subjected to multiple water circulation patterns each time they spawn in the year, providing their larvae with an opportunity to settle in different areas.

The nearest reef systems that are “upstream” of Gulf of Mexico reefs are the Lobos-Tuxpan Reef System (13 km east of Cabo Rojo, Mexico), Campeche Bank Reefs (181 km northwest of the Yucatan Peninsula), and Alacran (north of the Yucatan Peninsula). Other reefs are present in the northwest Gulf, but are not well-developed reef systems and do not contribute much to coral recruitment outside these areas. Oil platforms and other artificial reefs may provide stepping stones for corals to disperse throughout the Gulf of Mexico. It has been postulated that mesophotic reefs may seed their shallower counterparts for depth-generalist species, but data is lacking (Bongaerts et al., 2010).

Primary Production

Coral reefs have some of the highest rates of primary production of all the marine ecosystems—about 1,000 gC/m^2/yr (Lewis, 1981). Primary productivity depends strongly on light availability, so shallow, clear, tropical waters generally found with coral reefs contribute to the high productivity of this system. Gross primary productivity is largely controlled by light availability and nutrient cycling rates (Hallock and Schlager, 1986; Chiappone and Sullivan, 1996). Phytoplankton production rates are very low on reefs due to the low nutrient levels—most of the primary production comes from the benthos. The coral-zooxanthallae symbiosis contributes to much of the productivity in coral reefs—between 50 and 70% of the total primary production (Douglas, 2009). Most of the primary production is transferred directly to the coral as part of the symbiosis, where it is either released into the surrounding water column as organic material, stored, or respired (Douglas, 2009). The other main groups of primary producers on reef systems are calcareous algae, crustose coralline algae, macroalgae, turf algae, and blue-green filamentous algae, but mixotrophic sponges, foraminifera, and mollusks also contribute to primary production (Chiappone and Sullivan, 1996).

Secondary Production

Coral reefs are well-known for their diverse assemblage of reef inhabitants and support many species of fish, crustaceans, mollusks, and other invertebrates. Trophic flow in reef systems is primarily through grazing, not detritus pathways like in many other benthic marine systems (Hatcher, 1983). Secondary production organisms include herbivores/detritivores, herbivores, and omnivores who eat phytoplankton, detritus, micro and macrophytes, and other algae (Hatcher, 1983). Herbivores in reef systems include macro-herbivores like fishes, intermediate-size herbivores like urchins, and micro-herbivores like amphipods and polychaetes. Most of the suspended organic material in reefs are detrital and from that same reef system, namely turf algae and macroalgae, coral mucous, or fecal pellets from herbivores. Although the zooxanthellae inside corals are primary producers, the corals themselves can also function as secondary producers by feeding on this organic matter using mucous nets and strands. Benthic deposit feeders also ingest detritus among the sediments. Other secondary production pathways include the translocation of organic matter within corals between the coral animal and their zooxanthellae, decomposition of detritus, and utilization of suspended particulate matter (Lewis, 1981).

Herbivorous fishes and sea urchins are particularly important for coral reef systems. As a rule, macroalgae are competitors against coral for space on the reef, both for adult coral growth and coral settlement and recruitment. Herbivorous fishes and the long-spined sea urchin *Diadema antilarrum* are prolific grazers and help keep macroalgal populations in check, strongly affecting community structure. However, in the mesophotic reefs found in the Gulf, herbivorous fish communities are depauperate, although the reason is unknown, as macroalgae can be abundant and diverse (Kahng et al., 2010).

Tertiary Production

Tertiary producer biomass on coral reefs is comprised mainly by fish, but also includes invertebrates and reef transients. In mesophotic reef systems, plankton supplies most of the energetic demands of fish (Kahng et al., 2010), and thus planktivorous fish often dominate the fish assemblages on mesophotic reefs in the Gulf, composing up to 94% of the fish communities on some reefs (Weaver et al., 2006). Invertivores can compose up to half of fish assemblages on some reefs, eating urchins, corals, mollusks, and worms. Corals themselves contribute to tertiary production at night, when some species extend their polyps and feed on plankton and polychaetes in the water column.

Carnivore biomass, especially that of sharks, is often cited as an indication of overall reef health. Overexploited and overfished systems can have decreased predator populations, leading to an increase in prey abundance and cascading effects down the food web (Dulvy et al., 2004). Furthermore, Gulf of Mexico coral reef systems are documented grouper and red snapper spawning habitats (Simmons et al., 2013; Coleman et al., 2011).

Nutrient Cycling

Coral reefs generally occur in oligotrophic seas where nutrient concentrations are low, so the recycling of nutrients that occurs on reefs in these areas is critical to the reef ecosystem. Seawater concentrations of sulphate, magnesium, and potassium are generally high, but other essential nutrients like nitrogen, phosphorus, and iron can be limiting. Although coral reefs are surrounded by nutrient-poor waters, they have some of the highest biomass and productivity of any marine system, deemed the ‘paradox of the coral reef’ (Szmant Frelich, 1983). The high productivity of these systems is explained by the nutrient cycling rate—nutrients are tightly and efficiently recycled in coral reefs. Nutrient retention is facilitated by the mutualism between corals and their symbiotic zooxanthellae—the zooxanthellae uptake nitrate and other nutrients from the water and ammonium from the coral, using them for photosynthesis and keeping it within the system by allowing for coral growth (Chiappone and Sullivan, 1996, Jaap chapter). This relationship results in a recycling rate that is often 100%, reflected in the fact that corals do not excrete waste (Szmant Frelich, 1983). Some sponges, mollusks, and ascidians also have algal symbionts. In addition, new nutrients are supplied by nitrogen-fixing blue-green algae and bacteria who can fix nitrogen into its bioavailable form, nitrate (Mague and Holm-Hansen, 1975; Burris, 1976; Capone et al., 1977; Wiebe et al., 1975; Szman Frelich, 1983). Coral reef systems have exploited these low-nutrient areas with their efficient nutrient cycling rates. Besides recycling and regenerating nutrients, new sources of nutrients to the system include upwelling events and water flow from outside areas. Waste materials from fish and other larger organisms can fall into the reef structure, becoming entrapped in the cavities of the carbonate framework.

Because plankton growth stimulated by high nutrient levels will make the water more turbid and decrease light availability for corals, as well as favor coral predators, competitors, macroalgae, and bioeroders (Hallock and Schlager, 1986; Jaap and Hallock, 1990), reefs are not as well developed in the more eutrophied waters in the Gulf compared to the greater Caribbean region. The reefs in the Gulf of Mexico receive higher nutrient input from terrestrial sources, namely riverine input and runoff.

Factors Involved in Ecosystem Service Provision

Healthy coral reefs are among the most biologically diverse and economically valuable ecosystems on the planet, providing important services to human communities. At least 500 million people around the world rely on coral reefs for food, coastal protection, and their livelihoods (Millennium Ecosystem Assessment, 2005), and 30 million people are almost entirely dependent on coral reefs (Status of Coral Reefs of the World, 2008). Corals provide a myriad of ecosystem services, including benefits from tourism and recreation, coastal protection, fisheries, medicines, and biodiversity that combined are estimated to be valued around $29.8 billion per year on a global scale (Cesar Environmental Economics Consulting, NOAA). These services vary by region. A complete list of the services provided by corals in the Gulf of Mexico is provided by Yoskowitz et al. (2010), and below we provide an overview of the most important Key Ecosystem Services.

Supporting

Habitat

Scleractinians, or reef-building corals, are the main contributors to a reef's three-dimensional framework. This framework constitutes the structure that provides critical habitat for many reef organisms, including commercially important fish species. Stony corals contribute primarily to reef habitat heterogeneity, which has been referred to as the strongest factor structuring organism richness and abundance (Luckhurst and Luckhurst, 1978; Weiler, 2014). Coral cover varies across reef types and regional variance, but typically reef systems have high coral cover, moderate crustose coralline, calcareous, and short turf algae, and low fleshy macroalgae cover. Many studies have indicated that both coral cover and topographic complexity are particularly important in explaining local reef fish diversity and abundance (see references within Munday, 2004).

Provisioning

Food

Coral reefs provide the spawning and nursery grounds that economically important fish populations need to thrive. In the United States, commercial and recreational fisheries are estimated to be worth over $100 million a year each (National Marine Fisheries Service, 2001). Red snapper (*Lutjanus campechanus*) is one of the most iconic and valued reef fish in the Gulf of Mexico, contributing to a multibillion-dollar commercial fishery. This species uses primarily natural hard substrate and ridges of deep reefs in the Gulf. It is targeted by commercial fisherman as they are considered a prized offering at restaurants and seafood markets. These fish can weigh up to 50 pounds and live more than 50 years.

Regulating

Coastal Protection

The physical barrier formed by coral reefs helps protect coastal communities from storm surges and erosion from waves, both of which are likely to increase in the face of sea-level rise (Moberg and Folke, 1999). Coral reefs form natural barriers that protect nearby shorelines from the eroding forces of the sea, thereby protecting coastal dwellings, agricultural land, and beaches.

Cultural

Aesthetics-Recreational Opportunities

Coral reefs can be appreciated simply for the wonder and amazement they inspire, and exploring firsthand the underwater world of coral reefs has marveled people for centuries. Globally, coral reefs provide millions of jobs to local people through tourism, fishing, and recreational activities (Millennium Ecosystem Assessment, 2005). The reefs in the Florida Keys are estimated to be worth about $1.8 billion per year from tourism, recreational fisheries, and associated economic contribution from visitors spending money to participate in reef-related recreation, providing 10,000 jobs to the local community (Johns et al., 2001).

Snorkeling and SCUBA diving ecotourism encourages conservation, generates revenue, and supports local communities. The decrease in cost and widespread availability of SCUBA diving and snorkeling has made these habitats more accessible. Divers interested in learning more of the importance of reef ecosystems and their diverse habitats can take SCUBA diving courses that will teach them how they can contribute to coral reef conservation (e.g., PADI’s AWARE Coral Reef Conservation Specialty).

Educational Opportunities

Due to their biodiversity, coral reefs offer a large variety of educational opportunities at all levels, including K-12 programs, informal environmental education programs, and academic scientific programs. Coral reefs are complex habitats that maintain large trophic communities of invertebrates and vertebrates in a relatively small area, creating a natural laboratory to study many different aspects of biology, species management, threats, and habitat conservation. Environmental education provides benefits to students, including increasing student engagement in science, improving student achievement in core subject areas, and providing critical tools for a 21st-century workforce (http://www.fundee.org/campaigns/nclb/brief2b.htm). Additionally, the International Society for Reef Studies (ICRS) promotes the production and dissemination of scientific knowledge and understanding of coral reefs useful for their management and conservation (http://coralreefs.org/).

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 coral ecosystems across the NGoM. Table 6.2 provides a summary of the indicators and metrics proposed for assessing ecological integrity and ecosystem services of coral 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 the 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 coral ecosystems. Figure 6.5 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 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.

Note that coral ecosystems were not the focus of the initial Ocean Conservancy monitoring program inventory. Our search for coral programs may not have been exhaustive. Note that we limited our spatial analysis only to programs that were actively collecting data on corals. We did not include water quality monitoring data that may be currently collected in the vicinity of coral monitoring programs if we could not verify that they were being collected in conjunction with the coral data. These factors may contribute to an under-representation of existing coral monitoring programs.

Much of the coral reefs in the Gulf of Mexico waters remain under-studied. With the exception of the Flower Garden Banks National Marine Sanctuary and Florida Keys, most of the reef systems in the Gulf of Mexico are deep and/or farther offshore, equating to more expensive and time-intensive research.

Table 3.19. *Summary of Coral Reef Metrics Based on the Conceptual Ecological Model*

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

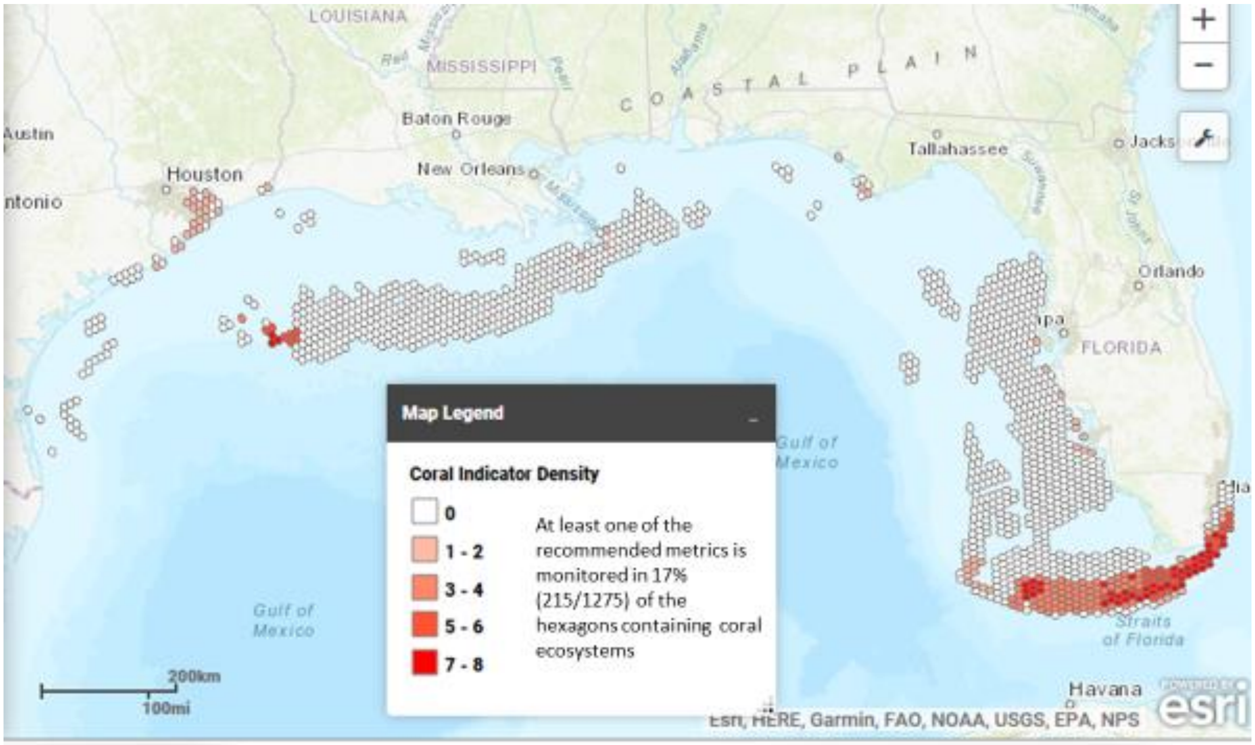


Figure 3.32. *Density of the recommended indicators being collected in coral ecosystems in the NGoM. Shaded hexagons indicate the number of the recommended indicators that are collected by monitoring programs in each hexagon.*

Ecological Integrity Indicators

Indicator: Nutrient Enrichment

MEF: Abiotic Factors
KEA: Water Quality
Metric: Chlorophyll *a* Concentration

Definition: Nutrient enrichment, or eutrophication, is defined as excessive nutrients in a body of water outside the norm which causes dense growth of plant and algal life. Chlorophyll *a* is the main photosynthetic pigment in plants and other photosynthetic organisms and can indicate phytoplankton biomass and nutrient rich conditions.

