Chapter 5. Ecological Resilience Indicators for Oyster Reefs

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Ecosystem Description

Oyster reefs and beds are intertidal or subtidal biogenic structures formed by living oysters that provide habitat with significant structural complexity (Galtstoff, 1964; Chestnut, 1974). For this project we include “oyster reefs,” “oyster beds,” and “attached oysters” as defined by CMECS (2012). Eastern oysters, *Crassostrea virginica*, are natural components of estuaries along the Gulf of Mexico and mostly tend toward forming reefs. These reef structures accrete shell material via recruitment and growth, which is in turn degraded at varying rates (Powell et al., 2006; Powell and Klinck, 2007). The balance between degradation and accretion from recruitment and growth of oysters (shell budgets) is critical to developing carbonate-dominated habitats and determines the long-term stability of the reef (see Powell and Klinck, 2007; Powell et al., 2006; Waldbusser et al., 2013). In some intertidal locations, reefs are exposed to the point where accretion is limited and the reef height does not increase over time.

An oyster reef *system* is an area of ecologically connected reefs or beds and oyster shell–dominated bottom, and may include small areas of bare mud, sand, or shelly substrates that may offer benefits to neighboring submerged aquatic vegetation, marsh grass, and mangrove habitats. While reefs are normally an integral part of such diverse landscapes (Puckett and Eggleston, 2012), areas of oyster shell bottom with low densities of live oysters (1–10 m^{-2}) are classified in CMECS as attached oyster faunal beds. Oyster reef and oyster bed systems occur in all states in the Northern Gulf of Mexico (NGoM) (Figure 5.1).

Oysters provide considerable ecosystem services to humans. Benefits include essential habitat and enhanced production of fish and invertebrates of commercial, recreational, and ecological significance; water quality improvement; removal of excess nutrients from coastal ecosystems; and shoreline stabilization and/or facilitation of adjacent habitats such as seagrass beds and salt marshes. Increasingly, these ecosystem services are cited as the principal or secondary goal(s) of oyster habitat restoration projects.

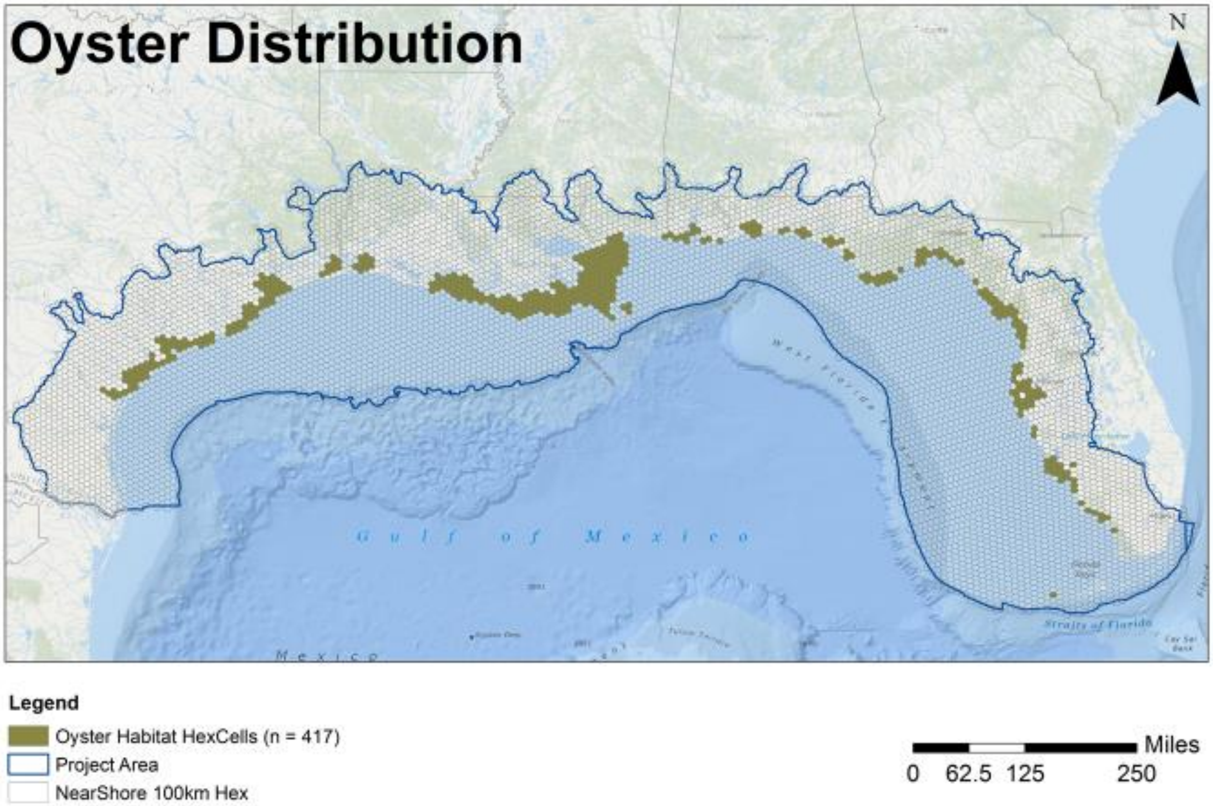


Figure 5.25. *Distribution of oyster ecosystem within the Northern Gulf of Mexico*

Although commercial landings of wild oysters in the Gulf of Mexico are the highest in the world (Beck et al., 2011), the region has suffered serious declines in overall oyster biomass (zu Ermgassen et al., 2012) and abundance (Beck et al., 2011). Degradation has been primarily driven by anthropogenic factors such as destructive and excessive harvest, changes to hydrology and salinity regimens, pollution, and introduced disease. While oyster restoration efforts have historically focused on improving harvests, in recent decades there has been an increasing recognition and better quantitative description of a broader array of ecological functions and services provided by oysters.

As the pace of oyster restoration increases across the Gulf of Mexico, restoration managers need to systematically monitor indicators of condition across the Gulf's oyster reef systems to understand how oyster health and condition are changing over time and allow for adaptive management and evaluation of restoration investments. To understand the ecological and human processes that affect the NGoM oyster ecosystem, we developed a conceptual ecological model. We present the model as a diagram (Figure 5.2) that accompanies the following description of oyster ecosystem attributes or factors and their interactions. This diagrammatic representation of the ecosystem was designed to guide the selection of indicators of the ecosystem condition and associated ecosystem services. In the following narrative, we describe the most direct or strongest linkages between the ecosystem components, including those between ecosystem processes and the largely external environmental drivers, such as climatic, hydrogeomorphic, and anthropogenic drivers. From a monitoring perspective, these linkages are particularly important, because they illustrate how indicators that track one factor within the ecosystem can directly and indirectly serve as indicators of the overall ecosystem condition. Oyster reef restoration monitoring has been thoroughly addressed in the *Oyster Habitat Restoration Monitoring and Assessment Handbook* (Baggett et al., 2014) developed by a group of oyster experts (some of whom were also a part of this project team). Many of the selected indicators have been previously addressed in the restoration handbook. In such cases, we adopted the indicators, metrics, and measurement approaches verbatim, where possible.

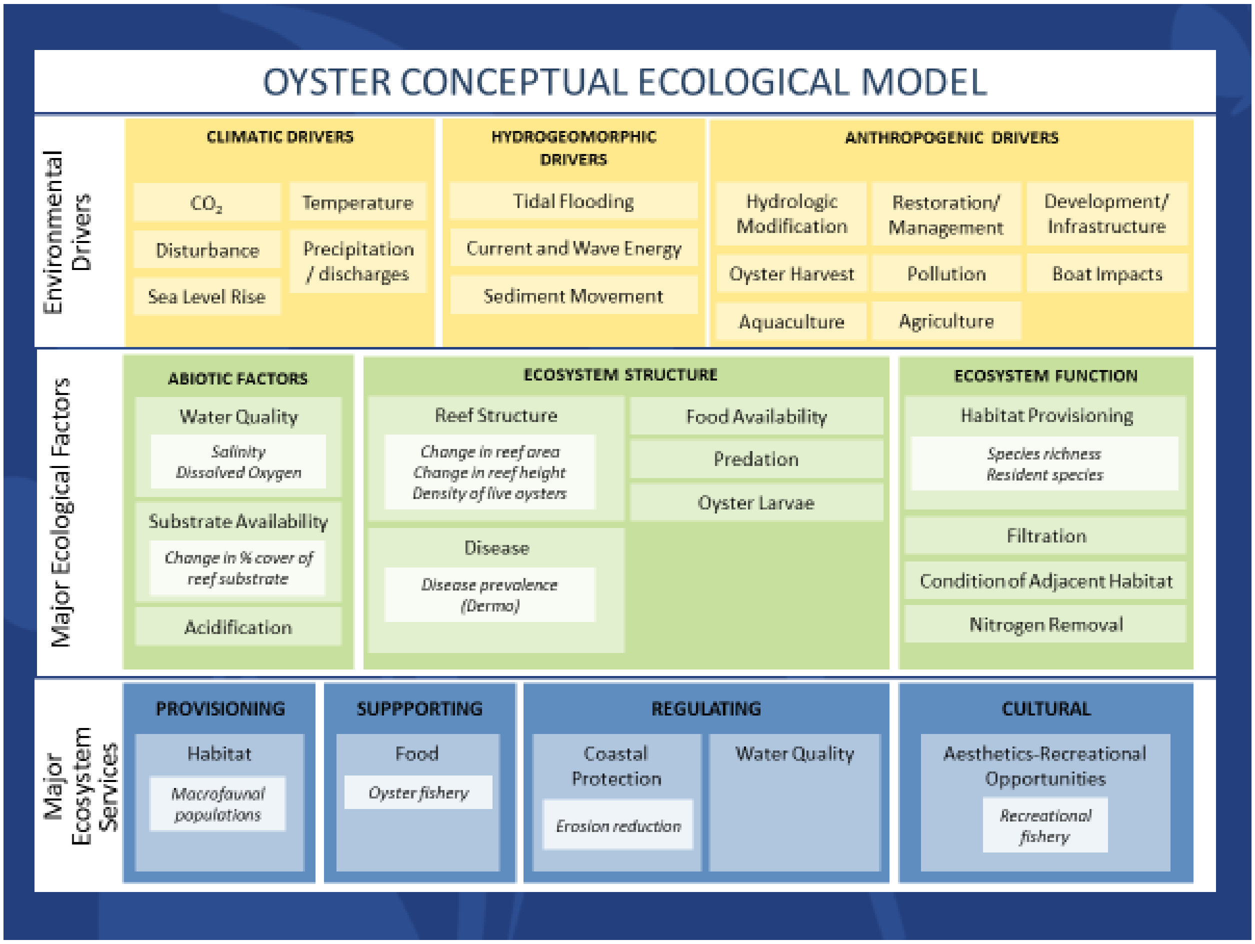


Figure 5.26. *Oyster Conceptual Ecological Model*

Factors Involved in Ecological Integrity

Abiotic Factors

Water Quality

Adult oysters normally occur at salinities between 10 and 30‰, but they tolerate salinities of ~2 to 40‰ (Gunter and Geyer, 1955). Occasional, short pulses of freshwater inflow can greatly benefit oyster populations by reducing predation and disease; however, extended durations of high or low salinities can affect the growth and survival of oysters and the persistence of the reef structure itself. Sustained periods of low salinity (increased freshwater inflow) can reduce spat survival and cause sedimentation, while extended periods of high salinity (drought) can result in increased predation and prevalence and intensity of diseases such as *P. marinus* infections (Chu and Volety, 1997; Soniat, 1996; La Peyre et al., 2003; Volety et al., 2009; La Peyre et al., 2009; La Peyre et al., 2013).

Dissolved oxygen (DO) can be an indication of disruption of the equilibrium in the estuary and how well the estuary can support benthic aquatic plant and animal life. Higher levels of DO generally are considered better water quality. Low DO can have lethal and sublethal effects on oysters, including reduced growth, reduced feeding, and increased susceptibility to disease. Low DO can be driven by anthropogenic factors such as nutrient input. Large nutrient inputs, such as those containing sewage and/or fertilizer, can stimulate algal blooms. When the algae comprising the bloom die, they decompose and diminish oxygen levels.

Substrate Availability

Young oysters, known as spat, need a hard surface or a living oyster reef on which to settle and grow. Oyster shells themselves (both living and dead) provide a suitable hard substrate for the attachment and growth of oyster larvae over time. Historically, spat settled on the shells of oysters in precisely this way, but sedimentation and removal of oyster shells across the Gulf has resulted in a shortage of hard substrate for spat to settle.

Acidification

The oceans have absorbed approximately 30% of anthropogenic CO_2, altering oceanic carbonate chemistry and lowering pH. This lower pH, or ocean acidification, can negatively impact oysters and other shell building organisms. Ocean acidification can cause reduced growth rates in adult oysters and developmental abnormalities and mortality in larval oysters. In addition, some bays and estuaries along the Gulf Coast will experience acidification earlier than global projections indicate because of local drivers such as coastal eutrophication, upwelling, and discharge of low-ΩAr river water (Ekstrom et al., 2015).

