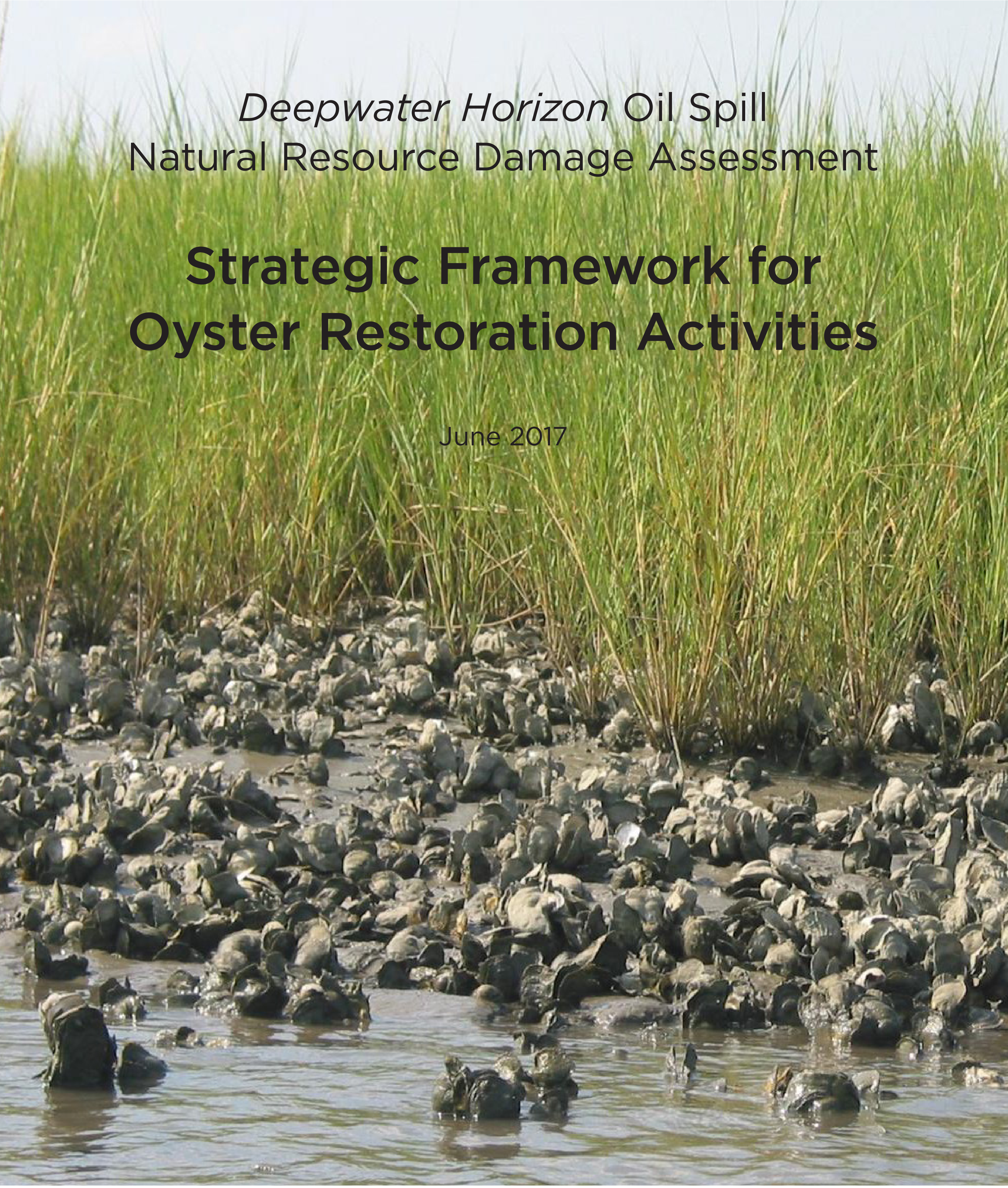
Deepwater Horizon Oil Spill
Natural Resource Damage Assessment

Strategic Framework for Oyster Restoration Activities

June 2017



The *Deepwater Horizon* (DWH) oil spill Natural Resource Damage Assessment (NRDA) Trustees (Trustees) developed a set of strategic frameworks for oysters, birds, marine mammals, and sea turtles to provide context for prioritization, sequencing, and selection of projects within future Trustee Implementation Group (TIG) restoration plans. The strategic frameworks also consider coordination across Restoration Areas, common monitoring standards and approaches, and opportunities for adaptive management. As established in the DWH oil spill Programmatic Damage Assessment and Restoration Plan and Programmatic Environmental Impact Statement (PDARP/PEIS), these frameworks will help the Trustees consider each resource at the ecosystem level, while implementing restoration at the local level.

The Regionwide TIG authorized the creation of these strategic frameworks to promote information sharing and coordination across TIGs for the four resources (oysters, birds, marine mammals, and sea turtles) that will receive restoration funding allocated to the Regionwide TIG. The Trustees also anticipate that the strategic frameworks will be useful for restoration planning and implementation by all TIGs. Developed by teams of Trustee scientists and resource experts, each framework includes four modules with information for the TIGs to consider for planning, implementing, and monitoring restoration activities:

Module 1: A brief summary of the information in the PDARP/PEIS related to each resource, including an overview of the injury, restoration goals, restoration approaches and techniques, and monitoring considerations

Module 2: Biological and ecological information on each resource, including geographic distribution, life history, and key threats

Module 3: An overview of other recent and ongoing conservation, restoration, management, and monitoring activities related to each resource in the northern Gulf of Mexico

Module 4: Considerations for the prioritization, sequencing, and selection of restoration projects to benefit the resource, including additional information on restoration approaches and techniques, potential project concepts, and monitoring needs.

Citations and references are included throughout the modules, so that the reader can easily investigate each topic in more detail. The strategic frameworks may be updated based on new knowledge obtained by Trustee efforts or the broader science community, and updates to relevant species recovery or management plans prepared under other statutes.

Strategic frameworks are not intended to exhaustively present all possible restoration techniques and project concepts, nor to prescriptively describe the complete restoration plan for the resource across all TIGs. Readers are encouraged to submit restoration projects to the Trustee Project Portal (http://www.gulfspillrestoration.noaa.gov/restoration/give-us-your-ideas) or to state-specific project portals, as available.

Please visit www.gulfspillrestoration.noaa.gov for the latest version of this document.

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Module 1

Summary of Information from the PDARP – Oysters

KEY ASPECTS OF OYSTER INJURY THAT INFORMED RESTORATION PLANNING

Nearshore Oyster Injury

Shoreline oiling and cleanup actions significantly reduced the presence of nearshore oysters in the adjacent intertidal zone over approximately 155 miles (250 kilometers). An estimated 8.3 million adult equivalent oysters* were lost along marsh shorelines where oyster cover was injured by oiling or cleanup actions. An additional estimated 5.7 million oysters per year (adult equivalents*) are unable to settle because of the loss of oyster shell cover. The injuries to nearshore oysters resulted in a lack of recruitment and recovery throughout the region. As shown by the *Deepwater Horizon* (DWH) oil spill Natural Resource Damage Assessment (NRDA) modeling studies, larvae produced from nearshore oysters settle and grow in subtidal areas to contribute to subtidal oyster populations. Recovery of these nearshore oysters is not expected to occur without intervention or restoration actions.

*(*The number of adult-equivalent oysters is the sum of oysters across all size classes, with spat and seed numbers adjusted for the proportion of those oysters that would have been expected to survive to adulthood.)*

Subtidal Oyster Injury

Between 4 billion and 8.3 billion subtidal oysters (adult equivalents*) were lost due to direct mortality and a lack of reproduction. DWH studies indicate that direct mortality injury was most pronounced in Barataria Bay and Black Bay/Breton Sound in Louisiana; and oyster reproduction has been most severely affected in Barataria Bay, Breton Sound, and Mississippi Sound. The dramatic decreases in oyster densities and the associated reproductive injury imperils the sustainability of oysters in the northern GOM. Subtidal injury impacted at least three generations of oysters.

Oysters in the Gulf of Mexico (GOM) are an ecological keystone species that are widely distributed throughout all five GOM states, and contribute to the integrity and healthy function of the nearshore ecosystem. Healthy, interconnected oyster populations form reefs that provide the hard substrate needed for oyster larvae to settle, grow, and sustain the population. In addition to providing habitat for oysters, these reefs (1) serve as habitat for a diversity of marine organisms, from small invertebrates to large, recreationally and commercially important species (e.g., stone crab, blue crab, red drum, and black drum); (2) provide structural integrity that reduces shoreline erosion; and (3) improve water quality and help recycle nutrients by filtering large quantities of water.

Although native oyster reefs have declined in many regions, GOM oyster reefs are among the most productive in the world, with subtidal reefs supporting a robust oyster fishery. In addition, oyster habitat that fringes salt marsh is one of the most common habitat couplings along the U.S. Gulf Coast. Nearshore oysters form fringing reefs or smaller hummocks on salt marsh shorelines, on intertidal mudflats, and between salt marshes and seagrass beds. In most Gulf States, these fringing reefs are not harvested and thus serve as de facto sanctuary areas for oysters. These oysters contribute larvae that eventually settle in subtidal areas and are especially important in stabilizing marsh shorelines by providing hard structure and trapping sediment.

Settlement funding allocation for oyster restoration (millions $)

Restoration will be implemented by all five state Trustee Implementation Groups (TIGs) and the Regionwide TIG to provide benefits across the interconnected northern GOM ecosystem.

	Restoration Funds	Early Restoration Oysters
Regionwide TIG	64.4	–
Alabama TIG	10.0	3.3
Florida TIG	20.0	5.4
Louisiana TIG	26.0	14.9
Mississippi TIG	20.0	13.6
Texas TIG	22.5	–
Total funding	**162.9**	**37.2**

Funding allocation is approximate. Numbers are rounded.

The Trustees initiated oyster projects under Early Restoration with an emphasis on subtidal reefs, providing for oyster restoration projects in Florida, Alabama, Mississippi, and Louisiana. Subtidal oyster cultch placement projects in Louisiana, Florida, Alabama, and Mississippi were approved in Phases I and III; and living shoreline projects incorporating oyster reef components in Florida, Alabama, and Mississippi were approved for Phases III and IV. Although these Early Restoration projects will restore some of the injury to oysters and the services they provide, they will not fully address the oyster injury. This Restoration Type will implement additional and strategically targeted restoration projects designed to restore oyster recruitment and nearshore cover that are required to address the remaining oyster injury.

Reproductive Injury

Injuries to oysters resulted in a lack of recruitment and population recovery. Because larvae produced from nearshore oysters settle and grow in subtidal areas, the permanent loss of nearshore oysters disrupted the regional larvae pool and contributed to the lack of recovery via oyster recruitment. In addition, extended periods of failure of any part of the reproductive cycle can lead to sedimentation of existing reefs, removing substrate for settlement and further reducing oyster cover over time. The long-term sustainability of nearshore and subtidal oysters throughout the north-central GOM has been compromised as a result of the combined effects of reduced spawning stock, larval production, spat settlement, and spat substrate availability caused by the spill.

Lost Ecological Services

Nearshore and subtidal oyster reefs provide a wide range of ecological functions that support other GOM coastal habitats and species. The loss of subtidal and nearshore oysters reduced the adult oyster spawning stock available to maintain healthy populations throughout the region. Therefore the pivotal role oyster reefs play in the ecosystem and food web was disrupted by this loss and, to date, the lack of a full recovery of both oyster reefs and oyster populations. With the injury to both subtidal and nearshore oyster reefs, a multitude of ecosystem services were lost, including improved water quality, stabilization of marsh shorelines, and habitat for economically and ecologically important marine species such as finfish and crustaceans.

For additional information, see Section 4.6 in the Final Programmatic Damage Assessment and Restoration Plan and Final Programmatic Environmental Impact Statement (PDARP/PEIS).

Trustees are using a nested framework of programmatic restoration goals, restoration types, and restoration approaches and techniques to guide and direct the subsequent phases of restoration:

Trustees' Programmatic Restoration Goal:

Replenish and protect living coastal and marine resources.

Restoration Type: Oysters

The goals of the Oyster Restoration Type include:

- Restore oyster abundance and spawning stock to support a regional oyster larvae pool sufficient for healthy recruitment levels to subtidal and nearshore oyster reefs.
- Restore resilience to oyster populations that are supported by productive larval source reefs and sufficient substrate in larval sink areas to sustain reefs over time.
- Restore a diversity of oyster reef habitats that provide ecological functions for estuarine-dependent fish species, vegetated shoreline and marsh habitats, and nearshore benthic communities.

For additional information on oyster restoration goals, see Section 5.5.9.1 in the Final PDARP/PEIS.

Strategy to Achieve Goals

The Oyster Restoration Type will address the range of injuries to oysters, emphasizing projects that address recruitment issues by restoring oyster reef habitat. The restoration of oyster reef habitats that were lost or injured across the region will be conducted to restore oyster abundance and the services oyster reefs provide. The lack of oyster recruitment recovery is likely due in large part to the direct loss of nearshore oysters, which would otherwise serve as a regional source of larvae. Therefore, to address the regional impairment of oyster recruitment, restoration of nearshore oyster reefs will be prioritized. Implementing oyster restoration in both nearshore and subtidal areas will help ensure the recovery of the ecological processes and conditions required for both oysters and associated fish and invertebrates. The restoration of oyster reef habitat could also be implemented in combination or in association with other restoration approaches under the Wetlands, Coastal, and Nearshore Habitats Restoration Type to increase overall service flows and benefits to other injured resources, such as fish and shallow benthic communities.

Restoration Approaches and Techniques

The restoration approach includes: Restore oyster reef habitat. The potential restoration techniques include:

1. Restore or create oyster reefs through placement of cultch in nearshore and subtidal areas.

This restoration technique places cultch material in areas with appropriate conditions to provide a hard structure for oyster recruitment and to restore or create three-dimensional oyster reef habitat. This technique can be used to restore lost oyster reef habitat, expand existing oyster reef habitat, or enhance oyster abundance at existing reefs. Cultch material can consist of either loose or contained oyster or other bivalve shell, limestone rock, crushed concrete, and other similar material that, when placed in areas with adequate larval supply, provides a substrate on which free-floating oyster larvae can attach and grow. This technique can be used in areas such as the margins of marshes, tidal creeks, estuaries, and bays.

2. Construct living shorelines.

This restoration technique involves the construction of living shorelines to (1) reduce/attenuate wave energy reaching the shoreline, thereby inducing sediment deposition and stabilizing shoreline habitats; (2) create substrate for colonization by oysters and other reef organisms; (3) provide shelter for benthic and fish communities; and (4) reestablish ecological connections at the land-water interface. Living shorelines can include a variety of shoreline stabilization and habitat restoration techniques that span coastal habitat zones and use both structural and organic materials.

3. Enhance oyster reef productivity through spawning stock enhancement projects.

Planting spat on shell/cultch or cultchless seed oysters can improve oyster abundance and density at existing or restored oyster reefs. This technique can be used on existing reefs with low productivity, in combination with cultch placement for new reefs, or as part of a living shoreline project. Planted oysters may be moved from reefs in areas of poor habitat conditions, or obtained through hatcheries or oyster gardening programs. To protect public health, the Trustees will follow best management practices to ensure compliance with regulations and shellfish control authorities.

4. Develop a network of oyster reef spawning reserves.

This restoration technique would identify specific, limited areas that would be closed to harvest to protect spawning oysters and serve as sources of oyster larvae to other reefs (including public oyster grounds). Reserves should be designed using a network approach to enhance the regional larval pool and maintain oyster populations over a large area, and to increase the likelihood of successful oyster recruitment during periods of adverse conditions. In order to maximize benefits to oyster populations, distances between reserves would be compatible with local oyster larvae dispersal dynamics to maximize reserve connectivity and restore metapopulation dynamics.

Additional Activities to Support Restoration Techniques

Shell recycling programs

The availability of oyster or other bivalve shell for restoration is often limited, especially for large restoration efforts; therefore, increasing the capacity of existing shell recycling programs, establishing new shell recycling programs, or implementing actions to increase shell availability for restoration may be necessary.

Enhancement of regional hatchery capacity and remote setting facilities

Large-scale use of techniques to enhance oyster reef productivity may require enhancement of regional hatchery capacity to produce sufficient oyster larvae. In addition to hatchery capacity, the development of facilities for production of spat on shell and remote setting facilities may be needed.

Oyster gardening programs

Oyster gardening is the recreational culture of oyster seed to adult size. Commonly, the "oyster gardener" obtains seed and places it in homemade oyster floats tied to piers or docks. Enhancing and expanding oyster gardening programs can provide a source of oysters for restoration, while also engaging and educating the public about oyster restoration.

Partnerships to implement the oyster restoration strategy

Opportunities for restoration and long-term success can be increased through the development of innovative partnerships with stakeholders, industry associates, universities, state and local resource programs, and oyster resource managers to plan and implement projects. It is also critical to involve and work closely with the oyster industry and other stakeholders to develop projects that build on local knowledge, current uses, and other environmental management and restoration projects that may affect oyster resources. Public outreach will also be essential to increase awareness of the importance of restoring oyster reefs.

For additional information on oyster restoration approaches and techniques, see Section 5.5.9.2 and Appendix 5.D in the Final PDARP/PEIS.

Monitoring and Adaptive Management

A monitoring and adaptive management framework will be used to support restoration implementation and provide the DWH Trustees with a flexible, science-based decision-making approach to ensure that the restoration portfolio provides long-term benefits to the natural resources and services injured by the spill. Monitoring will be conducted on all oyster restoration projects to support the evaluation of restoration progress and determine the need for corrective actions.

Project-level monitoring

The Oyster Restoration Type consists of well-established restoration approaches for which performance monitoring at the scale of the individual project will be sufficient to evaluate restoration outcomes and determine the need for any corrective actions. Performance monitoring will be designed to determine if projects, individually and together, are meeting their objectives with respect to the restoration of oyster resources and services. Monitoring and scientific support for project planning could be used to resolve key uncertainties during the planning of restoration projects. Although project-level objectives will vary, common metrics will be used, where possible, to evaluate and compare the performance success of oyster restoration projects.

More intensive and expanded validation monitoring conducted on a subset of projects to better characterize ecological function and address critical uncertainties may also be helpful in evaluating project performance, and informing the design and implementation of future oyster restoration projects.

Resource-level monitoring

Collection of resource-level monitoring information may allow for adaptive management and inform future restoration decisions. Although oyster restoration is frequently conducted throughout the GOM, the recruitment failure caused by the spill has created a critical uncertainty for restoration project performance and resource recovery. This monitoring and scientific support could include tracking recruitment trends in locations targeted for restoration, identifying oyster larvae source and sink areas, and identifying areas with healthy oyster spawning populations. The information provided by such recruitment studies would support effective adaptive management for project implementation, and inform the selection and design of oyster restoration projects.

For additional information on oyster restoration monitoring, see Section 5.5.9.4 in the Final PDARP/PEIS.

PHOTO CREDITS.

Page 1 (top). *Dr. Earl Melancon, Nicholls State University.*

Page 1 (bottom). *Thomas Mohrman, The Nature Conservancy.*

Module 2

Biological and Ecological Information – Oysters

1. Introduction

The eastern oyster (*Crassostrea virginica*) is an ecological keystone species that is widely distributed throughout all five Gulf of Mexico (GOM) states and contributes to the integrity and healthy function of estuarine ecosystems. The *Deepwater Horizon* (DWH) oil spill and response efforts severely affected nearshore oysters, subtidal oysters, and oyster recruitment in the northern GOM. Restoration of oyster reef habitats that were lost or injured will be conducted across the region to restore oyster abundance and the services oyster reefs provide (DWH NRDA Trustees, 2016).

This module provides biological and ecological information to support the design, implementation, and management of oyster restoration projects intended to address injuries caused by the DWH oil spill. Most of the information herein is adapted from the *Deepwater Horizon* Programmatic Damage Assessment and Restoration Plan/Programmatic Environmental Impact Statement (PDARP/PEIS; DWH NRDA Trustees, 2016) or from other relevant published literature and agency reports cited in the text.

2. Ecological, Cultural, and Economic Importance

Oyster reefs provide a broad variety of ecosystem services, including water quality improvement, shoreline stabilization (and associated habitat protection), carbon burial, habitat provisioning for fish and mobile invertebrates (including commercially and recreationally important species), habitat for epibenthic fauna, diversification of the landscape, and oyster production for commercial and recreational harvest (Grabowski et al., 2012).

Because of their reef-building capabilities, oysters are commonly referred to as natural ecosystem engineers. The complex habitat formed by oysters enhances the recruitment and growth of economically valuable and ecologically important finfish and crustaceans, thereby increasing these species' productivity (Coen et al., 1999; Breitburg et al., 2000; Harding and Mann, 2001; Peterson et al., 2003; Soniat et al., 2004; Grabowski et al., 2005; Tolley and Volety, 2005; Humphries and La Peyre, 2015; zu Ermgassen et al., 2016). Oysters filter sediments, phytoplankton, and detrital particles from the water column, potentially reducing turbidity and improving water quality (Dame and Patten, 1981). Oyster reefs also promote bacterially mediated denitrification, thereby counteracting nitrogen loading (Newell et al., 2002; Piehler and Smyth, 2011; Carmichael et al., 2013; Kellogg et al., 2013; Smyth et al., 2013; Humphries et al., 2016). By filtering water and enhancing light penetration, oysters promote other valuable estuarine habitats such as submerged aquatic vegetation (Newell, 1988; Everett et al., 1995; Newell and Koch, 2004; Carroll et al., 2008; Wall et al., 2008). Nearshore oyster reefs can reduce erosion and stabilize coastal shorelines through sediment trapping and accretion, and by adding hard substrate adjacent to marsh edges (Meyer et al., 1997; Piazza et al., 2005; Stricklin et al., 2010; Scyphers et al., 2011, 2015; La Peyre et al., 2015;

Figure 1). Intertidal oyster beds provide foraging sites at low tide, when the shellfish are accessible, to shorebirds such as the American oystercatcher (*Haematopus palliatus*).