Background: Nutrients are one of the five "first-order determinants of reef distribution at the global scale," along with temperature, salinity, light, and aragonite saturation state (Kleypas et al., 1999). Nutrient enrichment (especially increases in the commonly limiting nutrients N and P) can cause dense growth of algae in marine and coastal systems. For coral reefs, this can lead to 1) reduced light availability (critical for the photosynthesizing zooxanthellae that live inside hermatypic coral tissue) (Bell 1992; Hallock and Schlager, 1986); 2) coral smothering from increased organic sediment load (Endean, 1976); 3) increased competition for available substrate with macroalgae and other benthic organisms (Brown and Howard, 1985; Bell, 1992; Dubinsky and Stambler, 1996); 4) reduced coral growth rates (Tomascik and Sander, 1985; Stambler et al., 1991); 5) reduced coral recruitment (Hallock and Schlager, 1986; Tomascik, 1991); 6) bioerosion of the reef structure (Hallock and Schlager, 1986; Bell 1992); 7) changes in the zooxanthellae-coral symbiosis such as lower allocation of photosynthetic energy to the coral (Dubinsky and Stambler, 1996); and 8) enhanced disease outbreaks (black band disease; Antonius, 1985).

Rationale for Selection of Variable: Reef growth in the Gulf of Mexico is limited by excess nutrients and consequent increase in bioerosion (Hallock and Schlager, 1986; Hallock 1988). Parts of the Gulf of Mexico are strongly influenced by allochthonous input from major river systems that flow into the Gulf, which can bathe corals in low salinity water, bring in excess nutrients, and increase turbidity. In the northern Gulf, some of the banks are far enough offshore and have significant vertical relief to be outside the zone of coastal influence from the Atchafalaya and Mississippi River. However, freshwater plumes have occasionally been shown to reach offshore to depths of 15–20 m (McGrail and Horne, 1981), the depth of the shallowest cap on the Flower Garden Banks. Annual river discharge from the Atchafalaya River has been negatively correlated with annual coral growth on the Flower Garden Banks (Dodge and Lang, 1983) due to coral's low tolerance to salinity fluctuations (Vaughn, 1916; Wells, 1932; Johannes, 1975), and decreased light availability from suspended sediment (Dodge and Lang, 1983). Reef communities on Claypile, Sonnier, Coffee Lump, Southern Bank (a South Texas bank) and Alderdice are all partially inundated with river run-off at depths where reefs are present (Rezak et al., 1990). Nutrient input does not pose a risk to more offshore banks because nutrients have already been depleted by the time the water mass reaches the banks (Deslarzes and Lugo-Fernandez, 2007), but banks closer to shore on the mid-shelf may be affected. The mesophotic community structure of banks located in the northwest Gulf of Mexico are highly influenced by terrigenous inputs from major rivers (i.e., Mississippi-Atchyafalaya). Banks that are too near these outflows or have lower elevation experience more sedimentation and have depauperate coral communities (Rezak et al., 1990; Kahng et al., 2010). Reefs on the southern part of the West Florida Shelf are not as likely to be affected by low salinities or allochthonous sedimentation, as the major rivers discharging into the eastern Gulf are not large enough to impact systems further offshore; however, the Florida Middle Grounds are often affected by Mississippi River in the spring (Jaap, 2015; Coleman et al., 2005). Nutrient input on the northwest Florida Shelf can also come from upwellings of high-nutrient water masses and seasonal chlorophyll plumes (Gilbes et al., 1996).

Chlorophyll *a* is a commonly used indicator for phytoplankton biomass in aquatic and marine systems (Megard and Berman, 1989; Balali et al., 2012; Boyer et al., 2009; Steele, 1962) and as an indicator for eutrophication (Bell, 1992; Tomascik and Sanders, 1985; Laws and Redalje, 1979). Increases in algal biomass occur as a direct result of eutrophication and are easier to measure than the soluble inorganic nutrients themselves because they are so quickly taken up by algae (Bell et al., 2013). Futhermore, chlorophyll *a* and particulate matter concentrations are inversely correlated to coral growth rate (Tomascik and Sander, 1985).

Measure: Chlorophyll *a* concentration monitored ideally monthly, or at minimum quarterly, seasonally, or in conjunction with episodic events

Tier: 2 (rapid field measurement)

Measurement: Chlorophyll *a* can be measured using spectrophotometry. Water samples are collected from the same depth as the reef, then filtered to concentrate the chlorophyll-containing organisms and mechanically rupture the collected cells. Chlorophyll is then extracted from the disrupted cells with acetone. The extract is then analyzed by either a spectrophotometric method (absorbance or fluorescence), using the known optical properties of chlorophyll, or by high performance liquid chromatography (YSI Environmental).

Metric Rating and Assessment Points:

Metric Rating	Chlorophyll *a* Concentration
Good	<=0.05 mg/m^3
Fair	0.06 to < 0.2 mg/m^3
Poor	>=0.2 mg/m^3

Scaling Rationale: An annual mean of 0.2 mg/m^3 is an agreed-upon value for the Eutrophication Threshold Concentration for the wider Caribbean, including the Florida Keys (Lapointe et al., 2007; Lapointe and Mallin, 2011). Above this value, eutrophication starts to affect the reef through increases in macroalgal cover and concomitant decreases in coral cover (Lapointe and Mallin, 2011). Various studies have found significantly decreased coral growth rates with chlorophyll *a* levels > 0.4mg/m^3 in Barbados (Tomascik and Sander, 1985), and > 0.68 mg/m^3 of chlorophyll *a* in Kaneohe Bay, Hawaii (Laws and Redalje, 1979). Bell (1992) suggests a chlorophyll *a* threshold value at an annual mean of 0.5 mg/m^3, although caveats that reefs with better flushing and higher turbulence would have higher thresholds.

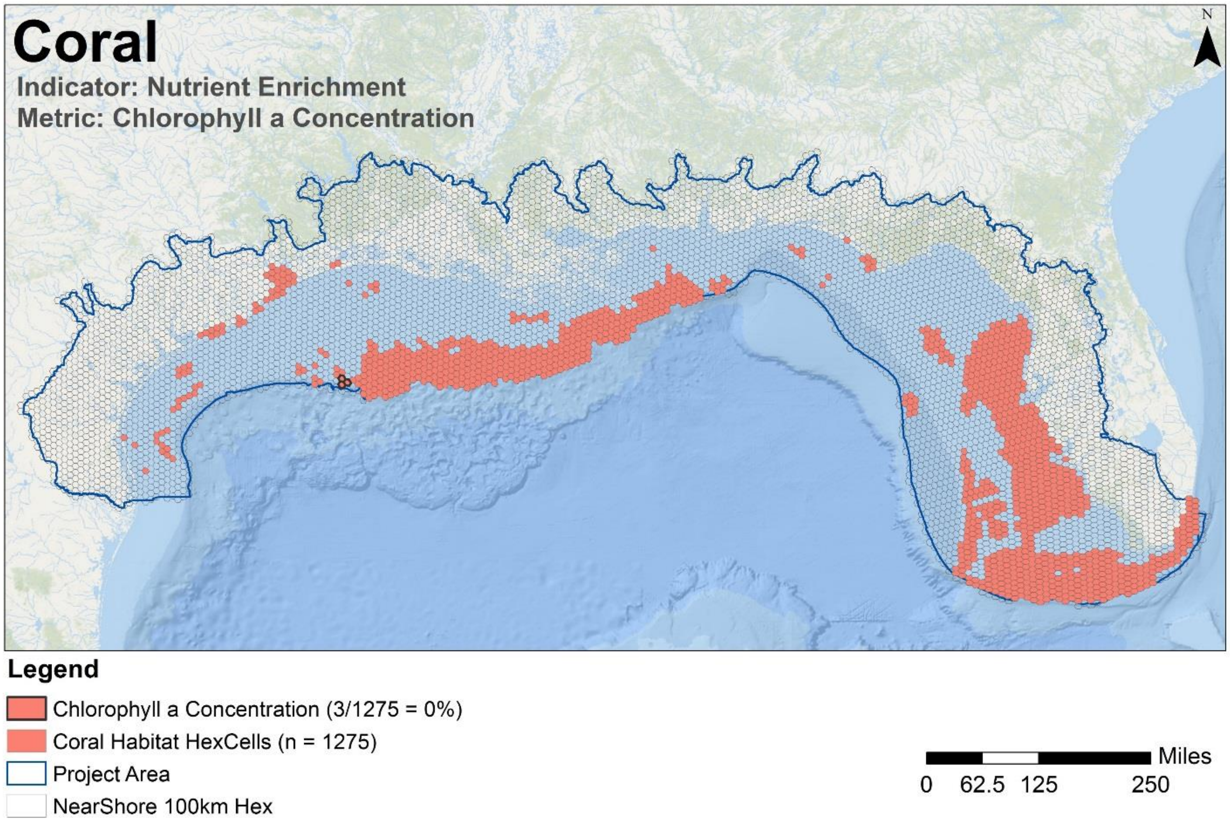
Less than 0.05 µg/l of chlorophyll *a* is within the typical range of regional observations, while 0.06 to > 0.2µg/l is higher than normal, and some minor eutrophication impacts may be present. A profile study of chlorophyll *a* concentrations off the Florida Keys showed a strong chlorophyll *a* peak of 0.8 µg/L at approximately 60–70 m depth, with values falling to roughly 0.1 µg/L at the surface and 0.05 µg/L at 150 m (Leichter et al., 2007; Lesser et al., 2009).

Analysis of Existing Monitoring Efforts:

Geographic*:* Chlorophyll *a* concentration is not well collected geographically in the NGoM, with less than 1% of habitat hexagons containing at least one monitoring site. Monitoring locations for this metric are clustered in only one area within Flower Gardens National Marine Sanctuary.

Programmatic: Data for this metric are collected by 1/18 (6%) of the programs collecting relevant coral data in the NGoM.

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



Metric	Total Relevant Coral 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
Chlorophyll *a* Concentration	18	1	6%	< 1%

Indicator: Light Attenuation

MEF: Abiotic Factors
KEA: Water Quality
Metric: Water Transparency

Definition: Water transparency describes the clarity and degree of particulate matter in the water. It is a measure of how far light can penetrate the water column.

Background: Light is one of the five "first-order determinants of reef distribution at the global scale," along with temperature, salinity, nutrients, and aragonite saturation state (Kleypas et al., 1999). Light availability depends on the amount of light reaching the ocean surface (itself a function of the angle of the sun and atmospheric attenuation), light attenuation (a function of the optical properties of the water itself and absorption due to dissolved and particulate matter), and the depth of the reef (Lesser et al., 2009; Kleypas et al., 1999). Water transparency, or water clarity, is expressed as the attenuation of light through each meter of water.

Rational for Selection of Variable: Hermatypic corals are restricted to the photic zone due to the light requirements of *Symbiodinium*, their symbiotic dinoflagellates. The zooxanthellae harbored within the coral tissue photosynthesize, sharing sugars and energetic byproducts of photosynthesis with their hosts. Corals respond to decreased light availability by decreased growth rates (Dustan, 1979; Hubbard and Scaturo, 1985), morphometric changes from mounded to flat, platy forms (Grauss and Macintyre, 1982), and increasing the density of zooxanthellae within coral tissue and altering chlorophyll concentrations inside their cells (Mass et al., 2007; Lesser et al., 2009).

Measure: Water transparency, K

Tier: 2 (rapid field measurement)

Measurement: For reefs shallower than 30 m, water transparency (K) can be calculated inexpensively by Secchi depth (d) using the following equation:

$$K = 1.5/d$$

Following Beer's Law, the light intensity at the surface, available from existing monitoring efforts, can be used with the K values obtained with the Secchi disk to calculate light intensity at depth using the following equation:

$$\text{Light Intensity at depth} = \text{Light intensity at surface} \times \exp^{-Kd \times \text{depth}}$$

On mesophotic reefs deeper than 30 m, characteristics of the water column may change and preclude the use of surface measurements. We recommend light meters (for example LI-COR quantum counter Li-185 and sensor Li-192 or PAR sensor from Biospherical Instruments, Inc.) to measure light intensity at depth in µ mol/m^2/second.

This indicator should be monitored ideally monthly or at minimum quarterly, seasonally, or in conjunction with episodic events. Monthly monitoring has been found to be good for trend detection, but more frequent monitoring can lose efficiency due to autocorrelation (Reckhow and Stow, 1990).

Metric Rating and Assessment Points:

Metric Rating	Water Transparency		
	Shallow Water Reefs	Mesophotic Reefs	
Good–Excellent	400–600+ µ mol/m^2/s	Pass	Above 1% surface irradiance
Fair	250–400 µ mol/m^2/s	Fail	Below 1 % surface irradiance
Poor	50–250 µ mol/m^2/s		

Scaling Rationale: According to a worldwide survey of reef habitats done by Kleypas et al. (1999), light limits range from 50–450 µ mol/m^2/s. The minimum PAR necessary for reef growth is 250 µ mol /m^2/s (Kleypas, 1997; Guan et al., 2015), although this value does not include the "reef community" systems found in the Gulf of Mexico nor deepwater corals. The 250 µ mol/m^2/s limit restricts reef growth to 30 m or shallower, but corals can grow down to 50 µ mol/m^2/s, roughly 10% surface irradiance at the Equator (Kleypas, 1997). 600 µ mol/m^2/s produces the best match for models' predicted reef area with actual observations (Guan, 2015). Light saturation curves for the Pacific coral *Acropora formosa* show that net photosynthesis plateaus at peak efficiency from about 400–600 µ mol/m^2/s and reaches zero at just under 100 µ mol/m^2/s at shallow depths (Chalker et al., 1988), following the idealized photosynthesis-irradiance curve for corals shown below (Figure 6.6; Falkowski et al., 1990).