Ecosystem Structure

Disease

Oyster diseases are widespread throughout the Gulf of Mexico. It is important to measure disease prevalence and intensity to better understand mortality patterns and inform adaptive management decisions. Dermo disease, which is caused by the endoparasitic protozoan *Perkinsus marinus*, is prevalent in the region and can cause massive mortality in oyster populations (Mackin, 1961; Mackin, 1962). Dermo outbreaks are often associated with higher temperatures and salinities (Soniat, 1996).

Food Availability

Chlorophyll *a* concentration is an indicator of phytoplankton abundance and biomass in coastal and estuarine waters. Chlorophyll *a* has been used as a proxy for food availability in models of bivalve growth (Hofmann et al., 2006) and carrying capacity (Smaal et al., 2001) and has been shown to limit growth when concentrations are too high or too low. Although chlorophyll *a* is measured for many oyster restoration projects in the Gulf, our expert group has not found chlorophyll *a* measurements to be very informative for predicting reef performance. Most of the time that chlorophyll *a* is measured on restored reefs and reference sites, it is being used as a filtration indicator rather than an indicator of food availability.

Reef Structure

Reef structure can be characterized using established metrics that measure reef area, relative height (relief), and density. Each of the structural characteristics can influence oyster attachment, establishment, and growth. Measurements of reef area, height, and density are critical to assessing reef persistence through time, oyster population abundance, and ultimately the quantity of the ecosystem services provided by the restored oyster reef (Coen and Luckenbach, 2000; Grabowski and Peterson, 2007; Grabowski et al., 2012). However, harvest and non-harvest oyster reefs may have different characteristics, and the timing of sampling should be considered relative to harvest seasons.

Oyster Larvae

Some bays and estuaries have seen such dramatic declines in naturally occurring oysters reef (from overharvest, water quality issues, and/or dredging) that the existing population of oysters does not produce enough larvae to sustain further reef production. In some cases, the existing reefs are too small and/or too far apart to allow the larvae to reach adjacent reefs or other suitable substrate. These systems are described as “larval limited.” Oyster restoration in these systems requires significant investment in hatcheries and remote setting techniques.

Predation

Predation can have dramatic effects on the structure of oyster reefs. Predators influence the size structures of oyster populations and affect overall abundance and distribution patterns (Gosling, 2003). Oysters are vulnerable to different predators at different phases of their life cycle. Predation is strongest during the larval stage, in which an estimated 99% of oyster larvae are consumed before settlement (Kennedy, 1991). Oyster spat (larvae that have settled successfully on substrate) are targeted by carnivorous worms and small crabs, while larger invertebrates such as blue crabs, whelks, oyster drills, rays, and several sciaenid fish prey on some spat and adult oysters. Predation causes significant natural mortality; however, the type and intensity of predation can vary with environmental impacts such as salinity.

Ecosystem Function

Habitat Provisioning

Habitat-forming species are widely recognized to support high levels of biodiversity, which is also an indicator of ecosystem function in both nature and commodity producing landscapes (Fischer et al., 2006). Numerous coastal species, such as blue crab (*Callinectes sapidus*) and red drum (*Sciaenops ocellatus*), among others, utilize intertidal and subtidal oyster habitats for shelter and feeding or reproduction grounds (Coen et al., 1999; Breitburg, 1999; Peterson et al., 2003; Humphries et al., 2011; McCoy et al., 2017). Species that are not commercially or recreationally important are still ecologically important in that they may feed on zooplankton or serve as prey for larger fish (Breitburg, 1999; Harding and Mann, 2000; Harding, 2001), thus functioning as important links in the food chain. Oyster reefs also directly and indirectly provide food resources for numerous waterbirds (e.g., herons, oystercatchers, gulls, and terns), and aggregations of dead oysters can provide nesting and roosting sites. Both species richness (the total number of species) and biomass (the mass of the species residing in the reef) indicate the capacity of the oyster reef to provide habitat for species.

Filtration

Oysters can play an important role in regulating local water clarity through their filtration activities. They can decrease turbidity, and thus improve water clarity, by removing seston—minute living (e.g., plankton) and non-living (e.g., sediment) particles—from the water column (see discussion in Grabowski and Peterson, 2007; Kellogg et al., 2013; zu Ermgassen et al., 2012b, 2013). The decreased turbidity, along with the transfer of particulate material including nutrients from the water column to the sediment (benthic-pelagic coupling) provided by bivalve filtration, can have beneficial effects on nearby benthic habitats such as seagrass beds (Peterson and Heck, 2001; Newell and Koch, 2004; Wall et al., 2008; Booth and Heck, 2009). Bivalves also aid in removing heavy metals, toxins, and fecal coliform from the water column through their filtration activities, and, as such, have been utilized in the bioremediation of effects of industrial or other anthropogenic pollution (e.g., Gifford et al., 2005), (Oyster Habitat Restoration Monitoring and Assessment Handbook, 2014).

Nitrogen Removal

Oysters play an important role in coastal biogeochemical cycles by regulating carbon, nitrogen, and phosphorous fluxes through the sequestration of C, N, and P in their shells and tissues, and by contributing to denitrification processes. While some of the nitrogen that oysters filter from organic matter in the water column is retained in their tissues, other nitrogen is delivered to the sediments in the form of bio-deposits (feces and pseudo-feces). The nitrogen present in these bio-deposits may then be converted into nitrogen gas through nitrification and denitrification. This nitrogen gas diffuses from the sediment into the water column and then into the atmosphere (see Sisson et al., 2011 and references therein for more detailed information). The methodologies for measuring the denitrification and nutrient fluxes associated with oyster reefs are developing, with likely advances in the near future. As a result, no standard technique for the measurement of denitrification is provided. This does not detract from the importance of denitrification by oyster habitats and the utility of measuring this ecosystem service (Oyster Habitat Restoration Monitoring and Assessment Handbook, 2014).

Condition of Adjacent Habitat

Intertidal and subtidal oyster reefs can help protect adjacent vegetated habitats from natural and anthropogenic-derived waves, currents, and tides (e.g., Piazza et al., 2005; Scyphers et al., 2011). This lessening of wave action may also allow sediments to accumulate inshore (landward) of the reef, stabilizing the shoreline. This shoreline stabilization and sediment accumulation can benefit nearby marsh habitat by both protecting the marsh from erosion and even possibly allowing the marsh to expand due to the accretion of sediments. Oyster habitats may also aid in the creation or protection of submerged aquatic vegetation (SAV) habitat through sediment stabilization and improvements in water quality that often occur as a result of water filtration by the oysters (Oyster Habitat Restoration Monitoring and Assessment Handbook, 2014).

Factors Involved in Ecosystem Service Provision

Supporting

Habitat

Oyster reef habitat is utilized by many vertebrate and invertebrate species of commercially and recreationally importance for shelter (i.e., refugia), feeding, and reproduction (Coen and Luckenbach, 2000). In 1961, Wells collected more than 300 species that use oyster reefs. This work included a list of species that use oyster reefs primarily as habitat, versus those that depend on the reef for food (transient species). In the Gulf of Mexico, important ecological and commercial species use intertidal and subtidal oyster reefs as resident or transient habitats—e.g., naked goby (*Gobiosoma bosc*), blue crab (*Callinectes sapidus*), red drum (*Sciaenops ocellatus*), striped bass (*Morone saxatilis*), and multiple bird species (Coen et al., 1999). Small fish and invertebrates that are residents of oyster reefs are ecologically important because they serve as food for large fish (Breitburg, 1999; Coen and Luckenbach, 2000). Although oyster reefs are considered a renewable resource, the destruction of oyster reef habitat impacts the habitat of numerous other marine species (VanderKooy, 2012).

Provisioning

Food

Although oyster reefs provide a multitude of services to people and nature, the production of oysters for food constitutes the primary benefit perceived by people (Grabowski and Peterson, 2007; Yoskowitz et al., 2010). From 2012 through 2016, more than 91 million pounds of oysters worth more than $435,000,000 in revenue were harvested in Gulf states (NOAA National Marine Fisheries Commercial Landing Statistics, https://www.st.nmfs.noaa.gov/pls/webpls/MF_ANNUAL_LANDINGS.RESULTS). They are also part of the rich cultural heritage of coastal communities along the Gulf of Mexico, whose economies and populations grew in part because of the bountiful oyster reefs in this region (Coen et al., 2007). Overharvesting has reduced the number of oysters in the population and, in turn, reduced the amount of substrate available on which new larvae can settle, thus perpetuating the decline of the population.

Oysters also provide habitat for commercial fisheries species (Grabowski et al., 2007). The loss of oyster reefs means more than just the loss of an important commodity. It can also cause decline in habitat for sustaining other commercially important species and species important to ecosystem stability (Beck et al., 2011).

Regulating

Coastal Protection

Oyster reefs benefit humans by stabilizing shorelines and preventing erosion, and by acting as a buffer against hurricanes and tropical storms. Intertidal and shallow subtidal oyster reefs serve as breakwaters that protect coastlines against the impacts of waves. They also promote shoreline accretion during non-storm periods, which, in turn, protects the coast by absorbing the impact of storms.

Water Quality

As described above, oysters improve water quality by filtering plankton and particles from the water for food. At the same time, they also remove nutrients, chemicals, and other pollutants from the water (Grabowski et al., 2012). Mineral accretion is important to long-term oyster sustainability and is dependent on flood regime and the availability of mineral sediments in the water column (Childers and Day, 1990).

Cultural

Aesthetics-Recreational Opportunities

Recreational fishing is a favorite pastime in the U.S. (NAS, 2016). Oyster reefs are fish-attracting structures that create habitat for large fish. The cavities created by their complex reef structure provide the environment needed for fish and invertebrates to seek shelter, reproduce, and feed.

Indicators, Metrics, and Assessment Points

Using the conceptual model described above, we identified a set of indicators and metrics that we recommend for monitoring oyster ecosystems across the NGoM. Table 5.1 provides a summary of the indicators and metrics proposed for assessing ecological integrity and ecosystem services of oyster 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 indicator evaluation criteria. In some instances, the name of the indicator and the name of the metric are the same, which simply reflects that the indicator is best known by the name of the metric used to assess it. Below we provide a detailed description of each recommended indicator and metric(s), including 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 oyster ecosystems. Figure 5.3 provides an overview of the overall density of indicators monitored. Each indicator description also includes a more detailed spatial analysis of the geographic distribution and extent to which the metrics are currently (or recently) monitored in the NGoM, as well as an analysis of the percentage of active (or recently active) monitoring programs that are collecting information on the metric. The spatial analyses are also available in interactive form via the Coastal Resilience Tool (http://maps.coastalresilience.org/gulfmex/), where the source data are also available for download.

Table 5.17. *Summary of Oyster Metrics Based on the Conceptual Ecological Model*

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

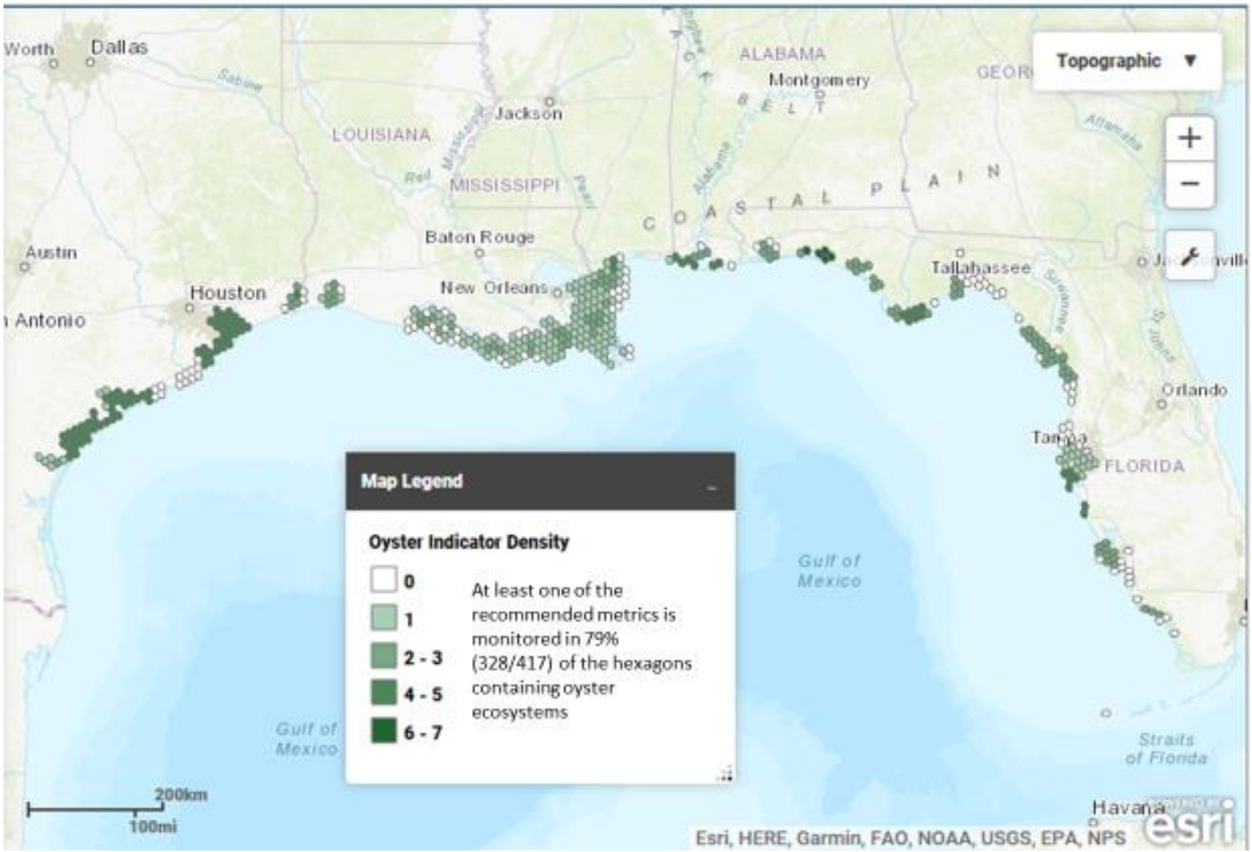


Figure 5.27. *Density of the recommended indicators being collected in oyster ecosystems in the NGoM. Shaded hexagons indicate the number of the recommended indicators that are collected by monitoring programs in each hexagon.*

Ecological Integrity Indicators

Indicator: Salinity

MEF: Abiotic Factors
KEA: Water Quality
Metric: Salinity (Summer Mean)

Definition: Salinity is the concentration of dissolved salts of a body of water.