Figure 1. Oysters along the marsh edge in the Sabine National Wildlife Refuge, Louisiana.

Source: USFWS.

Although native oyster reefs have declined in many regions, the GOM oyster reefs are among the most productive in the world, with subtidal reefs supporting a robust oyster fishery (Beck et al., 2011; VanderKooy, 2012; LDWF, 2015). In 2015, the Gulf States produced 53% (14.7 million pounds of meat) of the total U.S. oyster landings (NMFS, 2016), with a dockside value of $99.3 million (NMFS Commercial Fisheries Statistics Division, 2016). The eastern oyster also has cultural and historical importance to the GOM region. Oysters, along with other mollusks, have been an important food resource for Native Americans for thousands of years, as evidenced by shell middens at many sites along or near the Gulf Coast (Felder and Camp, 2009). The calcium carbonate shell of the oyster has also long been used for a variety of non-food purposes (MacKenzie, 1996). For example, Native Americans used oyster shells, either whole or ground, as construction material for houses and other structures (VanderKooy, 2012); and early European settlers used oyster shells for roads and footpaths, as filling for wharfs and fortifications, and as raw material for lime (MacKenzie, 1996). Current day commercial and recreational oyster harvesting is an essential component of many communities' way of life.

3. Species Biology

3.1 Life History

> Settlement vs. recruitment
>
> - Settlement occurs once the larva becomes permanently attached to the substrate or metamorphoses into its final benthic form (Baggett et al., 2014).
> - The term "recruitment" is used in this document to indicate that post-settlement growth has occurred.

As sessile organisms for the majority of their life, oysters rely on broadcast spawning to generate a regional larval pool that sustains populations. Although many variables can be influential, the two main drivers of oyster reproduction are water temperature and salinity, which act synergistically to create the optimal conditions for spawning and larvae survival. Temperature has a seasonal influence on oyster spawning in the northern GOM, usually producing two peak spawning seasons typically in May–June and again in September–October, although some spawning activity is found in most months (Cake, 1983; Stanley and Sellers, 1986). When water temperatures exceed 35°C during the summer months and fall below 20°C during the winter months, spawning may be limited (Stanley and Sellers, 1986). Similarly, salinity has also been observed to influence spawning, with optimal spawning salinity ranges from 10 to 30 parts per thousand (ppt) (Cake, 1983). The timing and duration of spawning can vary regionally, both longitudinally and latitudinally, due to differences in environmental conditions across bays or estuaries.

Following spawning, planktonic, free-swimming oyster larvae are carried by currents and tides across large areas. Oyster larvae remain in the water column for two–three weeks and then settle on suitable substrate, such as shell or other firm surfaces, and are called spat (Stanley and Sellers, 1986; Figure 2). The growth of oysters is dependent on environmental conditions and their position and density in the oyster reef (Stanley and Sellers, 1986). The term “recruitment” is used in this document to indicate that post-settlement growth has occurred. Under good conditions in the northern GOM, spat grow to seed size (26 mm) in about 3 months, and to market size (75 mm) around 15 months (Casas et al., 2015; Leonhardt et al., 2017). Oysters can live up to 10 years in the GOM (Cake, 1983). The eastern oyster is protandrous, such that it first matures as a male, and then changes to female later in life, while retaining the ability to revert to male (Bahr and Lanier, 1981; VanderKooy, 2012). Thus, typically the young adults are predominantly males; and the number of females increase with age (Stanley and Sellers, 1986).

Figure 2. Oyster larvae, transported by currents and tides, settle onto existing oyster shells to grow into spat. This picture from Barataria Bay, Louisiana, shows numerous live, one- to two-month-old oyster spat on one shell.

Source: Dr. Earl Melancon, Nicholls State University.

3.2 Feeding Behavior

Juvenile and adult oysters are filter feeders, exposed to a variety of food sources through each tidal cycle, as well as seasonally and annually in an estuary. Phytoplankton are considered a principal food source for the species; however, oysters are omnivores and can obtain food from other sources, such as bacteria, protozoans, and detritus (Langdon and Newell, 1996). Feeding is selective, targeting particulates approximately 1–3 µm (Jorgensen, 1966; Haven and Morales-Alamo, 1970), with a preference for organic molecules over mineral and detrital particles (Newell and Jordan, 1983). More recently, evidence indicates selective feeding, primarily based on cell surface biochemical signatures (Shumway et al., 1985; Ward and Shumway, 2004; Pales Espinosa et al., 2008, 2016). Through the filtering of phytoplankton and other suspended particulate matter, oysters play a critical role in the transfer of nutrients and energy from the pelagic food web to the benthic food web.

3.3 Habitat Suitability

Methods to evaluate habitat suitability for oysters have been developed in several areas within the GOM. Cake (1983) developed an oyster Habitat Suitability Index (HSI) model for the northern GOM to assess the potential for long-term success or failure of oyster reefs. Eight habitat characteristics were included in the HSI model, including (1) cultch availability,

(2) summer water salinity, (3) live oyster density, (4) historical mean water salinity, (5) intervals between mortality-inducing floods of extremely low salinity waters, (6) substrate firmness, (7) predator abundance, and (8) disease intensity. Soniat and Brody (1988) later field-tested Cake's model on oyster reefs in Galveston Bay and suggested modifications in a Modified Habitat Suitability Index model. Since then, others have used many of those parameters along with others to develop metrics for the northern GOM that explain success or failure of subtidal and intertidal oyster reefs (e.g., Livingston et al., 2000; Klink et al., 2002; Barnes et al., 2007; Scyphers et al., 2011; Beseres Pollack et al., 2012; Soniat, 2012; Volety and Haynes, 2012; Soniat et al., 2013; LaPeyre et al., 2015; Melancon et al., 2015). There were similarities and differences in the environmental metrics measured within each study; however, the two dominant environmental parameters that were identified as universal to oyster habitat and population survival were water temperature and salinity. These results were also supported by Shumway (1996). Secondary factors that may also affect oyster settlement and growth include dissolved oxygen (DO), pH, turbidity, and sedimentation; total suspended solids, total organic matter, and phytoplankton; substrate firmness and subsidence rates; sedimentation; shoreline wave exposure; and competition, predation, and disease. Many of these secondary factors vary in predictable ways with salinity and thus reinforce the importance of salinity characterization.

3.4 Environmental Tolerances

The eastern oyster can tolerate a range of environmental conditions that allows it to survive in a variable environment (Eastern Oyster Biological Review Team, 2007). Tolerance to changes in variables can differ based on life stage and the duration of extreme conditions. See VanderKooy (2012) for more information on environmental tolerances.

3.4.1 Salinity and Temperature

Oysters can tolerate a very large temperature range, typically observed between -2°C and 36°C (Shumway, 1996), but become less tolerant if the temperature change is abrupt. As water temperature increases, there is a corresponding increase in metabolism, which therefore influences physiological responses for oysters as well as increases in predation and disease. Temperature is the primary factor governing spawning, although salinity also has an influence. Oysters enter into mass spawning mode during the spring and fall, when water temperatures are near 25°C. Cold fronts with winds that push waters out and leave intertidal oysters exposed to freezing temperatures for several days can result in oyster die-offs.

Oysters can temporarily tolerate a wide range of salinities ranging from 0 to 42.5 ppt, but are mostly found in the 10–30 ppt range (Cake, 1983). Optimal salinities are usually in the 10–20 ppt range for subtidal oysters to allow for avoidance of physiological stress (lower salinity values), and predators and disease (higher salinity values). However, Butler (1952) documented exceptions to this salinity rule during cold water times, and observed oyster survival in salinities as low as 0.2–3.5 ppt for up to five consecutive months in winter temperatures (as reported by Barnes et al., 2007).

Salinity and temperature alone control many physiological responses in oysters, but their interaction, and differences in tolerance by life history stage, are equally important to consider. For example, field and laboratory studies of spat in Louisiana estuaries indicate a high tolerance to both low salinity and high temperatures for spat, whereas market-size oysters from the same oyster population had a much lower tolerance to low salinity, particularly during hot summer temperatures (Rybovich et al., 2016). Similarly, adult oysters have been found to have high mortality when salinities are outside the 10–15 ppt range and temperatures exceed 25°C, and similar mortality across the salinity spectrum (0–20+ ppt) when temperatures are low (~ < 15°C; La Peyre et al., 2016).

Oyster larval development requirements occur over a narrower temperature and salinity range than those commonly experienced by juveniles and adults. During their larval and spat stages, oysters are at their most vulnerable to fluctuating low salinities (Dekshenieks et al., 1996). Larvae and recently set spat are most sensitive to low salinity during the late spring through early fall when temperatures are relatively high, which coincides with spring and fall major spawns. Oyster larvae can tolerate salinity ranges between 5 and 35 ppt (Calabrese and Davis, 1970), but to successfully develop, a minimum salinity of 8 ppt is considered necessary for physiological function once fertilized eggs are viable and larvae begin to metamorphose and grow (Cake, 1983). Optimal salinity for metamorphosis is between 10 and 30 ppt.

In addition to acting as the two main synergistic drivers of oyster settlement, survival, and reef development (Shumway, 1996), water temperature and salinity also govern the prevalence of predators, shell pests, and diseases.

3.4.2 DO

Langdon and Newell (1996) documented that low DO can influence oyster larvae and adult survival. However, over relatively short periods, oysters have the ability to respire anaerobically to cope with hypoxia (Widdows et al., 1989). Temperature also affects the oyster’s response to DO, such that with increasing temperature the tolerance to low DO decreases. This biological response is due to increased metabolism with higher temperatures, which can increase the organism’s susceptibility to physiological stress. For example, when water temperatures are at 10°C, juvenile and adult oysters may tolerate hypoxic conditions for a month or more, while at 30°C they can survive for a week or less (Dunnington, 1968).

3.4.3 pH

From a physiological perspective, the most vulnerable life stage of an oyster to pH is as larvae, when the calcium-based shell is initially forming. Calabrese and Davis (1966) documented that oysters will spawn within a pH range between 6.0 and 10.0, but eggs lose viability and sperm lose mobility rapidly outside the range of 6.75–8.75; the best pH range for eggs and sperm are between 8.25 and 8.50. There is also a legacy issue for oyster shell if it is chronically exposed to waters with a pH < 8.0 (Davies et al., 1989), as this has been observed to increase the shell dissolution rate (Waldbusser et al., 2011).

3.4.4 Turbidity

Oyster larvae are often considered the most vulnerable to turbidity levels. Oyster larvae may have enhanced growth and shortened planktonic time in low levels of turbidity, whereas consistent high levels can create the opposite response and reduce growth rate (Dekshenieks et al., 1993).

4. Oyster Management in the GOM

The oyster fishery in the U.S. portion of the GOM is managed by the five individual Gulf States. As such, specific management measures vary by state, as dictated by the state's specific laws and regulations. Additional federal laws, regulations, and policies may also affect the oyster fishery in the region. For example, the production of oysters for consumption is closely regulated by federal and state agencies to minimize the occurrence of public health incidents. The Gulf State Marine Fisheries Commission (GSMFC), composed of members from each of the Gulf States, can also recommend and coordinate programs helpful to the management of the fishery. The states, however, do not lose any of their rights or responsibilities to manage their own fishery as a result of being a member of the GSMFC. For a detailed description of fishery management jurisdictions, laws, and policies, see Chapter 7 of *The Oyster Fishery of the Gulf of Mexico United States: A Regional Management Plan* (VanderKooy, 2012).

5. GOM Regional Distribution

For the DWH NRDA effort, oyster reefs were defined as:

- Nearshore reefs, found within 50 m of shore
- Subtidal reefs, found > 50 m from shore.

Oysters in the northern GOM form nearshore and subtidal reefs and are widely distributed throughout all five Gulf States. Subtidal oysters are most abundant in semi-enclosed bays, preferring water depths less than 12 m and salinities between 15 and 30 ppt; these oysters generally do not tolerate sustained freshwater inputs (VanderKooy, 2012). However, in some areas, occurrence of subtidal oyster beds in salinities greater than 15 ppt may be limited due to high disease and predation rates (discussed in more detail below). Nearshore oysters form fringing reefs or smaller hummocks on salt marsh shorelines, on intertidal mudflats, and between salt marshes and seagrass beds (or other types of submerged aquatic vegetation; Figure 3). Oyster habitat that fringes salt marshes is one of the most common habitat couplings along the U.S. Gulf Coast (Grabowski et al., 2005; Geraldi et al., 2009). DWH natural resource damage assessment (NRDA) studies estimated that 76% of salt marsh habitat in the northern GOM had adjacent oyster cover within 50 m, with the majority occurring within 3 m of the marsh edge (Powers et al., 2015b).

Figure 3. Fringing oyster reef, Grande Terre Island, Louisiana.

Source: Dr. Earl Melancon, Nicholls State University.

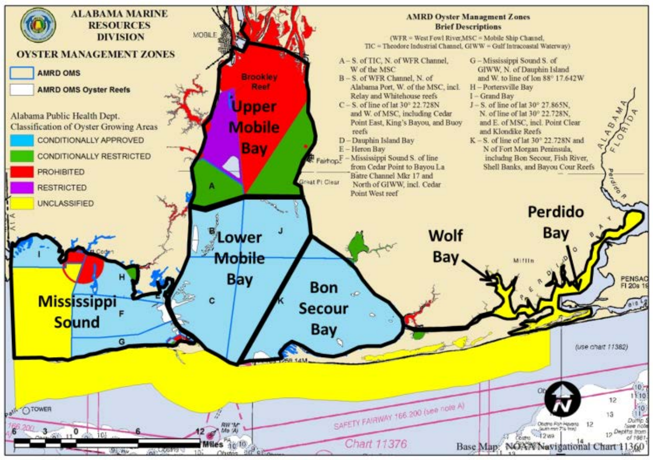
Oysters thrive in the GOM, especially where there is adequate hard substrate for spat to attach; and where salinity and freshwater inflow regimes allow for favorable conditions for growth, reproduction, and survival. GOM oyster populations also have demonstrated long-term resilience. For example, although oyster reefs were historically affected by predation, it did not impact population sustainability over time. Storms, natural changes to freshwater inflow, and large erosive events also affected oysters and their habitat; however, regionally, oyster populations were able to recover from these events. In Beck et al. (2011), the Gulf States were the only coastal region within the United States to receive a “fair” rating for its oyster reef habitat, based on a global assessment that estimated that 85% of oyster reef habitat has been lost globally over the past 130 years. However, as used in Beck et al. (2011), a fair rating implies that only 11–50% of historically known reefs still exist.

5.1 Sub-Regional Distribution

5.1.1 Alabama

Oysters can be found in Alabama waters from Upper Mobile Bay, including the Mobile-Tensaw River Delta to Lower Mobile Bay, Mississippi Sound, Bon Secour Bay, Wolf Bay, and the Perdido Bay system (Figure 4). However, there are specific areas in which the natural hydrology and bottom substrate have provided ideal conditions for the establishment of thriving oyster reefs that have historically produced oysters in a quantity sufficient to harvest commercially. Oyster reefs in Alabama waters can be found at depths ranging from 0 to 5 m. The extent of Alabama’s oyster reefs has been surveyed and mapped a number of times since the late 1800s. The first extensive effort to map Alabama’s oyster reefs was made in 1896 (Ritter, 1896). Alabama’s oyster reefs were mapped subsequently in 1913 (Moore, 1913), 1952 (Bell, 1952), 1968 (May, 1971), and 1995 (Tatum et al., 1995) by various agencies.

Figure 4. General area designations for Alabama’s inshore waterbodies.



During the 1968 survey, conducted by the Alabama Marine Resources Division (AMRD), scattered shell deposits were found but very few productive oyster reefs were located in the Upper Mobile Bay area. In addition, under the National Shellfish Sanitation Program (NSSP), the waters of Upper Mobile Bay are classified as Conditionally Restricted, Restricted, or Prohibited to the harvest of shellfish. Alabama waters are classified by the Alabama Department of Public Health according to various criteria that include, but are not limited to, proximity to possible point source pollution and calculated dilution rates of potential pathogens, which is based on river output and other flow data. During recent (2009 to the present) unpublished surveys, some oyster reefs of relatively high oyster density have been found to exist within one mile of the western shore of Mobile Bay. Small oyster reefs and shell deposits have also been found on the western edge of the Mobile Ship Channel. Currently the AMRD is using side-scan sonar and other survey methods to reevaluate the extent of the oyster reefs and shell deposits located in Upper Mobile Bay. Brookley reef, one of the oyster reefs located in Restricted waters near the western shore, consists of a hard oyster shell base that rises from 0.3 to 1 m in relief from the bottom. It has been hypothesized that the oyster resources in Upper Mobile Bay contribute a significant amount of oyster larvae to oyster reefs in Lower

Mobile Bay and Mississippi Sound. As surveying continues, the AMRD will be better able to make estimates as to the actual contribution of oyster larvae and overall oyster productivity from this area to Mobile Bay as a whole.

Productive reefs in Lower Mobile Bay predominantly occur along the western shore of Mobile Bay and near Dauphin Island Bridge. Three subtidal reefs, Cedar Point East, Buoy Reef, and King's Bayou Reef, are the predominant productive reefs currently and historically. Of these three reefs, Cedar Point East is currently the most productive and has contributed to the majority of oyster harvest in Lower Mobile Bay since 2011. Cedar Point East consists of a hard shell base with some gradual variation in relief. The swift currents that occur during the tidal flux under the Dauphin Island Bridge create conditions conducive to oyster growth, including access to nutrients, oxygenated waters, and larval input. Because of these ideal conditions, Cedar Point East has been identified as a reef that is a high priority for cultch planting and restoration. Buoy Reef and King's Bayou Reef are subject to periodic silting and productivity on these reefs has been variable since 2011. Approximately two miles north of the Dauphin Island Bridge is the historically productive reef footprint of Whitehouse Reef. This reef was harvested and productive during the 1968 survey; however, quadrat dives in the mid- to late 1970s have shown it had declined to zero productivity. Studies (e.g., Johnson et al., 2009a) have shown a hypoxic zone that occurs up to a meter off of the bottom. Recently, the AMRD has deployed data sondes to provide continuous monitoring of hydrological conditions on this reef. Just west of Whitehouse Reef is Relay Reef. This is a created reef zone in which oysters were relayed in 2010 and 2011 from restricted waters, including Brookley Reef in Upper Mobile Bay. The purpose of creating a reef in this area is to provide a possible refuge from drill predation when salinities are high and conducive to drill proliferation on the southernmost reefs of Lower Mobile Bay such as Cedar Point East, King's Bayou, and Buoy reefs. Due to being in close proximity to the freshwater flow of the Mobile-Tensaw Delta, the Relay Reef maintains a lower average salinity that controls drills. This area has a hard sandy bottom that can readily hold cultch; however, it is prone to shifting sands during storm events. During recent cultch plantings, cultch was deployed at a higher relief to counteract coverage by shifting sands. Point Clear and Klondike reefs near the eastern shore of Mobile Bay were surveyed in 1968 and determined to be live oyster reefs. Recent surveys have shown that remnants of the reef footprint exist but live oysters were absent. A six-acre fishing reef called Grey Cane Reef was built on a northern portion of Klondike. Surveys did show the presence of some harvestable oysters naturally growing on cultch planted within this ring of riprap.

In the waters of Mississippi Sound, Cedar Point West and Heron Bay reefs consistently have had the highest oyster harvest since 2011. Cedar Point West, which is continuous with Cedar Point East, is located on the west side of Dauphin Island Bridge. Cedar Point West is subject to the same tidal flows and conditions as Cedar Point East and, likewise, the bottom of Cedar Point West shares the same consistency of a hard shell base. It too has been identified as a high-priority site for reef restoration. Heron Bay, which is a grouping of subtidal patch reefs ranging from hard sandy bottom to soft mud, has been identified as a high-priority site for reef restoration as well. Recent cultch planting activities have taken place only on bottoms ranging from hard sand to firm mud. Heron Bay receives adequate flow through the Dauphin Island Bridge and the Cut-off Bridge, spanning a cut between Mon Louis island and Cedar Point, and from numerous small bayous that flow into Heron Bay from the north. The bayous flowing into Heron Bay contain populations of intertidal oysters that help to reseed the small bay and parts of Cedar Point. To the west of Heron Bay is Portersville Bay. Historically, an area designated as Middle Ground, located near the mouth of West Fowl River, was a productive area for oyster harvest. Recent drought conditions have given rise to high average salinities that have made conditions conducive to oyster drill proliferation in this area; however, due to the high incidence of drill predation in this area, Middle Ground has shown little recent productivity.