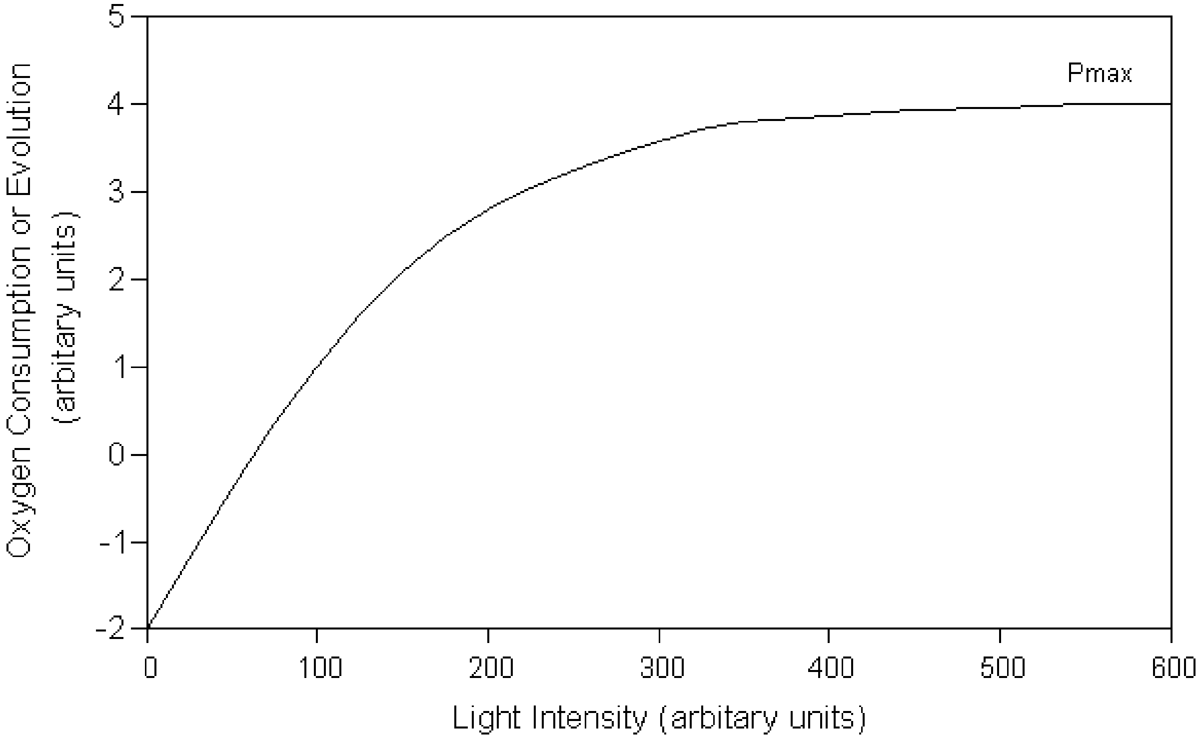


Figure 6.33. *Idealized photosynthesis-irradiance curve for corals (adapted from Falkowski et al., 1990)*

Corals found at mesophotic depths have adaptions that allow them to live in darker environments, including growing in platy forms which provide more surface area to the diffuse light and greater efficiency of zooxanthellae in whole-cell light absorption (Dustan, 1982). Although mesophotic reefs are specially adapted to low light environments, they still require clear water in order to receive enough light for zooxanthellate photosynthesis. In the ‘Au’au Channel off Hawaii, average light intensity values were 245 µ mol/m^2/s at 34 m, 25 µ mol/m^2/s at 90 m, and 2.5 µ mol/m^2/s at 147 m (Pyle et al., 2016). The average daily PAR at 60 m on Pulley Ridge is about 45 µE/m^2/s (3.9 mol/m2/day; Gattuso et al., 2006). A study of *Madracis* spp. on reef slopes of Curacao found that the minimum light intensity found where *Madracis pharaensis* occurred was 1.5 µE/m^2/s (Vermeij and Bak, 2002), although the study only assessed corals up to 50 m depth. A more general, but possibly more meaningful, threshold would be to establish 1% of surface irradiance as the threshold for reef growth, as this is also the lower limit of the euphotic zone (Kirk, 1994). The bottom of the euphotic zone is where photosynthesis equals respiration, so strictly autotrophic organisms cannot survive below this depth. Corals can still be found below the euphotic zone, but must acquire mixotrophic methods, i.e., use heterotrophy in addition to photosynthesis to meet their energy requirements (Lesser et al., 2009).

Analysis of Existing Monitoring Efforts:

No programs in the monitoring program inventory specifically noted collection of water transparency.

Indicator: Temperature Regime

MEF: Abiotic Factors
KEA: Water Quality
Metric: Temperature Range (of Suitable Temperatures for Coral Survival)

Definition: Temperature is the degree of heat present in an object.

Background: Temperature is one of the five “first-order determinants of reef distribution at the global scale,” along with light attenuation, salinity, nutrients, and aragonite saturation state (Kleypas et al., 1999). Corals and other benthic organisms have physiological limits to temperature that can negatively affect growth, reproduction, and survival if they experience temperatures outside of their ideal temperature range.

Rational for Selection of Variable: Corals are very sensitive to changes in temperature and have a narrow tolerance to conditions beyond their temperature limits. The corals of the Gulf of Mexico occur near the northern limit of their range. Consequently, in winter months, temperatures can drop to near or below the minimum temperature for vigorous coral reef growth (18°C; Stoddart, 1969). Temperature is a major control on coral growth in the northern Gulf of Mexico, with marked declines in growth occurring every winter on the Flower Garden Banks (Dodge and Lang, 1983). Cold-water upwellings can also lead to mortality events—there is evidence that a cold-water upwelling in 1977 locally extirpated benthic flora and fauna on the Florida Middle Grounds (Rezak et al., 1990).

Measure: Water temperature at depth

Tier: 1 (collected by temperature loggers)

Measurement: Water temperature can be measured using in situ temperature loggers placed at the depth of the reef, such as the HOBO Temperature Loggers. Temperature can be measured hourly and loggers should be collected and redeployed on an annual basis.

Metric Rating and Assessment Points:

Metric Rating	Temperature Range (assessed as daily means)
Good–Excellent	25–29°C
Fair	16.1–24.9°C and 29.1–30.4°C
Poor	< 16 and > 30.5°C

Scaling Rationale: Generally, the optimal temperature range of most zooxanthellate corals is between 25–29°C (Wells, 1957). Temperatures below 16–18°C exclude vigorous coral growth (Hubbard, 1997; Wells, 1957), with prolonged exposure to colder temperatures leading to coral death (Hubbard, 1997), although a few hermatypic coral species can survive at even lower temperatures than this (Wells, 1957). Temperature over 30°C can lead to decreases in coral growth rates (Huang et al., 1991), and temperatures over 30.5°C (Manzello et al., 2007) can lead to coral bleaching and reduced growth and reproductive potential, and in some cases the eventual death of the coral (Brown, 1997). It should be noted however, that bleaching can occur whenever the mean monthly maximum temperature exceeds the norm for the specific reef in question, so temperature thresholds can change on a case-by-case basis (Hoegh-Guldberg, 1999).

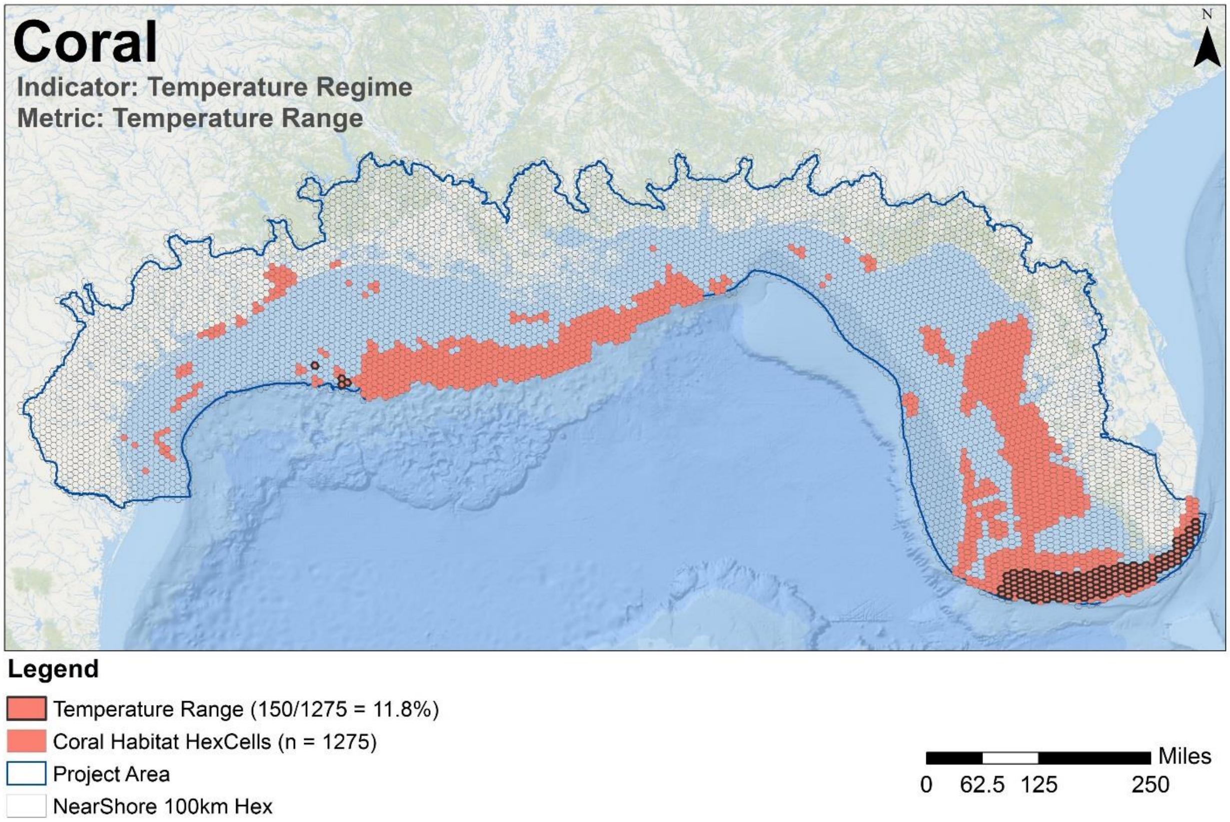
Although temperature limits may be slightly different for mesophotic reefs, which have organisms that are adapted to both low light and colder temperatures, more research is needed to determine if temperature ranges on mesophotic reefs parallel those in shallow water systems. The broad metric ratings listed here can be applied, but may need to be adjusted with further research and monitoring.

Analysis of Existing Monitoring Efforts:

<u>Geographic</u>*:* Temperature is less well collected geographically in the NGoM, with 12% of habitat hexagons containing at least one monitoring site. Monitoring locations for this metric are clumped in the Florida Bay and Florida Keys and around Flower Garden Banks National Marine Sanctuary.

<u>Programmatic:</u> Data for this metric are collected by 7/18 (39%) of the programs collecting relevant coral data in the NGoM.

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



Metric	Total Relevant Coral 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
Temperature Range	18	7	39%	12%

Indicator: Carbonate Chemistry

MEF: Abiotic Factors
KEA: Water Quality
Metric: Aragonite Saturation State, Ω

Definition: The saturation state of seawater with respect to aragonite is defined as the product of the seawater concentrations of dissolved calcium and carbonate ions divided by the seawater concentration of their product at equilibrium, calcium carbonate.

Background: When Ω is 1, seawater is in equilibrium (or saturation) with respect to aragonite—it will not dissolve or precipitate out of solution. When Ω is greater than 1, seawater is supersaturated with respect to aragonite, and aragonite can precipitate out of solution. When Ω is less than 1, the seawater is undersaturated with respect to aragonite, and aragonite minerals will dissolve.

Rational for Selection of Variable: Aragonite saturation state is one of the five “first-order determinants of reef distribution at the global scale,” along with light attenuation, salinity, nutrients, and temperature (Kleypas et al., 1999). Corals are animals that produce a calcium carbonate skeleton. Carbonate chemistry is therefore extremely important in determining coral growth and the potential for dissolution of the reef structure. This is of particular concern with the increased burning of fossil fuels in the past century, resulting in higher inputs of CO_2 into ocean waters. The more CO_2 in water and the more acidic seawater becomes, the harder it is for calcifying organisms like corals to deposit calcium carbonate, which can even lead to the dissolution of the existing calcium carbonate skeletons. Net erosion is already occurring on part of the Florida Keys during certain seasons (Muehllehner et al., 2016), but data is currently absent for the rest of the Gulf of Mexico.

Measures: Temperature, salinity, and two of the following: total alkalinity, dissolved inorganic carbon, pCO_2, or pH.

Tier: 2 (rapid field measurement)

Measurement: Aragonite saturation state can be found by first calculating the full seawater carbonic system. First, a water sample should be collected at the depth of the reef in question. Water temperature should be collected from depth, and salinity measured. Using gran titration, measure alkalinity. A small amount of seawater should be put in a beaker and the pH measured. Sulfuric acid should be added to the water until the pH is lowered to 4.5. The amount of sulfuric acid it took to turn the pH of the water to 4.5 can be converted to units of alkalinity. Enter the salinity, pH, temperature, and alkalinity into the software program CO2SYS to get the aragonite saturation state and other variables within the carbonic system (http://cdiac.ornl.gov/oceans/co2rprt.html).

$$[Ca^{2+}] \times [CO_3^{2-}]\ )\ /\ [CaCO_3] = \Omega$$

Sampling frequency should be on the same timescale as chlorophyll *a* concentration and water transparency sampling. We recommend this indicator to be monitored ideally monthly, or at minimum quarterly, seasonally, or in conjunction with episodic events. Monthly monitoring has been found to be good for trend detection, but more frequent monitoring can lose efficiency due to autocorrelation (Reckhow and Stow, 1990).