Background: Although *C. virginica* occurs in a range of salinity from 0 to 40 practical salinity units (psu), little to no growth occurs when salinities drop below 5 ppt (Watson et al., 2015).

Rationale for Selection of Variable: This metric was chosen because salinity influences *C. virginica's* growth and mortality, and, to a lesser degree, reproduction (Shumway, 1996). In the Gulf of Mexico, several studies have documented limited or no recruitment when salinity is below 10 (Cake, 1983; Chatry et al., 1983; Pollack et al., 2011), which can affect oyster size and availability of hard substrate. Also, more so than temperature, higher salinities can be associated with greater instances of disease and predation in *C. virginica* (Ewart and Ford, 1993; Shumway, 1996).

Measure: Salinity in ppt (parts per thousand) or psu (note: salinity measurements from an instrument that utilizes a conductivity ratio, such as a CTD, are unitless)

Tier: 1 (monitoring stations) or 2 (rapid field measurement)

Measurement: If no suitable monitoring station is nearby, salinity measurements should be taken near the substrate as close to the reef as possible and should be reported in ppt or psu, with a 1 ppt or 1 psu resolution. Measurements may be taken using a permanently deployed in situ instrument with a datalogger, a refractometer, or with other instrumentation. Samples should be taken between May and August to calculate summer means.

Metric Rating and Assessment Points:

Metric Rating	Salinity (ppt or psu)
Excellent	Between 12 and 20
Good	Between 5 and 25
Fair	Periods between 3–7 days outside 5–25 range
Poor	Periods exceeding 8 days outside 5–25 range

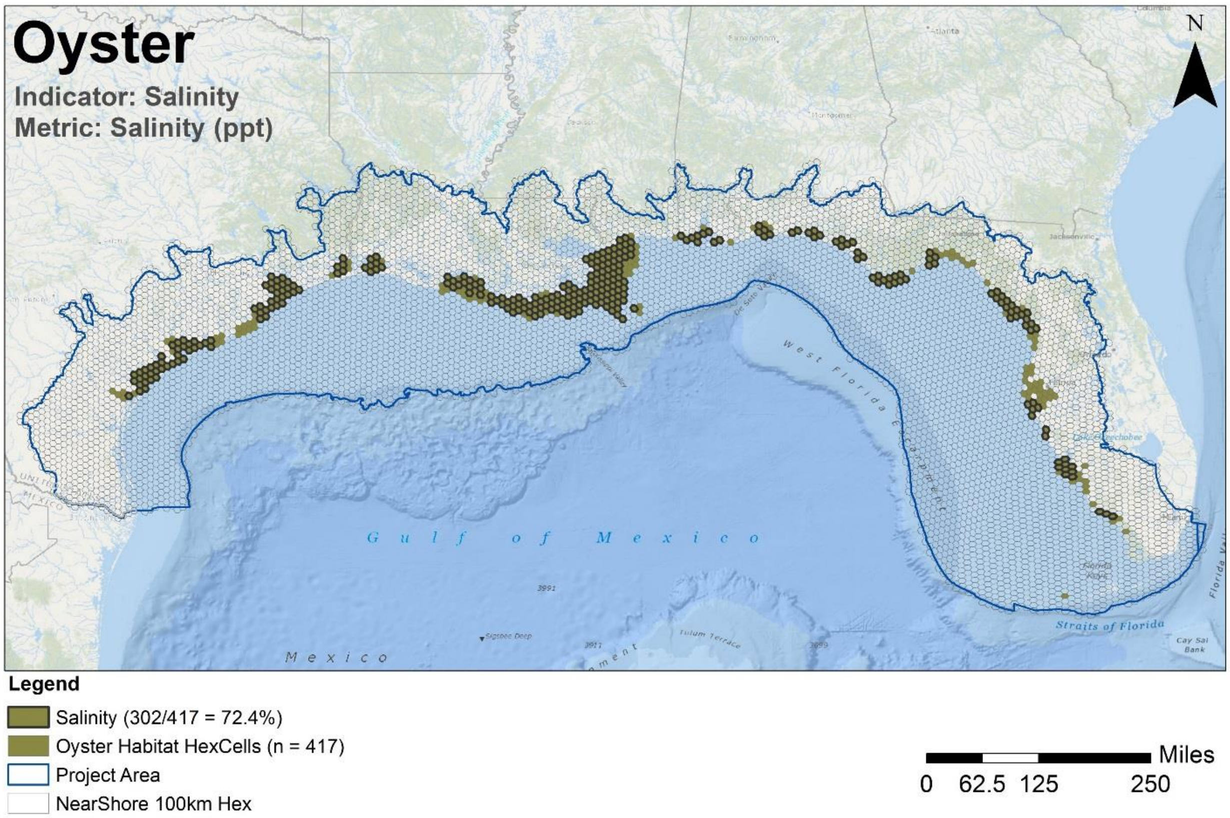
Scaling Rationale: Brief exceedances of the optimal salinity range can be tolerated by oysters (reviewed in Shumway, 1996). However, the longer these periods last, the more likely they are to negatively affect oyster health and condition (LaPeyre et al., 2013).

Analysis of Existing Monitoring Efforts:

<u>Geographic</u>*:* Salinity is very well collected geographically in the NGoM, with 72% of habitat hexagons containing at least one monitoring site. Monitoring locations for this metric are very well distributed across the NGoM, with multiple monitoring sites in each state.

<u>Programmatic:</u> Data for this metric are collected by 16/27 (58%) of the programs collecting relevant oyster data in the NGoM.

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



Metric	Total Relevant Oyster 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
Salinity	27	16	59%	72%

Indicator: Dissolved Oxygen

MEF: Abiotic Factors
KEA: Water Quality
Metric: Dissolved Oxygen (DO)

Definition: DO is the amount of oxygen dissolved in a body of water.

Background: DO can be an indication of how polluted the water is and how well the water can support aquatic plant and animal life. Higher levels of DO generally indicate better water quality. Low DO can have lethal and sublethal effects on oysters, including reduced growth, reduced feeding, and increased susceptibility to disease.

Rational for Selection of Variable: This metric was chosen because hypoxia has been shown to have detrimental effects on the settlement, growth, and survival of oysters (e.g., Baker and Mann, 1992; Johnson et al., 2009). For bivalves, a low oxygen event can be classified according to severity: moderate hypoxia (4 mg L^{-1} to 2 mg L^{-1}), severe hypoxia (< 2 mg L^{-1} to 0.5 mg L^{-1}) and anoxia (< 0.5 mg L^{-1}) (Renaud, 1986; Diaz and Rosenberg, 1995; Turner et al., 2005). It is assumed that low DO is less likely to be a problem for intertidal oyster reefs.

Measure: Dissolved oxygen in mg L^{-1}

Tier: 1 (monitoring station) or 2 (rapid field measurement)

Measurement: If no suitable monitoring station is nearby, dissolved oxygen measurements should be taken near the substrate as close to the reef as possible and should be reported in mg L^{-1}. Time of day and tidal stage during which the measurements were taken should be noted. Measurements may be taken using a permanently deployed in situ instrument with a datalogger, or with instrumentation such as a DO meter.

Metric Rating and Assessment Points:

Metric Rating	Dissolved Oxygen (Subtidal Reefs Only)
Good	> 4 mg L^{-1}
Fair	1–7 consecutive days < 4 mg L^{-1}
Poor	> 7 consecutive days < 4 mg L^{-1}

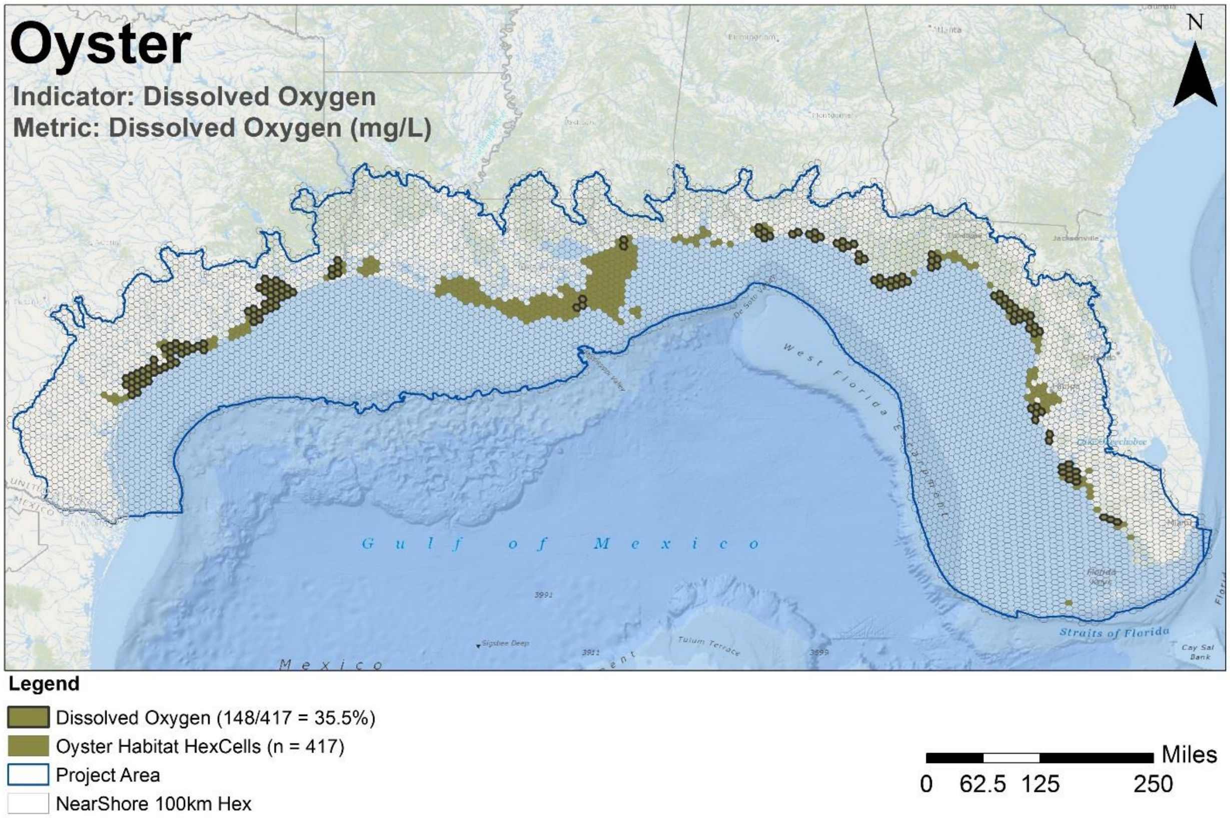
Scaling Rationale: Extended periods of hypoxia have been shown to reduce both survival and growth, although further research is needed to examine the cumulative effects of repeated exposure to moderate hypoxia (Johnson et al., 2009). Therefore, we took a conservative approach in determining these assessment points.

Analysis of Existing Monitoring Efforts:

Geographic*:* Dissolved oxygen is well collected geographically in the NGoM, with 36% of habitat hexagons containing at least one monitoring site. Monitoring locations for this metric are mostly in Florida and Texas.

Programmatic: Data for this metric are collected by 6/27 (22%) of the programs collecting relevant oyster data in the NGoM.