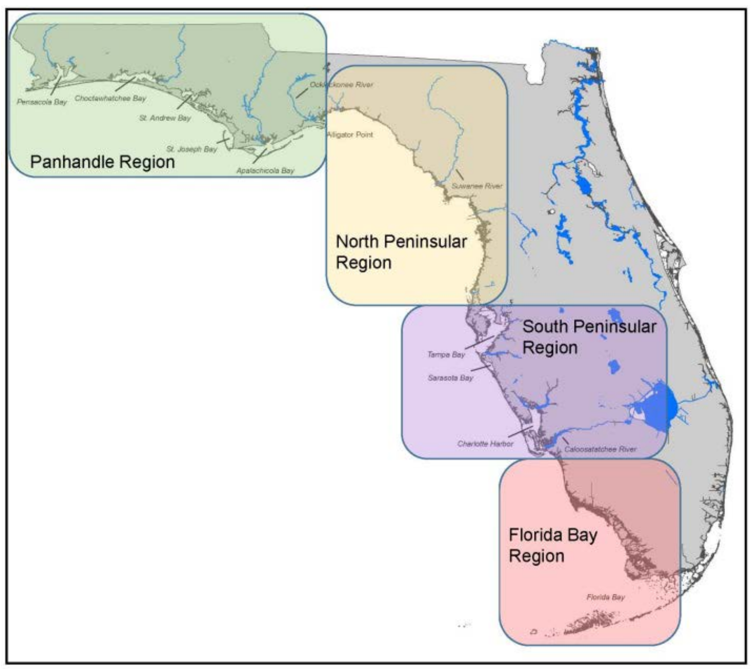
Reefs in Bon Secour Bay include Fish River Reef, Bayou Cour Reef, Bon Secour Reef, Shell Banks, Three Rivers, and Navy Cove. Fish River, Bayou Cour, Bon Secour, and Shell Banks reefs were surveyed in 1968 and oysters were found to be present. These subtidal reefs have been marked, ringed with rip rap, and planted with limestone and oyster shell as a part of the artificial fishing reef program. Recent surveys of these reefs have shown that oysters are absent and that the shell material found within has deteriorated. Three Rivers and Navy Cove are located at Little Point Clear on the Fort Morgan Peninsula. Intertidal and subtidal oysters are located within the small bayous extending to the northwest from Little Point Clear.

Wolf Bay and Perdido Bay are located in Unclassified waters, as termed by NSSP, and are therefore prohibited for the harvest of shellfish. These zones are not extensively surveyed due to the nature of their classification. No known continuous oyster reefs have been located. However, oyster growth does occur readily on piers, pilings, bulkheads, boulders, and riprap. The bottom ranges from hard and sandy to soft and muddy.

5.1.2 Florida

Oysters are present along the entire length of the Gulf Coast in Florida but can be grouped into four major regions based on geographic characteristics: Panhandle, North Peninsular, South Peninsular, and Florida Bay (Figure 5).

Figure 5. Major regions along Florida's Gulf Coast.



The Panhandle region extends from the western boundary of the Florida Panhandle to Alligator Point in the easternmost Panhandle. Within this region, oysters are found in several bays and estuaries including Pensacola Bay (Big Lagoon, Santa Rosa Sound, Escambia Bay, and East Bay), Choctawhatchee Bay, St. Andrew Bay (West Bay, North Bay, and East Bay), St. Joseph Bay (limited oysters due to limited freshwater sources), and the Apalachicola Bay system (Indian Lagoon, Apalachicola Bay, and St. George Sound through Alligator Harbor). In this region, most commercially fished oysters are harvested from subtidal reefs. There are some intertidal oysters, but generally they are not extensive, and are largely limited to creek mouths or marshes. Apalachicola Bay contained the most productive commercial reefs in Florida for many years, but oyster abundance and subsequent harvest rates declined sharply in 2012 due to a variety of environmental and anthropogenic factors. There is a limited but growing aquaculture community in Alligator Harbor. The Pensacola Bay and St. Andrew Bay systems also support some commercial harvest from subtidal reefs. Apalachicola Bay, Pensacola Bay, and St. Andrew Bay have all been recipients of shell plantings, or cultching, since the early 1900s, though most cultch was planted in Apalachicola Bay. Choctawhatchee Bay does not have large abundances of oysters, and only occasionally reports landings. All of the bays, except St. Joseph Bay, are recipients of flow from rivers with very large watersheds, and are thus influenced by periods of above- and below-normal flow, which subsequently impacts salinities in those bays.

The North Peninsular region is comprised of rivers and creeks with open coastal discharges, including the Ochlockonee, St. Marks, Wacissa, Aucilla, Econfina, Steinhatchee, Suwannee, Wacasassa, Withalacoochee, Crystal, Homosassa, Chassahowitzka, Pithlachascotee, and Anclote rivers. Each river has a mix of spring-fed and riverine flows with a wide range of watershed sizes, the largest of these being the Suwannee. Due to the high magnitude flow of the springs, most rivers maintain some flow even during dry periods, and localized rainfall events can lead to large discharges. The Suwannee has periods of extreme flood stage. In the mouths of these systems, a series of shallow intertidal oyster fringing shoreline and discrete bars occur; most are of limited commercial value. The main exception is the area around the Suwannee and southward to Cedar Key, where many of those reefs have been maintained by cultching. Additionally, this area is home to many aquaculture operations. The main species of focus is hard clams (*Mercenaria mercenaria*) but with recent declines in state and Gulf oyster resources, there is growing interest in oyster aquaculture. Minor resources are found in the area of St. Marks and Ochlockonee.

The South Peninsular region is comprised of three relatively large embayments: Tampa Bay, Sarasota Bay, and Charlotte Harbor. Rivers with large watersheds feed Tampa Bay (Hillsborough, Alafia, Little Manatee, and Manatee) and Charlotte Harbor (Myakka, Peace, and Caloosahatchee) and all three bays have many small urbanized creeks. Most of the rivers have modest flow, and are prone to periods of drought and short (frontal) to long (seasonal climatic cycle) flood stages. The historically present oyster bars of commercial value were depleted quickly in the late 1800s and early 1900s. This depletion occurred by a combination of harvest for food and dredging for fill material. There are still fairly extensive intertidal oysters, but the commercially viable subtidal reefs reported in early surveys are no longer present. Harvest is minimal and many areas are classified as prohibited waters due to legacy pollution and fecal coliform risk. The Caloosahatchee River, which enters the GOM near Fort Myers, has been highly altered through channelization and connection via canal to Lake Okeechobee. As a result, the Caloosahatchee estuary experiences altered patterns of freshwater quantity and quality, which in turn negatively affect the ecology and health of the estuary. The Comprehensive Everglades Restoration Plan (CERP), enacted in December 2000, aims to restore, preserve, and protect the South Florida ecosystem. One specific goal of CERP is to restore natural hydrology to the Caloosahatchee estuary in an effort to improve oyster recruitment and survivorship.

The Florida Bay region, south of Sanibel Island, is comprised of a series of small embayments and coastal mangrove forests. This region has been negatively affected by alterations of natural water flow through the Everglades and south Florida. Oysters persist as small intertidal bars, and frequent fringing patch reef and mangrove-associated oysters. The extent and quality of oysters is very poorly documented, but limited freshwater supply and seasonal hypersaline conditions likely limit their abundance and distribution.

5.1.3 Louisiana

Oysters in Louisiana are located throughout the coast at depths of 0–5 m. Statewide, peak oyster reproduction is typically first observed each year in April and May, and again later usually during the fall from September to October, with primary spatfall occurring sequentially in June and again in late September to early November. Population stressors are primarily related to freshwater inflow and temperature, where spring floods and high temperatures can cause summer mortality through physiological stress. Additionally, high salinities, coupled with high summer temperatures, increase predation, disease, and the potential for hypoxia. Where hydrologic conditions are conducive to oyster survival, suitable substrate is frequently the limiting factor in oyster distribution, as opposed to larval oyster abundance (Soniat et al., 2012). Oyster populations within Louisiana can be grouped into three major areas based on geographic location: southwest Louisiana, the Vermilion/Atchafalaya Bay area, and the Deltaic Region.

In southwest Louisiana, known as the Chenier Plains region of the state, two isolated coastal state-managed (public) waterbodies contain the majority of concentrated oyster populations, Sabine Lake and Calcasieu Lake. Sabine Lake, with mostly subtidal reefs, has been closed to oyster harvest since the early 1960s due to past public health concerns. These reefs represent one of the most extensive “natural” reef systems remaining in North America, if not the world (Beck et al., 2011). Continuing eastward, the oyster population in Calcasieu Lake exists on numerous small reef areas, some available for harvest in the central and southern portion of the lake, while other areas in the northern portion are closed to harvest because of public health concerns. There are also large areas of scattered shell/soft bottom habitats in areas open to harvest on the southern portion of the lake. Historically productive reef areas have become less productive in recent years, presumably due to issues associated with saltwater intrusion (predation/disease), combined with harvest pressure. Moving east, the oyster population is sparse, existing primarily in small, isolated shoreline tributaries.

In the Vermilion/Atchafalaya Bay area, centrally located in the state, the oyster population is heavily influenced by seasonal spring floods discharging from the Atchafalaya Basin, resulting in high mortality rates, especially on public grounds. However, fall recruitment is regularly observed. Oysters are present primarily in Southwest Pass, on the exposed Gulf-side of Marsh Island; and in scattered open-water areas to Point au Fer, typically on raised mounds of historical reef intermixed with large amounts of shell hash. In the early 1900s, these historical reefs were much more extensive and formed massive reef complexes. These reef areas were substantially reduced during fossil shell mining during the mid-to-late 1900s. Very little harvest activity is observed here, and few private leases exist.

The Deltaic Region is the largest oyster habitat region in the state and encompasses the eastern half of the Louisiana coast from Terrebonne Parish to the Mississippi border. In this area the oyster population is present in coastal lakes and bays, and fragmented marsh areas. Oyster populations are abundant in these areas and private leases are prevalent. The highest concentrations of oysters on public water bottoms typically occur on cultch material that is regularly deployed throughout the state; however, much of the population exists on leased historical reefs and scattered shell/soft bottom habitats. Leaseholders frequently move oysters and deposit cultch depending on hydrologic conditions. In the Barataria and Terrebonne estuaries, oyster production areas and how they fluctuate with hydrologic conditions were defined in Melancon et al. (1998). Oyster populations in Barataria and Breton Sound estuaries are heavily influenced by Mississippi River levels, and respectively, by two water diversions, Davis Pond and Caernarvon. The influence by freshwater will be greatly increased by two proposed sediment diversions, mid-Barataria and mid-Breton Sound, if and when constructed. Breton Sound was the most productive public oyster area in Louisiana 10–15 years ago, but the population has declined substantially over the past several years due primarily to increased river influence that lowered salinities throughout the spring and summer. Mississippi Sound/Biloxi Marsh areas contain the most productive and extensive public oyster areas in the state that are open to harvest. These reef areas are primarily influenced by the Pearl River, but can also be affected by the Mississippi River during periods of extreme flooding if the Bonnet Carre spillway is opened. Additional possible stressors to the oyster population in the Deltaic Region are associated with marsh erosion, where shoreline retreat is removing protected backwaters where intertidal oysters are prevalent. Several living shoreline projects have been implemented in the Deltaic Region, as well as other parts of the state, in an attempt to simultaneously reduce erosion rates and restore intertidal oyster populations, resulting in varying levels of success.

5.1.4 Mississippi

According to the Mississippi Department of Marine Resources (MDMR), the shellfish resource management agency for the state, there are approximately 23,930 acres of existing and historical subtidal oyster reefs in Mississippi waters. Small intertidal reefs, though not well-documented, have also historically been present in the shallow estuaries along the Mississippi Gulf Coast, including Back Bay, Graveline Bay, and Grand Bay; as well as tidal inlets on Cat Island, which is located approximately seven miles off the coastline in the Mississippi Sound (the Sound).

The primary oyster reefs are located in the western portion of the Sound where large, subtidal reefs exist, some of which are several feet thick (Demoran, 1979). Currently around 7,500 acres of harvestable reefs exist in this area of the Sound, representing 97% of the harvestable reefs in Mississippi state waters.

Mississippi oyster reefs have seen considerable decline in productivity in the past decade, primarily due to Hurricane Katrina in 2005, the BP oil spill in 2010, and freshwater inflow from the Bonnet Carre Spillway in 2011 (MDMR, Unpublished data). The spillway opened on May 9, 2011, and closed on June 20, 2011, and, at its peak flow rate, reached a maximum discharge rate of 316,000 cubic feet per second of freshwater. The MDMR stated that the influx of freshwater from this flood event resulted in the mortality of approximately 86% of the live oysters in the western Sound. Overall, the Mississippi oyster fishery in 2004 yielded over 400,000 sacks of oysters; in the 2015 season, that yield was approximately 38,000 sacks, a reduction of over 90%. According to studies, there has been a 47% increase in area of oyster grounds but a 97% decrease in oyster density (zu Ermgassen et al., 2012).

Over the last century, Mississippi oyster reefs have been impacted by many factors. During the first half of the century, there was intensive fisheries extraction (Kirby, 2004), followed by concentrated dredging of reefs (1951–1973) for building blocks, poultry feed, and other products (Demoran, 1979). This impact was exacerbated by coastal degradation from urban and industrial development, and altered hydrological regimes. In a review of historical abundance of oyster reefs compared to current abundance remaining, Beck et al. (2009) estimated that the Sound has lost at least 90% of its oyster reefs. The Pearl River, which drains approximately 8,600 square miles, experiences frequent flooding due to upstream flows as well as anthropogenic diversions in the lower basin. Flooding events are frequent in both the West and East Pearl rivers and have immediate adverse impacts to estuarine resources (specifically oysters), as increased freshwater flows into the Sound result in commercial oyster reef closures, an increased risk of oyster mortality due to freshets, sedimentation, and a reduction in water quality. Current stressors to Mississippi's oyster population also include competitors such as hooked mussels and predators such as oyster drills, as well as disease such as Dermo (caused by *Perkinsus marinus*), and hypoxia/anoxia events.

5.1.5 Texas

Oysters exist in every major bay system along the Texas coast and can be found in both subtidal and intertidal areas. However, they are not evenly distributed among or within bays. In Sabine Lake, a small estuary that straddles the Texas/Louisiana border, oysters have not been commercially harvested since at least the 1960s due to pollution concerns. Because of this, an extensive complex of relatively high vertical relief oyster reefs has been able to persist. These reefs are concentrated mainly in the southernmost portion of the lake. The Texas portion of the lake is estimated to have about 1,100 acres of oyster habitat. Moving down the coast from north to south, Galveston Bay is Texas' largest estuary and has historically been the state's largest producer of oysters. Powell et al. (1995) surveyed Galveston Bay oyster habitat using acoustic techniques and estimated that Galveston Bay (not including West Bay and Pelican Island embayment) contained about 14,220 acres of subtidal oyster habitat. Since this survey was done, Galveston Bay's oyster reefs have experienced impacts from drought, heavy fishing pressure, and hurricanes. In particular, Hurricane Ike, which passed directly over Galveston Bay in September 2008, produced a storm surge that caused major sedimentation impacts. Approximately 8,000 acres of oyster habitat were estimated to have been damaged or destroyed in this event. Since the storm, the Texas Parks & Wildlife Department has been conducting side-scan sonar surveys of Galveston Bay oyster habitat. Preliminary results indicate that many of the East Bay reefs that were impacted by Ike's storm surge have not recovered. However, the survey results also detected many small reef patches in other regions that have heretofore not been recorded, making before and after comparisons of the two surveys complicated.

Matagorda Bay is the next major bay complex south of Galveston Bay. This system was last surveyed in 1976, at which time it was estimated to support 6,505 acres of oyster habitat (Benefield and Hofstetter, 1976). Continuing south, San Antonio Bay was last surveyed in 1982, when 2,011 acres of oyster habitat were reported (Burg and Crowe, 1982). Aransas Bay was surveyed in 1962, when 840 acres were reported (Diener, 1975). Copano Bay, a sub-estuary of Aransas Bay, was surveyed in 2014, when 6,392.5 acres of oyster habitat were observed along with 2,867.5 acres of "shell" habitat (Legare and Mace, 2017). In this survey, oyster habitat was defined as any consolidated hard substrate that supports or is capable of supporting oyster growth, and shell habitat was defined as substrates composed of unconsolidated whole shells or shell fragments (Legare and Mace, 2017). Oyster habitat in Corpus Christi Bay was surveyed in 1961, when 566 acres were reported (Martinez, 1961). No data exist for oyster habitat acreage in the Upper Laguna Madre estuary. In the Lower Laguna Madre estuary, about 50 acres of oyster habitat have been reported (Benefield and Hofstetter, 1976).

These data are restricted to subtidal oyster habitat only. Reliable information on intertidal oyster habitat acreage in Texas does not currently exist. Since many of these surveys were conducted several decades ago, the results should be interpreted with caution.

Scientific studies have documented the existence of two separate oyster (*Crassostrea virginica*) genotypes in Texas, one from Sabine Lake to Corpus Christi Bay and one in the lower Laguna Madre (Groue and Lester, 1982; Buroker, 1983). These results imply that oyster larvae move between bay systems except for between the lower Laguna Madre and the rest of the Texas coast. However, the mechanism of larval transport remains unknown. Anderson et al. (2014) examined allelic and genotypic patterns from 11 microsatellite markers to assess genetic structure and migration between the 2 populations within a zone of secondary contact in the Corpus Christi/Aransas Bay estuarine complex. In addition to confirming the existence of the two genotypes in the area, they found that the distribution of genotypes in the contact zone suggests that hybridization between the two populations is limited. They proposed that differences in the time of spawning may have limited hybridization over the time since the opening of the Gulf Intracoastal Waterway in 1949, when contact between the two populations was restored. The study also pointed out that the zone of secondary contact has apparently migrated about 27 km over approximately 23 years compared to a previous study (King et al., 1994), suggesting that the southern genotype is migrating northward.

5.2 Population Connectivity

In the GOM, nearshore (includes intertidal) and subtidal oyster populations are believed to form a single larval pool, with nearshore oyster reefs serving as an important source of larvae to subtidal reefs (Murray et al., 2015). As a part of the DWH NRDA, Murray et al. (2015) used the Advanced Circulation (ADCIRC) model to simulate oyster larval transport in the waters of Louisiana, Mississippi, and Alabama; and to analyze the percentage of larvae originating in a basin or sub-basin that remain in that location and what fraction travel to, and potentially settle within, a new basin or sub-basin. In several basins or sub-basins, released larvae tended to stay within the boundaries of the release area; however, in some cases, particularly within large embayments, larval exchange across sub-basins was observed. Murray et al. (2015) also observed that nearshore oyster habitat tends to be a net contributor of larvae to subtidal oysters. Figures 6 and 7 provide examples of connectivity results of the ADCIRC modeling for the Barataria Bay sub-basins. In each figure, the pie charts show the ultimate disposition of particles released within each sub-basin. For example, Figure 6 shows that in 2010, about two-thirds of larvae released from the northwest sub-basin of Barataria Bay (BBNW shown in purple) were likely to settle in that same sub-basin, while the remaining third were distributed among the other three Barataria Bay sub-basins. The pie charts in Figure 7 show the proportion of oyster larvae released from nearshore habitat areas in 2010 that would be expected to settle within nearshore habitat (gray) and the portion that would be expected to settle in subtidal oyster habitat (black). As shown in the figure, about half or more of the releases of larvae from nearshore habitat in Barataria Bay in 2010 were expected to settle on subtidal reefs, emphasizing the importance of the nearshore habitat to healthy subtidal oyster populations. Such sub-basin connectivity becomes critical to population recovery after catastrophic events such as excessive precipitation or excessive Davis Pond Diversion flow.

Murray et al. (2015) also investigated average displacement of larvae for low-energy periods and high-energy (e.g., tropical storm or hurricane) periods using both nearshore and subtidal larval origin locations. In the low-energy event (June 5, 2010), they found that the vast majority of settled larvae across all of the basins are displaced ≤ 50 km (displacement = difference between the initial release point and the final settlement location). In the high-energy event (June 24, 2010), the displacement distances range from ≤ 50 km to ≤ 150 km, depending on the basin.

Figure 6. Average sub-basin to sub-basin settlement potential of larval releases from within subtidal habitat in Barataria Bay (BB), based on releases modeled in 2010 using the ADCIRC model. Pie charts represent the average final settlement locations of larvae originating from the labeled sub-basin. Averaged across 27 releases, April–October 2010. ADCIRC modeling results from 3/25/2015, adjusted for estimated oyster habitat percent cover.