Metric Rating and Assessment Points:

Metric Rating	Aragonite Saturation State (Ω)
Good–Excellent	> 3.5
Fair	3.3 < Ω < 3.5
Poor	2.5 < Ω <3.3
Threshold for Coral Presence	< 2.5

Scaling Rationale: Shallow-water zooxanthellate corals are not found in seawater with a Ω under 2.5–2.82 (Hall-Spencer et al., 2008; Shamberger et al., 2011; Guan, 2015), although deep sea corals can be found in waters with Ω < 2.5 (Sandra Brooke, personal communication). Reef to coral community transition occurs near an aragonite saturation state of 3.4 (Kleypas et al., 1999), and few reefs are found lower than this value. They further define marginal reef environments as those with an aragonite saturate state less than 3.5.

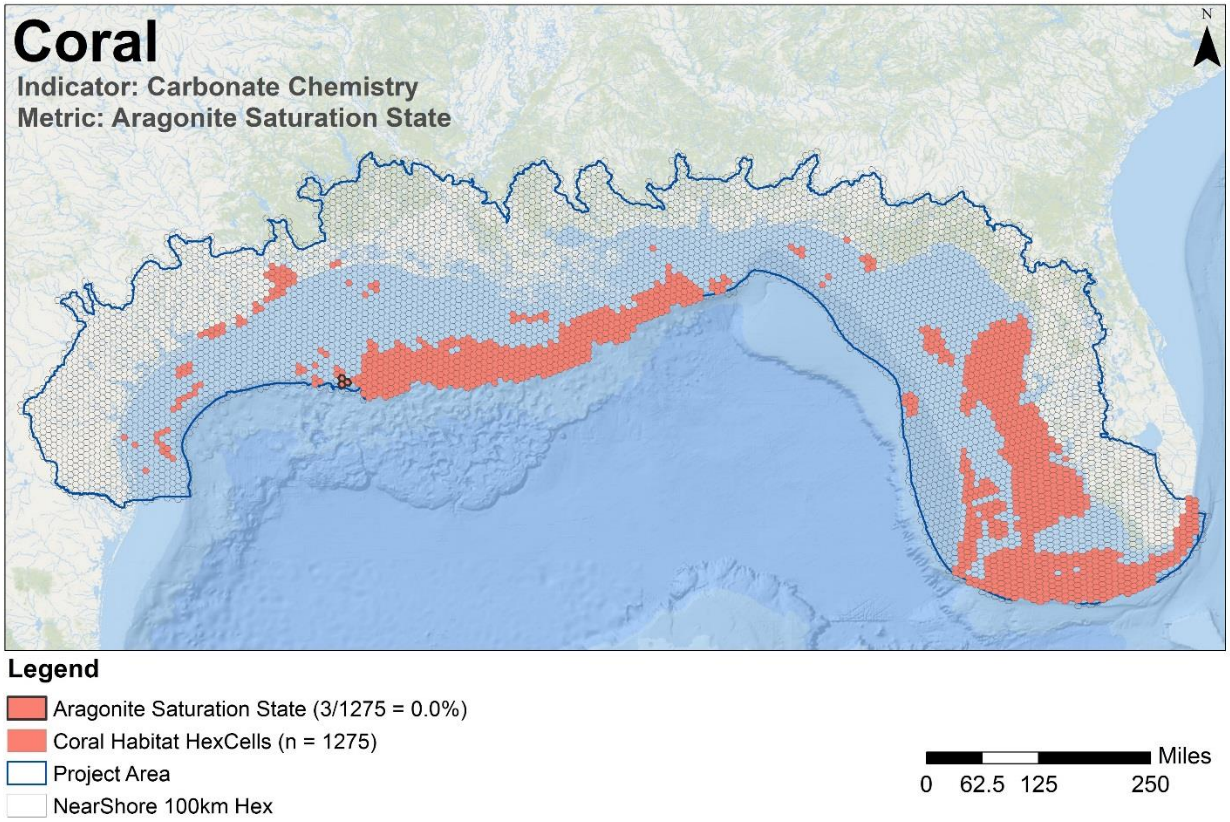
Some studies corroborate these values, finding net erosion occurring below values of 2.5 (mesocosm study by Yates and Halley, 2006), 2.8 (field study by Falter et al., 2012), 3.2–3.4 (field study by Albright et al., 2013). However, numerous mesocosm and field-based studies indicate these values could be even lower, finding a tipping point between net carbonate accretion and erosion at values between 1.2–2.5 (Shaw et al., 2012; Andersson et al., 2009, Langdon et al., 2000; Shamberger et al., 2011). Other studies have found accretion/erosion tipping points at even higher values, ranging from 3.4–4.9 from field based studies (Ohde and van Woesik, 1999; Silverman et al., 2007; Guan, 2015; Muehllehner et al., 2016). Variation is likely site specific and due to the interacting effects on coral accretion rates by aragonite saturation state with temperature and light. Furthermore, not all of these studies include Caribbean, mesophotic, or Gulf corals.

Analysis of Existing Monitoring Efforts:

Geographic*:* Aragonite saturation state is not well collected geographically in the NGoM, with less than 1% of habitat hexagons containing at least one monitoring site. Monitoring locations for this metric are only found in Flower Gardens Bank National Marine Sanctuary.

Programmatic: Data for this metric are collected by 1/18 (6%) of the programs collecting relevant coral data in the NGoM.

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



Metric	Total Relevant Coral 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
Aragonite Saturation State	18	1	6%	< 1%

Indicator: Epibenthic Sessile Community Structure

MEF: Ecosystem Structure
KEA: Benthic Community Structure
Metric: Living Biota Percent Cover

Definition: Community structure can be defined by its species richness and diversity. Percent cover is a measure of the relative abundance and contribution to overall ecosystem structure by a given species or species group.

Background: Reef communities vary greatly throughout the Gulf of Mexico and strongly depend on depth and distance from shore. In West Florida Shelf communities, octocorals are dense and are the dominant taxa group, followed by large sponges (Phillips et al., 1990). Below 20 m however, octocorals decrease markedly in abundance (Phillips et al.. 1990). Stony corals are a minor component on these reefs and are mostly composed of the hydrozoan corals from the genus *Millepora* (fire corals) (Coleman et al., 2005).

Although some reefs in the upper mesophotic zone may have similar composition to their shallow water counterparts, reefs in the lower mesophotic zone become more specialized to deal with the lower light conditions (Bongaerts et al., 2015). Evidence is also lacking for a genetic linkage between adjacent, mesophotic, and shallow reefs, as most brooding coral larvae have limited dispersal ability (Bongaerts et al., 2010). In the Gulf of Mexico, mesophotic reefs can range from having very high coral cover, like the average of 70% seen in parts of the Flower Garden Banks, down to an average of 10%, as seen on Southern Pulley Ridge. Some mesophotic reefs are dominated by stony corals, while others are composed mainly of algae, sponges, octocorals, and coralline algae.

The banks of the NGoM can vary dramatically based on their distance from shore and depth of the reef crest. Communities on these banks have been described by Rezak et al. (1990) and are strongly controlled by depth. The *Millepora*-Sponge zone is characterized by higher abundances of hydrozoan corals and sponges, and limited abundance of stony corals and corraline algae and is found from 20–50 m. The low diversity Stephanocoenia-Montastrea-Agaricia zone is found from 20–35 m and is dominated by the stony corals *Stephanocoenia intersepta, Montastrea* sp., and *Agaricia* sp., abundant coralline algae, and limited abundances of *Millepora alciornis* and leafy algae. The *Madracis* and Leafy Algae zone (dominated by *Madracis mirabilis,* abundant leafy algae) is found at depths of 28–46 m, and the *Stephanocoenia-Millepora* zone (low diversity reef dominated by hermatypic corals; abundant coralline algae; limited leafy algae; high abundance of thorny oysters) from 36–52 m. Into the mesophotic zone, the Algal-Sponge zone (dominated by crustose coralline algae; limited hermatypic corals and *Millepora*; abundant leafy algae) stretches from 46–82 m. Below this depth, only minor reef-building activity occurs. The Antipatharian Transitional zone, dominated by antipatharian corals with sponges, coralline algae, and azooxanthellate stony and soft corals, is present from 82–86 m, while the Nepheloid Layer (a layer of water with significant amounts of suspended sediment with no reef building activity and depauperate benthic communities with scattered octocorals and solitary stony corals) starts at 86 m, with soft bottom habitats emerging at 100 m.

Rational for Selection of Variable: The structure of the benthic community itself—including the key species of scleractinians, hydrozoans, octocoralians, and poriferans—is critical in understanding changes to the reef over time. Scleractinian corals, octocorals, and sponges all provide structure, refugia, and food sources to other organisms living on the reef. By assessing the structure of the reef, we also indirectly assess the rugosity and structural complexity that is important for the function of the coral reef ecosystem as a whole (Kramer, 2003). Epibenthic sessile community structure falls under the "Organization" variable that defines ecosystem health as defined by Rapport (1998), which is widely accepted in ecosystem health science (Sweatman, 2007). Many other coral reef monitoring efforts use this as an indicator of reef health, including the Atlantic and Gulf Rapid Reef Assessment (AGGRA), Hawai'i Coral Reef Assessment and Monitoring Program (CRAMP), the Mesoamerican Coral Reef Watch Program (MAR), the Caribbean Coastal Marine Productivity Program (CARICOMP), Reef Check (Sweatman, 2007), and the Coral Reef Evaluation and Monitoring Project (CREMP).

Measure: Percent cover and abundances of the key species of the benthic community (including scleractinians, hydrozoans, octocoralians, and poriferans)

Tier: 3 (intensive field measurement)

Measurement: For shallow water reefs accessible by SCUBA gear, these measures can be gathered by divers following similar protocols to the CREMP survey methodology. CREMP utilizes metal stakes drilled into the reef substrate, between which a chain is laid and corals are surveyed in a 10x1m transect. All corals within 0.5 m are surveyed on either side of the chain up to the 10m mark. This ensures that the same area of the reef is being surveyed over the years of the monitoring effort. A similar survey methodology could be developed for a subset of Gulf of Mexico reefs.

For deeper mesophotic reefs, technical diving or surveys through the use of remotely operated and autonomous underwater vehicles or manned submersibles could be used

Although all living biota will be used as our metric, during the surveys data should be separated by species and genera (scleractinian corals, hydrozoan corals, octocorals, and sponges). These surveys should be conducted on an annual basis.

Metric Ratings and Assessment Points:

Metric Rating	Living Biota Percent Cover
Excellent	Increasing: Positive rate of change
Good/Fair	Stable: No rate of change; rate of change is not statistically significant
Poor	Decreasing: Negative rate of change

Scaling Rationale: Baseline information on community structure is lacking for much of the Gulf of Mexico, necessitating a "rate of change" approach. A metric rating can only be assigned after multiple years of data have been collected as part of the monitoring program. A long-term dataset will be necessary to understand population trends – too short a dataset may lead to the wrong conclusions due to seasonal or natural variability within a system. It will take a few years of data in order to determine directionality and whether or not the reef systems are continually improving and moving (presumably) towards a state of health, or if they are in decline. The number of years required will depend on the data itself, as some organisms and systems necessitate only a few years of data, while others would require at least 20 years to make meaningful observations (White, 2017). After monitoring data has been collected, it will be necessary to develop metrics for each reef type in the Gulf of Mexico: West Florida

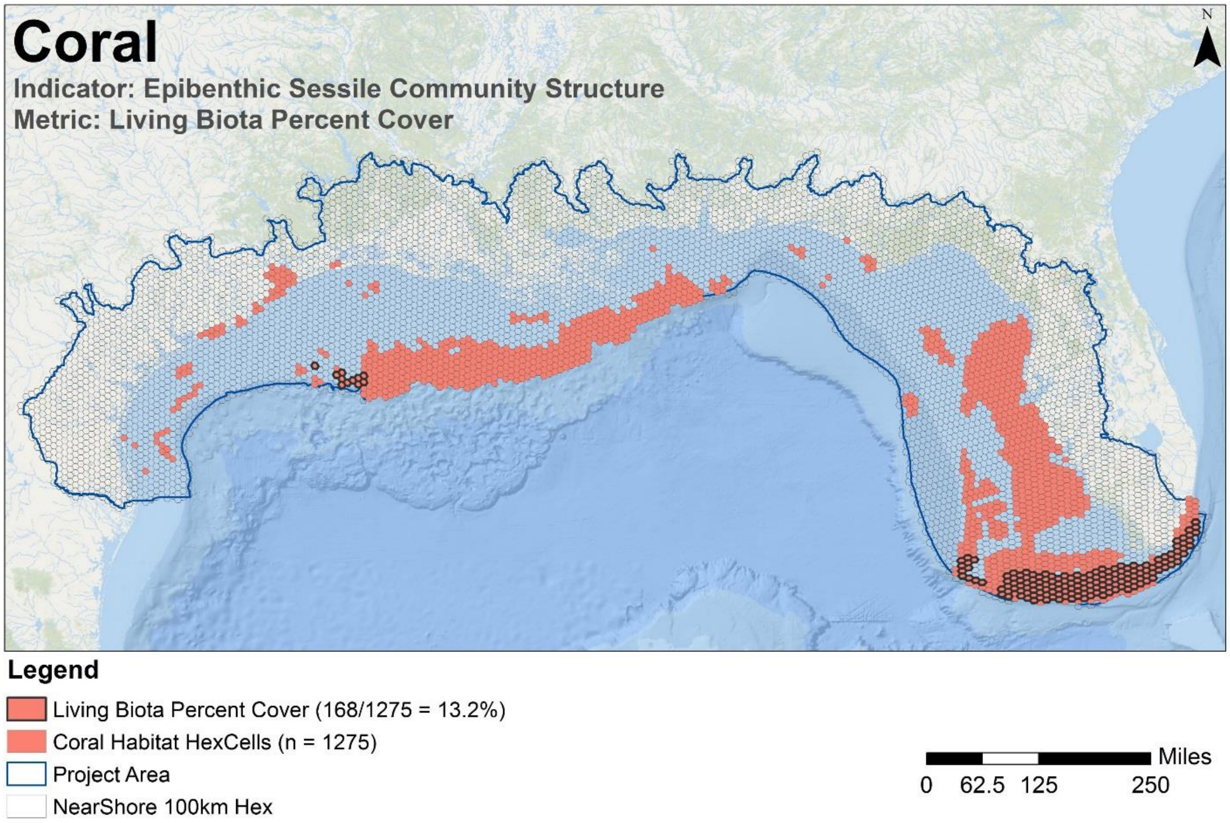
Shelf reefs, mesophotic reefs, the Flower Garden Banks National Marine Sanctuary, and reefs found in the northern Gulf of Mexico.