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



Metric	Total Relevant Oyster 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
Dissolved Oxygen	27	6	22	36%

Indicator: Change in Percent Cover of Reef Substrate

MEF: Abiotic Factors
KEA: Substrate Availability
Metric: Percent Cover of Reef Substrate

Definition: The percentage of the reef footprint covered in hard substrate suitable for oyster settlement.

Background: Measurement of the percent cover of reef substrate (both living and non-living) provides a quick estimate of the habitat available for oyster settlement. This measurement also provides information concerning smaller-scale patchiness of reef substrate within the larger project footprint/reef area.

Rational for Selection of Variable: Reef substrate is a key indicator of reef vulnerability, as hard substrate availability is critical for oyster settlement.

Measure: Percent cover

Tier: 2 (rapid field measurement)

Measurement: Record a visual estimation of the percent coverage of reef substrate (including living oysters and non-living hard substrate) within the same quadrats used for measures of oyster density. Percent coverage estimate must be made before oysters are excavated for the oyster density samples. To aid in determination of percent coverage, a quadrat with a delineated (usually with string) grid pattern can be used in areas of sufficient water clarity. Count the number of squares in the grid in which shell is present, and from that determine the percentage of the substrate within the grid covered by shell.

Metric Rating and Assessment Points:

Metric Rating	Percent Cover of Reef Substrate
Good	Increasing/stable
Poor	Decreasing

Scaling Rationale: Assessment points were established based on the trend in hard substrate availability. Decreases in hard substrate can lead to reduced settlement and deteriorating reef condition (Baggett et al., 2014).

Analysis of Existing Monitoring Efforts:

No programs in the monitoring program inventory specifically noted collection of change in percent cover of reef substrate.

Indicator: Disease Prevalence (Dermo)

MEF: Ecosystem Structure
KEA: Disease
Metric: Weighted Prevalence

Definition: Disease prevalence, or percent infection (PI), is the number of diseased oysters per sample divided by the total number of oysters in the sample. The weighted prevalence is the mean infection intensity of the oysters in the sample.

Background: Monitoring for the presence of oyster disease may not be necessary if disease prevalence and/or intensity are not thought to be high in or near the reef area. If the reef site is in a state that has a disease monitoring program and has monitoring sites near the reef, consultation with the staff of their state's disease monitoring program can inform on the need for reef site disease monitoring. If disease is suspected or known to be present at or near the reef site(s), and state disease monitoring data are not available, then monitoring the presence and intensity of disease should be considered.

Rational for Selection of Variable: Oyster disease is cited as one of the major causes of oyster population decline, particularly along the Gulf coast of the United States. Dermo, caused by the protozoan *Perkinsus marinus*, can cause high levels of mortality among infected oyster populations. *Perkinsus marinus* is prevalent throughout the Gulf of Mexico.

Measure: Disease prevalence (%), weighted prevalence (unitless)

Tier: 3 (rapid field sampling that requires further laboratory analysis)

Measurement: Randomly collect a minimum of 25 adult oysters from across the reef for analysis of Dermo prevalence and intensity (see Marques and Cabral [2007] for information regarding sample size determination for disease sampling). Oysters should be transported to a local testing lab (check with local universities or extension offices) as per the lab's instructions. Alternatively, if practitioners have the ability, they may determine disease prevalence using Ray's fluid thioglycolate method (Ray, 1952; Bushek et al., 1994; Bobo et al., 1997). Where a small piece of tissue is removed and assayed for disease after incubation in fluid thioglycollate and antibiotics for one week, *P. marinus* intensity is scored using a 0 to 5 scale developed by Mackin (1962), where 0 is no infection and 5 is an infection in which the oyster tissue is almost entirely obscured by the parasite. Calculations are made of percent infection (PI) and weighted prevalence (WP), which is the sum of the disease intensity numbers divided by the total number of oysters in the sample.

Metric Rating and Assessment Points:

Metric Rating	Weighted Prevalence
Excellent	< 1
Good	1–2
Poor	> 2

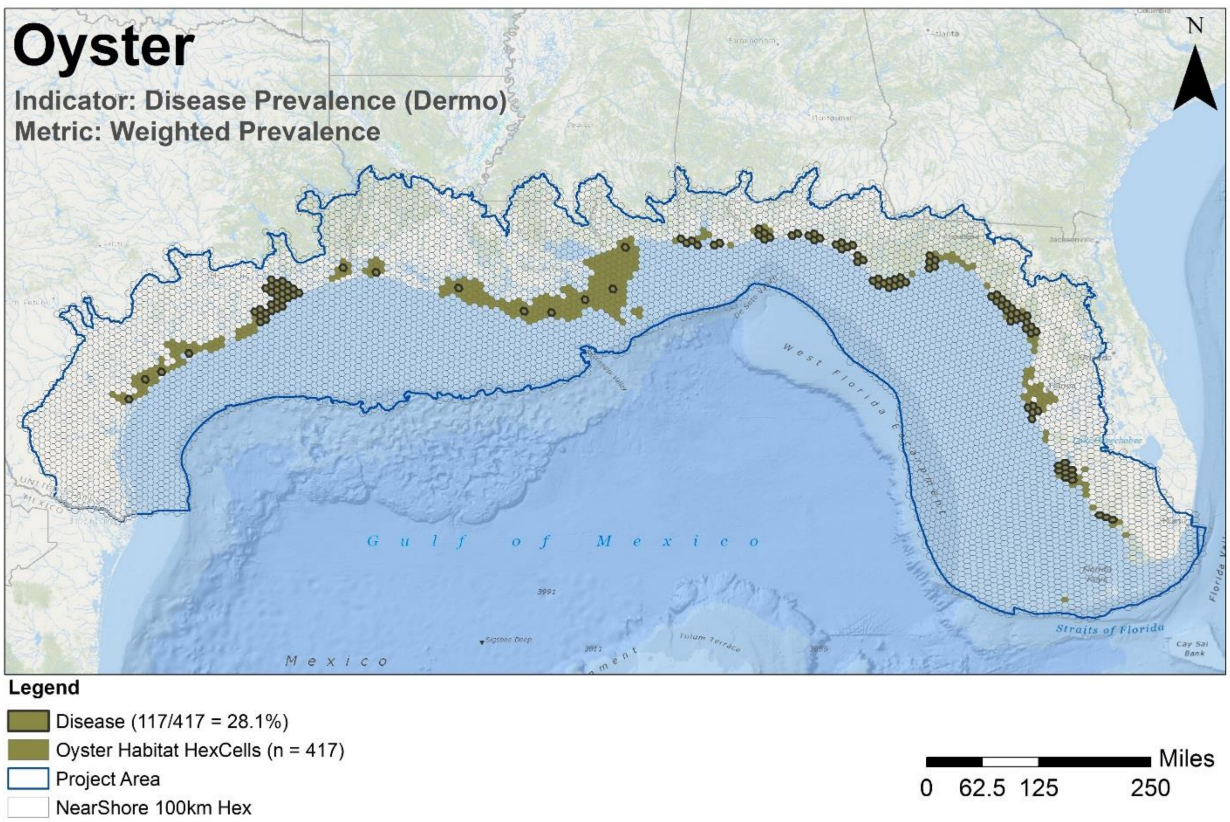
Scaling Rationale: Dermo infection intensity should be ranked according to Mackin's scale (Ray et al., 1953): 5 = Heavy Infection, 4 = Moderate to Heavy Infection, 3 = Moderate Infection, 2 = Light to Moderate Infection, 1 = Light Infection, 0.5 = Very Light Infection. The weighted prevalence is the mean infection intensity of the oysters in the sample. A WP of 1.5 could be considered a level at which disease-related mortalities are occurring. For example, Mackin (1962) claims a population of live oyster with a weighted prevalence of 2.0 "contains an intense epidemic, and more than half of the population may be in advanced stages of the disease, with all of the individuals infected."

Analysis of Existing Monitoring Efforts:

Geographic*:* Disease prevalence of Dermo is moderately well collected geographically in the NGoM, with 28% of habitat hexagons containing at least one monitoring site. Monitoring locations for this metric are somewhat well distributed across the NGoM, but are less collected in Louisiana and Mississippi.

Programmatic: Data for this metric are collected by 7/27 (26%) of the programs collecting relevant oyster data in the NGoM.

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



Metric	Total Relevant Oyster 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
Weighted Prevalence	27	7	26%	28%

Indicator: Change in Reef Area

MEF: Ecosystem Structure
KEA: Reef Structure
Metric: Area

Definition: Reef area is the summed area of patches of living and non-living oyster shell within the reef footprint.

Background: In some cases, the project footprint and the reef area may be the same. However, when the reef is comprised of reef patches, the reef footprint area and actual reef area may be quite different. Reef footprint is the maximum areal extent of the reef. Reef area is the actual area (summed) of patches of living and non-living oyster shell within reef footprint.

Rational for Selection of Variable: This metric was chosen because stable or increasing reef area indicates that conditions are sustaining or increasing the oyster population.

Measure: Reef area in meters^2

Tier: 2 (rapid field measurement)

Measurement: Measure area of each patch reef using GPS, surveyor's measuring wheel or transect tape, or aerial imagery; for subtidal areas, use sonar or depth finder with ground truthing, or SCUBA. Sum all patches to get total reef area.

Metric Rating and Assessment Points:

Metric Rating	Area
Good	Increasing/stable
Poor	Decreasing

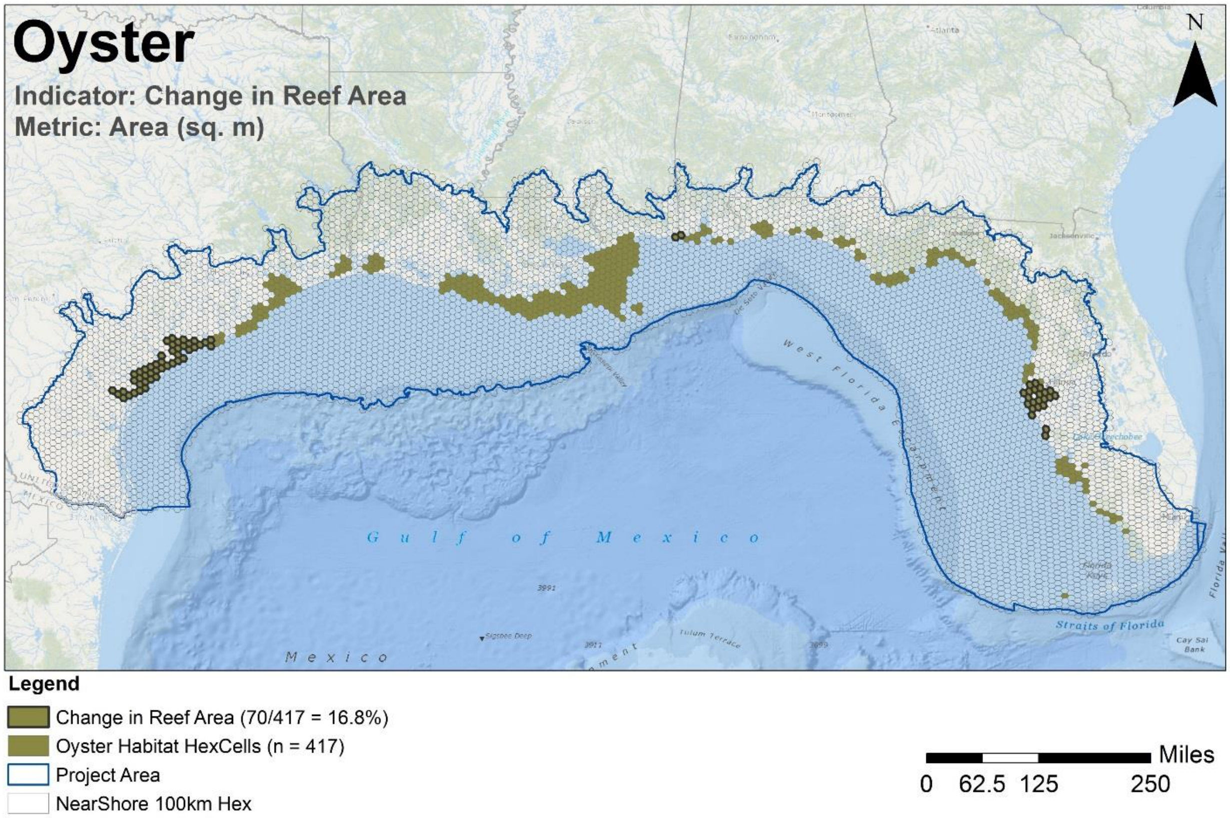
Scaling Rationale: The assessment points were chosen because a stable or increasing reef area indicates that conditions are sustaining or increasing the oyster population. Decreasing reef area indicates poor conditions and/or oyster condition (Baggett et al., 2014).

Analysis of Existing Monitoring Efforts:

<u>Geographic</u>*:* Reef area is less well collected geographically in the NGoM, with 17% of habitat hexagons containing at least one monitoring site. Monitoring locations for this metric are primarily clustered in Florida and Texas.