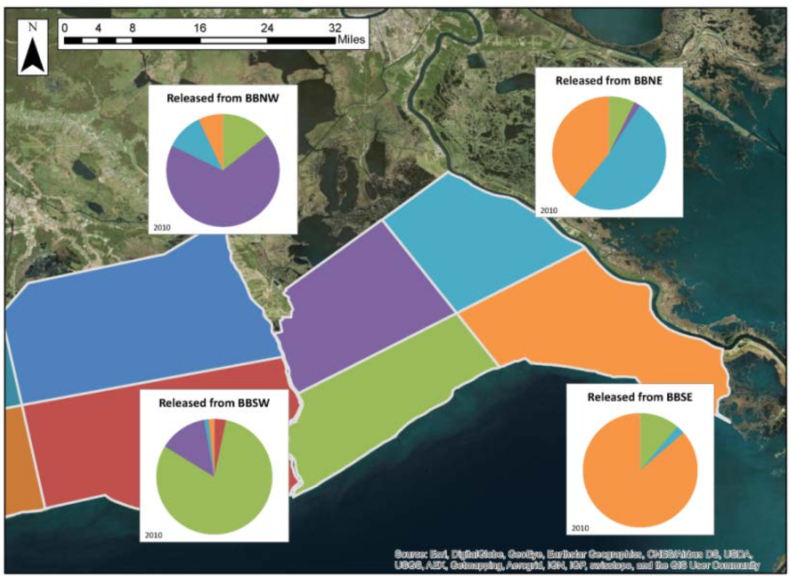
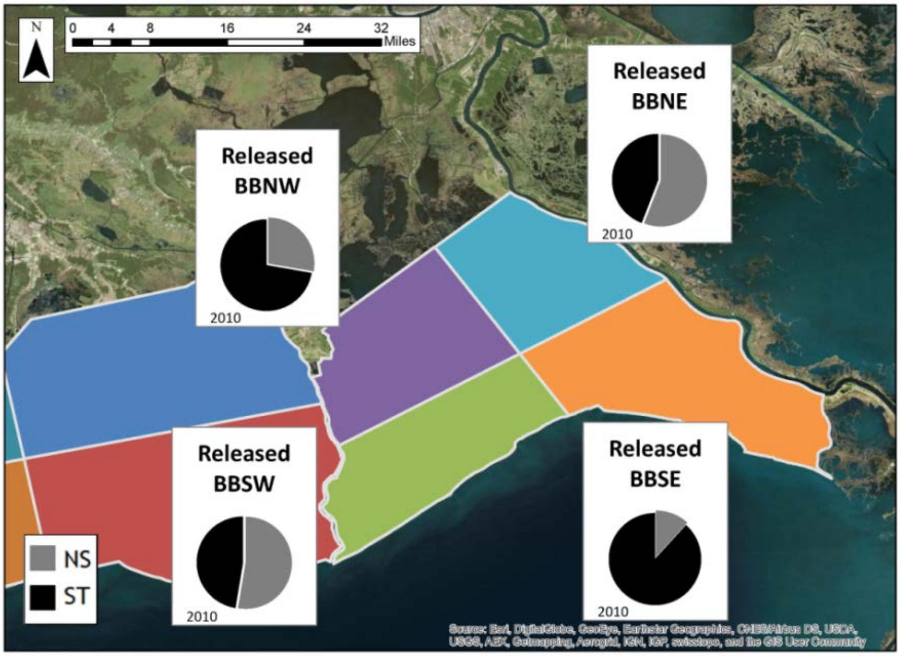


Figure 7. Average nearshore to subtidal settlement potential of larval releases from within nearshore habitat in Barataria Bay (BB), based on releases modeled in 2010 using the ADCIRC model. Pie charts represent the average final settlement locations of larvae originating from the labeled nearshore area. Averaged across 27 releases, April–October 2010. ADCIRC modeling results from 3/25/2015, adjusted for estimated oyster habitat percent cover. Solid gray represents settlement in nearshore habitat; black represents settlement in subtidal habitat.



5.3 Population Genetics

Eastern oysters, like other sessile organisms with planktonic larvae, have the capacity for dispersal during their several-week planktonic larval stage prior to settlement on hard substrate (Buroker, 1983). Studies have been equivocal regarding the number of genetically distinct populations across the range of the eastern oyster (Murray and Hare, 2006); however, the bulk of the evidence suggests genetic differentiation between Atlantic and Gulf populations (Reeb and Avise, 1990; Karl and Avise, 1992; Hoover and Gaffney, 2005), with eastern Florida as the transition zone (Hare and Avise, 1996; Anderson et al., 2014). This differentiation of Atlantic and Gulf populations has been explained as a result of the combined effects of marine currents and natural selection maintaining genetic population differentiation; however, genetic evidence [multiple allozyme loci, single-copy nuclear (scn) DNA; Buroker, 1983; McDonald et al., 1996] suggests potential gene flow between Gulf and Atlantic populations with a transition cline along eastern Florida, but that natural selection ultimately maintains genetic differences (Hare and Avise, 1996).

Across the northern GOM specifically, only a few studies have examined eastern oyster genetics across the coast. Grady et al. (1989) surveyed 10 populations from Galveston Bay to Mississippi Sound and concluded that all populations were genetically very similar (Nei's genetic similarity values: 0.94 to 0.98). However, studies encompassing bays to the Mexico border found a genetically distinct population in the Laguna Madre area (Groue and Lester, 1982; Buroker, 1983; King et al., 1994; Hoover and Gaffney, 2005; Varney et al., 2009).

Genetic differentiation of the Laguna Madre population may be due to adaptation to hypersaline conditions (up to 35 ppt) created by low levels of precipitation and lack of river inflow, as well as selection or genetic drift due to isolation from oyster populations farther north (King et al., 1994).

For more specifics on the genetic evidence, see the National Oceanic and Atmospheric Administration summary report (http://www.nmfs.noaa.gov/pr/species/Status%20Reviews/eastern_oyster_sr_2007.pdf).

6. Threats to Oyster Populations

Oysters and their habitats are threatened by natural causes and by human activities. Below is a discussion of general threats to oysters, impacts resulting from the DWH oil spill, and threats from long-term changes in climate.

6.1 General Threats to Oysters

General threats to oyster populations in the GOM include hydrologic changes; disease, predation, and competition; pollution, eutrophication, and hypoxia; sedimentation and burial; and physical disturbance/removal. See below and VanderKooy (2012) for more detail on threats to oyster populations.

6.1.1 Hydrologic Changes

Perhaps the greatest threat to oysters is prolonged and extreme changes in salinity, which can be caused by increased freshwater inflow producing low salinities or prolonged low freshwater inflow producing hypersalinity. These changes to the hydrologic system may be natural, such as significant/extended rainfall events or prolonged droughts, but may also be related to anthropogenic (i.e., human-caused) influences, such as hydrological alterations to freshwater inflow such as dams, impoundments, or river diversions. In some cases, hydrologic alterations may be associated with the restoration of other habitat types. For example, river diversions in Louisiana have been proposed to redirect sediment-rich river water to coastal marshes to build land for coastal restoration; however, they could also affect the salinity regimes and nutrient loads in estuaries and therefore may affect oyster populations.

At low salinities, decreased oyster survival and growth are primarily physiological responses. Even relatively small increases in sea surface temperature can affect oyster growth and survival, largely through the interactive effects of low salinities with high temperatures (La Peyre et al., 2013). If floods reduce salinity significantly, spawning and settlement may not occur during that year, affecting population dynamics. At higher salinities, decreased oyster survival and growth are primarily a response from increases in predation and disease (as discussed in the next sections).

6.1.2 Disease, Predation, and Competition

The prevalence of disease and predation is another threat to oyster populations, which is closely linked to changes in salinity and temperature. Higher temperatures and salinity are associated with outbreaks of *Perkinsus marinus*, a protist parasite that causes the disease known as Dermo or perkinsosis in oysters (Soniat, 1996). Predation by oyster drills (*Urosalpinx cinerea, Stramonita haemastoma*) can decrease oyster populations, especially subtidal populations. Oyster drills are most prevalent at higher salinities, and generally not found below a salinity of 15 ppt (Garton and Stickle, 1980). Water temperature also influences the predation rate of oyster drills, with drills more active at higher temperatures and dormant between 10°C and 12.5°C (Garton and Stickle, 1980).

Other organisms are known to cause physical stress to oysters. For example, Melancon et al. (2015) found that shell pests such as Gulf stone crabs (*Menippe adina*), polychaete worms (Class: Polychaeta), and boring sponges (*Cliona* spp.) can make shells brittle and more prone to loss by wave activity. The red boring sponge, *C. celata*, occurs more often when salinities are greater than 10–15 ppt, but suffers significant mortalities when consistently less than 10 ppt (Hopkins, 1962). The mud worm, *Polydora websteri*, thrives at a salinity of 20 ppt, but has shown sublethal stress when subjected to a salinity less than 10 ppt (Brown, 2012).

Lastly, oysters can also experience competition from other organisms for both space and food. Competitors for attachment space can hinder the settlement of oyster larvae. For example, acorn barnacles, *Balanus* spp., compete with oysters for attachment space and can render shells or other substrates unsuitable for spat settlement after only one month of immersion (Ingle, 1951). Another significant competitor in low to intermediate salinities favorable to oysters is the hooked mussel, *Ischadium recurvum*, which competes for food (Gedan et al., 2014) and limits shell space available for settlement of oysters in large numbers (Melancon et al., 2015).

6.1.3 Pollution, Eutrophication, and Hypoxia

Direct and indirect sources of pollution tied to coastal development and human population growth along estuaries and coasts can negatively affect water quality and, thus, oyster growth and survival. Coastal development not only increases sources of pollution, but also removes protective upland and nearshore habitats beneficial to water quality and sediment levels healthy for oyster reefs. Pollutants such as heavy metals, petroleum hydrocarbons, and pesticides that enter the bays and estuaries from coastal runoff and vessel discharge can negatively affect oyster growth and survival (VanderKooy, 2012). Increased nutrient supply from urban stormwater and agricultural runoff can lead to eutrophication, harmful algal blooms, and the development of hypoxic/anoxic conditions in coastal waters. In the bays and estuaries of the northern GOM, hypoxic/anoxic conditions mostly occur during the summer months in deeper, high-salinity waters. When exposed to low DO, juvenile and adult oysters can close their shells and respire anaerobically for a short time, with longer tolerances at low temperatures. For example, juvenile and adult oysters may tolerate hypoxic conditions for a month or more at water temperatures around 10°C, but this duration is dramatically reduced to a week or less at 30°C (Shumway and Koehn, 1982).

6.1.4 Sedimentation and Burial

Sedimentation from runoff and storm surge can smother reefs and is especially a risk to oyster reefs found in bays and enclosed areas. For example, Hurricane Ike, which passed directly over Galveston Bay in September 2008, produced a storm surge that caused major sedimentation impacts to the oyster reefs in the area. This increase in sedimentation can negatively affect oyster settlement, with as little as a 1–2 mm layer of sediment on cultch, having the potential to prevent the settlement of larvae (Cake, 1983). Lenihan and Peterson

(1998) demonstrated that reef height is of significant importance where sedimentation issues are common.

Sedimentation can also slow oyster growth and/or reduce survival, as oysters close their valves and stop filtering to avoid sediment concentrations that are too high (Beseres Pollack et al., 2011; Solomon et al., 2014).

6.1.5 Physical Disturbance/Removal

Oyster reefs may be affected by physical disturbance and/or removal of substrate during oyster harvesting and other human activities (VanderKooy, 2012). For example, oyster harvesting may reduce the vertical relief of reefs, reduce available substrate for settlement, and cause reef fragmentation due to the removal and/or spreading of oyster cultch. Additionally, other fishing activities, such as bottom trawling, boating activities, and dredging of navigational channels, can cause physical disturbance and damage to oyster reefs (VanderKooy, 2012).

Beck and La Peyre (2015), working in Louisiana, showed that reef substrate on harvested areas were more fragmented and had lower densities of live oysters and hooked mussels than non-harvested reefs. Oyster harvest also appeared to have decreased the number of large oysters in particular and to have increased the percentage of reefs that were nonliving. However, the differences in reef matrix composition had little effect on resident nekton communities and slightly greater invertebrate diversity was found on harvested reefs.

6.2 Long-Term Effects of the DWH Oil Spill

The DWH oil spill and associated response activities reduced oyster abundance and density in nearshore and subtidal areas that experienced oiling and were exposed to freshwater releases (DWH NRDA Trustees, 2016). The loss of these oysters decreased spawning stock biomass of oyster and has lowered larval recruitment of oysters across a large area. In addition to the loss of larvae as a result of decreased spawning stock biomass, loss of larvae exposed to oil as well as suppressed reproduction of subtidal oysters exposed to freshwater in 2010 has contributed to the low levels of natural recruitment seen in many areas since the spill.

6.2.1 Loss of Nearshore Oyster Cover

Shoreline oiling and cleanup actions significantly reduced nearshore oyster habitat over an estimated total of 250 km of shoreline (Roman, 2015; DWH NRDA Trustees, 2016). Fringing oyster habitat occurs, often in a patchy configuration, along marsh shorelines in shallow waters within 3 m from shore. Although fringing oyster habitat is common within the nearshore environment, it is fragile and has natural recovery times that can take decades (Powers et al., 2015b). The physical destruction of oyster cover during cleanup activities further impacted the potential recovery of this type of oyster habitat. The loss of oyster shell cover reduced settlement of larvae needed to form new reefs. Further natural growth (or spreading) of existing habitat occurs at a very slow rate in these systems (i.e., centimeters per year). Consequently, the recovery of nearshore fringing oyster habitat is not expected to occur without restoration actions.

Injury assessment surveys and sampling provide information about the shoreline locations injured. However, the supply of larvae to these sites is a critical consideration due to the need to rapidly colonize reefs to be restored. Oyster recruitment can stabilize the fringing reef structure by minimizing fouling by other sessile invertebrates and preventing the physical loss of cultch from the sinking of exposed shell in the nearshore environment. In addition, because of the reduction in nearshore oyster reefs where these impacts occurred, shoreline erosion rates approximately doubled along at least 174 km of vegetated shoreline over at least three years, resulting in wetland loss that cannot recover naturally (Powers et al., 2015b; Roman, 2015; DWH NRDA Trustees, 2016).

6.2.2 Recruitment Failure

The DWH oil spill and associated response activities severely affected the standing stock biomass of nearshore and subtidal oysters. One effect of this loss of adult equivalent oysters was reduced larval production and spat settlement, and diminished recruitment beginning in 2010 and continuing at least into 2014 (DWH NRDA Trustees, 2016). The lack of a robust oyster recruitment recovery since the spill is likely due in large part to the direct loss of the spawning stock biomass in both nearshore and subtidal areas. However, nearshore oysters are likely critically important in producing oyster larvae because these oysters do not experience the harvest pressure of their subtidal counterparts in commercially fished areas. The reproductive output of subtidal oyster populations may gradually recover without intervention, provided the available substrate does not degrade prior to a successful recruitment event. However, the decreased reproductive output from nearshore oysters and the larvae they would have produced are expected to persist until restoration rebuilds spawning oysters in the intertidal zone, where oil and response actions eliminated oyster shell cover (Powers et al., 2015a, 2015b; DWH NRDA Trustees, 2016).

6.2.3 Loss in Abundance of Market Size Oysters

Between 4 billion and 8.3 billion subtidal oysters (adult equivalents) were estimated to have been lost as a result of the DWH oil spill; this loss accounts for subtidal oysters directly killed by river water releases, the lost reproductive output from those oysters, and the reduced egg output of surviving oysters that experienced low-salinity conditions in 2010 (DWH NRDA Trustees, 2016). DWH NRDA studies indicate that the direct oyster mortality injury is most pronounced in Barataria Bay and Black Bay/Breton Sound; and oyster reproduction has been most severely affected in Barataria Bay, Breton Sound, and Mississippi Sound. Subtidal injury impacted at least three generations.

6.3 Long-Term Changes in Climate

A long restoration period, coupled with a dynamic and changing environment, will present planning and implementation challenges. As discussed above, the eastern oyster can tolerate a range of environmental conditions, allowing it to survive in a variable environment (Eastern Oyster Biological Review Team, 2007). With temperature and salinity having the greatest influence on oyster growth and survival, long-term changes to these variables could have potential impacts on oyster populations in the GOM. Below we present past and projected changes in climate, potential responses of oysters, and potential restoration actions.

6.3.1 Past and Projected Changes in Climate

On average, air temperatures in the southeastern United States cooled during the 20th century, especially from the 1950s to the late 1960s (Karl et al., 1996; Rogers, 2013). Powell and Keim (2015) examined trends in daily temperature and precipitation extremes for the southeastern United States from 1948 to 2012 and found that since the mid-1900s, warming across the region could be attributed to increases in the daily minimum temperature. Extreme hot and cold spells are also getting shorter. Over the entire region, extreme rainfall events increased while the duration of wet spells decreased. An east-to-west pattern was detected with Texas, Louisiana, and Mississippi becoming wetter due to increases in total annual precipitation and the number of days with rainfall exceeding 10 mm and 20 mm. Florida has become drier overall, but also more variable in rainfall by season. Between 1941 and 1965, the GOM experienced active hurricane seasons followed by a calm period until the 1990s. Hurricanes are influenced by several climatic factors, and no historical trend in the number or location of tropical storms has been identified (Henderson-Sellers et al., 1998).

These observed trends are likely to continue, and using sophisticated climate models, a number of recent studies and assessment reports project future changes to the climate along the GOM and southeastern United States over the next several decades. These changes include:

- ***Increased air temperatures*.** Air temperatures are expected to rise by 2.2–4.4°C in the southeastern United States by the year 2100 (Carter et al., 2014). Increased occurrence of the La Niña phase of the El Niño Southern Oscillation may also lead to warmer, drier conditions that may increase the salinity of estuarine and coastal waters.
- ***Increased sea surface temperatures*.** Sea surface temperatures in the GOM may rise by 2–3°C by the latter half of the 21st century (Biasutti et al., 2012). This warmer water, coupled with associated decreases in DO, could affect oyster survival and reproduction via a variety of mechanisms, which are described in more detail in the next section.
- ***Changes in precipitation.*** Although annual precipitation may remain relatively constant in the Gulf Coast region, climate simulations suggest that both the seasonality and intensity of precipitation are likely to change in the future (Walsh et al., 2014). This will lead to larger pulses of freshwater run-off to coastal ecosystems, mainly in estuaries drained by large watersheds. Greater run-off can decrease estuarine and coastal salinity, pH, and DO, while simultaneously increasing turbidity. Increased run-off could also facilitate the spread of pathogens and contaminants that are known to reduce oyster survival and reproduction (Chatry et al., 1983; Hofmann et al., 1994; Kim et al., 1999; Wilson et al., 2005; Soniat et al., 2009; Apeti et al., 2011; Beseres Pollack et al., 2011; Waldbusser et al., 2013; Ren et al., 2015).
- ***Increased coastal storm intensity.*** In the GOM, tropical storms and hurricanes may become more intense in the future (Biasutti et al., 2012; Walsh et al., 2014; CPRA, 2017). This will likely lead to higher storm surges and coastal flooding, which can increase the turbidity of estuarine and coastal waters. Because more intense storms are also associated with greater precipitation events, there may also be more freshwater run-off and related changes in salinity, temperature, pH, DO, and turbidity, as described above (Chatry et al., 1983; La Peyre et al., 2003; Apeti et al., 2005; Johnson et al., 2009b; Beseres Pollack et al., 2011; Van Hooidonk et al., 2014).

- ***Sea level rise.*** Sea level rise estimates for coastal Louisiana over the next 50 years range from 0.43 to 0.83 m (CPRA, 2017), and may approach 0.8 m (Vermeer and Rahmstorf, 2009). This will increase the salinity of estuaries, with implications for oyster disease and predation (Chu et al., 1993; Beseres Pollack et al., 2011; La Peyre et al., 2013; Solomon et al., 2014).

6.3.2 Potential Responses of Oysters to Changes in Climate

The long-term environmental changes described above could either directly stress oyster populations or create indirect, localized stressors, including changes in salinity, pH, and DO. Localized increases in freshwater run-off and/or coastal flooding can also stress oysters by increasing turbidity and the distribution of toxins, contaminants, and disease. Oyster reefs may be able to adapt to changes in climate by recolonizing new areas; however, this would be dependent on a healthy regional larvae pool and the availability of hard substrate.

Potential oyster responses to direct and indirect stressors caused by projected changes in climate include:

- ***Changes in spawning timing and frequency.*** Warmer sea surface temperatures (> 20°C) may promote an earlier onset of oyster spawning, starting as early as March (Galtsoff, 1938; Hofmann et al., 1994; Wilson et al., 2005). However, higher water temperatures in the GOM could also lead to more frequent spawning pulses throughout the spawning season, which is currently between April and October (Hofmann et al., 1992).
- ***Changes in feeding and growth rate.*** Increased sediment loads in estuarine and coastal waters can slow oyster growth and/or reduce survival, as oysters close their valves and stop filtering to avoid sediment concentrations that are too high (Beseres Pollack et al., 2011; Solomon et al., 2014). Salinity levels lower than 10 ppt may lead to oyster closure, and reduced filtration and growth rates (Chatry et al., 1983; La Peyre et al., 2009). Warmer water is known to slow the growth rates of adult oysters if water temperatures exceed biological tolerances, which have yet to be defined, but are likely somewhere above 30°C (Shumway, 1996; Rybovich et al., 2016).
- ***Reduced larval survival and changes in spat settlement*.** Oyster larvae and spat can be negatively affected by climate change via a number of mechanisms. Warmer water, coupled with decreases in DO, may reduce larval survival and spat settlement (Shumway and Koehn, 1982; Baker and Mann, 1992, 1994; Beseres Pollack et al., 2011). Warmer temperatures and higher salinity may lead to increased predation on spat (Gunter, 1955; Garton and Stickle, 1980; Shumway, 1996; La Peyre et al., 2013; Solomon et al., 2014). Larval survival and spat settlement are known to decline in turbid or eutrophic conditions, which may increase under climate change (La Peyre et al., 2009; Beseres Pollack et al., 2011; Waldbusser et al., 2013; Van Hooidonk et al., 2014; Ekstrom et al., 2015). Sudden decreases in surface water temperatures, associated with intense coastal storms, can also reduce spat survival (Hayes and Menzel, 1981; Wilson et al., 2005; Beseres Pollack et al., 2011).
- ***Increased mortality and reduced reproduction with exposure to oyster pathogens*.** Warmer (> 25°C) and more saline (> 15 ppt) estuarine water creates more favorable conditions for harmful algal blooms and the disease *Perkinsus marinus*, both of which can increase oyster mortality and reduce oyster reproduction (Soniat, 1985; Chu et al., 1993;

Burreson and Ragone Calvo, 1996; Ford and Tripp, 1996; Cook et al., 1998; Woodward-Clyde, 1998; Glibert et al., 2007; Pierce and Henry, 2008; La Peyre et al., 2013).