Analysis of Existing Monitoring Efforts:

<u>Geographic</u>*:* Living biota percent cover data are less well collected geographically in the NGoM, with 13% of habitat hexagons containing at least one monitoring site. Monitoring locations for this metric are clustered in Florida Bay and Florida Keys and Flower Garden Banks National Marine Sanctuary.

<u>Programmatic:</u> Data for this metric are collected by 11/18 (61%) of the programs collecting relevant coral data in the NGoM.

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



Metric	Total Relevant Coral 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
Living Biota Percent Cover	18	11	61%	13%

- Spatial footprint unavailable for one monitoring program. Percent of hexagons containing monitoring sites may be an underestimate.

Indicator: Grazing

MEF: Ecosystem Structure
KEA: Benthic Community Structure
Metric: Echinoid Abundance

Definition: The consumption of macroalgae by herbivores on the reef, here defined specifically by echinoids such as sea urchins.

Background: We chose to assess populations of echinoids because they represent the primary grazers on Gulf of Mexico reefs. Grazing keeps algal populations in check, which are spatial competitors with coral. The data can easily be collected in conjunction with assessments of benthic cover and condition, and urchins have high reef fidelity, unlike transient fish. Although we don't yet know which echinoid species can serve as "key indicator species," monitoring can focus effort on key indicator species of reef health after baseline studies are conducted.

Rational for Selection of Variable: Invertebrates are important coral reef community members and interact on a number of scales with corals, algae, and other reef inhabitants. Here we focus specifically on echinoids, or sea urchins. Sea urchins can be prodigious grazers on reef substrates (e.g. Lessios et al., 2015; Sangil and Guzman, 2016). A degraded reef will have different invertebrate community structure than a healthy reef, with consequent changes in their functional abilities, such as increased algal cover and decreased coral abundance (as seen in the Caribbean in the 1980's with the severe decline of Diadema antillarum contributing to the phase shift of many reefs from coral to algal-dominated communities; Lessios et al., 1984; Hughes, 1994). Echinoid abundance, a subset of benthic community structure falls under the "Organization" variable that defines ecosystem health as defined by Rapport (1998), which is a widely accepted resource on ecosystem health science (Sweatman, 2007). Although the species will be different from those that would be monitored in the Gulf of Mexico, many other coral reef monitoring efforts assess invertebrate communities as an indicator for reef health, including AGGRA, MAR, Reef Check (Sweatman, 2007), and CREMP.

Measure: Abundance

Tier: 3 (intensive field measurement)

Measurement: Collecting abundance data will allow calculation of other metrics, such as diversity, richness, evenness, dominance, and relative abundance. Abundance surveys can be conducted by divers or using videos and/or photography on the same transects of the reef utilized in the other benthic surveys on an annual basis. Again, for deeper reefs where it is unsafe or not possible to send divers down, data can be collected from ROVs or manned submersibles. A long-term dataset will be necessary to understand population trends. Too short a dataset may lead to the wrong conclusions due to seasonal or natural variability within a system. It will take a few years of data in order to determine directionality and whether or not the reef systems are continually improving and moving (presumably) towards a state of health, or if they are in decline. The number of years required will depend on the data itself, as some organisms and systems necessitate only a few years of data, while others would require at least 20 years to make meaningful observations (White, 2017).

Metric Rating and Assessment Points:

Metric Rating	Echinoid Abundance
Excellent	Increasing: Positive rate of change
Good/Fair	Stable: No rate of change; rate of change is not statistically significant
Poor	Decreasing: Negative rate of change

Scaling Rationale: Echinoid abundances on reef communities in the Gulf of Mexico are largely unknown at this time and will likely differ between reef types and region of the Gulf. Using a rate of change approach would be more appropriate given the paucity of information.

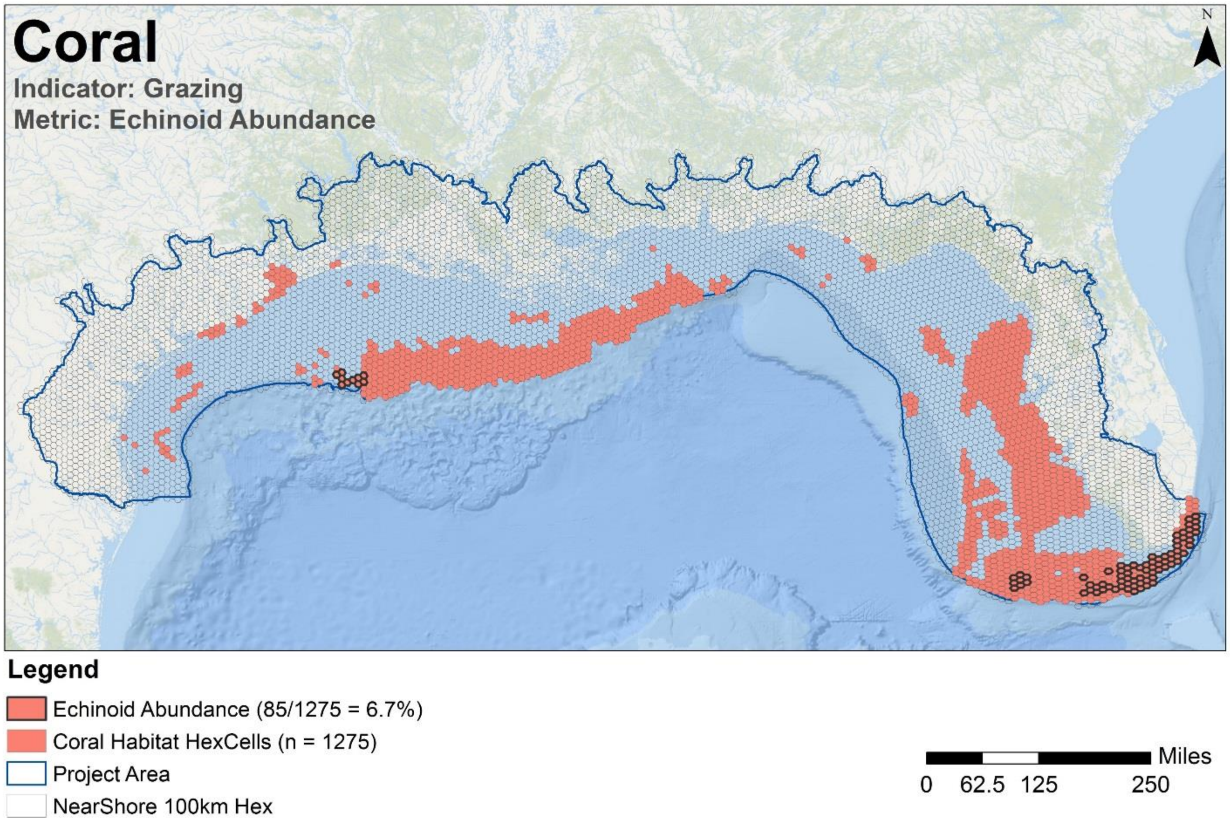
As a reference point, *Diadema antillarum* mean population densities in the Florida Keys were 1.7 urchins/m^2 from 1970–1978 (Bauer, 1980), < 0.001 urchins/m^2 from 1990–1991 (Forcucci, 1994), and 0.02 urchins/m^2 in 2011 (Chiappone et al., 2013; Lessios 2015). *Diadema antillarum* is an important macroalgal grazer found throughout the tropical Western Atlantic. A severe die-off in the 1980's led to an explosion of macroalgae on Caribbean reefs.

Analysis of Existing Monitoring Efforts:

Geographic*:* Echinoid abundance is not yet very well collected geographically in the NGoM, with 7% of habitat hexagons containing at least one monitoring site. Monitoring locations for this metric are clustered in the Florida Bay and Florida Keys and the Flower Garden Banks National Marine Sanctuary.

Programmatic: Data for this metric are collected by 4/18 (22%) of the programs collecting relevant coral data in the NGoM.

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



Metric	Total Relevant Coral 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
Echinoid Abundance	18	4	22%	7%

Indicator: Macroalgal Cover

MEF: Ecosystem Function
KEA: Benthic Community Condition
Metric: Macroalgal Percent Cover

Definition: Macroalgae are large algae that can make up a large component of the benthos, including the commonly found Western Atlantic genera *Dictyota*, *Halimeda, Caulerpa*, and *Lobophora*.

Background and Rationale for Selection of Variable: The structure of the benthic community is critical to understanding changes to the reef over time. The percent cover of scleractinian corals and macroalgae are often negatively correlated in reef systems, and macroalgae can directly compete with corals for space on the reef (e.g. Hughes, 1994; Adey, 1998; McCook et al., 2001; Bruno et al., 2009, Barott and Rohwer, 2012; Jackson et al., 2014), alter the coral-associated microbial community (Thurber et al., 2012), and reduce larval coral recruitment success (Hughes 1989, 1994). Many other coral reef monitoring efforts use this as an indicator of reef health, including the Atlantic and Gulf Rapid Reef Assessment (AGGRA), Hawai'i Coral Reef Assessment and Monitoring Program (CRAMP), the Mesoamerican Coral Reef Watch Program (MAR), the Caribbean Coastal Marine Productivity Program (CARICOMP), Reef Check (Sweatman 2007), and the Coral Reef Evaluation and Monitoring Project (CREMP).

Measure: Percent cover and abundance of key guilds of macroalgae

Tier: 3 (intensive field measurement)

Measurement: These measures can be gathered by divers following similar protocols to the CREMP survey methodology and collected on an annual basis. CREMP utilizes metal stakes drilled into the reef substrate, between which a chain is laid and the benthos is photographed along a 22 m transect. This ensures that the same area of the reef is being surveyed over the years of the monitoring effort. A similar survey methodology could be developed for a subset of Gulf of Mexico reefs.

For deeper mesophotic reefs, technical diving, or surveys through the use of remotely operated and autonomous underwater vehicles or manned submersibles could be used.

Metric Rating and Assessment Points:

Metric Rating	Macroalgal Percent Cover
Excellent	0–10% cover
Good	10–20% cover
Fair	20–50% cover
Poot	Over 50% cover

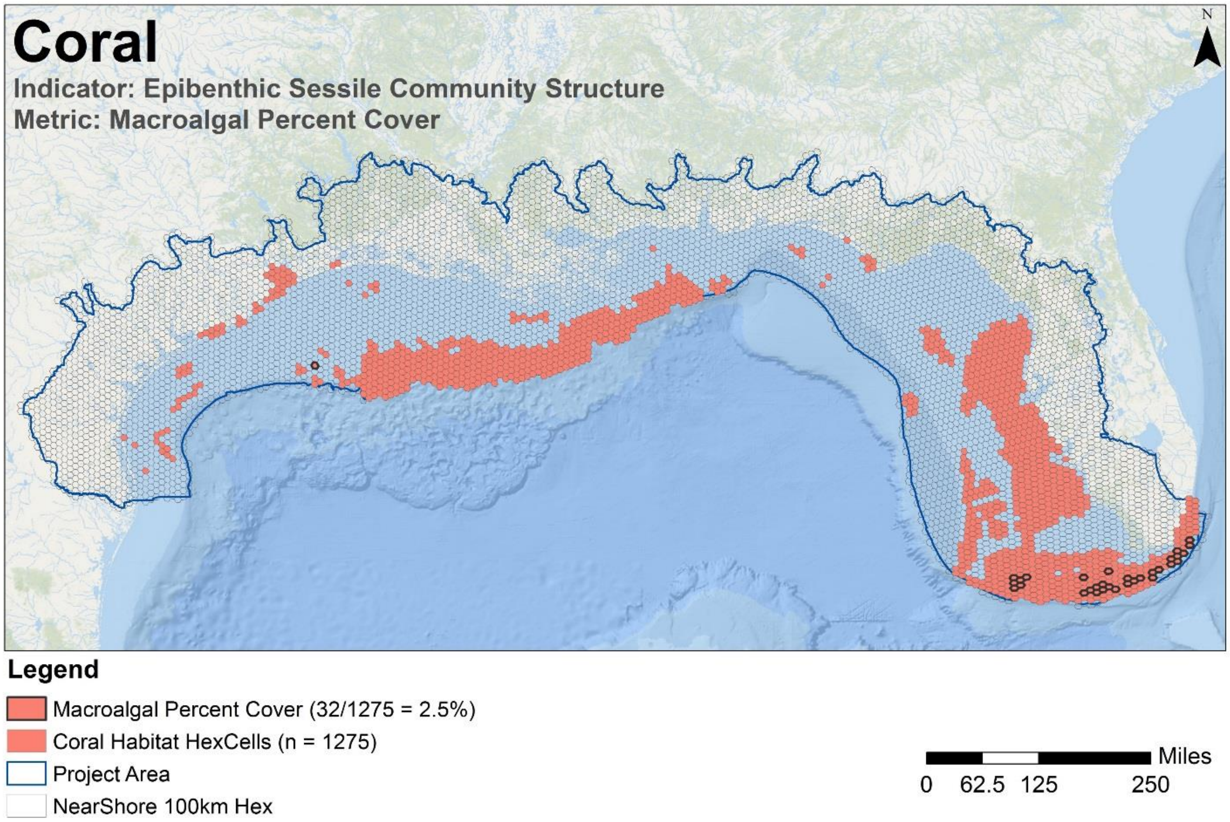
Scaling Rationale: The regional historic baseline for macroalgal cover in the Caribbean is calculated to range between 0–10% (Bruno et al., 2009), and macroalgal cover on the Flower Garden Banks never exceeded 6% up until 1998 (Johnston et al., 2015). Some studies have found coral recruitment to be impaired with 20-30% macroalgal cover. Algal dominance, and therefore a phase-shift from a coral dominated reef to algal-dominated reef, is established to be 50–60% in the Caribbean.

Analysis of Existing Monitoring Efforts:

<u>Geographic</u>*:* Macroalgal percent cover is not well collected geographically in the NGoM, with 3% of habitat hexagons containing at least one monitoring site. Monitoring locations for this metric are clustered in the Florida Bay and Florida Keys and in one hexagon around the Flower Garden Banks National Marine Sanctuary.

<u>Programmatic:</u> Data for this metric are collected by 4/18 (22%) of the programs collecting relevant coral data in the NGoM.

