CHAPTER 4: RESTORATION MONITORING OF OYSTER REEFS

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INTRODUCTION

Oyster reefs form when densely packed individual oysters grow adjacent to each other, thereby creating heterogeneous hard surface habitats (see Hargis and Haven 1999) (Figure 1). They are found in brackish to marine waters with salinities at 12-28 parts per thousand (ppt) or higher in some cases (Dame 1996), and are particularly abundant in estuarine systems along the Atlantic and Gulf of Mexico coasts of the United States. These reefs are three-dimensional, complex habitats in the intertidal and subtidal zones and vary in structure and function. Differences in oyster reef structure and function, such as patterns in species abundance and habitat use, have been attributed to the physical stress of exposure and the amount of time predators have to forage in the different habitats (Dame 1996). Natural oyster reefs are created and maintained by living oysters. Shells of living and deceased oysters provide protected habitat for oyster spat, larvae (veligers) that settle and recruit to hard substrates (Roegner and Mann 1990; Bartol and Mann 1997). Recruitment of oysters to the reef and subsequent survival of oysters to maturity provide the mechanism by which the reef's vertical relief is maintained and increased.

Oyster reefs are complex ecological systems that are highly optimized and evolutionarily selected for high productivity (Dame 1996). They are comprised of many interacting species, with feedback loops at many scales of observation, and the resulting dynamics are often non-linear (i.e., the causes are not proportional to the consequences). These characteristics can lead to unpredictable or surprising behavior, particularly when these systems are faced with environmental changes they have never experienced. Under such circumstances, these systems may shift to an alternate state or even collapse. Thus, the restoration and management of oyster reefs require flexible and innovative long-term planning and monitoring.

Historically, oyster reefs were the dominant ecological communities in many estuarine

Figure 1. Intertidal oyster reefs along fringing marsh tidal creeks in Charleston, SC. Photo courtesy of Loren Coen, Marine Resources Research Institute, South Carolina Department of Natural Resources.

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Figure 2 Picking oysters by hand at low tide. Photo courtesy of Bob Williams, Willapa Bay, WA. Publication of the NOAA Central Library. http://www.photolib.noaa.gov/fish/fish0744.htm

habitats because of the numerous and critical ecosystem services that they provide. Such services or functions include benthic-pelagic coupling (i.e., coupling of organisms between the bottom surface and water column) through the filtering activity of oysters (e.g., Newell 1988) and the provision of physical habitat for benthic invertebrates and numerous fish and bird species that use oyster reefs for feeding, breeding, and nursery grounds (Kaufman and Dayton 1997; Peterson and Lubchenco 1997; Harding and Mann 1999; Jackson et al. 2001; Coen and Luckenbach 2000). Additionally, the hard structure of the oyster reef stabilizes sediments (Hargis and Haven 1999), providing shoreline protection for adjacent fringing marshes. The reefs also have a significant economic value for the U.S. seafood industry as they support many recreationally and commercially valuable animals such as fish, crabs, shrimps, and oysters.

Oysters (e.g., eastern oysters, *Crassostrea virginica*) provide the main structural and functional components of oyster reefs. These animals are sessile molluscs in the class *Bivalvia*. They are suspension-feeders that consume food by removing floating (suspended) particulate matter from the water column (Newell 1988; Dame and Libes 1993; Mann 2000). There are approximately 100,000 species of molluscs of which approximately 8,000 are bivalves. Bivalves are characterized by their two opposing calcareous shells that protect the soft body mass. Their shells are joined by an elastic ligament, two adductor muscles acting in opposition to the ligament in order to close the shell (Figure 3), and an extendable foot to help these animals walk or bury themselves in