- ***Changes in sedimentation and oyster burial*.** Coastal flooding and sedimentation, as well as alterations in sediment dynamics from marsh loss and sea level rise, can lead to oyster reef burial and/or the increased deposition of toxins and contaminants on or near oyster beds, increasing oyster mortality (Weis et al., 1994; Kim et al., 1999; Encomio and Chu, 2000; La Peyre et al., 2003; Apeti et al., 2005, 2011; Bushek et al., 2007; Lannig et al., 2008; Johnson et al., 2009b).
- ***Increased predation on oysters*.** Higher salinity, from sea level rise (intertidal influence) or drier conditions, can create more favorable conditions for oyster predators (Gunter, 1955; Garton and Stickle, 1980; Shumway, 1996; Soniat et al., 2009; La Peyre et al., 2013).

6.3.3 Potential Restoration Actions

Environmental conditions across restoration project sites will likely be subject to much geographical (spatial) and temporal variability. Given this variability, and the differential impacts of a changing climate on different life stages of oysters, it will be critical to ensure restoration actions maintain or enhance productive reef networks that are well-connected. Appropriate connectivity among reefs, both restored and existing, will allow for oysters at different life stages to best take advantage of the variability across sites. For example, larval supply from a reef that is impaired in one year due to a killing flood may be replaced by larval supply from a nearby unaffected reef. Similarly, higher predation in a given reef due to increased salinity could be offset by stronger growth and/or recruitment in a nearby site not suffering from similar conditions. A number of adaptive management actions could help ensure restoration activities have lasting benefits, including:

- Ensure spatial connectivity among reefs to foster resilience
- Anticipate potential short- and long-term changes in climate during project siting and design, and monitor key environmental variables to detect changes or shifts in oyster habitat over time
- Account for temporal changes in oyster spawning when planning implementation of projects such as the timing of cultch placement
- Incorporate spatial distribution across habitat gradients (e.g., salinity gradients) into the siting of restoration projects.

7. Key Sources for More Information

Below are a few key documents with biological and ecological information for the eastern oyster:

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Module 3

Overview of Related Activities – Oysters

1. Background

This module is intended to summarize available information on existing management, assessment, and monitoring programs; *Deepwater Horizon* (DWH) Natural Resource Damage Assessment (NRDA) Early Restoration projects; other funding mechanisms related to restoration and/or management; and restoration and industry stakeholders related to the restoration of the eastern oyster (*Crassostrea virginica*) in the northern Gulf of Mexico (GOM). It does not contain a comprehensive list of all individual oyster restoration and management projects, but does include links to individual programs that provide more details. This module can be used to identify and leverage existing opportunities, incorporate inherent efficiencies, and evaluate potential cumulative benefits and project synergies. Further, it has the potential to limit project selection redundancy, promote wise stewardship of available resources, and promote the sharing of monitoring data among programs (see DWH NRDA Trustees, 2016; pp. 5-379, and 7-16 to 7-17).

2. National/Regional Management Programs

2.1 National Programs

While oyster management is accomplished by individual state regulations, various federal agencies, through their administration of laws, regulations, and policies, may affect the oyster fishery. For example, the production of oysters for consumption is closely regulated by federal and state agencies to minimize the occurrence of public health incidents. Below is a summary of key national programs. For a detailed description of fishery management jurisdictions, laws, and policies, see Chapter 7 of *The Oyster Fishery of the Gulf of Mexico, United States: A Regional Management Plan* (VanderKooy, 2012).

2.1.1 National Shellfish Sanitation Program

The National Shellfish Sanitation Program (NSSP) is the federal/state cooperative program recognized by the U.S. Food and Drug Administration (FDA) and the Interstate Shellfish Sanitation Conference (ISSC) for the sanitary control of shellfish produced and sold for human consumption. The purpose of the NSSP is to promote and improve the sanitation of shellfish (i.e., oysters, clams, mussels, and scallops) moving in interstate commerce through federal/state cooperation and uniformity of state shellfish programs. Participants in the NSSP include agencies from shellfish producing and non-producing states, FDA, the U.S. Environmental Protection Agency (EPA), the National Oceanic and Atmospheric Administration (NOAA), and the shellfish industry.

Source:
https://www.fda.gov/Food/GuidanceRegulation/FederalStateFoodPrograms/ucm2006754.htm.

2.1.2 ISSC

The ISSC is a voluntary organization that brings together state shellfish agencies to participate in the regulatory guidelines and procedures for shellfish regulatory programs. It develops and reviews shellfish regulatory guidelines that are approved by the FDA and published in the NSSP Model Ordinance to ensure that the shellfish produced in U.S. states are in compliance with the guidelines and are safe and sanitary. In addition to producing the Model Ordinance, the NSSP includes programs for the designation of state growing area classification, dealer certification programs, and FDA evaluation of state program elements.

Source: https://www.fda.gov/downloads/Food/GuidanceRegulation/FederalStateFoodPrograms/UCM505093.pdf.

2.2 Gulf States Marine Fisheries Commission

The Gulf States Marine Fisheries Commission (GSMFC) is an organization of the five states that border the GOM (Texas, Louisiana, Mississippi, Alabama, and Florida). The GSMFC was established in 1949 and has as its principal objective the conservation, development, and full utilization of the fishery resources of the GOM, to provide food, employment, income, and recreation to the people of these U.S. states. One of the most important functions of the GSMFC is to serve as a forum for the discussion of various problems and needs of fisheries management programs, industry, and researchers; and to develop a coordinated policy to address those issues for the betterment of the resource and all who are concerned.

Source: http://www.gsmfc.org/about.php.

Published Reports

- The *Oyster Fishery Management Plan*, revised in 2012, was developed by the Oyster Technical Task Force to summarize relevant scientific information for the management of GOM oysters and provide an understanding of past, present, and future management efforts (http://www.gsmfc.org/publications/GSMFC%20Number%20202.pdf).

3. State Oyster Management, Assessment, and Monitoring Programs

Below we provide information on oyster management, assessment, and monitoring programs for each Gulf state. For more detailed information on oyster fishery management jurisdictions, laws, and policies, see Chapter 7 of *The Oyster Fishery of the Gulf of Mexico, United States: A Regional Management Plan* (VanderKooy, 2012). State agencies should be consulted for specific and current state laws and regulations.

3.1 Alabama

The Alabama Department of Conservation and Natural Resources (ADCNR) manages Alabama's oyster resources. The Commissioner of ADCNR has the responsibility to put into operation state laws and regulations for the protection and conservation of oysters and all seafood. The ADCNR Marine Resources Division specifically enforces state laws and regulations pertaining to marine resources as set forth by the Commissioner. The Marine Resources Division is also responsible for conducting biological research and collecting fishery-independent and fishery-dependent data (reference Code of Alabama 1975, Title 9, Sections 2 and 12, and AL regulations 220-3). The Alabama Department of Public Health classifies shellfish growing areas and monitors oysters and oyster growing waters for bacteriological contamination.

ADCNR engages in oyster reef restoration and enhancement activities such as cultch planting, oyster relay, reef cultivation, and remote setting techniques; and conducts statewide monitoring of public oyster areas including recent cultch planting and unplanted reefs. Monitoring includes pre- and post-monitoring of recruitment on restored oyster reefs in comparison to non-planted oyster reefs. Monitoring is conducted on reef areas in which cultch, seed, or remote set oysters have been planted, as well as sites that have been cultivated. This includes quadrat sampling, hand dredge sampling, cane pole sounding, deployment of settlement tiles, and gillnet surveys over project areas to assess finfish diversity.

3.2 Florida

Oyster harvest in Florida is managed by the Florida Fish and Wildlife Conservation Commission (FWC), which manages commercial fishing licenses and establishes fishing seasons and harvest limits. The Florida Department of Agriculture and Consumer Services (FDACS) manages area closures, harvest area classification, product processing, plant certifications and inspections, and water quality monitoring in harvest areas; and is responsible for managing public oyster reefs and aquaculture on sovereign submerged lands.

Within the FWC, the Division of Marine Fisheries Management develops regulatory and management recommendations designed to ensure the long-term conservation of valuable marine fisheries resources. The FWC Division of Law Enforcement is responsible for the enforcement of marine resource-related laws, rules, and regulations. Commercial harvest rules for oysters are detailed in Chapter 68B-27 of the Florida Administrative Code.

Allowable shellfish harvesting areas are established and managed for public health purposes by FDACS' Division of Aquaculture. Shellfish harvesting areas are opened and closed in accordance with NSSP guidelines, and the open or closed status applies to both recreational and commercial harvest.

In July 2015, a state oyster monitoring program was established to assess oysters in Apalachicola Bay for fisheries management purposes. This monitoring is conducted by FWC's Fish and Wildlife Research Institute. Prior to July 2015, this type of monitoring was conducted by FDACS.

3.3 Louisiana

The Louisiana State Legislature (Legislature), the Louisiana Wildlife and Fisheries Commission (LWFC), and the Louisiana Department of Wildlife and Fisheries (LDWF) are responsible for managing the oyster fishery in Louisiana state waters (Banks et al., 2016). The Legislature has sole authority to establish management programs and policies; however, the Legislature has delegated certain authority and responsibility to the LDWF. The LWFC, a seven-member board appointed by the Governor, is a policy-making board with no administrative functions. LDWF is one of the major administrative units of the Louisiana government. The Secretary of the LDWF is the executive head and chief administrative officer of the department; and is responsible for the administration, control, and operation of the functions, programs, and affairs of the department. Within the administrative system of LDWF, an Assistant Secretary is in charge of the Office of Fisheries with assistance from a Deputy Assistant Secretary and Fisheries Division Administrator. Within this office are several Sections headed by Biologist Directors performing the functions of the state relating to the administration and operation of programs, including research relating to oysters, water bottoms, and seafood, including, but not limited to, the regulation of oyster, shrimp, and marine fishing industries. The Enforcement Division, in the Office of the Secretary, is responsible for enforcing all marine fishery statutes and regulations. Louisiana has habitat protection and permitting programs and a federally approved Coastal Zone Management (CZM) program administered by the Louisiana Department of Natural Resources. LDWF is a commenting agency on coastal use permits and consistency determinations under the CZM program (VanderKooy, 2012).

The Louisiana Department of Health and Hospitals is responsible for enforcing laws, rules, and regulations related to public health within the State of Louisiana. Concerning oysters, this represents regulations for public health from initial harvest to consumption. The Office of Public Health is responsible for these regulations via its Sanitarian Services, including the Commercial Seafood Program and the Molluscan Shellfish Program (VanderKooy, 2012).

LDWF conducts statewide monitoring of public oyster areas, including stock assessment sampling and dredge sampling. For the annual oyster stock assessment, quantitative data are collected through square meter sampling and used to estimate stock size. Stock assessment data are also incorporated into a shell budget model (Soniat et al., 2012) to generate sustainable harvest estimates. Dredge sampling is conducted monthly and is used primarily to monitor recruitment, mortality, and growth throughout the year. Additional sampling is conducted in association with assessing impacts of integrated coastal restoration projects. LDWF is typically the lead agency when conducting oyster restoration projects on public oyster areas of the state, where leaseholders maintain oyster populations on their private leases. Other natural resource agencies and conservation groups have attempted oyster restoration projects largely in the form of living shoreline reefs after LDWF provides input.

3.4 Mississippi

The Mississippi Department of Marine Resources (MDMR) administers coastal fisheries and habitat protection programs through the authority of the Mississippi Commission on Marine Resources (MCMR). The MCMR consists of five members appointed by the Governor. The MCMR has full power to “manage, control, supervise and direct any matters pertaining to all saltwater aquatic life not otherwise delegated to another agency” (Mississippi Code Annotated 49-15-11).

The Governor’s Oyster Council was created in 2015 to discuss and analyze environmental and economic factors, and influences on the oyster resource, while exploring the role aquaculture and emerging technologies will play in growing the industry. In June 2015, it issued a Restoration and Resiliency Report (http://www.dmr.ms.gov/images/dmr/Oyster-Council-report-final.pdf).

The Shellfish Bureau of MDMR is responsible for the management of Mississippi's marine shellfish resources with two primary functions: (1) maintaining and enhancing the resource, and (2) maintaining compliance with the ISSC/NSSP Model Ordinance requirement for shellfish-growing waters.

Unlike other states, the Mississippi State Department of Health plays no role in monitoring and controlling shellfish growing areas. All of the following responsibilities for seafood sanitation and processing are addressed by MDMR (VanderKooy, 2012): designation of harvest areas and classification (including opening and closing criteria), processing plant certifications and inspections, and water quality monitoring. MDMR is also authorized for the following oyster resource management activities, including projects to create or establish new oyster beds and culling requirements, molluscan depuration facilities, and lease of water bottoms for the growing and harvesting of oysters.

MDMR conducts routine assessments of oyster population structure by conducting one-minute dredge-tow surveys as well as square-meter (quadrat) sampling for oyster density.

3.5 Texas

In the State of Texas, two independent agencies share responsibility for the management of oysters in state waters. The Texas Parks and Wildlife Department (TPWD) manages the coastal resource and enforces the legislative and regulatory aspects of the fishery, while the Texas Department of State Health Services is responsible for product safety and the classification and closure of resource areas in the interest of human health.

The TPWD is the administrative unit of the state charged with management of coastal fishery resources and enforcement of legislative and regulatory procedures under the policy direction of the Texas Parks and Wildlife Commission (Commission). The Commission consists of nine members appointed by the Governor for six-year terms. The Commission selects an Executive Director who serves as the chief administrative officer of the department. The Executive Director selects a Deputy Executive Director for Natural Resources who, in turn, selects the Directors of the Coastal Fisheries, Inland Fisheries and Wildlife, and the Law Enforcement Divisions. In these divisions, each branch is headed by a Deputy Director.

The Coastal Fisheries Division of the TPWD collects fishery-dependent data from commercial fishermen and routinely collects fishery-independent data by sampling oyster reef habitat in order to ascertain the status of the population. The Texas fishery independent oyster monitoring program has been sampling oyster populations since the early 1950s and has been using its current standardized methodology since 1986. The survey uses a smaller version of the oyster dredges used by the commercial oyster industry. Samples are collected from randomly selected areas within areas known to contain consolidated oyster reef. The dredge is pulled for 30 seconds at 3 mph and then retrieved. These procedures are described in greater detail in the TPWD Coastal Fisheries Division's *Marine Resources Sampling Manual* (TPWD, 2009).

4. DWH NRDA Early Restoration

On April 20, 2011, the first anniversary of the DWH oil spill, BP and the DWH Trustees signed a "Framework Agreement" for early restoration under NRDA. The agreement provided a

$1 billion down payment on restoration and required BP and the Trustees to work together to identify early restoration projects that would provide "meaningful benefits to accelerate restoration in the Gulf as quickly as practicable."

Approximately $866 million and 68 projects were selected for early restoration in five phases. Four subtidal oyster cultch placement projects in Louisiana, Florida, Alabama, and Mississippi were approved in Phases I and III:

- Louisiana Oyster Cultch Project (including oyster hatchery), Phase I: $15,582,600
- Mississippi Oyster Cultch Restoration Project, Phase I: $11,000,000
- Florida Oyster Cultch Placement Project, Phase III: $5,370,596
- Alabama Oyster Cultch Restoration, Phase III: $3,239,485.

Seven living shoreline projects incorporating habitat components to support benthic secondary productivity in Florida, Alabama, and Mississippi were approved in Phases III and IV:

- Alabama Swift Tract Living Shoreline, Phase III: $5,000,080
- Alabama Shell Belt and Coden Belt Roads Living Shoreline Project, Phase IV: $8,050,000
- Alabama Point aux Pins Living Shoreline Project, Phase IV: $2,300,000
- Florida Cat Point Living Shoreline Project, Phase III: $775,605
- Florida Pensacola Bay Living Shoreline Project, Phase III: $10,828,063
- Mississippi Hancock County Marsh Living Shoreline Project, Phase III: $50,000,000
- Restoring Living Shorelines in Mississippi Estuaries Project, Phase IV: $30,000,000.

For more information, see the DWH NRDA websites:

- http://www.gulfspillrestoration.noaa.gov/restoration/early-restoration/
- http://www.restoration.noaa.gov/dwh/storymap/.

5. Funding Programs

This section provides a high-level overview of programs funding restoration and restoration science activities across the GOM. It is not intended to capture the work of every researcher working on oyster restoration/research, but rather provide context to the work that the DWH NRDA Trustees will be funding. For more details on project and research funded through the programs below, please visit the links below or the *Deepwater Horizon* Project Tracker maintained by the Gulf of Mexico Alliance (GOMA).

5.1 National Academies of Science's Gulf Research Program

"Over its 30-year duration, the Gulf Research Program works to enhance oil system safety and the protection of human health and the environment in the Gulf of Mexico and other U.S. outer continental shelf areas by seeking to improve understanding of the region's interconnecting human, environmental, and energy systems; and fostering application of these insights to benefit Gulf communities, ecosystems, and the Nation."

Source: http://www.nationalacademies.org/gulf/index.html.

Published Reports

- *Effective Monitoring to Evaluate Ecological Restoration in the Gulf of Mexico* (https://www.nap.edu/catalog/23476/effective-monitoring-to-evaluate-ecological-restoration-in-the-gulf-of-mexico). Part II of the report includes good practices for oyster reef restoration monitoring (pp. 151–161).

Recently Funded Oyster Research Projects

- Living Shorelines: Synthesizing the Results of a Decade of Implementation in Coastal Alabama, 2015.

For more information, see the program's website: http://www.nationalacademies.org/gulf/grants/index.html.

5.2 National Fish and Wildlife Foundation's Gulf Environmental Benefit Fund

"In early 2013, a U.S. District Court approved two plea agreements resolving certain criminal cases against BP and Transocean that arose from the 2010 *Deepwater Horizon* explosion and oil spill. The agreements direct a total of $2.544 billion to the National Fish and Wildlife Foundation (NFWF) to fund projects benefiting the natural resources of the Gulf Coast that were impacted by the spill. Between 2013 and 2018, NFWF's newly established Gulf Environmental Benefit Fund will receive a total of $1.272 billion for barrier island and river diversion projects in Louisiana; $356 million each for natural resource projects in Alabama, Florida, and Mississippi; and $203 million for similar projects in Texas. Now in its fourth year, the Gulf Environmental Benefit Fund has supported 101 projects worth nearly $880 million. In making the awards, NFWF has worked closely with key state and federal resource agencies to select projects that remedy harm and eliminate or reduce the risk of future harm to Gulf Coast natural resources."

Source: http://www.nfwf.org/gulf/Pages/home.aspx.

Recently Funded Oyster Restoration Projects

Alabama

- Restoration and Enhancement of Oyster Reefs in Alabama, 2013.

Florida

- Apalachicola Bay Oyster Restoration, 2013
- Oyster Reef Habitat Restoration in Saint Andrew Bay, 2014
- Pensacola East Bay Oyster Habitat Restoration Project – Phase I, 2015
- Recovery and Resilience of Oyster Reefs in the Big Bend of Florida, 2016.

Mississippi

- Oyster Restoration and Management – Phase I, 2015.

Texas

- Oyster Reef Restoration in East Bay, 2013.

For more information, see the program's website: http://www.nfwf.org/gulf/Pages/gulf-projects.aspx.

5.3 National Fish and Wildlife Foundation's Gulf Response Grants

"From 2010 to 2012, NFWF invested $22.9 million in conservation actions in the Gulf of Mexico to minimize the effects of the *Deepwater Horizon* oil spill on key fish and wildlife species. Our projects focused on the species most at risk, including shorebirds, waterfowl and marsh birds; seabirds; sea turtles; marine mammals, oysters, and others. They are designed to boost these populations outside the direct spill zone and promote their long-term survival. Strategic investments were funded through the Recovered Oil Fund for Wildlife and other sources."

Source: http://www.nfwf.org/gulf/Pages/projectlist.aspx.

Recently Funded Oyster Restoration Projects

Alabama

- Oyster Reserve Establishment in Mississippi Sound, date not specified.

Florida

- Schultz Nature Preserve Oyster Reef Creation, 2010
- Oyster Restoration in the Pensacola Bay System, 2011
- Yellow River Aquatic Preserve Shoreline Restoration, date not specified.

Louisiana

- Evaluation and Creation of Alternative Gulf Oyster Habitat, 2011
- Coalition to Restore Coastal Louisiana's (CRCL's) Oyster Shell Recycling Pilot Program, 2014
- Shell Budgets as a Tool in Oyster Restoration, 2012.