<u>Programmatic:</u> Data for this metric are collected by 4/27 (15%) of the programs collecting relevant oyster data in the NGoM.

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



Metric	Total Relevant Oyster 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
Area	27	4	15%	17%

Indicator: Change in Reef Height

MEF: Ecosystem Structure
KEA: Reef Structure
Metric: Height (Relative to Bottom)

Definition: Reef height is a measure of the mean height of the reef above the surrounding substrate (in relation to the substrate immediately adjacent to the reef, not the shoreline).

Background: Along with reef footprint and reef area, measurement of reef height provides valuable information regarding changes in the reef over time, such as the persistence of a reef after storms, as well as the habitat provided for resident and transient finfish and invertebrate species. In addition to reporting the mean reef height, reporting the minimum and maximum reef heights is recommended.

Rational for Selection of Variable: This metric was chosen because stable or increasing reef height indicates that conditions are sustaining or increasing the oyster population.

Measure: Reef height in centimeters

Tier: 2 (rapid field measurement)

Measurement: Measure using ruler, graduated rod and transit, or survey equipment; for subtidal areas, use sonar or depth finder.

Metric Rating and Assessment Points:

Metric Rating	Height (cm)
Good	Stable or increasing height
Poor	Decreasing height

Scaling Rationale: The assessment points were chosen because a stable or increasing reef height indicates that conditions are sustaining or increasing the oyster population. Decreasing reef area indicates poor conditions and/or oyster condition. Practitioners need to consider the degree of oyster seeding and harvest (if any) when assessing this metric (Baggett et al., 2014).

Analysis of Existing Monitoring Efforts:

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

Indicator: Density of Live Oysters

MEF: Ecosystem Structure
KEA: Reef Structure
Metric: Density of Live Oysters Relative to the Regional Mean (Including Recruits)

Definition: Live oyster density is the number of live oysters, including recruits, in m^{-2}. Relative oyster density is the density at the assessment site divided by the regional mean.

Background: The mean density of live oysters provides information concerning oyster population size, survivorship, and recruitment of oysters on reefs. Comparison to a regional mean controls for regional variation in expected oyster densities.

Rational for Selection of Variable: This metric was chosen because mean density of live oysters provides information on the health, condition, and trajectory of the reef.

Measure: (individuals m^{-2}/regional mean density) X 100%

Tier: 2 (rapid field measurement)

Measurement: Utilize quadrats. Collect substrate to depth necessary to obtain all live oysters within quadrat, and enumerate number of live oysters, including recruits. Ensure time of year consistent and accounted for as midsummer densities may be strongly influenced by a single settlement event.

Metric Rating and Assessment Points:

Metric Rating	Density of Live Oysters Relative to the Regional Mean
Good	> 80%
Fair	20–80%
Poor	< 20%

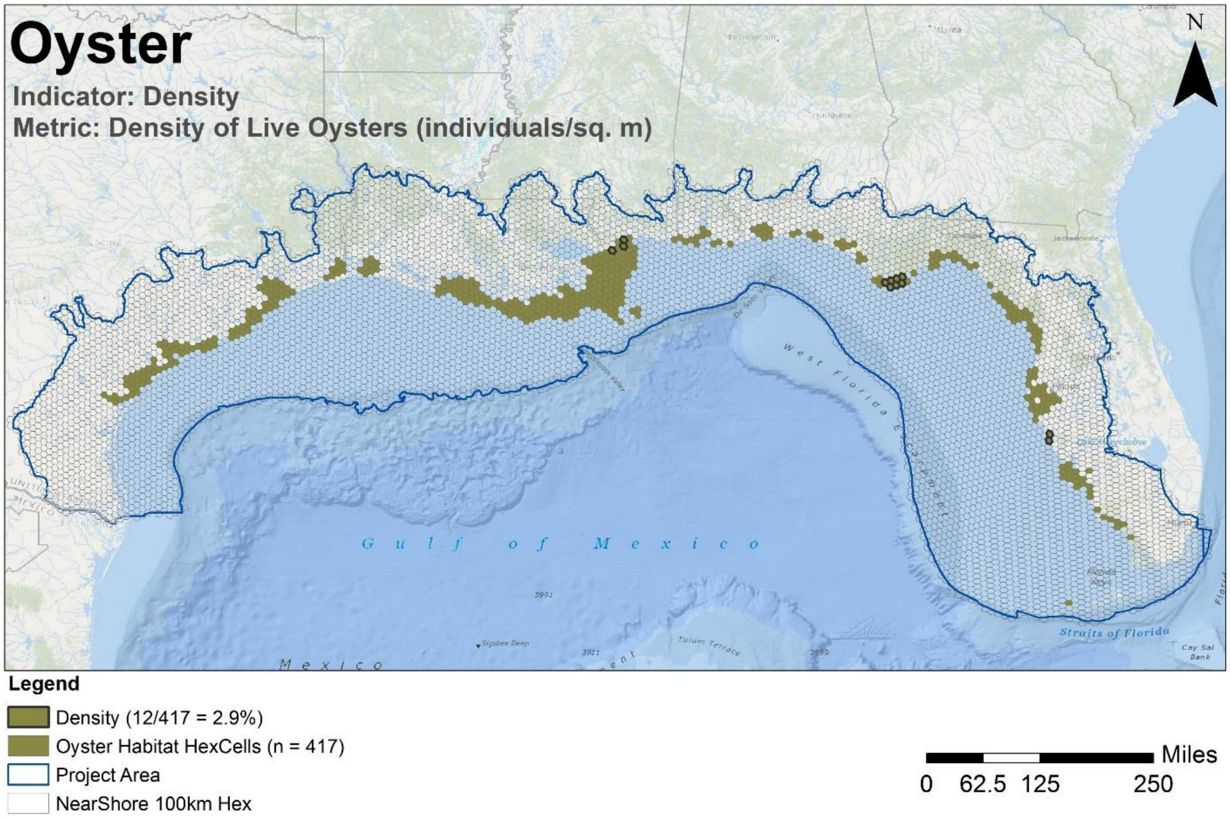
Scaling Rationale: Relative density assessment points were developed by the expert team during the workshop. If possible, refer to available density data for natural and/or restored reefs in nearby locations with similar environmental conditions as well as historical data (Baggett et al., 2014). Historical densities may be different than those we could expect to see today, and target densities will vary by project type and location. It is therefore necessary to consider the full range of data available. There are numerous data sources available regionally through state fisheries management agencies, and nationally from zu Ermgassen et al. (2012). Practitioners need to consider the degree of oyster seeding and harvest (if any) when assessing this metric.

Analysis of Existing Monitoring Efforts:

Geographic*:* Density of live oysters is not well collected geographically in the NGoM, with only 3% of habitat hexagons containing at least one monitoring site. The few monitoring locations for this metric occur in Mississippi and Florida.

Programmatic: Data for this metric are collected by 6/27 (22%) of the programs collecting relevant oyster data in the NGoM.

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



Metric	Total Relevant Oyster 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
Density of Live Oysters	27	6	22%	3%

Indicator: Species Richness

MEF: Ecosystem Functions
KEA: Habitat Provisioning
Metric: Number of Species per Unit Area

Definition: Species richness is the count of different species represented in an ecological community, landscape, or region. Species richness is the number of species and does not take into account the abundances of the species or their relative abundance distributions.

Background: Numerous coastal species, many of which are commercially or recreationally important, such as blue crab (*Callinectes sapidus*) and red drum (*Sciaenops ocellatus),* among others, utilize intertidal and subtidal oyster habitats for shelter and feeding or reproduction grounds (Coen et al., 1999b; Breitburg, 1999; Breitburg et al., 2000; Peterson et al., 2003; Humphries et al., 2011; McCoy et al., 2017). Species that are not commercially or recreationally important are still ecologically important in that they may feed on zooplankton or serve as prey for larger fish (Breitburg, 1999; Coen and Luckenbach, 2000; Harding and Mann, 2000; Harding, 2001), thus functioning as important links in the food chain. Oyster reefs also directly and indirectly provide food resources for numerous waterbirds (e.g., herons, oystercatchers, gulls, and terns), and aggregations of dead oysters can provide nesting and roosting sites.

Rational for Selection of Variable: Oyster reefs provide habitat and food for a range of species including fish, invertebrates, and birds. Species richness is a straightforward metric for the diversity of species utilizing the oyster reef as habitat and/or food source.

Measure: Number of species m^{-2}

Tier: 2 (rapid field measurement)

Measurement: Count number of target species/faunal groups using quadrat samples (epifaunal sessile invertebrates); core samples (infaunal invertebrates); substrate baskets (small resident mobile fish and invertebrates); seines, lift nets, etc. (transient crustaceans and juvenile fish); gillnets (transient adult fish); or visual surveys (waterbirds).

Metric Rating and Assessment Points:

Metric Rating	Number of Species per Unit Area
Good	Increasing or stable
Poor	Decreasing

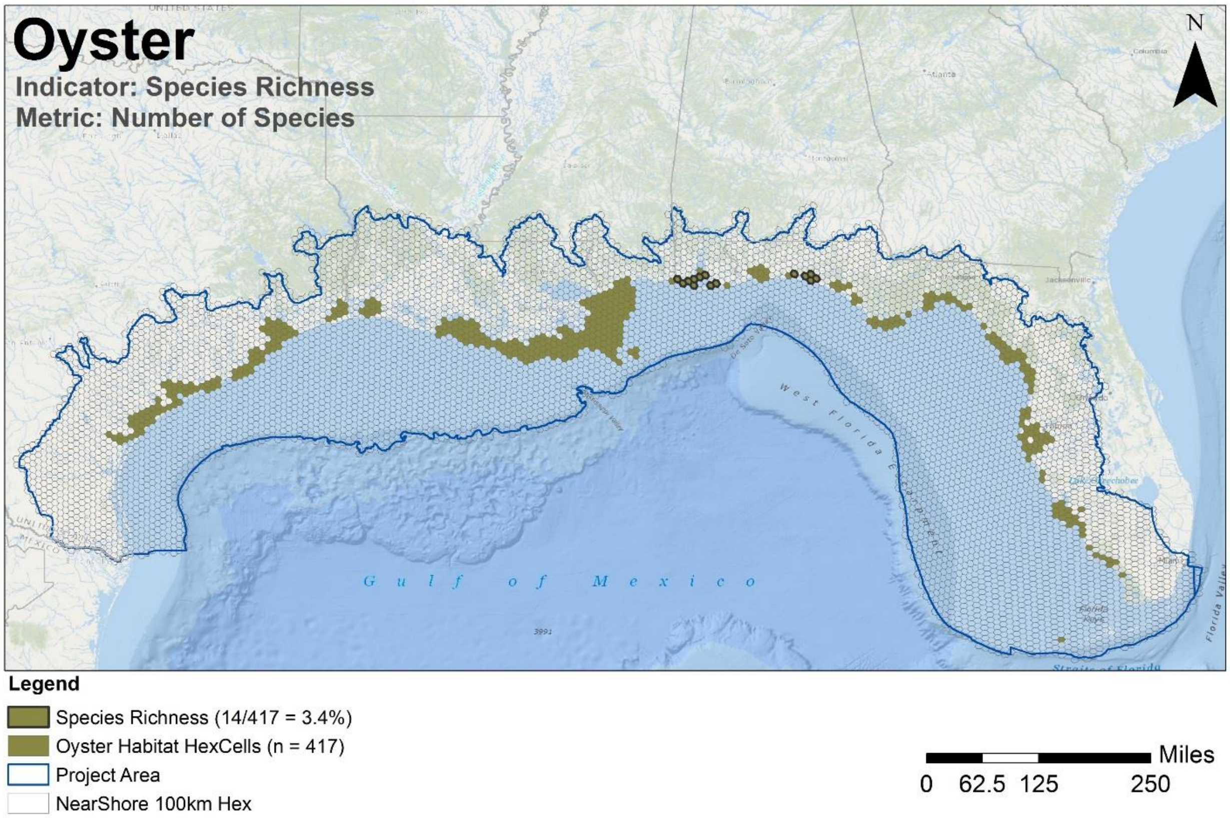
Scaling Rationale: Species richness should be stable or increasing over time on a healthy reef. There is not strong guidance available on the expected time period needed to assess trends. Control or reference site data may also be considered if previous survey data is not available (Baggett et al., 2014).

Analysis of Existing Monitoring Efforts:

<u>Geographic</u>*:* Number of species is not well collected geographically in the NGoM, with only 3% of habitat hexagons containing at least one monitoring site. The few monitoring locations for this metric occur in Alabama and Florida.

Programmatic: Data for this metric are collected by 2/27 (7%) of the programs collecting relevant oyster data in the NGoM.

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



Metric	Total Relevant Oyster 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
Number of Species	27	2	7%	3%

Indicator: Resident Species

MEF: Ecosystem Function
KEA: Habitat Provisioning
Metric: Biomass of Resident Species

Definition: Biomass of resident species is the total mass of resident organisms in a given reef area.