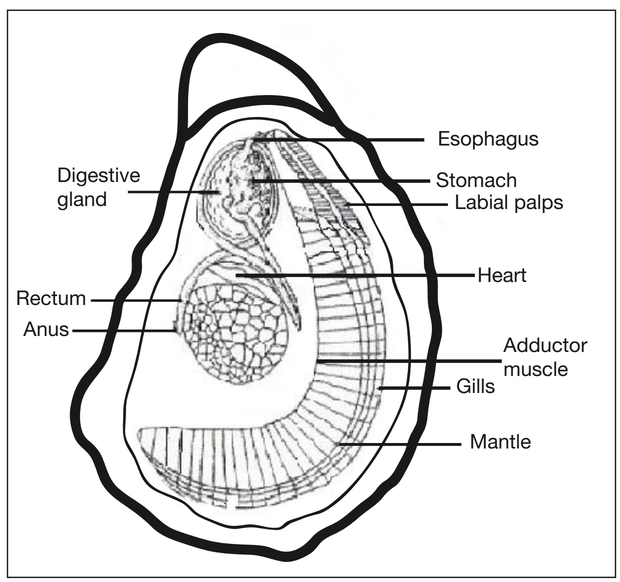

Figure 3. Oyster anatomy. Diagram courtesy of Felicity Burrows, NOAA National Centers for Coastal and Ocean Science. Modified from Galtsoff 1964.

sediment. Of all the bivalves, only the oysters and scallops have forsaken both an adductor muscle and the foot, thus limiting burial as a form of predator protection. Scallops generally compensate by swimming. Oysters, however, have extraordinary plasticity in morphological form. Their diversity and aggregative settlement behavior results in reef formation over extended periods of time. The resulting reefs are biological and geological features that, prior to estuarine degradation by human actions, served to dominate the benthos (i.e., biota on the bottom of lakes, estuaries, and seas) of temperate and subtropical estuaries worldwide. The strange limitations of this single muscle (monomyarian) form are countered by the advantages of reef formation.

Eastern oysters (Figure 4) are native to the United States and occupy habitats from Prince Edward Island, Canada to the Yucatan peninsula, Mexico and beyond, depending on taxonomy opinions. This species has also been introduced in other locations for aquaculture purposes such as on the U.S. west coast. Their range is set by thermal tolerances and habitat requirements necessary for adult growth, reproduction, and larval survival (e.g., salinity and substrate).

Adult eastern oysters are broadcast spawners and generally reproduce when water temperatures are between 20 and 30°C (Galtsoff 1964; Mann et al. 1994; Dame 1996; Kennedy et al. 1996; Luckenbach et al. 1999) (Figure 5). If the optimum temperature of a particular oyster species is exceeded, spawning may be limited and larval development may be reduced (Kennedy et al. 1996). After fertilization, the zygote develops into a planktonic (free-swimming) ciliated larva in about six hours. A fully shelled veliger (i.e., the larval stage of a mollusc identified by its velum) is formed within 12 to 24 hours. The larva is planktonic for about two to three weeks during which it is dispersed by the tidal currents. At the end of the planktonic larval period, the larva develops a foot, then settles to the bottom of the water column, searching for a suitable hard substrate (preferably clean oyster shell) and attaching itself (Bahr and Lanier 1981; Kennedy et al. 1996; Kennedy 1996).

Site selection for settlement from the plankton to the benthos by the oyster larva is influenced by a suite of environmental factors including substrate type and location. Once a larva permanently cements itself to hard substrate, it

Figure 4. Oysters recruited onto newly planted shell (cultch) during restoration efforts. Photo courtesy of Loren Coen, Marine Resources Research Institute, South Carolina Department of Natural Resources, Charleston, SC.

Figure 5. A natural bed of healthy intertidal oyster clusters in South Carolina. Photo courtesy of Ray Haggerty (retired), South Carolina Department of Natural Resources.

remains fixed in that location for life (Roegner and Mann 1990; Bartol and Mann 1997; Baker 1997; Baker and Mann 1999). The duration of the larval period is influenced by environmental conditions including water temperature, salinity, and dissolved oxygen concentration (Baker and Mann 1992; Baker and Mann 1994). Temperature and salinity also influence growth of oyster larvae (Davis and Calabrese 1964). Eastern oyster larvae, for example, can grow between 30 and 32.5°C (i.e., the upper thermal limit), although the suggested range for optimal growth is in water temperatures between 14 and 28˚C (Shumway 1996) and in water salinity between 12 and 28 ppt (parts per thousand) (Dame 1996). Any abrupt change in salinity or temperature above or below their optimum level may influence larval development.