Mississippi

- Biloxi Bay Oyster Habitat Restoration, date not specified.

Texas

- Sabine Lake Oyster Restoration and Enhancement, date not specified.

Multiple Gulf states

- Oyster Restoration in the Gulf of Mexico, 2011
- The Oyster Opportunity: Uncovering Business Solutions that Drive Reef Restoration in the Gulf, date not specified.

For more information, see the program's website: http://www.nfwf.org/gulf/Pages/projectlist.aspx.

5.4 NOAA's RESTORE Act Science Program

"The research portfolio for the NOAA RESTORE Act Science Program currently contains seven projects funded through the Science Program's first federal funding opportunity (FFO-2015). These projects were selected following a rigorous and highly competitive process which included a review by a panel of outside experts. In total, approximately $2.7 million has been awarded to seven research teams. Each of the research teams will be addressing one or more of the Science Program's short-term priorities which focus on assessing ecosystem modeling, evaluating indicators for ecosystem conditions, and assessing and developing recommendations for monitoring and observing in the Gulf of Mexico. These projects will synthesize current scientific understanding and management needs and inform the future direction of the NOAA RESTORE Act Science Program as well as the other science and restoration initiatives in the region. The results from these projects will also inform the development of management strategies to support the sustainability of the Gulf of Mexico ecosystem, including its fisheries."

Source: https://restoreactscienceprogram.noaa.gov/research.

Recently Funded Oyster Research Projects

- Inventory of Gulf of Mexico Ecosystem Indicators Using an Ecological Resilience Framework, 2015.
- Applications for NOAA RESTORE Act Science Program's FFO-2017 were due September 27, 2016, which was focused on living coastal and marine resources and their habitats. The program anticipates making awards in March 2017, with the earliest possible start date being June 2017.

For more information, see the program's website: https://restoreactscienceprogram.noaa.gov/research.

5.5 RESTORE Council

"The RESTORE Act establishes the Council as an independent entity in the federal government. The council is charged with helping to restore the ecosystem and economy of the Gulf Coast region by developing and overseeing implementation of a comprehensive plan and carrying out other responsibilities. The council is chaired by the Secretary of the U.S. Department of Commerce and includes the Governors of the States of Alabama, Florida, Louisiana, Mississippi, and Texas; the Secretaries of the U.S. Departments of Agriculture, Army, Homeland Security, and the Interior; and the Administrator of the U.S. Environmental Protection Agency. The council has responsibilities with respect to 60% of the funds made available from the Gulf Restoration Trust Fund. Thirty percent of the Trust Fund, plus interest, will be administered for ecosystem restoration and protection by the council (known as the Council-Selected Restoration Component). The other 30% of the Trust Fund will be allocated to the Gulf Coast States under a formula described in the RESTORE Act and spent according to individual State Expenditure Plans (Spill Impact Component). The state Expenditure Plans must be consistent with the goals and objectives of the Initial Comprehensive Plan and are subject to the Council's approval."

Source: https://www.restorethegulf.gov/our-work.

Recently Funded Oyster Restoration Projects

Alabama

- Alabama Living Shorelines Program Construction Planning Component, 2015
- Alabama Living Shorelines Program Implementation, 2015
- Comprehensive Living Shoreline Monitoring Planning, 2015
- Comprehensive Living Shoreline Monitoring Implementation, 2015.

Florida

- Apalachicola Bay Oyster Restoration Planning, 2015
- Apalachicola Bay Oyster Restoration Implementation, 2015.

Louisiana

- Biloxi Marsh Living Shoreline Planning, 2015.

For more information, see the program's website: https://www.restorethegulf.gov/our-work.

Other Relevant Information

- One of the Council's primary responsibilities is to develop a Comprehensive Plan to restore the ecosystem and the economy of the Gulf Coast region. The Council approved the Initial Comprehensive Plan in August 2013, and a Comprehensive Plan Update in December 2016.

5.6 Gulf of Mexico Research Initiative

On May 24, 2010, shortly after the DWH oil spill, BP announced a commitment of up to $500 million over 10 years to fund an independent research program designed to study the impact of the oil spill and its associated response on the environment and public health in the GOM.

The Gulf of Mexico Research Initiative (GOMRI) investigates the impacts of oil, dispersed oil, and dispersant on the ecosystems of the GOM and affected coastal states in a broad context of improving the fundamental understanding of dynamics of such events and their environmental stresses and public health implications. GOMRI also has the objective to develop improved spill mitigation, oil and gas detection, characterization, and remediation technologies. Knowledge accrued will be applied to restoration and to improving the long-term environmental health of the GOM.

Source: http://gulfresearchinitiative.org/.

Recently Funded Oyster Research Projects

- Oyster Health and Reproduction One Year after the *Deepwater Horizon* Oil Spill, 2011
- Recovery: Sentinel Macrofauna, 2011
- The *Deepwater Horizon* Oil Spill: Assessing Impacts on a Critical Habitat, Oyster Reefs and Associated Species in Florida Gulf Estuaries, 2010
- The Impact of Crude Oil and the Dispersant Corexit® on Three Key Gulf of Mexico Invertebrate Species, 2010.

For more information, see the program's website: http://research.gulfresearchinitiative.org/research-search/research-searchtool.php.

5.7 Additional Research/Restoration Grant Programs

A number of other state, federal, and nonprofit funding programs support oyster restoration and research projects in the northern GOM.

6. Oyster Restoration Programs/Stakeholders

This section provides a high-level overview of oyster restoration programs and stakeholders in the GOM. It is not intended to capture every program/stakeholder, but rather highlight a few federal, regional, and state entities that are significantly involved in oyster restoration in the GOM.

6.1 Federal Programs/Stakeholders

6.1.1 EPA's National Estuaries Program

"The National Estuary Program (NEP) is an EPA place-based program to protect and restore the water quality and ecological integrity of estuaries of national significance. Currently, 28 estuaries located along the Atlantic, Gulf, and Pacific coasts and in Puerto Rico are designated as estuaries of national significance. Each NEP focuses within a study area that includes the estuary and surrounding watershed. The NEPs are located in a variety of institutional settings, including state and local agencies, universities and individual nonprofits. In overseeing and managing the national program, EPA provides annual funding, national guidance and technical assistance to the local NEPs. The 28 NEPs develop and implement Comprehensive Conservation and Management Plans (CCMPs), which are long-term plans that contain actions to address water quality and living resource challenges and priorities. The NEP challenges and priorities are defined by local, city, state, federal, private and non-profit stakeholders." NEPs located in the GOM include:

- Barataria-Terrebonne National Estuary Program, Louisiana
- Charlotte Harbor National Estuary Program, Florida
- Coastal Bend Bays and Estuaries Program, Texas
- Mobile Bay National Estuary Program, Alabama
- Galveston Bay Estuary Program, Texas
- Sarasota Bay Estuary Program, Florida
- Tampa Bay Estuary Program, Florida.

Source: https://www.epa.gov/nep/overview-national-estuary-program.

6.1.2 NOAA's National Estuarine Research Reserves

"The National Estuarine Research Reserve System is a network of 29 coastal sites designated to protect and study estuarine systems. Established through the Coastal Zone Management Act, the reserves represent a partnership program between NOAA and the coastal states. NOAA provides funding and national guidance, and each site is managed on a daily basis by a lead state agency or university with input from local partners." National Estuarine Research Reserves (NERRs) located in the GOM include:

- Apalachicola NERR, Florida
- Rookery Bay NERR, Florida
- Grand Bay National Estuarine Research Reserve, Mississippi
- Mission-Aransas National Estuarine Research Reserve, Texas
- Weeks Bay NERR, Alabama.

Source: https://coast.noaa.gov/nerrs/.

6.1.3 NOAA's National Sea Grant College Program

"Sea Grant's mission is to enhance the practical use and conservation of coastal, marine and Great Lakes resources in order to create a sustainable economy and environment. Environmental stewardship, long-term economic development and responsible use of America's coastal, ocean and Great Lakes resources are at the heart of Sea Grant's mission. A network of 33 Sea Grant programs in the coastal US States and territories carries out this mission through research, extension and education activities." Sea Grant programs located in the GOM include:

- Florida Sea Grant, University of Florida
- Louisiana Sea Grant, Louisiana State University
- Mississippi-Alabama Sea Grant Consortium
- Texas Sea Grant, Texas A&M University.

Source: http://seagrant.noaa.gov/WhoWeAre.aspx.

6.2 National/Regional Nongovernmental Programs/Stakeholders

6.2.1 GOMA

"The Gulf of Mexico Alliance is a Regional Ocean Partnership working to sustain the resources of the Gulf of Mexico. Led by the five Gulf States, the broad partner network includes federal agencies, academic organizations, businesses, and other non-profits in the region. Our goal is to significantly increase regional collaboration to enhance the environmental and economic health of the Gulf of Mexico. The Gulf of Mexico Alliance is also a 501c3 non-profit organization. The Governors of the five Gulf States identified six priority issues that benefit from regional collaboration." GOMA administers GOMRI (see Section 5.6).

Source: http://www.gulfofmexicoalliance.org/about-us/organization/.

Other Relevant Information

- GOMA has developed the *Deepwater Horizon* Project Tracker as a tool to track restoration, research, and recovery projects resulting from the DWH oil spill. We have included any directly oyster-related project found in the Project Tracker in the other sections of this document.

6.2.2 The Nature Conservancy's Gulf of Mexico Program

"The Nature Conservancy's Gulf of Mexico Program is a partnership among our five Gulf State Chapters to accomplish conservation across the entire Gulf ecosystem. The Gulf Program employs conservation professionals who work as part of a team with their colleagues in

Florida, Alabama, Mississippi, Louisiana, and Texas to restore and protect natural systems and natural areas across political boundaries. The Gulf Program works also with The Nature Conservancy's global and U.S. science and advocacy programs to restore the Gulf. And we work with TNC state chapters up the Mississippi to reduce the flow of nutrients into the Gulf's waters." Restoration strategies include restoring shorelines, protecting freshwater resources, and helping communities benefit from Gulf restoration.

Source: http://www.nature.org/ourinitiatives/regions/northamerica/areas/gulfofmexico/about/index.htm.

6.2.3 Oyster Restoration Workgroup

"The Oyster Restoration Workgroup was established to address questions related to shellfish restoration success, especially all pertinent issues associated with the restoration of both intertidal and subtidal oyster reefs. This website was created to: (1) enable visitors to view findings from past meetings and workshops; (2) share and see upcoming events (e.g., workshops, meetings, publications, findings, etc.); (3) obtain contact information for professionals and experts working in the field; and (4) find links to the latest literature, including suggested approaches for measuring restoration success based on a suite of agreed upon goals and associated metrics from a workshop that included a group of restoration practitioners. We are currently working to expand the site with the help of NOAA, TNC and others to meet the needs of the shellfish community."

Source: http://www.oyster-restoration.org/mission/.

6.2.4 Coastal Conservation Association

"The purpose of CCA is to advise and educate the public on conservation of marine resources. The objective of CCA is to conserve, promote, and enhance the present and future availability of those coastal resources for the benefit and enjoyment of the general public. Coastal Conservation Association (CCA) is a non-profit organization with 17 coastal state chapters spanning the Gulf of Mexico, the Atlantic seaboard, and the Pacific Northwest."

Source: http://www.joincca.org/about.

6.3 State Nongovernmental Programs/Stakeholders

6.3.1 Alabama

6.3.1.1 Alabama Coastal Foundation's Oyster Shell Recycling Program

"In August 2016, the Alabama Coastal Foundation received a grant from the National Fish and Wildlife Foundation (NFWF) to establish an oyster shell recycling program for local restaurants! NFWF is providing the funding for this project as a part of the Gulf Coast Conservation Grants Program. Oyster shells that are collected through this program will go back into Alabama waters to help more oysters grow, provide habitat, limit erosion and improve water quality."

Source: http://www.joinacf.org/oyster-shell-recycling-program.

6.3.1.2 Mobile Bay Oyster Gardening Program

"In the Mobile Bay Oyster Gardening Program, volunteers who have access to waterfront property in Mobile or Baldwin counties grow oysters in gardens that hang from their piers. They clean the gardens weekly from June to November by pulling the gardens out of the water and rinsing off mud, algae and any other fouling material. After visually inspecting the gardens and removing predators, such as blue crabs, stone crabs and oyster drills, the gardeners return the gardens to the water. On average, each volunteer grows 250 oysters per garden. At the end of the gardening season, the oysters are collected from the volunteers and planted on restoration reefs in Mobile Bay and the Mississippi Sound. This education and research program has planted more than 600,000 oysters since it began in 2001. Program partners include the gardeners and adopters (people who make donations to sponsor gardens), as well as the Alabama Cooperative Extension System, Mississippi-Alabama Sea Grant Consortium, Mobile Bay National Estuary Program and Auburn University."

Source: http://oystergardening.org/.

6.3.2 Florida

6.3.2.1 Keep Pensacola Beautiful: Offer Your Shell to Enhance Restoration

"The Offer Your Shell to Enhance Restoration (OYSTER) Project is a cooperative effort between Keep Pensacola Beautiful, Florida Department of Environmental Protection (FDEP), Southern Company and the National Fish and Wildlife Foundation, our local sponsors and partners. The project seeks to collect oyster shell from local restaurant partners which is used as substrate to restore oyster reefs in the Pensacola Bay System."

Source: http://keeppensacolabeautiful.org/what-we-do/beautification/oyster_1/shell-recycling.html.

6.3.2.2 Sanibel-Captiva Conservation Foundation

"The Sanibel-Captiva Conservation Foundation, Inc. is dedicated to the conservation of coastal habitats and aquatic resources on Sanibel and Captiva and in the surrounding watershed. Since incorporating in 1967, SCCF has acquired and preserved environmentally sensitive land on and around the islands. This land includes critical wildlife habitats, rare and unique subtropical plant communities, tidal wetlands, and freshwater wetlands along the Sanibel River. Without protection, many of these areas would have been lost to residential and commercial development, either directly or by fragmentation of habitat." The Sanibel-Captiva Conservation Foundation has a small-scale shell collection program. These shells are used in habitat restoration projects in the Pine Island Sound and San Carlos Bay area.

Source: http://www.sccf.org.

6.3.3 Louisiana

6.3.3.1 CRCL's Oyster Shell Recycling Program

"Launched in June 2014, CRCL's Oyster Shell Recycling Program recycles shell from participating New Orleans-based restaurants and uses that shell to restore oyster reefs and shoreline habitat across Coastal Louisiana. This is the first program of its kind in Louisiana and in its pilot year, it became the largest shell recycling program in the nation."

Source: http://www.crcl.org/programs/oyster-shell-recycling.html.

6.3.4 Texas

6.3.4.1 Galveston Bay Foundation

"The Galveston Bay Foundation is a 501(c)(3) non-profit organization established in 1987 under the laws of the State of Texas. The Foundation's strength is that it involves a true cross-section of Bay interests to address issues and concerns related to Galveston Bay. It is managed by a strong Board of Directors whose members represent sport and commercial fishing groups, government agencies, recreational users, environmental groups, shipping, development, and business interests.

The mission of the Galveston Bay Foundation is to preserve and enhance Galveston Bay as a healthy and productive place for generations to come."

Source: http://www.galvbay.org/about/about-us/overview/.

6.3.4.2 Sink Your Shucks Oyster Recycling Program

"The oyster recycling program "Sink Your Shucks" was founded by the Harte Research Institute in 2009 by Dr. Jennifer Pollack, Assistant Professor in the Department of Life Sciences at Texas A&M University-Corpus Christi (TAMUCC) and Dr. Paul Montagna, HRI's Endowed Chair for Ecosystems and Modeling at Harte Research Institute. The program was the first in Texas that reclaims oyster shells from local restaurants and returns them to our local waters providing both substrate to form new reefs and habitat for fish, crabs and other organisms."

Source: http://oysterrecycling.org/.

7. Oyster Industry Stakeholders

This section provides a high-level overview of oyster industry stakeholders in the GOM. It is not intended to capture every stakeholder, but rather highlight a few entities that are involved in the region.

7.1 Gulf Oyster Industry Council

"The Gulf Oyster Industry Council (GOIC) serves to support, promote and protect the regulatory, legislative and economic interests of oyster farmers, processors, dealers and retailers living and operating in Texas, Louisiana, Mississippi, Alabama and Florida. We are committed to offering the nation's consumers the highest quality, safest and most flavorful oysters available anywhere year-round, ensuring the sustainability of America's shellfish resources, and to protecting and preserving the sensitive coastal environments in which our members live and work."

Source: http://gulfcoastoysters.org/.

7.2 State Oyster Industry Stakeholders

7.2.1 Alabama

7.2.1.1 Organized Seafood Association of Alabama

"Mission: To promote, protect, and market Alabama's seafood industry and related activities. Organized Seafood Association of Alabama (OSAA) was established in 2002 as a non-profit organization. Membership is open to folks who share our mission. OSAA has 4 advisory boards serving the following fisheries: (1) oyster, (2) crab, (3) shrimp and (4) gill net and hook & line. The objective of each board is to identify issues and obtain fisheries input. OSAA then has the opportunity to interact with the appropriate federal, state and local leaders, boards or committees in an effort to lead discussions that have the potential to create new laws/regulations or change existing laws and regulations."

Source: http://www.eatalabamawildseafood.com/about-us.html.

7.2.2 Florida

7.2.2.1 Cedar Key Oystermen's Association

The Cedar Key Oystermen's Association (CKOA), a registered Florida not-for-profit corporation, has been directly involved with oyster resource management projects for more than 30 years. The mission of the CKOA is to encourage and participate in activities that (1) sustain the area's oyster fishery, (2) promote prudent management of oyster resources, (3) support businesses that depend on the oyster fishery, and (4) sustain the socio-cultural heritage of fishing communities that rely on seafood for their livelihoods. The CKOA includes oyster fishers, commercial fishers, seafood processors, seafood workers, and interested members of the community. The CKOA and Suwannee Oyster Association will plan and implement a project in the Dixie and Levy county area to improve oyster reef substrate and the oyster fishery in the region by re-seeding depleted oyster reefs with juvenile oysters.

Source: https://www.restorethegulf.gov/sites/default/files/Suwannee%20River%20Watershed%20Restoration.pdf.

7.2.2.2 The Seafood Management Assistance Resource and Recovery Team

"To fight back for a better future for Apalachicola Bay, local seafood industry workers launched a community based collaborative effort to build local capacity/consensus. The goal of this initiative is to develop a sustainable and resilient resource management plan to ensure the future of Franklin County's seafood heritage. The Seafood Management Assistance Resource and Recovery Team (SMARRT) includes seafood and tourist industry user groups dependent on Apalachicola Bay." Established in 2012.

Source: http://www.franklinspromisecoalition.org/index.cfm/pageId/111/SMARRT%20History/.

7.2.3 Louisiana

7.2.3.1 Louisiana Fisheries Forward

"Louisiana Fisheries Forward (LFF) is a voluntary educational program for members of the commercial seafood community. A collaboration of the Louisiana Department of Wildlife and Fisheries (LDWF) and Louisiana Sea Grant College Program at LSU (Sea Grant), LFF was established with the goal of improving the economic success of Louisiana's commercial fishing industry. LFF provides a structured mechanism to develop and deliver relevant and timely information to the seafood industry. Content is presented via the Internet, using training videos and fact sheets, and directly to communities with hands-on workshops, training days and demonstration projects that showcase new technology and best practice methods."

Source: http://www.lafisheriesforward.org/about-us/.

7.2.3.2 Louisiana Oyster Dealers and Growers Association

"Established in 1952, the Louisiana Oyster Dealers and Growers Association's purpose is to promote, protect, foster, and advance the interest of the oyster industry. Thereby, increase the use of the products and by-products of the oyster industry, and to improve the conditions under which the industry operates."

Source: http://www.louisianaoystersdealersandgrowersassn.org/.

7.2.3.3 Louisiana Oyster Task Force

The Oyster Task Force was established in 1999 to monitor the oyster industry and to make recommendations that maximize benefits from that industry to Louisiana and its citizens. It also coordinate efforts to increase oyster production and saleability, study declines in oyster saleability, and make recommendations to the state to resolve problems. Oyster Task Force meetings are open to the public.

Source: http://www.wlf.louisiana.gov/fishing/oyster-task-force.

7.2.3.4 Louisiana Seafood Promotion & Marketing Board

In 1984, the State of Louisiana created the Louisiana Seafood Promotion & Marketing Board to support Louisiana's world-class commercial fisheries industry and respond to changes in the marketplace and in the environment. This board is composed of members appointed by the Lieutenant Governor representing all the different sectors of the industry.

Source: http://www.louisianaseafood.com/.

7.2.3.5 Louisiana Oystermen Association

"The association aims to strengthen growth of the Southeastern Louisiana oyster industry by helping its members to optimize their returns on the oyster seafood harvest through developing innovative, value-added seafood and marine products that utilize, and extract optimum value from, every part of the oyster."

Source: http://www.louisianaoyster.org/.

7.2.3.6 United Commercial Fishermen's Association

"The United Commercial Fishermen's Association (UCFA) is the oldest trade association for commercial fishermen in the state of Louisiana. For over 25 years, UCFA has been working to preserve the heritage and business of the commercial fishing industry. UCFA's membership includes commercial shrimpers, oyster farmers, crabbers, fin fishermen, dock owners, processors, restauranteurs, business owners and individuals concerned with preserving the culturally and economically vital commercial fishing industry."