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



Metric	Total Relevant Coral 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
Macroalgal Percent Cover	18	4	22%	3%

Indicator: Coral Disease

MEF: Ecosystem Function
KEA: Benthic Community Condition
Metric: Disease Prevalence

Definition: Disease here is defined broadly as abnormal condition of a coral caused by infection of a pathogen, stress, pollution, congenital defects, or combinations of multiple factors that impairs function of the organism. Note: Bleaching is assessed separately.

Background: Diseases can be assigned to five categories: 1) Non-infectious diseases: physiological and/or morphological changes due to pollution or toxins; 2) Trauma: predation, groundings, etc.; 3) Parasitic infections: infestation by protozoans, metazoans, or parazoans; 4) Growth anomlies; and 5) Infectious disease: disease and associated mortality caused by bacteria, fungi, or viruses (Woodley et al., 2008).

Rational for Selection of Variable: Although background levels of disease incidence are present on all reef systems, even healthy ones, disease outbreaks are a major contributor to coral reef decline worldwide (ICRI, 2010). The condition of the key species of these reefs is very important for assessing the integrity of the system as a whole (Kramer, 2003; Dustan and Halas, 1987; Done, 1997). Scleractinian corals, hydrozoan corals, octocorals, and sponges all provide structure, refugia, and food sources to other organisms living on the reef. The health of these benthic species is important to their ability to function in these roles. Coral disease may reduce growth, reproduction, and recruitment success, can decrease coral resilience and resistance to other sources of stress, and can sometimes result in the death of the colony (Wheaton et al., 2001; Hoegh-Guldberg, 1999; Knowlton, 2001; Nystrom et al., 2000; Patterson et al., 2002; Porter and Tougas, 2001; Porter et al., 2001; Richmond, 1993). Sponge disease outbreaks can often lead to drastic population reductions, such as that seen in 1938 on Caribbean reefs which cause a population decline of 70–95% (Galstoff, 1942 in Webster, 2007). Many other coral reef monitoring efforts use disease as an indicator of reef health, including AGGRA, Reef Check (mortality and disease) (Sweatman, 2007), CREMP, and the NOAA Coral Reef Conservation Program's National Coral Reef Monitoring Program.

Although data is lacking for the Gulf of Mexico, the Western Atlantic and Caribbean regions overall have become a hot spot for coral disease, with over 70% of all coral disease reports worldwide coming from these reefs (Weil, 2004; Miller et al., 2009; ICRI, 2010). Increased sponge disease may also be becoming more common along with other marine organisms (Lafferty et al., 2004), although baseline data is lacking, and it is impossible to determine whether sponge disease incidence is truly increasing or if sponge diseases are simply being studied more now than it was in the past (Webster, 2007). It is likely disease events will continue to be more common with climate change, as warming waters enhance growth rates of infectious diseases while simultaneously impairing defense mechanisms of corals (Boyett et al., 2007; Webster, 2007). Other stressors that become more prevalent under climate change make corals and sponges more susceptible to disease, including warming waters, nutrient enrichment, ocean acidification, algal competition, loss of biodiversity on the reef, and higher irradiance levels (Webster, 2007).

Measure: Prevalence of diseases

Tier: 3 (intensive field measurement)

Measurement: Prevalence of diseases should be measured by recording the presence of any stony coral, octocorals, or sponge with evidence of disease. We define prevalence as the percentage of colonies or individuals affected by disease out of the total number of colonies surveyed. This will allow calculation of the proportion of affected individuals in the greater population, as well as the frequency and extent of the disease, and what species are being affected. These surveys should be conducted on an annual basis on the same transects as indicators for epibenthic sessile community structure, grazing, and macroalgae through the use of divers on shallow reefs. Although it may be harder to identify diseases through the use of ROVs or manned submersibles, these tools may have to be used to assess mesophotic reefs that are not safely accessible by divers.

Metric Rating and Assessment Points:

Metric Rating	Disease Prevalence
Good–Excellent	0–5%
Fair	5–10%
Poor	Over 10%

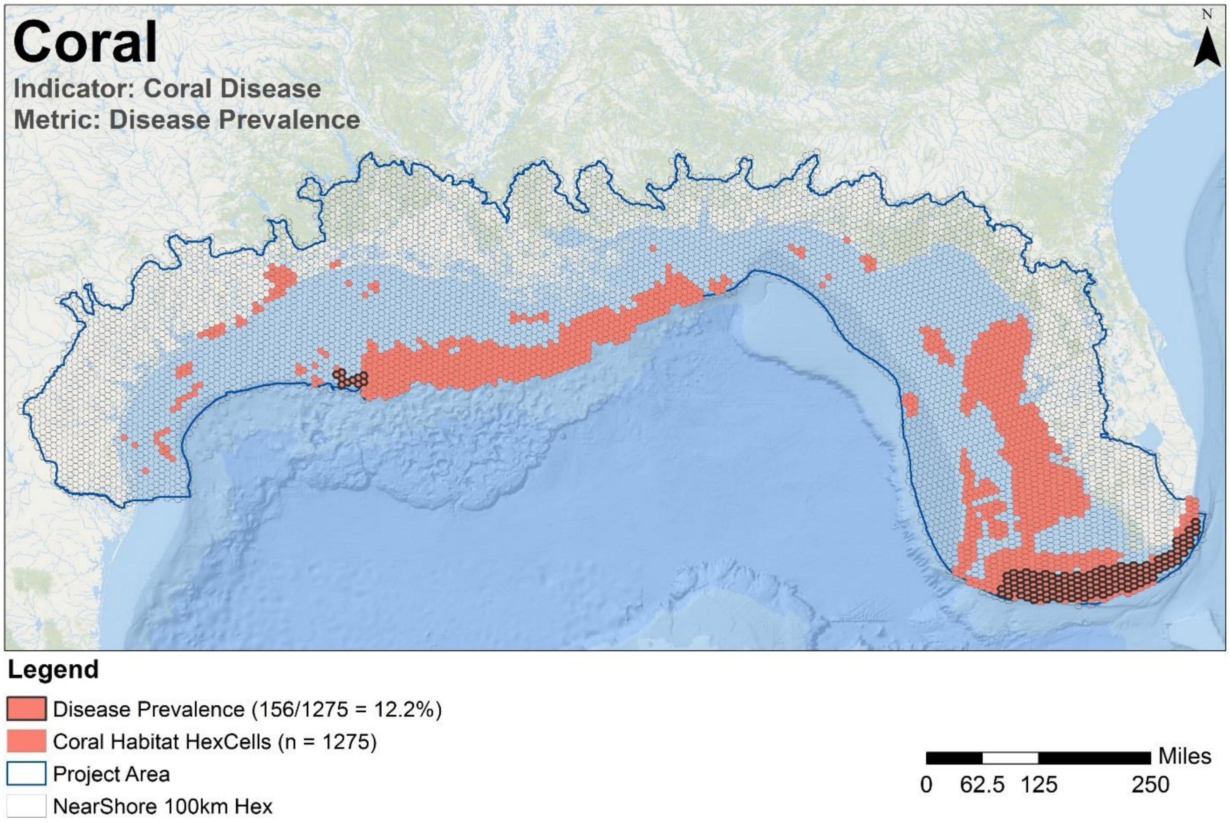
Scaling Rationale: We based our “Good–Excellent” rating on CREMP survey data and that from other data available from throughout the Florida Keys and Caribbean, which reported that the majority of surveyed sites had less than 5–6% disease prevalence (Santavy et al., 2005; Cróquer and Weil, 2009; Florida Reef Resiliency Program, 2015). Additionally, no coral disease was reported at the Flower Garden Banks until recently, indicating that background levels of disease are low here (or probably a product of the limited research and monitoring conducted on Gulf of Mexico reef communities). White plague was noted as present on *Montastraea annularis, M. cavernosa, Colpophylia natans,* and *Diploria strigosa* in 2002–2003 (Precht et al., 2008), and disease incidence was 0.07% in the Flower Garden Banks (Johnston et al., 2015). Although previous work suggests 13% disease prevalence to “signal critical conditions” and was the highest prevalence recorded in their surveys (Santavy et al., 2005), based on CREMP data we suggest a lower threshold of 10%.

Analysis of Existing Monitoring Efforts:

<u>Geographic</u>*:* Disease prevalence is less well collected geographically in the NGoM, with 12% of habitat hexagons containing at least one monitoring site. Monitoring locations for this metric are clustered in the Florida Bay and Florida Keys and Flower Garden Banks National Marine Sanctuary.

<u>Programmatic:</u> Data for this metric are collected by 8/18 (44%) of programs collecting relevant coral data in the NGoM.

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



Metric	Total Relevant Coral 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
Disease Prevalence	18	8	44%	12%
• Spatial footprint unavailable for one monitoring program. Percent of hexagons containing monitoring sites may be an underestimate.				

Indicator: Coral Bleaching

MEF: Ecosystem Function
KEA: Benthic Community Condition
Metric: Bleaching Prevalence

Definition: The loss of symbiotic algae (zooxanthellae) living within the coral tissue that provides much of the energy needs of the coral.

Background: As described above, orals have a mutualistic relationship with a single celled green alga known as zooxanthellae (Ruppert et al., 2004). Zooxanthellae are intracellular and provide corals with energy derived from photosynthesis, and the coral provides the algae with a ready source of nutrients and shelter. However, corals can tolerate only a relatively narrow temperature range and prefer water between 25–29°C, and water temperatures over 30°C or under 16°C can become stressful and eventually fatal for coral (Hubbard, 1997; Wells, 1957). As a result of stress, zooxanthellae produce reactive oxygen species to deal with excess heat energy, compounds that are harmful to the coral and necessitate their expulsion from the coral tissue (NOAA Coral Reef Watch, 2013). Coral can lose zooxanthellae in three ways: 1) as a response to higher than normal temperatures, 2) algal-stress bleaching under high light and/or temperature, and 3) coral-stress bleaching, where coral cells containing zooxanthellae are shed (Fitt et al., 2001). Although the coral is still alive, just colorless, it can die from starvation if the zooxanthellae does not return. However, coral bleaching is not strictly a temperature driven stress response and can also be caused by other sources of stress (Fitt et al., 2001), such as increased solar radiation (Brown et al., 1994), decreased salinity (Coles and Jokeil, 1992), exposure at low tide (Vaughan, 1914; Yonge and Nicholls, 1931), or sedimentation (Bak, 1978; Dollar and Grigg, 1981).

Rational for Selection of Variable: The condition of the key species of these reefs is very important for assessing the integrity of the system as a whole (Kramer, 2003; Dustan and Halas, 1987; Done, 1997). Scleractinian and hydrozoan corals provide structure, refugia, and food sources to other organisms living on the reef. The health of these benthic species is important to their ability to function in these roles. Corals are sensitive to even small temperature changes and can react through bleaching, reduced growth rates, reduced reproduction, increased vulnerability to diseases, and die-offs (Hubbard, 1997; Wells, 1957; Huang et al., 1991; Manzello et al., 2007; Brown, 1997). Although bleaching prevalence is rare in the Gulf of Mexico, bleaching events have been observed on the Florida Middle Ground and on hardbottom ledges between Naples and Bay Port, FL (Walt Jaap, personal communication). Additionally, massive, region-wide bleaching events have become more common on the Florida Reef Tract in recent years. Six extensive coral bleaching events have affected the entire Florida Reef Tract since 1987, with substantial mass coral mortality occurring during the global bleaching events of 1997/1998 and 2014/2015 (Manzello, 2015). Coral bleaching and die-off also began in 2016 in the East Flower Garden Bank (https://sanctuaries.noaa.gov/news/sep16/investigation-of-coral-die-off-continues-amid-bleaching-event.html).

Even beyond these major bleaching episodes, some level of bleaching is occurring nearly every year in the Florida Keys. Other coral reef monitoring efforts use bleaching as an indicator of reef health, including AGGRA (Sweatman, 2007) and CREMP.

Measure: Bleaching presence and prevalence

Tier: 3 (intensive field measurement)

Measurement: Bleaching should be surveyed at the same transects and time as the indicators of grazing, macroalgal cover, and coral disease, and monitored on an annual basis. Bleaching should be recorded as presence or absence and include completely and partially bleached coral colonies. Prevalence can be calculated using the percentage of colonies or individuals affected by bleaching out of the total number of colonies surveyed. This allows calculation of the proportion of affected individuals in the greater population, as well as the frequency and extent of the disease and/or bleaching event. We recommend diver surveys on permanently established belt transects on the shallower reefs. Although it may be harder to identify diseases through the use of ROVs or manned submersibles, these tools will have to be used to assess mesophotic reefs that divers cannot safely access.