Background: Numerous invertebrate and vertebrate species use structure provided by oyster reefs as habitat, with similar assemblages being supported by both historic and restored reefs (Brown et al., 2013). The complexity of the reef structures is thought to increase resident species by reducing predation (Grabowski et al., 2008), creating more foraging sites (MacArthur, 1958) and increasing larval retention (Tegner and Dayton, 1981). A list of fish species that have been identified as oyster reef residents is provided by Volety (2013).

Rational for Selection of Variable: Oyster reefs provide habitat for a range of resident species of invertebrates and fish. Wet weight gives an indication of the abundance and biomass of residence species.

Measure: Wet weight by species (g m^{-2})

Tier: 2 (rapid field measurement)

Measurement: Measure wet weight of target species/faunal groups using quadrat samples (epifaunal sessile invertebrates), core samples (infaunal invertebrates), and substrate baskets (small resident mobile fish and invertebrates).

Metric Rating and Assessment Points:

Metric Rating	Biomass of Resident Species
Good	Stable or increasing
Poor	Decreasing

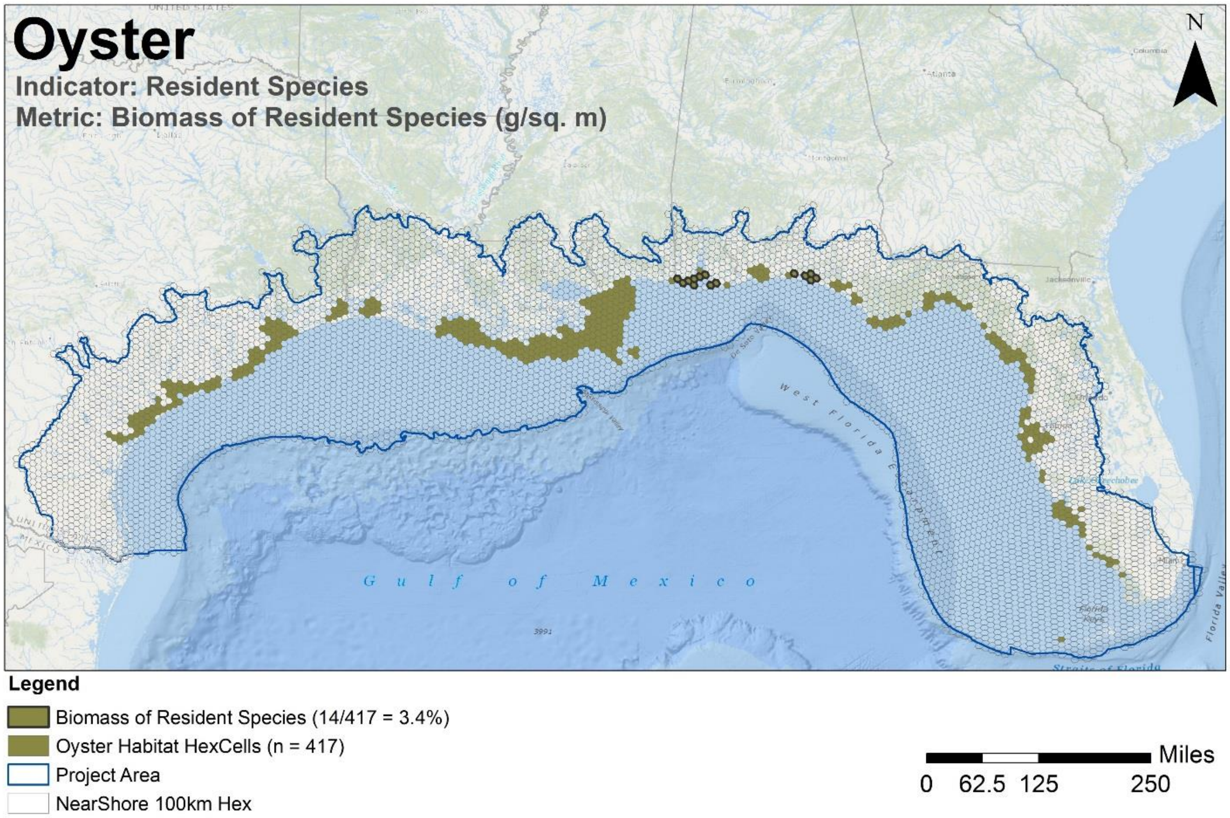
Scaling Rationale: Resident biomass should be stable or increasing over time on a healthy reef. There is not strong guidance available on the expected time period needed to assess trends. Control or reference site data may also be considered if previous survey data is not available (Baggett et al., 2014).

Analysis of Existing Monitoring Efforts:

<u>Geographic</u>*:* Biomass of resident species is not well collected geographically in the NGoM, with 3% of habitat hexagons containing at least one monitoring site. The monitoring locations for this metric occur in Florida and Alabama.

<u>Programmatic:</u> Data for this metric are collected by 2/27 (7%) of the programs collecting relevant oyster data in the NGoM.

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



Metric	Total Relevant Oyster 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
Biomass of Resident Species	27	2	7%	3%

Ecosystem Service Indicators

Indicator: Status of Macrofaunal Populations

MES: Supporting
KES: Habitat
Metric: Density of Naked Goby

Definition: Density (individuals per area unit) of naked goby (*Gobiosoma bosc*), a small oyster reef resident mobile fish.

Background: Naked goby is a species that has been associated with oyster reef habitat because it spawns inside remnant oyster shells, and its development depends on the habitat provided by the reef (Harding and Mann, 2000; http://txstate.fishesoftexas.org/gobiosoma%20bosc.htm). In estuarine waters, oyster reefs provide a habitat service to naked goby, a small resident fish that is commonly found along the reefs in the Gulf of Mexico coast and spawns primarily from late April to October inside shells.

Rationale for Selection of Variable: A variety of small resident fish and invertebrate species use oyster reefs for shelter (i.e., refugia), feeding, and reproduction (Coen and Luckenbach, 2000; VanderKooy, 2012). Density constitutes an important statistic to describe and understand wild populations. It allows for the assessment of population resource utilization at a specific habitat. Therefore, it is important to describing the current status of the population and for making predictions about how the population could change in the future. 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; Breitburg, 1999), and where visual census is not suitable. Measures of organism density allow for comparisons across multiple structurally complex habitats that characterize reef environments.

Measure: Number of individuals/m^2

Tier: 3 (intensive field measurement)

Measurement: Field-collected organisms should be identified and enumerated. Data should be presented on individuals/m^2.

Metric Rating and Assessment Points:

Metric Rating	Density of Naked Goby
Good–Excellent	>= 21.22 individuals/m^2
Poor	< 21.22 individuals/m^2

Scaling Rationale: The summer mean (21.22 fish/m^2; annual mean = 21.5 fish/m^2) of adult (> 40 mm) naked goby density in Palace Bar Oyster Reef, Piankatank River, Virginia in 1996 (Harding and Mann, 2000) was used to assign the assessment points. Densities above or equal to the mean are considered good population health. Values below the mean are considered poor. If local densities are significantly higher or lower than those provided, use a “stable or increasing vs. decreasing” metric rating instead.

Analysis of Existing Monitoring Efforts:

No programs in the monitoring program inventory specifically noted collection of density of naked goby.

Indicator: Oyster Fishery

MES: Provisioning
KES: Food
Metric 1: Site Harvest Status
Metric 2: Commercial Oyster Landings

Metric 1: Site Harvest Status

Definition: Determination of whether a specific oyster reef is currently commercially productive and contributes to oyster meat availability in public markets.

Background: Oyster meat for human consumption constitutes the main service received by humans from this fishery resource (Grabowski and Peterson, 2007). The Gulf has dominated U.S. oyster production since the early 1980s, when the northeast U.S. oyster fisheries began their decline. Total Gulf production has increased from this time period to present. The increase trend remains true after the hurricanes of 2004 and 2005, which destroyed a number of reefs in the northern Gulf, and production has remained fairly stable (VanderKooy, 2012).

Site level production statistics are not readily available for most sites.

Rationale for Selection of Variable: Harvest status provides an indication of whether a given site is contributing to commercial oyster production for human benefit. This metric is best used when it is important to tie the ecosystem service to a specific site, even when the total oyster production for the site is unknown.

Measure: Is site harvested for commercial production (Y/N)?

Tier: 2 (rapid assessment)

Measurement: Assess whether the site is actively harvested for commercial use.

Metric Rating and Assessment Points:

Metric Rating	Area commercially productive and contributes to oyster meat availability in public markets
Good–Excellent	Yes
Poor	No

Scaling Rationale: Harvestable reefs that contribute to oyster meat availability in markets provide food benefits to people.

Metric 2: Commercial Oyster Landings

Definition: Annual commercially landed pounds of meat of eastern oyster (*Crassostrea virginica*) in private and public leases in state waters. All gears are considered in these indicators—i.e., dredge, tong, and other.

Background: Oyster meat for human consumption constitutes the main service received by humans from this fishery resource (Grabowski and Peterson, 2007). The Gulf has dominated U.S. oyster production since the early 1980s, when the northeast U.S. oyster fisheries began their decline. Total Gulf production has increased from this time period to present. The increase trend remains true after the hurricanes of 2004 and 2005, which destroyed a number of reefs in the northern Gulf, and production has remained fairly stable (VanderKooy, 2012).

Site level production statistics are not readily available for most sites.

Rationale for Selection of Variable: Commercial landing statistics provide direct measure of the degree of service enjoyed by humans. At best, current statistics are available annually at the state level. This metric is best used to assess the potential contrition of oyster reefs to commercial landings at the state level on an annual basis.

Measure: Metric tons of meat landed per year

Tier: 3 (intensive field measurement)

Measurement: The Gulf States Marine Fisheries Commission repots landings in millions of pounds at the state level, and the NMFS aggregates it into metric tons. Federal and state data is available at the Annual Commercial Landings Statistics site of the National Marine Fishery Service (http://www.st.nmfs.noaa.gov/st1/commercial/landings/annual_landings.html). Principal landing statistics that are collected consist of the pounds of landings identified by species, year, month, state, county, port, water, and fishing gear.

Metric Rating and Assessment Points:

Metric Rating	Commercial Oyster Landings (Metric Tons)					
	Gulf (Northern)	Texas	Louisiana	Mississippi	Alabama	Florida (West Coast)
Good–Excellent	> 10,893	> 2,588	> 6,259	> 1,248	> 348	> 1,145
Fair (Q2-Q3)	9,963–10,893	2,233–2,588	5,831–6,259	1,038–1,248	260–348	881–1,145
Poor	< 9,963	< 2,233	< 5,831	< 1,038	< 260	< 881

Scaling Rationale: Landings used for ratings are based in eastern oyster commercial catch levels in Gulf states over the last two decades (1995–2015). Quartiles 2 and 3 of the catch were assigned a fair rating, whereas above and below those values were assigned good to excellent and poor ratings, respectively.

Analysis of Existing Monitoring Efforts:

No programs in the monitoring program inventory specifically noted collection of oyster fishery metrics.

Indicator: Erosion Reduction

MES: Regulating
KES: Coastal Protection
Metric: Shoreline Change

Definition: The statistically significant gain or loss in shoreline positions.

Background: Shallow reefs help stabilize the shoreline by reducing erosion and making the shoreline less vulnerable to other natural hazards (The Nature Conservancy, 2017). The protection benefit of any reef will depend on many factors, such as exposure, intensity, and local condition.

Rationale for Selection of Variable: Shoreline stabilization constitutes an important measure of the risk reduction benefits provided by the oyster reef. Nearshore shallow reefs absorb wave energy that otherwise would put at risk people, property, or landscapes (The Nature Conservancy, 2017).

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

Tier: 3 (intensive field measurement)

Measurement: Measurements should be performed on the shoreline of the area adjacent to the reef and at a control site with similar current and wave conditions in the region. For a complete description of the methods, see The Nature Conservancy (2017).