Native species of oysters that are locally or occasionally seen along American coastal waters (Carlton and Mann 1996) include the:

- Eastern oyster (*E. virginica*)
- Olympia oyster (*Ostrea conchaphila, O. lurida*) found on the west coast of North America between Sitka, Alaska, and Panama (Baker 1995; Turgeon et al. 1998; Gillespie 2000)
- Frond oyster (*Dendostea frons*) in the tropical Western Atlantic (e.g., the Caribbean)
- Crested oyster (*Ostrea equestris*) found naturally from the Carolinas to Texas, and
- Sponge oyster (*Cryptostrea (Ostrea) permollis*)

In the Pacific Northwest, several non-native or exotic oysters are commonly grown commercially for aquaculture, including the:

- Pacific oyster (*Crassostrea gigas*) (MacKenzie 1996)
- Asian oyster, also known as Suminoe oyster (*Crassostrea ariakensis*), and
- Crested oyster (*Ostrea equestris*)

Native species of oysters are the only species currently acceptable for oyster restoration. Non-native species, however, may eventually be used as candidates to rebuild reefs along the United States coasts (Luckenbach et al. 1999; National Research Council 2004) such as Virginia and Maryland. Before considering the use of non-native species for oyster reef restoration, one must be aware of the federal and local laws regulating and/or prohibiting introduction and transfer of invasive species because of the environmental impact they may have on native oyster populations. These non-native species can grow rapidly in cases where conditions are suitable and become problematic because their unlimited growth displaces and outcompetes native oyster species for food, habitat, and other resources. If the environmental tolerances of non-native species are matched to target certain habitats, however, environmental and political issues related to the intended introduction of these species may be resolved. Another important factor to consider when introducing a non-native or invasive species for any purpose - including restoration - is the substantial amount of formal scientific examination and review of the expected consequences (e.g., legal, ecological, economic) of their introduction.

Despite the importance of oyster reefs, they have been degraded in most of their natural range by various human activities including pollution, increased suspended sediment loading, and over-harvesting (Rothschild et al. 1994; Lenihan and Peterson 1998; Hargis and Haven 1999; Gagliano and Gagliano 2002). Because healthy oyster reefs support a thriving ecological community and are also economically important to the oyster and finfish industries, restoration efforts should be considered to ensure that these habitats and their estuarine environments are returned to a naturally sustainable functioning state and are then monitored and managed efficiently. Some researchers caution practitioners to clearly define their goals in order to differentiate between fisheries enhancement and ecological restoration of ecosystems (Coen and Luckenbach 2000).

In bays and sounds along much of the U.S. Atlantic and Gulf coasts, oyster reef restoration efforts are now underway to enhance or restore the ecosystem functions provided directly and indirectly by oyster reefs (Coen et al. 1999b). When restoring oyster reefs, the primary ecological goal is to restore oyster populations to self-sustaining levels that mimick historic (pre-exploitation) oyster populations in the same habitats because oysters are keystone species central to oyster reef communities. Improvement in water quality will follow the restoration of oyster populations because of their ability to filter water through benthic-pelagic coupling. Water quality may not improve, however, without healthy oyster populations and other filter feeders that use the hard substrate habitats provided by oyster shell (e.g., barnacles and mussels). Figures 7-10 show two methods to create oyster reefs. Figures 6 and 7 display the use of a high pressure water system to distribute oyster shells into the water from a barge along the nearshore.

Oyster reefs are created by recycling and bagging oyster shell and placing the shell bags on which oysters can settle (Figures 8 and 9). Over time, oysters will grow through the bags and attach themselves to one another and hard substrates to form a reef (Brumbaugh et al. 2000; Hadley and Coen 2002; Leslie et al. 2004). Trays filled with oyster shell rubble may also be placed along the coastline to create subtidal reefs (Lehnert and Allen 2002).

HUMAN IMPACTS TO OYSTER REEFS

Like other coastal habitats, oyster reefs are threatened by various human-induced impacts that can affect the physical structure and functionality of oyster reefs, as well as oyster growth rates. Some of these impacts include:

- Physical damage
- Water pollution, and
- Sedimentation

Restoration Strategies

Not all oyster reef restoration strategies work equally well across sites, but site selection is critical. Local hydrographic patterns as well as historical data on reef presence and success must be considered in selecting a site. Practitioners must also consider tidal, hydrographic/current conditions, depth, bottom condition, and substrate type in the development of restoration strategies.