Source: http://www.unitedcommercialfishermen.org/about-2/.

7.2.4 Texas

7.2.4.1 Union of Commercial Oystermen of Texas

Founded in 2011 to protect the interests of the Texas Gulf Coast oystermen and give them a stronger and more effective voice.

7.2.4.2 Oyster Advisory Workgroup

The Oyster Advisory Workgroup was created to advise TPWD on the preparation and formulation of the rules and regulations necessary to carry out the *Oyster Fishery Management Plan*. This workgroup is composed of persons from the oyster industry and individuals and groups interested in the oyster resources of Texas (as of January 15, 2015).

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Module 4
Considerations for Restoration – Oysters

1. Introduction

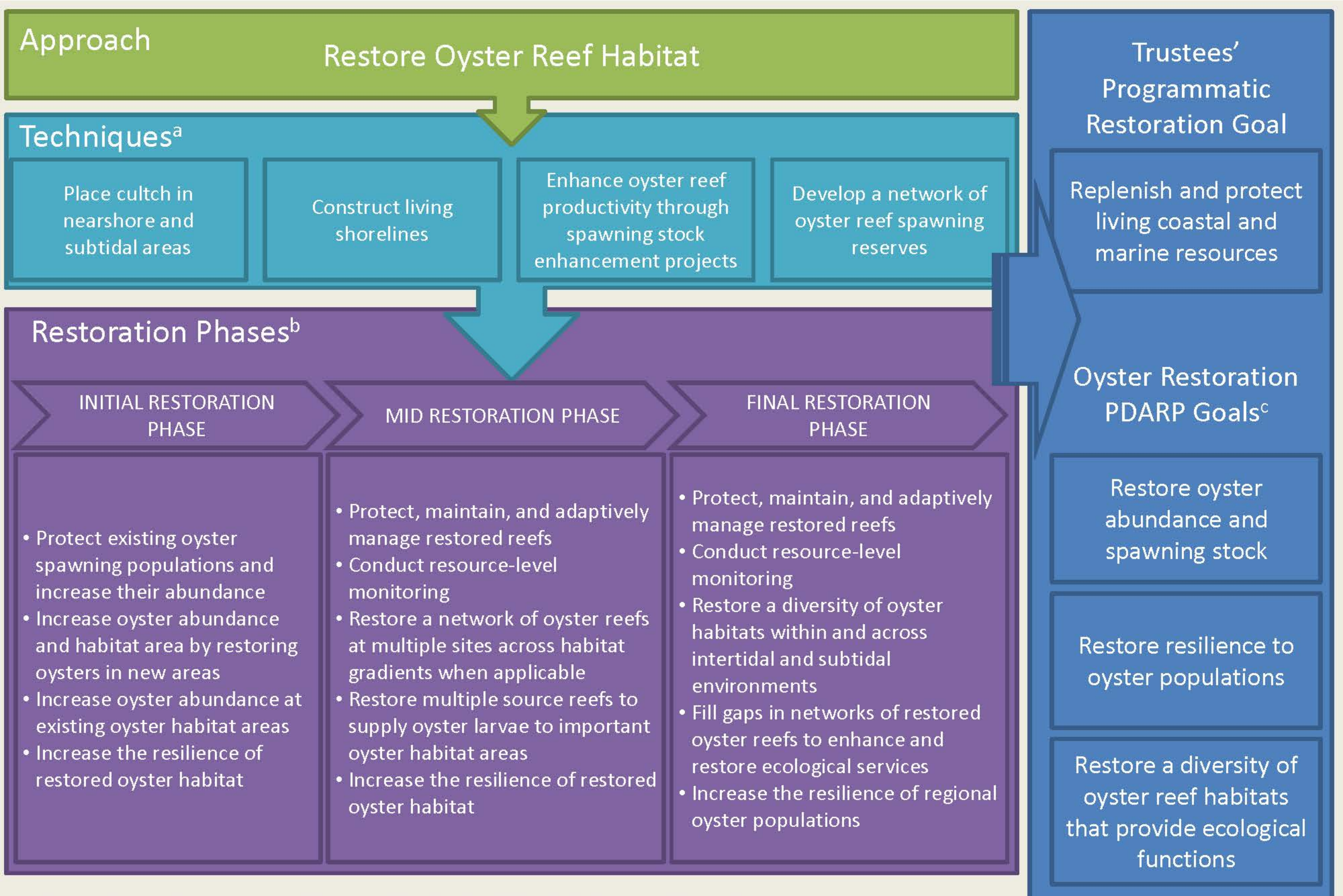
The purpose of Module 4 is to provide technical recommendations for approaching oyster restoration planning and implementation in the northern Gulf of Mexico (GOM). The Trustee Implementation Groups (TIGs) can use this information to develop and prioritize specific projects based on technical considerations and local conditions within a coordinated context across restoration planning efforts. Module 4 may be updated based on additional knowledge obtained through the *Deepwater Horizon* (DWH) Natural Resource Damage Assessment (NRDA) Trustees' efforts or the broader science community, as well as changes to relevant oyster management plans.

1.1 How to Use This Document

For the purposes of considering potential restoration activities to benefit oysters in the northern GOM, this document builds on the restoration approaches and techniques presented in the DWH *Programmatic Damage Assessment and Restoration Plan/Programmatic Environmental Impact Statement* (PDARP/PEIS; DWH NRDA Trustees, 2016) and Module 1 (Figure 1). In Section 2, we present an overall strategy to achieve the oyster restoration goals in the PDARP/PEIS. Considering the ecosystem context to restore this species, we present our strategy in terms of a temporal phasing, including the initial, mid, and final phases of restoration. Under each restoration phase, we describe restoration objectives, considerations for restoration area selection, and potential project concepts that could be pursued by the TIGs. Inherent in this phased approach is that different estuaries may use different phases as a starting point depending on the status of the oyster population. We also present monitoring recommendations to strive for consistent data collection and reporting across oyster restoration projects. In Section 3, we provide considerations for prioritizing oyster restoration areas and selecting restoration techniques.

This document is not intended to exhaustively present all possible restoration techniques and project concepts, nor to prescriptively describe the complete restoration plan for oysters in the northern GOM across all TIGs. This document provides relevant information for the Trustees and other stakeholders to consider when planning and evaluating oyster restoration projects. Readers are encouraged to submit restoration projects to the Trustee Project Portal and/or to state-specific project portals, as available.

Figure 1. Overview of strategies for achieving oyster restoration.



a. Restoration technique names are abbreviated. See Section 2.2 for the full names of the techniques.
b. The restoration phase is site-dependent. Different estuaries may use different phases as a starting point depending on the status of the oyster population. Not all areas will progress in sequence from initial to mid to final phases.
c. Oyster restoration PDARP goals are abbreviated. See Section 2.1 for the full names of the goals.

2. Strategies for Achieving Oyster Restoration Goals

2.1 Oyster Restoration PDARP/PEIS Goals

Figure 2. Oysters along the marsh edge in the Sabine National Wildlife Refuge, Louisiana.

Source: USFWS.

The eastern oyster (*Crassostrea virginica*), widely distributed throughout the coastlines of all five Gulf states, represents a unique component of the GOM ecosystem (Figure 2). Oysters are an ecologically and economically important species, creating and maintaining reef habitats that support a diversity of other organisms and ecosystem services (see Module 2 for more detail on the oyster's ecological and economic importance). The DWH oil spill severely affected nearshore and subtidal oysters as well as oyster recruitment. The combined effects of reduced larval production and spat settlement/spat substrate availability due to the DWH spill have compromised the long-term sustainability of oysters throughout much of the northern central GOM (see the PDARP/PEIS and Modules 1 and 2 for information about the oyster injury). Therefore, the following PDARP/PEIS goals emphasize the restoration of resilient oyster populations supported by healthy recruitment levels to subtidal and nearshore oyster reefs.

Goal 1: Restore oyster abundance and spawning stock to support a regional oyster larvae pool sufficient for healthy recruitment levels to subtidal and nearshore oyster reefs.

The DWH oil spill severely reduced the abundance of oysters, including spawning oyster populations, in nearshore and subtidal environments. This loss in the number of oysters reduced reproduction and the recruitment of new oysters over multiple generations and across a widespread area. Because the injury occurred across a large area within both nearshore and subtidal areas, oyster recovery was severely affected. Circulation modeling conducted for the injury assessment demonstrates that nearshore and subtidal oysters form a common regional larval pool (Murray et al., 2015; DWH NRDA Trustees, 2016). The reduction in spawning oyster populations, especially in the nearshore area, impacted the connectivity and abundance of the regional larval pool that maintains oyster populations. Under this goal, the Trustees seek to restore the regional larval pool by increasing the abundance of spawning oyster populations in both nearshore and subtidal environments. Conditions that support healthy spawning oyster populations include reefs with sufficient recruitment levels and a higher ratio of female to male oysters.

Goal 2: Restore resilience to oyster populations that are supported by productive larval source reefs and sufficient substrate in larval sink areas to sustain reefs over time.

The DWH injury assessment revealed the importance of connectivity between oyster populations. Through dispersal of oyster larvae, oyster reefs form a metapopulation (Mann and Powell, 2007; Schulte et al., 2009; Haase et al., 2012), which consists of larvae-exporting source populations with larvae-importing settlement areas (Lipcius et al., 2008). While there can be some self-recruitment of oysters on reefs (e.g., larvae recruiting back to the original reef), the level of self-recruitment is relatively small (Haase et al., 2012; Kjelland et al., 2015), except in relatively closed circulation systems (Puckett et al., 2014). The dispersal of oyster larvae among spatially distinct subpopulations is critical in the persistence of oyster reefs (Breitburg et al., 2000). It is also important that multiple areas are available to serve as sources of larvae due to the GOM's highly variable conditions. For example, one oyster reef may be impacted by a killing flood that prevents spawning, affecting the supply of larvae to connected reefs. However, if the regional larvae pool is fed by multiple reefs, recruitment may not be significantly impacted. Under this goal, the Trustees seek to restore resilient oyster populations by restoring a network of interconnected oyster reefs. The concept of a network incorporates multiple reefs that are sited to serve as sources of larvae to other reefs within a hydrologically connected area, and reefs that provide sufficient substrate in areas receiving oyster larvae to build new oyster populations.

Goal 3: Restore a diversity of oyster reef habitats that provide ecological functions for estuarine-dependent fish species, vegetated shoreline and marsh habitat, and nearshore benthic communities.

The DWH oil spill impacted not only oysters, but a multitude of species and other habitats that benefit from oyster reefs. Oyster reefs represent a critical component of the nearshore ecosystem and provide myriad ecological benefits for water quality, invertebrate and fish species, and other nearshore habitats, such as marsh and submerged aquatic vegetation beds. For example, where a reduction in nearshore oyster reefs occurred, shoreline erosion rates approximately doubled along at least 108 miles (174 km) of vegetated shoreline over at least three years, resulting in a loss of wetlands that cannot recover naturally (Powers et al., 2015; Roman, 2015; Baker et al., 2016; DWH NRDA Trustees, 2016). Under this goal, the Trustees seek to restore multiple ecosystem benefits by restoring a diversity of oyster reefs. A diversity of oyster reef habitats can be restored by incorporating the natural geographic distribution of oyster reefs and variety in reef types in restoration planning and implementation.

2.2 Overview of PDARP/PEIS Oyster Restoration Techniques

The oyster restoration approach describes four techniques that individually and together can be implemented to restore oyster reef habitat and achieve the PDARP/PEIS Oyster Restoration Type goals.

Technique 1: Restore or create oyster reefs through placement of cultch in nearshore and subtidal areas.

This restoration technique places cultch material in areas with appropriate conditions to provide hard structure for oyster recruitment and/or to restore or create three-dimensional oyster reef habitat.

Technique 2: Construct living shorelines.

Living shorelines can include a variety of shoreline stabilization and habitat restoration techniques, and use both structural and organic materials (Figure 3). The techniques for constructing living shorelines generally involve the restoration of nearshore oyster reefs using materials conducive to oyster colonization, and may be combined with restoration techniques for marsh and/or submerged aquatic vegetation restoration.

Figure 3. Gabion mats with oyster shell used to restore fringing oyster reefs on the north shore of Terrebonne Bay, Louisiana.

Source: Dr. Earl Melancon, Nicholls State University.

Technique 3: Enhance oyster reef productivity through spawning stock enhancement projects such as planting hatchery-raised oysters, relocating wild oysters to restoration sites, oyster gardening programs, and other similar projects.

This technique enhances oyster reef spawning stock by directly placing live oysters in areas with appropriate conditions.

Technique 4: Develop a network of oyster reef spawning reserves.

This technique would identify specific, limited areas that may be closed to harvest to protect spawning oysters and serve as sources of oyster larvae to other reefs, including public oyster grounds. Reserves may be designed using a network approach to enhance the regional larval pool and maintain oyster populations over a broad area.

2.3 Restoration Planning Phases

The PDARP/PEIS identified the restoration of oyster reef habitat as the primary approach to achieve the above goals. Restoration will be implemented in all five Gulf States to provide benefits across the interconnected northern GOM ecosystem. However, due to high natural variability in larval production, dispersal patterns, and subsequent recruitment, successful oyster restoration may require a phased approach, careful selection of restoration sites, and monitoring to assess the level of restoration achieved in each phase (USACE, 2012; Geraldi et al., 2013).

The following describes a phased approach to restoration that incorporates flexibility to address the specific needs of a restoration areas. Not all areas prioritized for oyster restoration will progress in sequence from initial to mid to final planning phases. For example, a specific estuary may be a high priority for oyster restoration, but based on its current conditions and needs, mid-restoration elements and project concepts may be more appropriate.

2.3.1 Initial Restoration Phase

The initial restoration phase focuses on restoring spawning oyster populations. This is a high priority in areas with larval availability limitation and where there are existing, productive spawning oyster populations that can be protected or enhanced.

Recommended Restoration Objectives

- Protect existing oyster spawning populations and increase their abundance to increase larval production and restore the regional larval pool
- Increase oyster abundance and habitat area by restoring oysters in new areas with suitable habitat conditions
- Increase oyster abundance at existing oyster habitat areas
- Increase the resilience of restored oyster habitat through reef design and siting strategies.

Considerations for Restoration Area Selection

- Habitat suitability (e.g., substrate; salinity; and other physical, chemical, and biological factors)
- Adequate larval availability (recruitment may serve as an indicator)
- Up-estuary position within a suitable salinity zone to take advantage of larval transport to downstream reefs
- Areas that reduce or prevent poaching (e.g., closed waters, shallow waters, or other passive approaches to protect spawning populations)
- Areas compatible with non-commercial uses of oyster reefs, such as recreational fishing reefs and existing habitat conservation areas.

Potential Initial Restoration Planning Project Concepts

- Identify priority areas for protecting/increasing spawning oyster populations
- Identify oyster populations, larval transport, or suitable habitat for regional oyster restoration projects, such as larval source areas for oyster populations near state boundaries
- Assess recruitment at potential restoration sites
- Assess population structure (e.g., size frequency, sex ratio) on reefs targeted for spawning stock enhancement
- Establish reference conditions or sites to set restoration targets and adaptive management approaches
- Assess hydrological conditions and predicted changes in the estuary to identify areas for restoration that have the potential to increase in suitability over time.

Potential Initial Restoration Implementation Project Concepts

Table 1. Potential implementation project concepts for the initial restoration phase

Potential project concepts	Implementation strategies	Potential PDARP/PEIS techniques[a]
Establish and manage spawning oyster populations within and adjacent to public oyster grounds	• Implement management and restoration measures at restored or existing reefs to increase the abundance of female oysters (higher ratio of female to male oysters)	• Enhance oyster reef productivity through spawning stock enhancement projects • Develop a network of oyster reef spawning reserves
Restore oyster reefs to increase spawning oyster populations	• Restore smaller and more numerous reefs with a range of reef elevations when applicable • Restore reefs in closed waters or other protected areas when applicable, such as state or federal conservation areas • Restore reefs using materials that prevent or discourage poaching of oysters by the use of dredges, tongs, or other harvesting methods	• Place cultch in nearshore and subtidal areas • Construct living shorelines • Enhance oyster reef productivity through spawning stock enhancement projects • Develop a network of spawning reserves
Restore fringing oyster reef habitat in suitable areas	• In areas that may have historically supported this oyster habitat type, restore small, patchy areas of loose shell adjacent to or parallel to vegetated shorelines	• Place cultch in nearshore areas • Construct living shorelines
Establish spatially and temporally redundant spawning oyster populations	• Restore multiple reefs at sites that are not likely to be impacted by environmental perturbations at the same time (e.g., freshets cycle, prolonged reduced flows, rising sea levels)	• Place cultch in nearshore and subtidal areas • Construct living shorelines • Place cultch in up-estuary, mid-estuary, and down-estuary areas

a. Restoration technique names are abbreviated. See Section 2.2 for the full names of the techniques.

2.3.2 Mid Restoration Phase

The mid restoration phase focuses on restoring one or more networks of oyster reefs to restore population connectivity and resilience. The following objectives are recommended to restore oyster reef connectivity and the sustainability of oyster populations over time.

Recommended Restoration Objectives

- Protect, maintain, and adaptively manage restored reefs to sustain investments made during the initial restoration phase (e.g., address threats such as poaching and management violations, and/or increase reef elevation as needed)
- Conduct resource-level monitoring to assess oyster recovery and restoration progress, and inform restoration planning and prioritization
- Restore a network of oyster reefs at multiple sites across habitat gradients when applicable to restore connectivity of oyster populations and increase oyster habitat in suitable areas
- Restore multiple source reefs to supply oyster larvae to important oyster habitat areas by considering larval transport dynamics in restoration site selection
- Increase the resilience of restored oyster habitat through reef design and siting strategies.

Considerations for Restoration Area Selection

- Habitat suitability (e.g., substrate; salinity; and other physical, chemical, and biological factors)
- Adequate larval availability (recruitment may serve as an indicator)
- Areas that reduce or prevent poaching (e.g., closed waters or other passive approaches to protect spawning populations)
- Areas that represent a priority position within the habitat (water depth, salinity) gradient to complete a network of reefs (e.g., up-estuary position for larval source reefs and down-estuary position for receiving reefs), both within and between hydrologic basins
- Areas that address gaps in optimal distance between reefs to establish a network of reefs connected by larval transport within a hydrological basin
- Areas that support larval transport between hydrological basins
- Areas with data to indicate oyster habitat previously existed.

Potential Mid Phase Planning Project Concepts

- Identify core oyster habitat areas and prioritize adjacent restoration sites to create a network of reefs connected by larval transport
- Identify and prioritize sites that will restore oyster reefs across a habitat gradient of salinities and water depths
- Evaluate nearby sources of larvae to prioritize restoration sites
- Identify larval receiving areas with insufficient cultch to establish new oyster reefs
- Conduct a gap analysis of projects and related restoration objectives to prioritize remaining needs to establish networks of interconnected reefs
- Reassess needs for regional oyster restoration based on restored habitat and population or larval transport characteristics
- Assess restoration outcomes for constructed projects to inform adaptive management
- Develop shell budgets for restoration areas to evaluate adaptive management needs
- Determine if poaching is occurring and increase enforcement and/or compliance at restored/protected reefs.

Potential Mid Phase Restoration Implementation Project Concepts

Table 2. Potential implementation project concepts for the mid restoration phase

Potential project concepts	Implementation strategies	Potential PDARP/PEIS techniques[a]
Restore oyster reefs at multiple sites along habitat gradients to complete networks of reefs connected through larval transport	• Restore smaller and more numerous reefs • Restore reefs an appropriate distance from and down-current of spawning oyster populations or oyster reef spawning reserves • Restore reefs at different positions along water depth and salinity gradients • Restore reefs at sites that are not likely to be impacted by environmental perturbations at the same time (e.g., freshets cycle, prolonged reduced flows, rising sea levels)	• Place cultch in nearshore and subtidal areas • Construct living shorelines • Develop a network of oyster reef spawning reserves
Increase oyster abundance/density at network reefs, as needed, to enhance or accelerate connectivity between sites	• Assess recruitment at potential restoration sites; if recruitment is limited, adding live oyster resource (e.g., seeding, live cultch, oyster relay) may accelerate restoration	• Place cultch in nearshore and subtidal areas • Enhance oyster reef productivity through spawning stock enhancement projects
Engage the public in oyster restoration activities, including off-bottom oyster gardening, shell recycling, and living shoreline restoration	• Contact conservation groups to start oyster gardening programs and work on living shorelines • Work with restaurants to form a shell recycling program	• Place cultch in nearshore and subtidal areas • Construct living shorelines • Enhance oyster reef productivity through spawning stock enhancement projects
Engage oyster fishing communities in restoration activities, including restoration of nearshore oyster reefs and fringing oyster habitat	• Evaluate opportunities to engage local oystermen in oyster reef restoration activities, such as placing cultch in shallow waters or monitoring	• Place cultch in nearshore and subtidal areas • Construct living shorelines
Enhance capacity and reduce costs to conduct oyster reef restoration	• Enhance or establish remote-setting facilities as needed • Establish oyster shell recycling and transport centers	• Enhance oyster reef productivity through spawning stock enhancement projects

a. Restoration technique names are abbreviated. See Section 2.2 for the full names of the techniques.