Metric Rating and Assessment Points:

Metric Rating	Shoreline Change
Good–Excellent	No change, gain (accretion)
Poor	Loss (erosion)

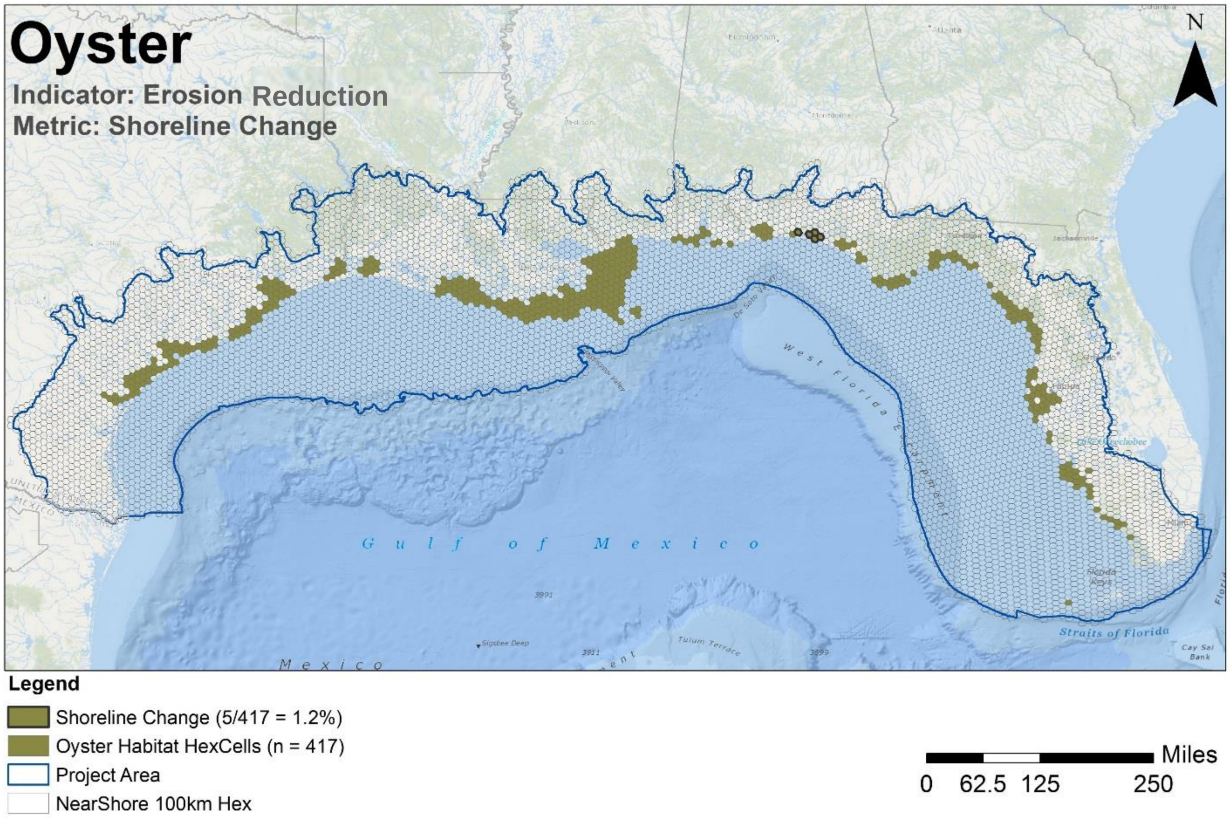
Scaling Rationale: Assessment points for indicator values constitute no change or gain (accretion) and loss (erosion) in shoreline areas adjacent to nearshore shallow oyster reefs.

Analysis of Existing Monitoring Efforts:

<u>Geographic</u>*:* Shoreline change is not well collected geographically in the NGoM, with only 1% of habitat hexagons containing at least one monitoring site. Monitoring locations for this metric are only in one small area in Florida.

<u>Programmatic:</u> Data for this metric are collected by 1/27 (4%) of the programs collecting relevant oyster data in the NGoM.

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



Metric	Total Relevant Oyster Monitoring Programs	Number of Programs Monitoring the Indicator	Percentage of Programs Monitoring the Indicator	Percent of Ecosystem Hexagons that Contain Monitoring Sites for the Indicator
Shoreline Change	27	1	4%	1%

Indicator: Recreational Fishery

MES: Cultural
KES: Aesthetics-Recreational Opportunities
Metric: Perception of Recreational Anglers Fishing in the Area of Influence of Oyster Reefs

Definition: Percentage of people that fish in the area of influence of oyster reefs (including natural and restored reefs) that have a positive experience. Fishing can be conducted using different gear types as defined and allowed by state regulations.

Background: Estuarine predators such as red and black drum, spotted seatrout, sheepshead, flounder, snapper, striped bass, and snook are seasonal visitors of oyster reefs. However, in the northern Gulf of Mexico, pelagic fish such as Spanish mackerel and cobia are also known to follow menhaden, mullet, and anchovies onto oyster reefs. The National Marine Fisheries Service (NMFS) of the National Oceanic and Atmospheric Administration (NOAA) is responsible for collecting information on marine recreational angling. The Marine Recreational Information Program (MRIP) is a survey program that consists of an in-person survey at fishing access sites and a mail survey, in addition to other complementary or alternative surveys conducted in some states (NMFS, 2016). Data collected from anglers through the MRIP supply fisheries managers with essential information for assessing fish stocks, fishing trips, fishing locations, and fishing gears/modes (NMFS, 2016). Although the MRIP provides a systematic national baseline of catch, effort, and participation angling data, it is limited in its current capacity to report data on the fishing habitats targeted (i.e., oyster reefs; NAS, 2016). At present, the opportunity for obtaining biological catch effort and economic data in a cost-effective manner comes from *ad hoc* access point intercept surveys targeting angles in estuaries where the reefs of interest occur. An example of such a survey is the recent assessment conducted by The Nature Conservancy (TNC) and Texas Sea Grant Program in Matagorda Bay, Texas. In this study, 400 anglers were surveyed about their perception of the benefits received while fishing in the TNC-restored oyster reef habitat (TNC, 2016).

Rationale for Selection of Variable: At present, the MRIP access point intercept survey of recreational anglers constitutes the most comprehensive sampling method for obtaining biological catch effort and economic data in a cost-effective manner.

Measure: Percent of anglers per site and year with positive perception of fishing in oyster reefs

Tier: 2 (rapid field measurement)

Measurement: On Gulf of Mexico coasts, the survey is conducted at public marine fishing access points (boat ramps, piers, beaches, jetties, bridges, marinas, etc.) to collect individual catch data. From these angler interviews, a catch per trip (catch rate) estimate is made for each type of fish encountered, either observed or reported (http://www.st.nmfs.noaa.gov/recreational-fisheries/data-and-documentation/queries/index). Although catch effort is reported in angler trips in MRIP, the number of anglers constitutes the basis of these statistics (NMFS, 2016).

Metric Rating and Assessment Points:

Metric Rating	Perception of Recreational Anglers Fishing in the Area of Influence of Oyster Reefs
Good–Excellent	> 90% positive
Fair	50–90% positive
Poor	< 50% positive

Scaling Rationale: If above 90% of anglers respond positively with a satisfying experience, the metric is considered good to excellent. If the majority of anglers (50–90%) respond positively, the indicator is considered fair. Below that, the experience is considered poor. These numbers are based on the proportion of recreational anglers in the intercept survey reporting that the oyster restored–habitat at Half Moon Reef offers a more satisfying experience than other fishing locations in Matagorda Bay, Texas (TNC, 2016).

Analysis of Existing Monitoring Efforts:

No programs in the monitoring program inventory specifically noted collection of recreational fishery metrics.

References

Baggett, L.P., S.P. Powers, R. Brumbaugh, L.D. Coen, B. DeAngelis, J. Greene, B. Hancock, and S. Morlock, 2014. *Oyster Habitat Restoration Monitoring and Assessment Handbook.* The Nature Conservancy, Arlington, VA, 96 pages.

Baker, S.M. and R. Mann, 1992. Effects of hypoxia and anoxia on larval settlement, juvenile growth, and juvenile survival of the oyster *Crassostrea virginica*. *Biological Bulletin* 182: 265–269.

Beck, M.W., R.D. Brumbaugh, L. Airoldi, A. Carranza, L.D. Coen, C. Crawford, O. Defeo, G.J. Edgar, B. Hancock, M.C. Kay, H.S. Lenihan, M.W. Luckenback, C.L. Toropova, and G. Zhang, 2009. *Shellfish Reefs at Risk: A Global Analysis of Problems and Solutions.* The Nature Conservancy, Arlington, VA.

Beck, M.W., R.D. Brumbaugh, L. Airoldi, A. Carranza, L.D. Coen, C. Crawford, O. Defeo, G.J. Edgar, B. Hancock, M.C. Kay, H.S. Lenihan, M.W. Luckenback, C.L. Toropova, G. Zhang, and X. Guo, 2011. Oyster reefs at risk and recommendations for conservation, restoration, and management. *BioScience* 61: 107–116.

Beck, M.W., K.L. Heck, Jr., K.W. Able, D.L. Childers, D.B. Eggleston, B.M. Gillanders, B. Halpern, C.G. Hays, K. Hoshino, T.J. Minello, R.J. Orth, P.F. Sheridan, and M.P. Weinstein, 2001. The identification, conservation, and management of estuarine and marine nurseries for fish and invertebrates: A better understanding of the habitats that serve as nurseries for marine species and the factors that create site-specific variability in nursery quality will improve conservation and management of these areas. *BioScience* 51(8): 633–641.

Borsje, B.W., B.K. van Wesenbeeck, F. Dekker, et. al., 2011. How ecological engineering can serve in coastal protection. *Ecological Engineering* 37: 113–122.

Bobo, M.Y., D.L. Richardson, L.D. Coen, and V.G. Burrell, 1997. A report on the protozoan pathogens *Perkinsus marinus* (Dermo) and *Haplosporidium nelsoni* (MSX) in South Carolina shellfish populations. *South Carolina Department of Natural Resources Technical Report* 86. Charleston, SC, 60 pages.

Breitburg, D.C., 1999. Are Three Dimensional Structure and Healthy Oyster Populations the Keys to an Ecologically Interesting and Important Fish Community? *In:* Luckenbach, M.W., R. Mann, and J.A. Wesson (editors). *Oyster Reef Habitat Restoration: A Synopsis and Synthesis of Approaches*. Virginia Institute of Marine Science Press, Gloucester Point, VA, 239–250.

Brown, L., J. Furlong, K. Brown, and M. LaPeyre, 2013. Oyster reef restoration in the northern Gulf of Mexico: Effect of artificial substrate and age on nekton and commensal community use. *Restoration Ecology*: 1–9.

Bushek, D., S.E. Ford, and S.K. Allen, Jr., 1994. Evaluation of methods using Ray's fluid thioglycollate medium for diagnosis of *Perkinsus marinus* infection in the eastern oyster, *Crassostrea virginica*. *Annual Review of Fish Diseases* 4: 201–217.

Cake, E.W., Jr., 1983. Habitat suitability index models: Gulf of Mexico American oyster. *FWS/OBS-82/10.57*. U.S. Fish and Wildlife Service, Washington, DC, 37 pages.

Chatry, M., R.J. Dugas, and K.A. Easley, 1983. Optimum salinity regime for oyster production on Louisiana's state seed grounds. *Contributions in Marine Science* 26: 81–94.

Chestnut, A.F., 1974. Oyster Reefs. *In:* H.T. Odum, B.J. Copeland, and E.A. McMahan. *Coastal Ecological Systems of the United States II.* The Conservation Foundation, Washington, DC, 171–203.

Childers, D.L. and J.W. Day, 1990. Marsh-water column interactions in two Louisiana estuaries. I. Sediment dynamics. *Estuaries* 13: 393–403.

Chu, F.L.E. and A.K. Volety, 1997. Disease processes of the parasite, *Perkinsus marinus* in eastern oyster *Crassostrea virginica*: Minimum dose for infection initiation, and interaction of temperature, salinity and infective cell dose. *Diseases of Aquatic Organisms* 28(1): 61–68.

Coen, L.D., M.W. Luckenbach, and D.L. Breitburg, 1999. The Role of Oyster Reefs as Essential Fish Habitat: A Review of Current Knowledge and Some New Perspectives. *In:* Benaka, L.R. (editor). *Fish Habitat: Essential Fish Habitat and Rehabilitation.* American Fisheries Society, Symposium 22, Bethesda, MD, 438–454.

Coen, L.D., D.M. Knott, E.L. Wenner, N.H. Hadley, and A.H. Ringwood, 1999. Intertidal Oyster Reef Studies in South Carolina: Design, Sampling and Experimental Focus for Evaluating Habitat Value and Function. *In:* Luckenbach, M.W., R. Mann, and J.A. Wesson (editors). *Oyster Reef Habitat Restoration: A Synopsis and Synthesis of Approaches*. Virginia Institute of Marine Science Press, Gloucester Point, VA, 131–156.

Coen, L.D. and M.W. Luckenbach, 2000. Developing success criteria and goals for evaluating oyster reef restoration: Ecological function or resource exploitation? *Ecological Engineering* 15: 323–343.

Coen, L.D., R.D. Brumbaugh, D. Bushek, R. Grizzle, M.W. Luckenbach, M.H. Posey, S.P. Powers, and S.G. Tolley, 2007. Ecosystem services related to oyster restoration. *Marine Ecology Progress Series* 341: 301–307.

Diaz, R.J. and R. Rosenberg, 1995. Marine benthic hypoxia: A review of its ecological effects and the behavioral responses of benthic macrofauna. *Oceanography and Marine Biology: An Annual Review* 33: 245–303.

Ewart, J.W. and S.E. Ford, 1993. History and impact of MSX and dermo diseases on oyster stocks in the Northeast region. *Northeastern Regional Aquaculture Center Fact Sheet* No. 200, www.nrac.umd.edu/files/Factsheets/fact200.pdf.