Figure 6. Large-scale oyster restoration shell planting in 2002 in Folly Creek, South Carolina. Photo courtesy of Loren Coen, Marine Resources Research Institute, South Carolina Department of Natural Resources.

Figure 7. Intertidal shell planting in 2002 along tidal creeks of Bull Creek, South Carolina. Photo courtesy of Ray Haggerty (retired), South Carolina Department of Natural Resources.

Physical Damage from Harvesting, Over-Harvesting, Boating Activities, and Coastal Development

Over-harvesting threatens reefs by reducing the reef acreage and changing reef structure which can ultimately reduce oyster standing stock and spawning biomass (Rothschild et al. 1994; Hargis and Haven 1999; Lenihan and Micheli 2000; Jackson et al. 2001). The size of the oyster spawning population is critical to egg production and density is directly related to fertilization efficiency in these broadcast spawners. If an oyster reef has a higher density, the chance of fertilization is increased. A reef with oysters spaced further apart will have decreased fertilization (Mann and Evans 1998). If both the reef and its oyster populations decline, the abundance and diversity of associated species living on or adjacent to the reef may also be reduced.

Figure 8. Volunteers use bags filled with recycled oyster shells to build large footprint reefs onto which oysters will settle, as part of South Carolina Oyster Restoration and Enhancement (SCORE) reef building project, South Carolina Aquarium. Photo courtesy of Loren Coen, Marine Resources Research Institute, South Carolina Department of Natural Resources.

Figure 9. Volunteers place bags filled with oyster shells along the shoreline to form reefs. SCORE reef building project, South Carolina Aquarium. Photo courtesy of Loren Coen, Marine Resources Research Institute, South Carolina Department of Natural Resources.

In some areas where oyster reefs may be frequently harvested, the acreage of oyster reefs as well as the number of organisms living there may also decrease (Rothschild et al. 1994). The continued decline of oyster reefs may shift the estuarine ecosystem to an alternate trophic structure (food webs) (Newell 1988; Dame 2004). Prior to the 1900s, for example, oyster reefs were dominant ecological units in the Chesapeake Bay and the benthic-pelagic coupling services provided by oyster populations were the major determinant in trophic structure (Baird and Ulanowicz 1989; Newell et al. 1999). In the absence of historic oyster populations (Hargis and Haven 1999), the Chesapeake Bay's trophic structure in the 21st Century is dominated by a planktonic community rather than a benthic oyster reef community (Baird and Ulanowicz 1989; Newell et al. 1999).

Oyster reefs have declined since the mid-1880s along the East and Gulf coasts of the U.S. (Bahr and Lanier 1981). This decline was due in part to the frequent mining of oyster reef resources and the techniques used. Many of these techniques are still being used for various reasons and in some cases, have damaged the reefs and caused ecological changes and a decline in the distribution of reefs (Lenihan and Peterson 1998; Hargis and Haven 1999; Lenihan and Micheli 2000). Dredging and building of ports for example, can disrupt or even destroy oyster reefs. If reefs are destroyed, important recreational and commercial fish species may also be directly damaged or may migrate to regions that are more favorable.

In North Carolina, researchers investigated popular oyster harvesting techniques such as dredging, hand-tonging, and diver-collecting to determine how these methods alter oyster reef morphology and cause incidental mortality to unharvested subtidal oysters (Lenihan and Peterson 2004). Reef height controls local hydrology flow, which in turn affects recruitment, growth, and survival of oysters. Reefs that were harvested by divers, rather than dredging, experienced the lowest incidental mortality (Lenihan and Peterson 2004). Boating activities (i.e., use of boat propellers and anchors) may also damage or destroy oyster reefs (Chose 1999; Grizzle et al. 2002). For example, in Mosquito Lagoon within the Canaveral National Seashore, Florida, some intertidal eastern oyster reefs adjacent to major navigation channels were severely damaged by boat anchors and propellers, causing oyster mortalities (Grizzle et al. 2002).