Metric Rating and Assessment Points:

Metric Rating	Bleaching Prevalence
Good	0–5%
Impaired	5–20%
Degraded	20–50%
Highly Degraded	Over 50%

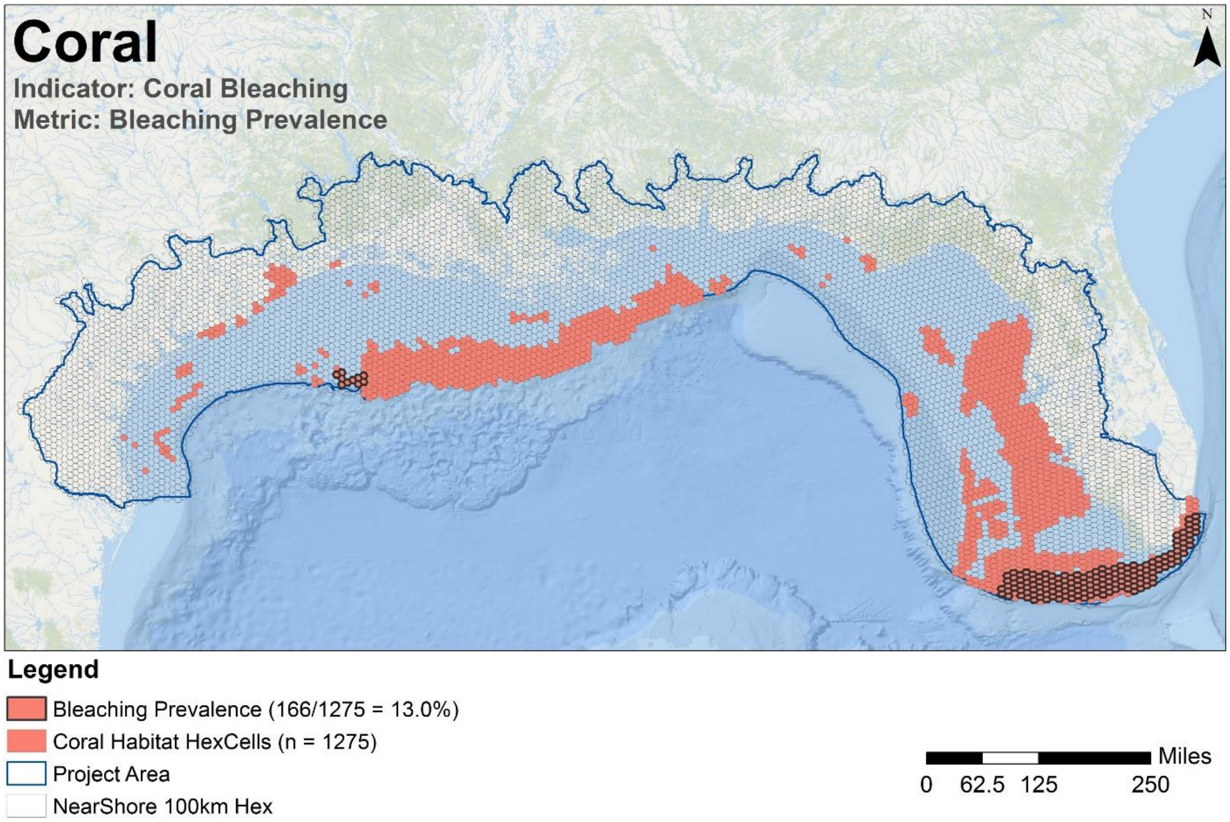
Scaling Rationale: We based our values on current knowledge of the Florida Reef Tract from programs that monitor bleaching. Santavy et al. (2005) suggests 3% bleaching or partially bleaching prevalence as a threshold signaling deleterious impacts to corals, but based on CREMP data for the Florida Keys background levels of bleaching range from 0–5%. Bleaching prevalence is largely unknown for the Gulf of Mexico, although monitoring conducted on the Flower Garden Banks showed that < 5% of corals exhibited bleaching, paling, or fish predation, falling within the range of our category of “Excellent”, and that bleaching prevalence from 1989–2003 only exceeded 4% in 2001 (Hickerson et al., 2008). The Nature Conservancy’s Florida Reef Resiliency Program uses a similar metric rating threshold values: 0–20% bleaching prevalence for their “Mild” rating, 20–50% for their “Moderate” rating, and over 50% for their “Severe” rating (Florida Reef Resilience Program, 2015).

Analysis of Existing Monitoring Efforts:

Geographic*:* Bleaching prevalence is less well collected geographically in the NGoM, with 13% of habitat hexagons containing at least one monitoring site. Monitoring locations for this metric are clustered in the Florida Bay and Florida Keys and Flower Garden Banks National Marine Sanctuary.

Programmatic: Data for this metric are collected by 8/18 (44%) of programs collecting relevant coral data in the NGoM.

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



Metric	Total Relevant Coral 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
Bleaching Prevalence	18	8	44%	13%
• Spatial footprint unavailable for one monitoring program. Percent of hexagons containing monitoring sites may be an underestimate.				

Indicator: Coral Mortality

MEF: Ecosystem Function
KEA: Benthic Community Condition
Metric 1: Mean recent mortality per colony (scleractinians, hydrozoans, and octocorallians)
Metric 2: Mean old mortality per scleractinian coral colony

Definition: For stony corals, old mortality is defined by the absence of any corallite structure and is often overgrown by algae or invertebrates. Recent mortality is defined by algae-free, intact or slightly eroded calyx structure in the absence of any living tissue.

Background: The condition of the key species of these reefs is important for assessing the integrity of the system as a whole (Kramer, 2003; Dustan and Halas, 1987; Done, 1997). Stony corals, octocorals, and sponges all provide structure, refugia, and food sources to other organisms living on the reef. The health of these benthic species is critically important to their functioning in these roles. Many other coral reef monitoring efforts use mortality as an indicator of reef health, including AGGRA, Hawai'i CRAMP, the MAR, Reef Check (Sweatman, 2007), and CREMP.

Rational for Selection of Variable: Each mortality type provides different information on the state of the reef. Recent mortality demonstrates that some sort of stressful event is either actively occurring or happened very recently. Old mortality demonstrates overall condition of the reef and provides a historical perspective on the size and health of the community. Greater frequencies of coral colonies with mortality indicate a reef that is subjected to more stress.

Measure: Average percent old and recent mortality per colony

Tier: 3 (intensive field measurement)

Measurement: Mortality should be recorded on the same transects used for grazing, macroalgal cover, coral disease, and bleaching, and monitored on the same annual recurrence. For each scleractinian and hydrozoan coral colony the surveyor should estimate the amount of old and recent mortality to the nearest percentage (for colonies exhibiting partial mortality). The estimate is based upon the entire size of the colony inclusive of dead areas. For stony corals, old mortality is defined by the absence of any corallite structure and is often overgrown by algae or invertebrates. Whole colonies that are 100% old-dead should not be recorded in the survey as timing or cause of mortality cannot be determined. When recent mortality is recorded, the disease, syndrome, or adverse condition responsible for the recent mortality should be identified for each species if possible.

Assessing mortality presence or absence can also be used to calculate the mortality prevalence. We define prevalence as the percentage of colonies or individuals affected by these mortality types out of the total number of colonies surveyed. This will allow calculation of the proportion of affected individuals in the greater population, as well as the frequency and extent of the mortality event. With percent cover estimates of partial recent mortality, the loss of benthic organisms over time can be determined. We recommend diver surveys on permanently established belt transects on the shallower reefs. Although it may be harder to identify diseases through the use of ROVs or manned submersibles, these tools will have to be used to assess mesophotic reefs that divers cannot safely access.

Estimates of percent old mortality should not be assessed for octocorals, as old dead branches eventually break off, resulting in unreliable estimates regarding the size of the absent portion of the colony. Recent mortality in octocorals is defined as newly exposed axis that has not been colonized yet by macroalgae or other sessile organisms. The amount of recent mortality is determined by estimating the percentage of the total colony affected (exposed axis and damaged tissues). When the condition responsible for causing the mortality can be determined, the condition should be recorded along with the percentage of recent mortality.

Metric Ratings and Assessment Points:

Metric Rating	Recent Scleractinian and Octocorallian Mortality – Average percent mortality per colony
Good-Excellent	0–4%
Fair	4–10%
Poor	> 10%

Metric Rating	Old Stony Coral Mortality
Good-Excellent	0–10%
Fair	10–22%
Poor	> 22%

Scaling Rationale: Averages of old mortality on coral colonies will generally be higher than recent mortality because old mortality is additive throughout the years and includes recent mortality from years past. Our values are based on AGGRA surveys throughout the Western Atlantic, which identified a 3% recent mortality prevalence for Gulf of Mexico reefs compared to a Western Atlantic regional average of 4%, with ranges up to 20% (Kramer, 2003). Old mortality in the Gulf of Mexico averaged 10%, with a regional average of 22% (Kramer, 2003).

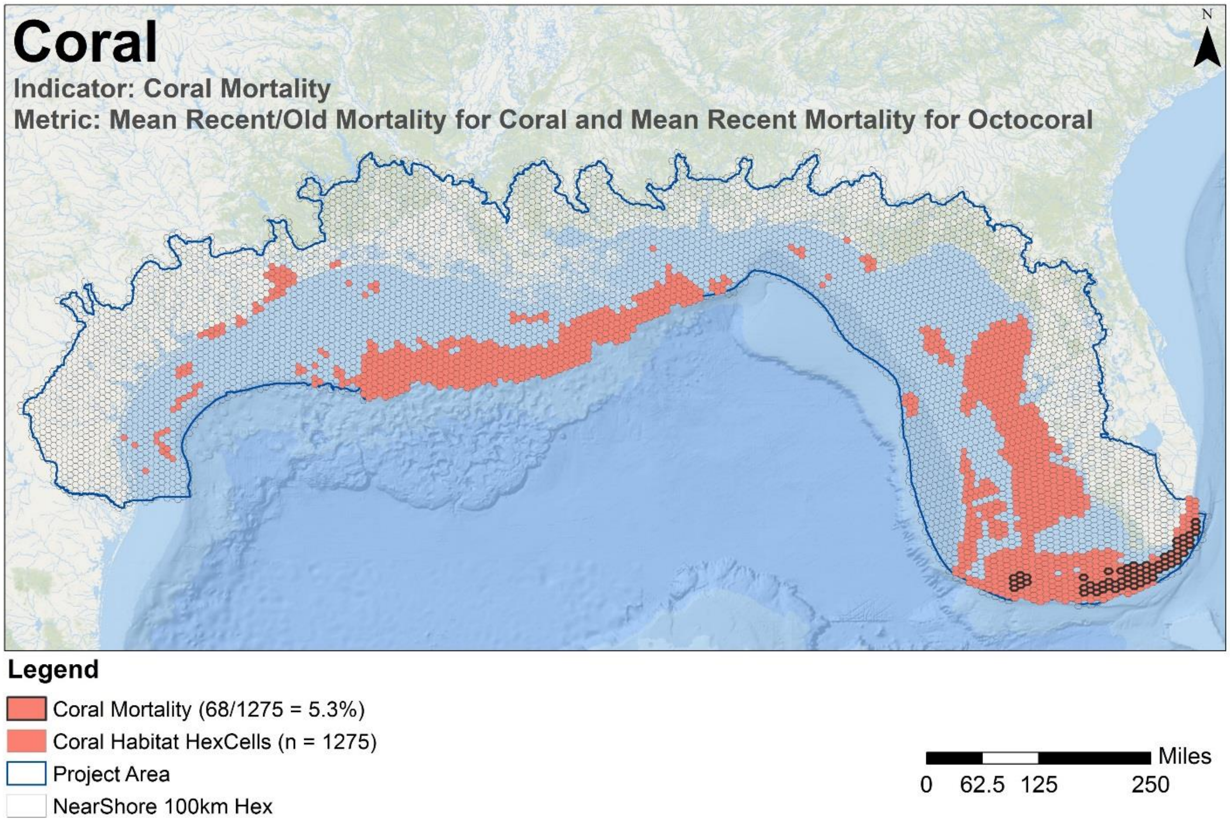
Analysis of Existing Monitoring Efforts:

Geographic*:* Coral mortality (based on either metric) is not well collected geographically in the NGoM, with 5% of habitat hexagons containing at least one monitoring site. Monitoring locations for this metric are clustered in the Florida Bay and Florida Keys.

Programmatic: Data for this metric are collected by 3/18 (17%) of programs collecting relevant coral data in the NGoM.

Note: This analysis was completed prior to the recent mass coral die-off event in Flower Garden Banks National Marine Sanctuary.

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



Metric	Total Relevant Coral 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
Coral Mortality	18	3	17%	5%
• The two metrics, Recent Mortality and Old Mortality, have been combined on this map.				

Ecosystem Service Indicators

Indicator: Status of Macrofauna Populations

MES: Supporting
KES: Habitat
Metric: Live Stony Coral Cover

Definition: Proportion of reef surface covered by live Scleractinian (i.e., stony) coral colonies as a measure of their relative abundance.

Background: In the context of reef degradation, the effects of coral cover loss and resulting decline in topographic complexity on reef fish biodiversity have been widely emphasized (Wilson et al., 2009). The species richness and abundance of reef fish communities have often been related to structural or topographic complexity provided by live coral colonies, a measure of variation in the vertical relief of the habitat (Gratwicke and Speight, 2005; Syms and Jones, 2000).

Rationale for Selection of Variable: Coral cover is expected to be particularly important in explaining the abundance of obligate coral-dwelling species and corallivorous fishes, or species reliant on coral habitat for recruitment (Munday, 2002; Pratchett et al., 2006).

Measure: Percent cover of scleractinian corals

Tier: 3 (intensive field measurement)

Measurement: For shallow water reefs accessible by SCUBA gear, live stony coral cover can be gathered by divers following similar protocols to the CREMP survey methodology. CREMP utilizes metal stakes drilled into the reef substrate, between which a chain is laid and corals are surveyed in a 10x1m transect. This ensures that the same area of the reef is being surveyed over the years of the monitoring effort. All corals within 0.5 m are surveyed on either side of the chain up to the 10-m mark. Overlapping photographs are then taken down the entire length of the chain. These photographs are run through the software program Point Count, which assigns 15 random dots on each picture. The benthic organism under each point is then identified, and percent cover estimates are gleaned from these points. A similar survey methodology could be developed for a subset of Gulf of Mexico reefs.

For deeper mesophotic reefs, technical diving or surveys through the use of remotely operated and autonomous underwater vehicles or manned submersibles could be used.

Metric Rating and Assessment Points:

Metric Rating	Live Stony Coral Cover (Percent)			
	West Florida Shelf*	Mesophotic*	Flower Garden Banks National Marine sanctuary (FGBNMS)**	Northwestern Gulf (northern)*
Excellent	16–30%	10–70%	> 50%	0–30%
Good	?	?	30–50%	?
Fair	?	?	10–30%	?
Poor	Less than 10%	Less than 10%	Less than 10%	?

*Reef communities in the Gulf of Mexico are highly variable even among reefs of the same general type. Using a rate of change approach would be more appropriate given the paucity of information on some of these reefs, when baseline data are not available.
**During the period 1978–2014 (*East & West FGBNMS, Johnston et al.)

Scaling Rationale: Reef communities vary greatly throughout the Gulf of Mexico and strongly depend on depth and distance from shore. In West Florida Shelf communities, octocorals are dense and are the dominant taxa group, followed by large sponges. Below 20 m however, octocorals decrease markedly in abundance. Stony corals are a minor component on these reefs and are mostly composed of the hydrozoan corals from the genus *Millepora* (fire corals). Note that values for ranking live coral cover do not exist in most reefs and coral communities along the Gulf and thus we suggest using values of “Increasing” (positive rate of change over defined period of time), “Stable” (no rate of change over defined period of time), or “Decreasing” (negative rate of change over defined period of time).

Mesophotic reefs are in some ways extensions of their shallow water reef counterparts, but can have differences in structure and composition. It is likely that mesophotic reefs that are downhill from more diverse and abundant coral reefs will also have higher coral cover than mesophotic reefs that are downhill of naturally more depauperate communities. Mesophotic reefs can range from having very high coral cover, like the average of 70% seen in parts of the FGBNMS**,** down to an average of 10%, as seen on Southern Pulley Ridge. Some mesophotic reefs are dominated by stony corals, while others are composed mainly of algae, sponges, octocorals, and coralline algae.