Ekstrom, J.A., L. Suatoni, S.R. Cooley, G.G. Waldbusser, J.E. Cinner, J. Ritter, R. van Hooidonk, C. Langdon, M.W. Beck, L.M. Brander, D. Rittschof, P.E.T. Edwards, and K. Wellman, 2015. Vulnerability and adaptation of US shellfisheries to ocean acidification. *Nature Climate Change* 5: 207–214. 10.1038/nclimate2508.

Fischer, J., D.B. Lindenmayer, and A.D. Manning, 2006. Biodiversity, ecosystem function, and resilience: Ten guiding principles for commodity production landscapes. *Frontiers in Ecology and the Environment* 4(2): 80–86.

Galtsoff, P.S., 1964. The American oyster *Crassostrea virginica* Gmelin. *U.S. Fish Wildlife Service Fishery Bulletin* 64: 1–480.

Gosling, E., 2003. *Bivalve Molluscs: Biology, Ecology, and Culture*. Fishing News Books, MA.

Gunter, G. and R.A. Geyer, 1955. Studies on fouling organisms of the Northwest Gulf of Mexico on platform and pile. *Publications of the Institute of Marine Science* 4(1): 37–67.

Grabowski, J.H. and C.H. Peterson, 2007. Restoring Oyster Reefs to Recover Ecosystem Services. *In:* Cuddington, K., J.E. Byers, W.G. Wilson, and A. Hastings (editors). *Ecosystem Engineers: Concepts, Theory and Applications.* ElsevierAcademic Press, Amsterdam, 281–298.

Grabowski, J.H., A.R. Hughes, and D.L. Kimbro, 2008. Habitat complexity influences cascading effects of multiple predators. *Ecology* 89: 3413–3422.

Grabowski, J.H., R. Brumbaugh, R. Conrad, A. Keeler, J. Opaluch, C. Peterson, M. Piehler, S. Powers, and A. Smyth, 2012. Economic valuation of ecosystem services provided by oyster reefs. *BioScience* 62: 900–909.

Hatton, R.S., R.D. DeLaune, and W.H.J. Patrick, 1983. Sedimentation, accretion, and subsidence in marshes of Barataria Basin, Louisiana. *Limnology and Oceanography* 28(3): 494–502.

Harding, J.M., 2001. Seasonal, diurnal, and tidal patterns of zooplankton abundance in distribution in relation to a restored Chesapeake Bay oyster reef. *Estuaries* 24: 453–466.

Harding, J.M. and R. Mann, 2000. Estimates of naked goby (*Gobiosoma bosc*), striped blenny (*Chasmodes bosquianus*) and eastern oyster (*Crassostrea virginica*) larval production around a restored Chesapeake Bay oyster reef. *Bulletin of Marine Science* 66: 29–45.

Humphries A.T., M.K. La Peyre, and G.A. Decossas, 2011. The effect of structural complexity, prey density, and ‘‘predator-free space’’ on prey survivorship at created oyster reef mesocosms. *PLoS ONE* 6(12): e28339. doi:10.1371/journal.pone.0028339.

Johnson, M.W., S.P. Powers, J. Senne, and K. Park, 2009. Assessing in situ tolerances of Eastern oysters (*Crassostrea virginica*) under moderate hypoxic regimes: Implications for restoration. *Journal of Shellfish Research* 28: 185–192.

Kennedy, V.S., 1991. Eastern Oyster. *In:* Funderburk, S.L., S.J. Jordan, J.A. Mihursky, and D. Riley (editors). *Habitat Requirements for Chesapeake Bay Living Resources*. Chesapeake Research Consortium, Inc., Solomons, Maryland.

Kennish, M.J., 2001. Coastal salt marsh systems in the U.S.: A review of anthropogenic impacts. *Journal of Coastal Research* 17: 731–748.

La Peyre, M.K., A.D. Nickens, G. Tolley, A. Volety, and J.F. La Peyre, 2003. Environmental significance of freshets in reducing *Perkinsus marinus* infection in eastern oysters (*Crassostrea virginica*): Potential management applications. *Marine Ecology Progress Series* 248: 165–176.

La Peyre, M.K., B. Gossman, and J.F. La Peyre, 2009. Defining optimal freshwater flow for oyster production: Effects of freshet rate and magnitude of change and duration on eastern oysters and *Perkinsus marinus* infection. *Estuaries and Coasts* 32(3): 522–534.

La Peyre, M.K., B.S. Eberline, T.S. Soniat, and J.F. La Peyre, 2013. Differences in extreme low salinity timing and duration differentially affect eastern oyster (*Crassostrea virginica*) recruitment, size class growth and mortality in Breton Sound, LA. *Estuarine Coastal and Shelf Science* 135: 146–157.

La Peyre, M.K., A.T. Humphries, S.M. Casas, and J.F. La Peyre, 2014. Temporal variation in development of ecosystem services from oyster reef restoration. *Ecological Engineering* 63: 34–44. doi:10.1016/j.ecoleng.2013.12.001.

La Peyre, M.K., K. Serra, T.A. Joyner, and A. Humphries, 2015. Assessing shoreline exposure and oyster habitat suitability maximizes potential success for sustainable shoreline protection using restored oyster reefs. *PeerJ* 3: e1317.

MacArthur, R.H., 1958. Population ecology of some warblers of northeastern coniferous forests. *Ecology* 39: 599–619.

Mackin, J.G., 1961. Mortality of oysters. *Proceedings of the National Shellfish Association* 50: 21–40.

Mackin, J.G., 1962. Oyster disease caused by *Dermocystidium marinum* and other microorganisms in Louisiana. *Publications of the Institute of Marine Science* 7: 132–299.

McCoy, E., S.R. Borrett, M.K. La Peyre, and B.J. Peterson, 2017. Estimating the impact of oyster restoration scenarios on transient fish production. *Restoration Ecology* 25: 789–809. doi: 10.1111/rec.12498.

Meyer, D.L., E.C. Townsend, and G.W. Thayer, 1997. Stabilization and erosion control value of oyster cultch for intertidal marsh. *Restoration Ecology* 5: 93–99.

Millennium Ecosystem Assessment, 2005. *Ecosystems and Human Well-being: Biodiversity Synthesis.* World Resource Institute, Washington, DC, 86 pages.

Milliman, J.D. and R.H. Meade, 1983. World-wide delivery of river sediment to the oceans. *The Journal of Geology* 91: 1–21.

NAS, 2016. *Review of the Marine Recreational Information Program (MRIP).* The National Academies (NAS). The National Academies Press, Washington, DC.

NMFS, 2016. *Marine Recreational Information Program: Data User Handbook*. National Marine Fishery Service – NOAA. Washington, DC, 68 pages.

Peterson, C.H., J.H. Grabowski, and S.P. Powers, 2003. Estimated enhancement of fish production resulting from restoring oyster reef habitat: Quantitative valuation. *Marine Ecology Progress Series* 264: 249–264.

Pollack, J.B., H.C. Kim, E.K. Morgan, and P.A. Montagna, 2011. Role of flood disturbance in natural oyster (*Crassostrea virginica*) population maintenance in an estuary in South Texas, USA. *Estuaries and Coasts* 34: 187–197.

Powell, E.N., J.N. Kraeuter, and K.A. Ashton-Alcox, 2006. How long does oyster shell last on an oyster reef? *Estuarine, Coastal and Shelf Science* 69: 531–542.

Powell, E.N. and J.M. Klinck, 2007. Is oyster shell a sustainable estuarine resource*? Journal of Shellfish Research* 26: 181–194.

Preston, S.D., R.B. Alexander, G.E. Schwarz, and C.G. Crawford, 2011. Factors affecting stream nutrient loads: A synthesis of regional SPARROW model results for the continental United States. *JAWRA Journal of the American Water Resources Association* 47: 891–915.

Puckett, B.J. and D.B. Eggleston, 2012. Oyster demographics in a network of no-take reserves: Recruitment, growth, survival, and density dependence. *Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science* 4(1): 605–627.

Ray, S.M, 1952. A culture technique for the diagnosis of infections with *Dermocystidium marium* Mackin, Owen, and Collier in oysters. *Science* 116: 360.

Ray, S., J.G. Mackin, and J.L. Boswell, 1953. Quantitative measurement of the effects on oysters of disease caused by *Dermocystidium marium. Bulletin of Marine Science of the Gulf and Caribbean* 13: 6–33.

Renaud, M.L., 1986. Hypoxia in Louisiana coastal waters during 1983: Implications for fisheries. *Fisheries Bulletin* (Washington, DC) 84: 19–26.

Shumway, S.E., 1996. Natural Environmental Factors. *In:* Kennedy, V.S., R.I.E. Newell, and A.F. Eble (editors). *The Eastern Oyster* Crassostrea virginica. Maryland Sea Grant College, College Park, MD, 467–513.

Soniat, T.M., 1996. Epizootiology of *Perkinsus marinus* disease of eastern oysters in the Gulf of Mexico. *Journal of Shellfish Research* 15: 35–43.

Tegner, M.J. and P.K. Dayton, 1981. Population structure, recruitment and mortality of two sea urchins (*Strongylocentrotus franciscanus* and *S. purpuratus*) in a kelp forest. *Marine Ecology Progress Series* 5: 255–268.

Theuerkauf, S.J., D.B. Eggleston, B.J. Puckett, and K.W. Theuerkauf, 2016. Wave exposure structures oyster distribution on natural intertidal reefs, but not on hardened shorelines. *Estuaries and Coasts:* 1–11.

The Nature Conservancy, 2016. *Half Moon Reef: Measuring the Recreational Fishing Benefits of a Restored Oyster Habitat.* The Nature Conservancy and Texas Sea Grant, Arlington, VA, 5 pages.

The Nature Conservancy, 2017. *Measures Guidebook for Flood and Storm Risk Reduction Projects.* The Nature Conservancy, Arlington, VA, 78 pages.

Turner, R.E., N.N. Rabalais, E.M. Swenson, M. Kasprzak, and T. Romaire, 2005. Summer hypoxia in the northern Gulf of Mexico and its prediction from 1978 to 1995. *Marine Environmental Research* 59: 65–77.

VanderKooy, S. (editor), 2012. *The Oyster Fishery of the Gulf of Mexico, United States: A Regional Management Plan – 2012 Revision.* Publication No. 202, Gulf States Marine Fisheries Commission, Ocean Springs, Mississippi, 375 pages.

Volety, A.K., M. Savarese, S.G. Tolley, W.S. Arnold, P. Sime, P. Goodman, R.H. Chamberlain, and P.H. Doering, 2009. Eastern oysters (*Crassostrea virginica*) as an indicator for restoration of Everglades ecosystems. *Ecological Indicators* 9(6)S: S120–S136.

Volety, A.K., 2013. Habitat: Oyster Reefs. *In: Southwest Florida Shelf Coastal Marine Ecosystem. MARES – MARine and Estuarine Goal Setting for South Florida* (http://www.aoml.noaa.gov/ocd/ocdweb/docs/MARES/MARES_SWFS_ICEM_20130913_Appendix_OysterReefs.pdf).

Watson, A., J. Reece, B.E. Tirpak, C.K. Edwards, L. Geselbracht, M. Woodrey, M. LaPeyre, and P.S. Dalyander, 2015. *The Gulf Coast Vulnerability Assessment: Mangrove, Tidal Emergent Marsh, Barrier Islands, and Oyster Reef.*

Waldbusser, G.G., E.N. Powell, and R. Mann, 2013. Ecosystem effects of shell aggregations and cycling in coastal waters: An example of Chesapeake Bay oyster reefs. *Ecology* 94(4): 895–903.

Wells, H.W., 1961. The fauna of oyster beds with special reference to the salinity factor. *Ecological Monographs* 31: 239–266.

Wright, L.D., 1977. Sediment transport and deposition at river mouths: A synthesis. *Geological Society of America Bulletin* 88: 857–868.

Yoskowitz, D., C. Santos, B. Allee, C. Carollo, J. Henderson, S. Jordan, and J. Ritchie, 2010. *Proceedings of the Gulf of Mexico Ecosystem Services Workshop: Bay St. Louis, Mississippi, June 16–18, 2010.* Harte Research Institute for Gulf of Mexico Studies, Texas A&M University-Corpus Christi, 16 pages.

zu Ermgassen, P.S.E., B. Hancock, B. DeAngelis, J. Greene, E. Schuster, M. Spalding, and R. Brumbaugh, 2016. Setting Objectives for Oyster Habitat Restoration Using Ecosystem Services: A Manager's Guide. The Nature Conservancy, Arlington, VA, 76 pages.

zu Ermgassen, P.S.E., M.D. Spalding, B. Blake, L.D. Coen, B. Dumbauld, S. Geiger, J.H. Grabowski, R. Grizzle, M. Luckenbach, K. McGraw, B. Rodney, J.L. Ruesink, S.P. Powers, and R. Brumbaugh, 2012.

Historical ecology with real numbers: Past and present extent and biomass of an imperiled estuarine habitat. *Proceedings of the Royal Society B* rspb.royalsocietypublishing.org on June 13, 2012