Impacts of Construction

Construction activities can damage reefs indirectly as well, as channelization associated with the building of dikes can divert freshwater into oyster reef communities, thereby significantly reducing salinity levels and making the environment unfavorable for oyster growth (Powell et al. 1995).

Water Pollution from Agricultural, Municipal, and Industrial Sources

Terrestrial runoff from various sources such as municipal sewage discharges, agricultural fertilizers, and industrial processes may affect the survival and growth of oysters by reducing dissolved oxygen levels. In many cases, runoff contains toxins or fertilizers (i.e., nutrients) which may promote algae growth and cause a reduction in oxygen levels around the reef (Lenihan and Thayer 1999). Sewage discharges may also promote algae growth which can then reduce oxygen levels and distribute coliforms into the water column, thus impairing water quality. As a result of algal overgrowth and low oxygen levels, oysters may be unable to grow, filter feed, and provide nutrients to other species that rely on them.

Chemicals such as tributyltin (TBT), a fouling inhibitor on painted ships, also negatively affect the growth of oysters if leached into the water. At low levels, TBT can cause structural changes, such as inhibiting growth and thickening oyster shells which increases their weight (Waldock and Thain 1983; Alzieu 1998). Oyster exposure to TBT may also affect its ability to resist diseases. Along the northern Gulf of Mexico and the Atlantic coast of North America where eastern oysters (*C. virginica*) are found, a protozoan pathogen, *Perkinsus marinus* infected these oysters, reducing oyster populations and depleting oyster fisheries in this area (Fisher et al. 1999). When exposed to environmental levels of TBT, increased infection intensity and oyster mortality occurred (Fisher et al. 1999). Oyster response to chemicals, however, will vary based on species type, as well as level and type of chemical. These examples depict how oysters may be affected by TBT and potentially other chemicals.

Sedimentation and Agriculture

Increased sedimentation may result from dredging. Constant dredging disturbs sediments and can bury oysters, reducing filtration efficiency and respiration/oxygen exchange for individual oysters. As a result of low oxygen, oyster growth, feeding, and ultimately survival rates are reduced. Another land-based activity that contributes to increased sedimentation affecting oysters is agriculture. The erosion of topsoil as a result of intensified agricultural activities has been identified as a major contributor to increased suspended sediment loads in the Chesapeake Bay and the subsequent demise of the Bay's oyster reefs (Rothschild et al. 1994).

MONITORING

When developing a restoration plan, practitioners should ensure that monitoring is included to track progress of the project. Monitoring the reef's structural and functional characteristics before, during, and after restoration at both the reference and restored sites should be conducted to:

- Evaluate the physical habitat
- Evaluate existing natural populations of target organisms
- Understand the role that each physical characteristic plays in supporting plants and animals, and
- Assess the interaction of organisms on and around the reefs

Adequate replication is often difficult to achieve in ecosystem experiments or restoration projects due to limitations such as small numbers of experimental systems, time, logistics, and expenses (Carpenter 1989). In such cases, paired-system experiments (one reference and one experimental system) are often preferable, even though classical statistics cannot be used to detect manipulation effects (Carpenter 1989). The Before After Control Impact (BACI) method with replicated controls can be used to identify non-random changes in manipulated systems (Stewart-Oaten et al. 1986; Underwood 1994; Dame et al. 2000; Dame et al. 2002). The resulting data can be used in various statistical tests to examine the efficacy of the restoration, including testing the differences in mean abundances of a particular species between the restoration and comparison sites (see Stewart-Oaten et al. 1986; Dame et al. 2000; Dame et al. 2002).

Parameters selected for monitoring should be based on the particular goals and objectives of the restoration project. Both project objectives and thresholds (i.e., points at which effects can be observed) to evaluate progress should be established *before* restoration and monitoring activities begin. Monitoring restoration efforts allows the practitioner to determine whether modifications must be made to the project and to track the success of the restoration project (Coen et al. 2004). Monitoring should also be conducted to (Luckenbach et al. 2004):