The banks of the northern Gulf of Mexico can vary dramatically based on their distance from shore and depth of the reef crest. Communities on these banks have been described by Rezak (1980) and are strongly controlled by depth. The *Millepora*-Sponge zone is characterized by higher abundances of hydrozoan corals and sponges, and limited abundance of stony corals and corraline algae and is found from 20–50 m. The low diversity Stephanocoenia-Montastrea-Agaricia zone is found from 20–35 m and is dominated by the stony corals *Stephanocoenia intersepta, Montastrea* sp., and *Agaricia* sp., abundant coralline algae, and limited abundances of *Millepora alciornis* and leafy algae. The *Madracis* and Leafy Algae zone (dominated by *Madracis mirabilis;* abundant leafy algae) is found at depths of 28–46 m, and *Stephanocoenia-Millepora* zone (low diversity reef dominated by hermatypic corals; abundant coralline algae; limited leafy algae, high abundance of thorny oysters from 36–52 m. Into the mesophotic zone, the Algal-Sponge zone (dominated by crustose coralline algae; limited hermatypic corals and *Millepora*; abundant leafy algae) stretches from 46–82 m. Below this depth, only minor reef-building activity occurs. The Antipatharian Transitional zone, dominated by antipatharian corals with sponges, coralline algae, and azooxanthellate stony and soft corals, is present from 82–86 m, while the Nepheloid Layer (a layer of water with significant amounts of suspended sediment with no reef building activity and depauperate benthic communities with scattered octocorals and solitary stony corals) starts at 86 m, with soft bottom habitats emerging at 100 m.

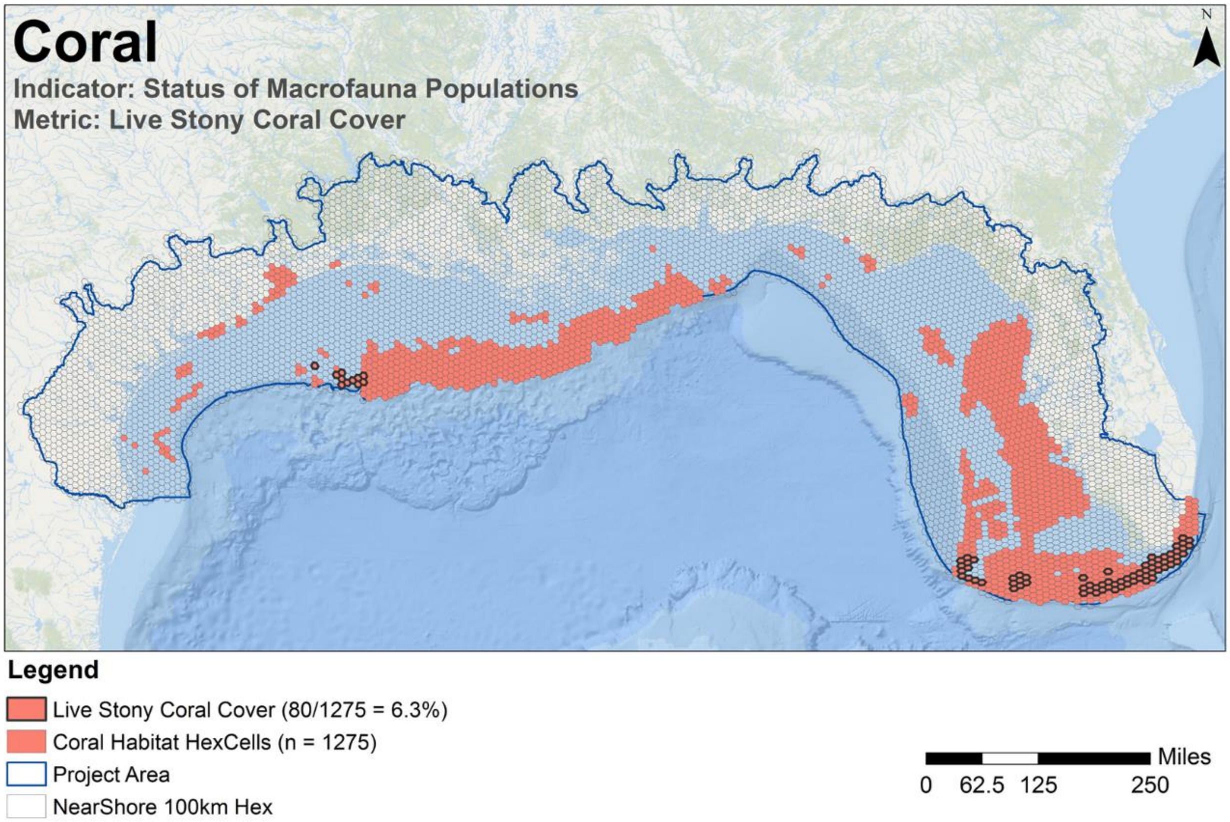
Determining if a reef is "healthy" or not will probably best be obtained by using a stoplight and rate of change approach for some of the lesser studied reefs in the Gulf of Mexico. When available, the baseline values given in the Metrics Rating tables or found in the Resource Information Briefs can be used. Rate of change and "healthy/not healthy" designations would be based upon differences between time periods, or between the baseline and the present. It will take a few years of data in order to determine directionality and whether or not the reef systems are continually improving and moving (presumably) towards a state of health, or if they are in decline.

Analysis of Existing Monitoring Efforts:

<u>Geographic</u>*:* Live stony coral cover is not well collected geographically in the NGoM, with 6% of habitat hexagons containing at least one monitoring site. Monitoring locations for this metric are clustered in the Florida Bay and Florida Keys and Flower Garden Banks National Marine Sanctuary.

<u>Programmatic:</u> Data for this metric are collected by 11/18 (61%) of programs collecting relevant coral data in the NGoM.

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



Metric	Total Relevant Coral 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
Live Stony Coral Cover	18	11	61%	6%
• Spatial footprint unavailable for one monitoring program. Percent of hexagons containing monitoring sites may be an underestimate.				

Indicator: Status of Snapper-Grouper Complex Commercial Fishery

MES: Supporting
KES: Food
Metric 1: Density of Red Snapper

Definition: Number of individuals of red snapper (*Lutjanus campechanus*), per unit area, in the Gulf of Mexico states and/or federal waters.

Background: Red snapper is a reef species that uses primarily natural hard substrate and ridges of deep reefs in the Gulf. As the discovery of these habitats in the Gulf expanded in the 1930's, the red snapper stock has been severely overfished throughout the Gulf (Gulf of Mexico Fishery Management Council, 1981). The most recent assessment completed in September 2015 has determined that the stock was no longer undergoing overfishing (Cass-Calay et al., 2015). In 2017, its annual catch limit has been set to 6,663,900 pounds (http://gulfcouncil.org/images/2017ACLBLOGGraphic_CS_Final.pdf). At the FGBNMS, mid to lower mesophotic reefs (>= 46 m depth), with relief ranging from 20 to over 100 cm, yield the highest fish density, biomass and species richness. Red snapper has the second highest density of all species present in mid to lower mesophotic reefs. Additionally, frequency of occurrence and density were significantly greater on hardbottom habitats than soft bottom at this depth range (Clark et al., 2014).

Rationale for Selection of Variable: Red snapper is common in warm temperate reefs throughout the entire Gulf of Mexico (Reef Fish Plan, 1981). Red snapper is an important commercial fishery species along the southeast US coast. Red 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 Gulf of Mexico by the Gulf of Mexico Fishery Management Council (2017; see for limits and closure information). 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).

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 recreational fishing. This metric is best used when it important to tie the ecosystem service to a specific site. It can be sensitive to fishery management policies and fishing pressures.

Measure: Individuals per square meter

Tier: 3 (intensive field measurement)

Measurement: 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 measures during months when populations are expected to be the highest.

Metric Rating and Assessment Points:

Metric Rating	Density of Red Snapper		
	FGBNMS		All Other Sites
	Coralline algal reef**	Deep reef (> 46 m depth)**	
Excellent/Good	>= 0.32	>= 0.61	Stable/Increasing
Fair/Poor	< 0.32	< 0.61	Decreasing

Scaling Rationale: Snapper densities vary by habitat within FGBNMS. The values correspond to mean fish density as reported by Clark et al. (2014). Specific expected densities at given sites are not available to establish assessment points. Decreases in red 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 commercial fisheries.

Analysis of Existing Monitoring Efforts:

No programs in the monitoring program inventory specifically noted collection of red snapper density.

Indicator: Number of Reef Visitors

MES: Cultural
KES: Aesthetics-Recreational Opportunities
Metric: Number of People Using the Reef System Recreationally

Definition: Annual number of persons using the reef system by reef type—i.e., shallow hermatypic reef, and mesophotic reef (> 30 m deep). Examples of reef use recreational activities considered are snorkeling, SCUBA diving, fishing, and glass bottom boats. Only natural coral reef habitat is considered.

Background: In the Gulf of Mexico, the FGBNMS off the Texas coast provides an excellent opportunity for divers to see a true coral reef ecosystem in the Gulf of Mexico (e.g., http://sanctuaries.noaa.gov/diving/). Although ecotourism or organized diving trips are not provided through the Sanctuary, visitors can book trips with selected diving and fishing charters that help protect the reefs and provide the Sanctuary with a voluntary vessel trip report after the trip (http://flowergarden.noaa.gov/document_library/forms/vesselreportform.pdf). Moreover, sanctuary management encourages people to send voluntary reports of their visits and interesting observations conducted using online forms (specially to report incidents in the water, invasive lionfish and key species; e.g., http://flowergarden.noaa.gov/visiting/reportobservations.html). Recreational fishing at the FGBNMS is permitted but regulated by specific rules (see http://flowergarden.noaa.gov/document_library/protdocs/fgbnmsfinalrule2012.pdf). It is estimated that the FGBNMS is visited by 1500 to 2000 sport divers each year (Ditton and Thailing, 2003; http://sanctuaries.noaa.gov/science/socioeconomic/factsheets/flowergardenbanks.html). It is unclear the extent to which other sites are used recreationally in the NGoM.

Rationale for Selection of Variable: Total number of visitors per site over time provides information on the extent to which the reef provides the recreational services.

Measure: Total number of visitors per site, per day, and per year. Data is assessed per reef site or system in one year.

Tier: 2 (rapid assessment through surveys or collection of trip data)

Measurement: At present, National Marine Sanctuaries in the Gulf do not collect systematic information on visitor activities and rely on voluntary reports to assess this activity. The assessment of the annual total number of visitors per day will require a variety of assessment techniques: 1) reef specific on-site field survey, 2) ecotourism agency and diving provider (or shop) trip surveys (e.g., diving shop), and 3) other surveys coordinated with diving and recreational fishing associations and local clubs. An example of the survey methods used to assess reef visitation and use in south Florida reef systems is provided by Johns et al. (2001).

Metric Rating and Assessment Points:

Metric Rating	Number of Reef Visitors	
	FGBNMS	All other sites
Good	>= 1500 persons per year	Stable/Increasing
Poor	< 1500 persons per year	Decreasing

Scaling Rationale: Due to the offshore location of most coral reefs in the northern Gulf of Mexico most sites (reef systems) lack specific data to assess the visitation effort, so "Increasing/Stable vs Decreasing" assessment points will be required until patterns are established through monitoring. Thresholds for the ratings for FGBNMS visitors are from a study conducted by Ditton and Thailing (2003; http://sanctuaries.noaa.gov/science/socioeconomic/factsheets/flowergardenbanks.html). The lower bound of the estimate from the only know study at the FGBNMS was used as a threshold of poor and good reef system visitation division.

Analysis of Existing Monitoring Efforts:

No programs in the monitoring program inventory specifically noted collection of the number of reef visitors.

Indicator: Educational Program Participation

MES: Cultural
KES: Educational Opportunities
Metric: Number of Visitors to a Coral Reef Participating in an Educational Program

Definition: Annual number of visitors of a coral reef (site or system level), demonstration site or management office participating in an educational program related to coral reef values (i.e., biological, economic, social, etc.). An educational program is defined as an environmental content-based program seeking to increase public awareness and knowledge about coral reef values, threats, and conservation that is offered by protected area educators or partner organizations. Educational programs range from interpretative paths or site-specific signage (e.g., plaques) to active educator-lead courses. Note: Offsite educational programs are not included.

Background: In the Gulf, the FGBNMS offers educational programs and materials that highlight the value of coral reefs and the threats that they face regionally (e.g., http://flowergarden.noaa.gov/education/education.html). Multiple other organizations support this effort by contributing content, equipment, facilities and field opportunities to study coral reefs in the Gulf of Mexico (e.g., http://www.reef.org/).

Rationale for Selection of Variable: Environmental education about specific ecosystems can best help individuals understand the complex, conceptual connections between economic prosperity, benefits to society, environmental health, and human well-being. Assessing the number of participants of coral reef educational programs along the Gulf of Mexico is important for understanding the potential impact of the programs in the communities both ecological and behavioral. For example, the number of participants can inform of the number of environmental stewards and changes in perception, should there be a need for follow up on any specific actions (Baugh et al., 2015).

Measure: Total number of visitors that participate in an educational program in one year

Tier: 2 (rapid field measurement)

Measurement: Data is assessed at specific reef system or the entire protected area.

Metric Rating and Assessment Points:

Metric Rating	FGBNMS: Number of Participants in Educational Programs
Good/Excellent	>=2580 (mean)
Fair/Poor	<2580

Metric Rating	All Other Sites: Type of Educational Programs and Infrastructure Available
Excellent	Active regularly-scheduled events (i.e., interactive and/or instructor-lead)
Good/Fair	Passive (e.g., signage)
Poor	No education programs available

Scaling Rationale: The mean of student and adult educational program participant data conducted by the FGBNMS between 2013 and 2016 was used to assess the Good/Excellent threshold. Below that amount it is considered Fair/Poor.

Specific expected densities at given sites beyond FGBNMS are not available to establish assessment points. For other sites, we use the type of educational programs available to assess the capacity of the ecosystem site to provide an educational benefit by the type of programming that is available for potential participants. It is assumed that passive educational infrastructure is the minimum capacity that educational programs need to provide the education service.

Analysis of Existing Monitoring Efforts:

No programs in the monitoring program inventory specifically noted collection of number of participants in educational programs.

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