2.3.3 Final Restoration Phase

The final restoration phase focuses on completing the restoration of oyster reef networks to restore habitat diversity and ecological functions.

Recommended Restoration Objectives

- Protect, maintain, and adaptively manage restored reefs to sustain investments made during the initial and mid restoration phases (e.g., address threats such as poaching and management violations, increase reef elevation to improve success as needed)
- Conduct resource-level monitoring to assess oyster recovery and restoration progress, and inform restoration planning and prioritization
- Restore a diversity of oyster habitats within and across intertidal and subtidal environments
- Fill gaps in networks of restored oyster reefs to enhance and restore ecological services for benthic communities, fish, birds, saltmarsh, and other vegetated shorelines
- Increase the resilience of regional oyster populations by restoring redundant larval source populations across disturbance regimes.

Considerations for Restoration Area Selection

- Habitat suitability (e.g., substrate; salinity; and other physical, chemical, and biological factors)
- Adequate larval availability (recruitment may serve as an indicator)
- Areas that fill gaps in restoring the diversity of oyster reef types across habitat gradients and within protected areas
- Areas where living shoreline techniques are most likely to sustain oysters and stabilize shorelines (e.g., sheltered areas such as small bays and estuaries, areas with low to moderate wave energy)
- Areas where restoration of other resource types has been conducted or is being planned, and is compatible with oyster restoration
- Areas where oyster habitat suitability factors are projected to improve
- Areas where there are gaps in the network of oyster reefs across a disturbance regime to increase resilience.

Potential Final Phase Planning Project Concepts

- Map oyster habitat to show restoration progress, identify gaps in the development of a network of reefs, and inform restoration planning
- Conduct gap analysis of remaining needs to restore a diversity of oyster reef types and regional oyster population resilience
- Assess restoration outcomes for constructed projects to inform adaptive management
- Develop shell budgets for restoration areas to evaluate adaptive management needs
- Enhance enforcement and/or compliance at restored/protected reefs, as needed (e.g., poaching, regulations, and/or patrols)
- Map restoration of other resource types within suitable oyster habitat to identify opportunities to leverage projects and implement multi-resource restoration projects.

Potential Final Phase Restoration Implementation Project Concepts

Table 3. Potential implementation project concepts for the final restoration phase

Potential project concepts	Implementation strategies	Potential PDARP/PEIS techniques[a]
Restore oyster reefs that are designed to increase ecological function	• Restore high-elevation reefs • Select cultch type and sizes to incorporate greater interstitial spaces and complexity for fish use • Design reef footprint and cultch placement to incorporate gaps between hard and soft substrate areas for diverse benthic communities	• Place cultch in nearshore and subtidal areas • Construct living shorelines
Restore nearshore oyster reefs that enhance connectivity between adjacent habitat types	• Restore oyster reefs within a complex of nearshore habitats in areas with suitable wave energy and exposure, and oyster habitat conditions • Select sites adjacent to seagrass beds to restore subtidal reefs • Select sites adjacent to marshes that are nurseries for fish	• Place cultch in nearshore and subtidal areas • Construct living shorelines • Develop a network of oyster reef spawning reserves
Restore subtidal reefs in areas that enhance recreational fish restoration efforts	• Restore subtidal oyster reefs in areas that support reef fish species • Restore oyster habitat within or adjacent to areas designated for recreational fishing reef construction	• Place cultch in subtidal areas • Develop a network of oyster reef spawning reserves
Restore oyster habitat that enhances bird restoration efforts (e.g., oystercatchers, wading birds, saltmarsh birds)	• Restore intertidal oyster reefs • Restore oyster habitat adjacent to barrier islands • Restore oyster habitat adjacent to bird islands	• Place cultch in nearshore and subtidal areas • Construct living shorelines • Develop a network of oyster reef spawning reserves
Restore fringing oyster habitat	• Place loose shell in very shallow waters using small-boat techniques • Implement projects as possible with local oyster fishermen	• Place cultch in nearshore areas • Construct living shorelines
Restore oyster reefs to stabilize shoreline wetlands and create saltmarsh habitat	• Construct living shoreline projects at sites with suitable oyster habitat to reduce wave energy affecting the shoreline • Restore high-relief oyster reefs parallel to shoreline to create saltmarsh habitat	• Construct living shorelines

a. Restoration technique names are abbreviated. See Section 2.2 for the full names of the techniques.

2.4 Monitoring and Adaptive Management

To increase the likelihood of successful oyster restoration, the TIGs will tailor monitoring to specific projects and, where applicable, monitor and evaluate restoration outcomes at the project level as well as at the broader restoration type and plan levels. As a part of the monitoring and adaptive management framework presented in the PDARP/PEIS (see Appendix 5.E), the Trustees committed to establish a suite of parameters and monitoring methods to be used on similar restoration projects, to the extent practicable, in order to evaluate restoration progress and facilitate the aggregation of monitoring results. Monitoring information collected at the project-level can also inform adaptive management by informing the selection, design, and implementation of future restoration projects. Implementing restoration projects within an adaptive management framework involves establishing feedback mechanisms to incorporate new information to inform current and future restoration project decisions. Decision-support tools such as models that describe expected outcomes for proposed restoration actions may be helpful in identifying key uncertainties, and developing monitoring and adaptive management strategies to manage these uncertainties. Section 2.4.1 describes core project-level parameters and additional parameters for consideration, as applicable. Section 2.4.2 describes parameters that can be aggregated across projects to assess progress toward the Oyster Restoration Type's goals and objectives.

2.4.1 Example Project-Level Parameters

To support consistent data collection and reporting, Table 4 presents a set of core parameters to be collected, as appropriate and to the extent practicable. These core parameters can be used to assess individual project performance and success, and may also be aggregated across projects (see Section 2.4.2). Additional parameters for consideration that may enhance understanding of project performance and inform adaptive management are also listed in Table 4. See Baggett et al. (2014) for more detailed information on standard methodologies and sampling frequency for the parameters presented in Table 4.

Table 4. List of core and additional parameters for consideration (as appropriate) to be collected on oyster restoration projects, including projects with a secondary objective. See Baggett et al. (2014) for detailed descriptions and methodologies for monitoring these parameters.

Category	Core parameters	Parameters for consideration (as appropriate)
Reef dimensions	• Project footprint (m^2) • Reef area (m^2) • Reef height (m) • Reef volume (m^3)	• Low tide exposure • Reef rugosity • Reef patchiness • Consolidation rate/subsidence of reef structure
Oyster demography	• Density of live and dead oysters (# of oysters/m^2) • Size frequency distribution (shell height, mm) • Mortality (%)	• Growth rates • Recruitment • Shell volume (for determination of shell budget) • Dermo disease prevalence and intensity
Benthic predatory, pest, or competitive species	–	• Presence, density, or percent cover of predatory, pest, or competitive species

Table 4. List of core and additional parameters for consideration (as appropriate) to be collected on oyster restoration projects, including projects with a secondary objective. See Baggett et al. (2014) for detailed descriptions and methodologies for monitoring these parameters.

Category	Core parameters	Parameters for consideration (as appropriate)
Environmental conditions	–	• Water temperature • Salinity • Dissolved oxygen • pH • Turbidity • Total suspended solids • Chlorophyll a • Flow rate
Secondary Project Objective: Habitat enhancement for fauna		
Species composition of target fauna (e.g., benthic invertebrates, nekton, birds)	• Species composition, density (# of individuals/m^2) or catch per unit effort (CPUE), and size (length mm, biomass g, etc.) of target faunal species/groups	–
Secondary Project Objective: Living shorelines		
Adjacent shoreline characteristics	• Shoreline loss or gain (m/year)	• Shoreline elevation change • Marsh vegetation species composition, density, and percent cover
Environmental conditions	–	• Wave height
Secondary Project Objective: Increased reef productivity		
Reproductive success characteristics	• Settlement (# of spat/m^2 per day or # of spat/m^2) • Density of "large" (defined based on local conditions) oysters (# of large oysters/m^2)	• Gonad development status • Sex ratio

2.4.2 Example Resource-Level Metrics

To support consistent reporting, Table 5 presents a series of potential metrics to be aggregated across projects to assess progress toward the PDARP/PEIS oyster restoration goals outlined in Section 2.1. These metrics were identified by first determining the specific outcomes the Trustees hope to achieve and then identifying specific metrics to quantify progress toward these outcomes. Table 5 also includes a list of data inputs/analyses that are needed to report on the metric. In most cases, these overlap with the parameters needed to evaluate individual project performance, but in some cases additional analyses may be required.

Table 5. List of resource-level metrics

Outcome	Metrics	Data inputs/analyses
Restore oyster reef habitat	• Acreage of reef area (total across projects; created, restored, and protected)	• Calculate total reef area (created, restored, and protected) by summing individual project reef area (in m^2) and converting to acres
Restore oyster abundance	• Oyster abundance (total across projects)	• Calculate total oyster abundance by estimating total abundance by project (i.e., multiply oyster density by reef area) and summing across projects; this will likely need to consider oyster growth/turnover in the calculations
Restore spawning stock	• # or % of reefs with multiple age/size classes	• Analyze and summarize oyster size distribution data across projects
Support healthy recruitment levels	• Abundance of spat oysters (total across projects)	• Calculate total spat abundance by estimating total spat abundance by project (i.e., multiply spat oyster density by reef area) and summing across projects; this will likely need to consider oyster growth/turnover in the calculations
	• # or % of reefs with multiple age/size classes	• Analyze and summarize oyster size distribution data across projects
Restore resilience to oyster populations by increasing connectivity	• Spatial distribution of reefs across habitat gradients	• Map location of reefs across habitat gradients (e.g., salinity, depth)
Restore a diversity of oyster reef habitat	• # and acreage of total different reef types across projects (e.g., structure, depth, salinity, proximity to other habitat, harvested/non-harvested)	• Calculate total number and acres of reefs by reef type across projects
Support ecological functions	• Diversity of different groups of species (e.g., epifauna, nekton, birds)	• Analyze and summarize species composition of fauna across projects
	• Linear miles of reef adjacent to vegetated shoreline (total across projects)	• Calculate total length of reef structure by summing individual project lengths (in meters) and converting to linear miles

3. Context for Project Development and Prioritization

The extent and magnitude of the DWH injury to oysters, delayed oyster population recovery, and ongoing threats to oyster populations and reef habitat require prioritization of restoration actions. While each TIG will determine the appropriate project(s) for its respective Restoration Area, the following information provides context for prioritizing restoration actions to achieve the PDARP/PEIS restoration goals and the greatest benefit for long-term ecosystem restoration.

3.1 Prioritizing Areas for Oyster Restoration

The evaluation of hydrological information is a cost-effective strategy to identify restoration areas in which one or more projects can contribute to restoring resilient and connected nearshore and subtidal oyster populations. Hydrological units representing basins provide a suitable scale within which oyster populations have the greatest connectivity and where the greatest opportunities exist to restore the regional oyster larvae pool. Within basins, a phased approach to restoration can be developed by determining the appropriate location, size, and type of multiple projects; distances between projects; extent of recruitment recovery; and the optimum timing for implementation of projects based on oyster recruitment, restoration needs, and coordination with adjacent projects.

The DWH circulation model incorporates estimated larval settlement within geographic sub-basins based on larval transport studies. This larval transport information, and information from other studies of larval transport in the GOM (e.g., Kim et al., 2013), can be used as an additional tool to identify potential areas with high larval retention, larval source areas, and areas with high larval settlement. Additional recruitment monitoring data from DWH and other monitoring programs can provide an additional layer of important information.

The suitability of an area for oyster settlement and survival is another factor to consider for siting oyster restoration projects. The suitability of sites for spat settlement, growth, and survival can be considered based on both physical and chemical parameters as well as biological parameters. Sections 3.3 and 3.4 in Module 2 provide additional information about habitat suitability models and the ability of oyster to tolerate a range of environmental conditions.

In addition to evaluating habitat suitability of restoration site locations, it is important to consider the site’s position with respect to existing oyster populations (and other restoration sites) so that they can successfully interact with the regional larval pool, either by receiving larval recruits from existing populations or donating larvae for settlement onto other reefs.

3.2 Selecting Restoration Technique(s)

Successful restoration of oysters depends on three major factors: (1) appropriate site hydrologic conditions, (2) adequate supply of oyster larvae to recruit to available cultch material, and (3) adequate amounts of substrate for recruitment (i.e., clean, unburied cultch) (Cake, 1983; Powell and Klinck, 2007; Brumbaugh and Coen, 2009). All the techniques recommended in the PDARP/PEIS may contribute to achieving oyster restoration goals; however, the selection of the most effective technique or combination of techniques will depend on site conditions and project-specific objectives, as determined by each TIG. For each technique, we present considerations for project design and site selection.

3.2.1 Technique 1: Restore or Create Oyster Reefs through Placement of Cultch in Nearshore and Subtidal Areas

This restoration technique involves the placement of cultch material in areas with suitable conditions for oysters to provide hard structure for larval settlement and to restore or create three-dimensional oyster reef habitat. This technique can be used to restore lost oyster reef habitat, expand existing oyster reef habitat, or enhance oyster abundance at existing reefs. Cultch placement projects should be sited and designed to maximize oyster recruitment and survival, serve as a source of oyster larvae to the regional larval pool, and restore injured benthic and fish communities. Cultch material can consist of any clean, hard substrate such as shell, limestone rock, crushed concrete, and other similar material. This technique can be used in areas such as the margins of marshes, tidal creeks, estuaries, and bays within optimal oyster habitat suitability zones.

To maximize the likelihood of success, projects should be carefully sited to take advantage of existing larval source and sink relationships. Selection of sites in reasonable proximity to, and down-current of, healthy populations of spawning oyster populations given typical circulation patterns will increase the likelihood of successful oyster recruitment. Studies have shown that oyster larvae can travel significant distances before settling (Kim et al., 2010; Murray et al., 2015), so determination of appropriate proximity may require information on settlement and/or recruitment rates in the area or observed or modeled estimates of the distribution of potential distance traveled prior to settlement.

Key Considerations

- Selection of sites where there is adequate larval supply and where substrate for recruitment is limited or lacking.
- The presence of firm bottom substrate to support restored reef structure and prevent/minimize potential loss from sinking/burial.
- Projects intended for oyster spawning reserves or for provision of ecosystem services can be designed with a higher relief to reduce the effects of sedimentation and hypoxia.
- If poaching is a concern, projects can be located at depths that deter harvest by hand. Larger cultch sizes or structures that deter harvest by tonging and dredging may also be used.
- Future conditions can be evaluated prior to site selection to identify potential changes in habitat suitability.

3.2.2 Technique 2: Construct Living Shorelines

This restoration technique involves the construction of living shorelines to restore oysters and provide secondary benefits such as reducing wave energy reaching the shoreline, thereby inducing sediment deposition and stabilizing shoreline habitats; creating substrate for colonization by other reef organisms; providing shelter for benthic and fish communities; and reestablishing ecological connections at the land-water interface. Living shorelines can include a variety of shoreline stabilization and habitat restoration techniques that span coastal habitat zones and use both structural and organic materials (Walker et al., 2011).

Two of the most important habitat suitability and siting factors for living shorelines are wave energy and salinity. Siting living shoreline projects at estuarine sites with relatively high degrees of wave exposure may reduce or prevent larval settlement and reduce growth of oysters. In some cases, wave exposure could ultimately limit reef development and the long-term persistence of living shoreline projects. Salinity can influence the oyster component of living shorelines (see Section 3.4 in Module 2 for more information). When salinities are too low, oyster settlement will not occur, substrate materials are not likely to become consolidated, and the living shoreline may not be self-sustaining. When salinities are too high, settlement will occur but predators, boring organisms, and disease will likely limit oyster survival and growth; and substrate materials will not become consolidated or will deteriorate over time. Potential siting and design considerations can address such risks to a degree. Some examples of siting and design considerations include the oyster restoration method used, the selection of cultch materials, and the siting of intertidal versus nearshore subtidal reefs.

Key Considerations

- Selection of sites, where appropriate, adjacent to wetland areas targeted for protection with moderate to low wave exposure.
- The sustainability of oysters on a living shoreline project is influenced by salinity, larval supply, wave exposure, tidal position, substrate firmness, subsidence, sea level rise, water circulation, and other factors.
- Projects should be designed to allow for the ingress and egress of marine organisms (e.g., by incorporating gaps or dips into the design) to avoid impairing the nursery function of shoreline habitats.
- Consideration should be made as to the overall purpose of the living shoreline project. The living shoreline may be for erosion control, ecological services, or a combination of the two. If the purpose is primarily for erosion control placement, the design and pre-siting variables such as wind intensity and direction may be more appropriate than pre-siting variables for an ecological service reef such as seasonal current patterns during peak oyster spawning.
- Successful living shoreline projects will inherently become non-harvestable sources of oyster larvae and should be considered in the development of spawning reef reserve networks.

3.2.3 Technique 3: Enhance Oyster Reef Productivity through Spawning Stock Enhancement Projects Such As Planting Hatchery-Raised Oysters, Relocating Wild Oysters to Restoration Sites, Oyster Gardening Programs, and Other Similar Projects

Planting spat on shell or cultch or transplanting oysters can improve oyster abundance and density at existing or restored oyster reefs. This technique can be used on existing reefs with low productivity, or to supplement cultch plants or living shoreline projects. If transplanting oysters or spat on shell or cultch, the size and density of the planted oysters are critical for survival and growth (Southworth and Mann, 1998; Puckett and Eggleston, 2012).

Oysters may be moved from reefs in areas of poor habitat conditions, or obtained from hatcheries or oyster gardening programs. Stocking juvenile or adult oysters on a restoration site may be more costly than seeding with spat on shell, but larger oysters have a much higher fecundity (VanderKooy, 2012); therefore, this technique may be warranted in some areas. Other factors in addition to site suitability that should be considered are whether oysters are large enough to survive relocation and the risk of transporting pathogens. To protect public health, the Trustees will follow best management practices to ensure compliance with regulations and shellfish control authorities (Leonard and Macfarlane, 2011; VanderKooy, 2012).

Key Considerations

1. Reef enhancement methods (transplanting oysters and seeding with spat on shell or other cultch) should primarily be considered in locations where recruitment is limited and adequate substrate exists either naturally or through cultch placement.
2. Relocation of oysters from poor habitats to project areas should be used in limited cases, and must comply with shellfish control regulations and best management practices.
3. Prior to reef enhancement, assess the environmental conditions at prospective sites for suitability for oyster survival and reproduction, including expected larval dispersal patterns. At sites with highly variable conditions, a high seeding density or spat on cultch should be considered.
4. Collecting implementation information about the size of seed at deployment, initial density, method of deployment, time out of water, and temperature is important for supporting adaptive management for this technique (Peterson et al., 1995).

3.2.4 Technique 4: Develop a Network of Oyster Reef Spawning Reserves

The effects of harvest on oyster reefs, the breakdown of reef structure, the reduction of reef height, the removal of shell, and the removal of oysters are well-documented (Rothschild et al., 1994; Lenihan et al., 1999; Powers et al., 2009). Because of these effects, harvest has two consequences: the first is that as market-sized oysters are removed from a reef, the proportion of females with the highest fecundity (and disease resistance) is reduced (Harding et al., 2013), reducing the reproductive potential of the reef (Breitburg et al., 2000). The second consequence is that the reduction in reef structure (height and volume) directly affects recruitment to that reef by impairing settlement and survival of oyster spat (Lenihan, 1999; Lenihan et al., 1999; Scyphers et al., 2011). Carefully managed harvested and non-harvested reefs can develop sustainable oyster spawning stock and serve as a regional source of larvae.

Implementation of this technique includes identifying specific areas that would be periodically or permanently closed to harvest to protect spawning oysters and serve as sources of oyster larvae to other reefs (including harvestable oyster grounds). A network approach to create reef reserves will increase success in enhancing the regional larval pool, maintaining oyster populations over a large area, and facilitating population recovery after mortality events by increasing the likelihood that a portion of the population will avoid adverse conditions. In order to maximize benefits to oyster populations, distances between reserve reefs need to be compatible with local oyster larvae dispersal dynamics to maximize reserve connectivity and restore metapopulation dynamics (USACE, 2012; Kim et al., 2013; Puckett et al., 2014).

Adequate spawning stock for a reserve reef should consist of a high density of oysters that are comprised of a higher ratio of females to males. Oysters are broadcast spawners and dense aggregations are necessary for the successful fertilization of eggs. Restoring nearshore oyster spawning stock will also be important in re-establishing the ability of these oysters to serve as a source of larvae to subtidal reefs. A robust reserve system of both nearshore and subtidal reefs can help support the longevity of oyster populations as well as the commercial and recreational oyster fisheries.

Key Considerations

- Optimal areas are those with oyster habitat and water circulation patterns that direct larvae to recruitment-limited reefs
- Collaboration and coordination with resource managers and the oyster industry are important for the identification and designation of spawning reserves
- Outreach efforts are essential to limit poaching and increase awareness of the importance of spawning reserves to restore recruitment to public oyster grounds and other oyster reefs
- Spatially explicit larval transport models may inform selection of source and sink reef locations
- The assessment of larval supply to prospective reserve reef sites, using settlement plates or similar methods, preferably for two or more years, may help to identify restoration sites
- The use of many small reserve reefs, appropriately located, rather than fewer larger ones, will maximize connectivity
- The use of larger cultch materials for subtidal reserve reefs may limit or discourage poaching where appropriate.

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