- **Evaluate sites proposed for restoration:** Assess the site-specific history of natural oyster population success (i.e., whether the site has ever supported a self-sustaining oyster population) as well as current conditions including tidal flow, local hydrographic conditions, bottom/substrate condition, water quality (e.g., dissolved oxygen), susceptibility to harmful algal blooms, and natural recruitment of oysters.
- **Evaluate stressors:** Assess conditions (e.g., salinity, dissolved oxygen levels, presence of disease, etc.) at existing, but degraded oyster reefs that may be targets for restoration.
- **Facilitate adaptive management:** Measure those elements that can be modified during the restoration process. For instance, monitoring the quality of the substrate in the years after initial planting can reveal whether or not it is necessary to add substrate to provide clean settlement sites. In addition, monitoring for oyster recruitment during the early years of the restoration process can indicate whether the site is recruitment-limited and brood stock enhancement might be justified. It is worth noting that years of data are required to practically evaluate

or describe a restoration project and its surrounding habitats.

- **Assess restoration efforts:** Track the reef's condition, as well as size and number of organisms utilizing the reef. Also determine whether any modifications should be made to the project (e.g., extend the project's timeframe, change methods used, monitor another parameter, etc.).

STRUCTURAL CHARACTERISTICS OF OYSTER REEFS

This section presents the structural characteristics of oyster reefs applicable to restoration monitoring. These characteristics refer to the biological, physical, hydrological, and chemical features of the habitat that may influence the oyster reef restoration project. They may be potential parameters used to gather baseline information and monitor restoration efforts. Not all structural characteristics described herein, however, must be measured or monitored in every restoration project. Additional information is provided to help educate the reader on the ecology of oyster reefs.

The practitioner must first identify a suitable area to locate reefs and then determine whether the site is appropriate for restoration by interpreting site-specific information. Following oyster reef restoration efforts, the structural characteristics of the habitat targeted for restoration in relation to the project goals are monitored (O'Beirn 1996; O'Beirn et al. 2000; Cressman et al. 2003; Coen et al. 2004; Nelson et al. 2004). Some structural characteristics of this habitat include:

Biological
- Habitat created by animals (i.e., oysters)
- Diseases

Physical
- Bathymetry/Topography
- Sediment (e.g., grain size, sedimentation and basin for materials)
- Turbidity/Light availability

Hydrological
- Tides and currents
- Water sources (e.g., upland, groundwater; as related to water quality)
- Water temperature

Chemical (as related to water quality)
- Dissolved oxygen
- Salinity

Ideally, a reference site should be identified and used as a comparative baseline for the restored site before restoration work begins. The reference site should be as pristine as possible and should have naturally occurring oyster populations and similar, well-documented physical, chemical, hydrological, and biological characteristics (see Chapter 15 for methods to select Reference Conditions). Practitioners should monitor structural characteristics such as settlement and growth at the reference site to determine if conditions are favorable for successful oyster reef restoration. Once reefs have been either built as three-dimensional shell piles or stocked with oysters, it could be years before complex communities that can perform various functions to support plants and animals are observed. Nevertheless, the practitioner can develop a timeline to begin monitoring the reef's functioning capacity over time, such as enhancing oyster survival and providing feeding, nursery, and breeding grounds for fish and other marine organisms. Long-term monitoring (multiple years) of restoration projects is vital for the practitioner to track improvements in the restored reef's condition (e.g., increased size, increased number of oysters and other organisms utilizing the reef, etc.) as compared to reference sites.

BIOLOGICAL

Habitat Created by Animals (i.e. oysters)

As mentioned in the introduction, oyster reefs are formed when individual oysters accumulate and form a complex structure that rises above the bottom of the estuary or channel. The structure of the reef forms a three-dimensional habitat that is an emergent property of the interactions of the organisms living on the reef and the surrounding aquatic environment. Both intertidal and subtidal reefs are composed of multiple year classes of oysters which also provide microhabitats for many different species of animals (Meyer 1994; Kennedy et al. 1996; Hargis and Haven 1999). Intertidal oyster reefs may be found throughout the entire intertidal zone, from near bottom to depths where the top of the reef breaks the surface of the water at low tide (Chesapeake Bay Program 2002). Subtidal oyster reefs extend slightly above the bottom yet below the intertidal zone; fringing oyster reefs extend directly outward from the shoreline in the direction of the current.

Recruitment, settlement, and growth of oysters over time increases the vertical relief and basal area of the oyster reef. Habitat used by reef-associated fauna may be monitored by recording their presence/absence, relative abundance, biomass, size of species, species richness/diversity, or percent cover for sessile/encrusting organisms. Such data collected by restoration practitioners can provide information on the types of organisms present and whether the constructed habitat supports these organisms.

Diseases

Oyster diseases can affect the survival and recruitment of eastern oysters and thus progress of oyster restoration efforts. There are two types of oyster diseases: the Dermo disease caused by the parasites *Perkinsus marinus,* and the MSX disease promoted by the *Haplosporidium nelson* parasites (Burreson et al. 2000). *P. marinus* is endemic to the Atlantic coast from Virginia to the Gulf of Mexico, but has spread throughout Maryland to the coast of Maine within the last ten to fifteen years (Reece et al. 2001). *H. nelsoni,* however, is a natural parasite of *Crassostrea gigas* in Korea and Japan, and was possibly introduced to the East coast of the United States when *C. gigas* was introduced (Burreson et al. 2000). Beginning in the 1960s, this parasite caused massive oyster mortalities in the Delaware and Chesapeake Bays. Since then, this parasite has spread through other natural populations. Disease outbreaks resulting from these parasites are one of the primary factors restricting the natural rebuilding of oyster reefs and challenging oyster reef restoration efforts. Once infected with any of these diseases, oyster functioning capacity, such as its ability to reproduce successfully (Kennedy et al. 1995) and filter feed, eventually deteriorates and may affect other animal communities. In cases when infections are severe, diseases cause oyster mortalities. This has been seen throughout the East coast of the United States (Burreson and Calvo 1994; Ford 1996; Andrews 1996; Soniat 1996; Bobo et al. 1997; Burreson et al. 2000).

In areas where oyster diseases may be a significant problem, practitioners should consider measuring disease prevalence and intensity because knowledge of disease levels can:

- Affect adaptive management decisions by understanding mortality patterns, and
- Help develop oyster populations with greater disease tolerance over time by following disease dynamics

Practitioners generally assess both types of oyster diseases by observing and documenting an infection level following the use of Ray's fluid thioglycollate medium culture method (see Ray 1956; Mackin 1962; Mackin 1971).

Monitoring: oyster populations

There are various structural characteristics that should be considered when conducting pre-and post-restoration monitoring. The characteristics that should be considered when evaluating and monitoring oyster reef restoration include (O'Beirn 1996; Coen et al. 2004):

- **Natural oyster recruitment levels**: The level of natural oyster recruitment should be evaluated before, during, and after restoration efforts. Data collected can be statistically analyzed using the BACI method (previously discussed in the "Monitoring" section). Without new recruits, the restoration effort - which in most cases involves planting some shell - is ineffective. Oyster recruitment should be monitored for a minimum of three to four years following the construction of reef foundation at both reference and restoration sites to allow the restored habitat to develop a natural scale of ecological services and allow comparisons between the reefs to be made (Newell et al. 1991; O'Beirn 1996; Harding and Mann 1999; Coen et al. 2004).

- **Availability and integrity of substrate** (O'Beirn et al. 1994; Wesson et al. 1999; Coen et al. 2004): The history of oyster growth and settlement at a site (i.e., whether the site historically supported oyster populations) should be evaluated. It is considered best to locate reef restoration projects where natural reefs formerly thrived to take advantage of inherent hydrographic and local circulation conditions that may enhance settlement, local recruitment, and overall population success. Where adequate substrate for settlement is limited, restoration efforts should begin with the addition of substrate(s), or cultch, to the site. Additional substrate(s) may not be necessary where oyster recruitment and survival rates are sufficient to maintain a self-sustaining natural oyster population where natural recruitment at least balances mortality, or where material is rapidly covered with oysters and provides substratum for additional oyster recruitment over time. Additional substrate(s) may be necessary where oyster recruitment and survival rates are low, and competition with other epifauna occurs. Substrate degradation caused by boring sponges and sedimentation may reduce the availability of clean substrate (generally oyster shell) for oyster settlement and may need to be supplemented. Assessing the availability of adequate substrate prior to recruitment each year can provide a basis for making adaptive management decisions (e.g., whether supplemental substrate is needed).

There are several components to this monitoring need that can lead to different adaptive management decisions and assessments of success (Luckenbach et al. 1999). The relevant components for a particular project should be established in advance with a clear progression of sampling and data analyses in support of the established goals. In all cases, multiple years of data using the same protocols are required for a particular site such that natural variability within a system is incorporated into the restoration strategy. These components may include:

Spat Abundance

- Spat collectors (e.g., shells, tiles, or other materials) may be placed near reef restoration projects to assess the "potential recruits" to the reef
- Predictions about the abundance of newly settled oysters will vary locally, but some minimal level of oyster recruitment will be required for successful restoration
- If oyster settlement rates are low over multiple years, the restoration project must either
  - be relocated, or
  - be enhanced by adding oyster brood stock seed or settling spat to the area

Spat Survival Post-Settlement and Through Recruitment

- Standard stock assessments of oysters (e.g., young-of-the-year recruits) provide a measure of success of the reef substratum and may suggest some remediation if the success is low. It is important to obtain quantitative estimates at sufficient frequency and over more than one recruitment season.
- If the number of settling oysters is sufficiently high, but the number of surviving new recruits is low, it may be

possible to identify the cause(s) of this mortality and changes may result.

For example, early post-settlement survival was observed in Virginia's Eastern shore, the Chesapeake Bay, and the James River in Virginia. Reef foundations were constructed of alternative substrates (surf clam shell and coal ash pellets) in the intertidal zone and found to have similar settlement abundances as reefs of oyster shell, but much higher predation-induced mortality rates (Wesson et al. 1999). The result was that restoration efforts using the alternative substrate as bases had chronically low recruitment, while those using oyster shells had greater recruitment levels (Luckenbach et al. 1999).

- **Abundance and distribution of oysters on the reef:** The size and number of oysters on the reef provide information on population age structure. Multiple years of data collection at the same sites with the same protocols provide valuable information on population age structure, growth rates, and mortality rates.

Sampling and Monitoring Methods

Calipers - Size-frequency and oyster recruitment may be determined by measuring the shell height (i.e., hinge to growth edge or beak, in millimeters) or other shell linear dimensions with calipers, a tool used to measure oyster shell height or length (Coen et al. 2004). Growth of the oysters may be monitored by first marking each oyster and then measuring the size of the oyster in each quadrat along transects at selected time intervals. Each measurement can be used to calculate the change in size between measuring dates.

Plankton tows - Plaknton tows may be used to sample oyster larvae in a restoration site to determine larval concentrations in a given area (Southworth and Mann 1998; Harding 2001). Plankton nets are generally towed horizontally below the water surface, in the direction of the currents and parallel to the oyster reef. Practitioners can determine how long (number of minutes) each tow should be and the frequency of tows per day.

Quadrats - Oyster density on intertidal reefs may be measured by counting live oysters with the use of quadrats. Quadrats are square or rectangular shaped frames, typically 0.25-1.0 square meters in size, and are placed randomly or at fixed positions. Oyster density can be determined by calculating the mean of samples collected from each study area. Oyster recruitment may also be measured by collecting, counting, and documenting the number of live oysters (O'Beirn 1996; Luckenbach et al. 1999). The use of quadrats for assessing the oyster size and abundance is shown in Figures 10 and 11.

Abundance and size data for subtidal oyster populations may also be determined using diver surveys, dredges, or patent tongs (Mann and Evans 1998; Mann and Evans 2004; Mann et al. 2004).

Diver surveys - Diver surveys may involve scuba divers using underwater digital cameras or video recordings to permanently document reef subtidal areas along transect lines or grids. The diver then swims along the transect line and photographs subtidal oyster populations in a selected area. Each study site can be revisited over time to document the condition of the oyster reef. Comparisons of photographs or video recordings from multiple site visits allow change in reef conditions to be identified.

Dredges - A dredge contains a metal rectangular frame with a net of metal rings attached to it. The frame is connected to a towing cable that drags it along the bottom. The lower end of the frame is commonly called a raking bar and usually has a jaw-like structure used to dig up the bottom. Dredges can be used to collect semi-quantitative

Figure 10. Assessing oyster recruitment in 2003 at large-scale restoration effort by sampling shell planted one year earlier in Hamlin Creek, South Carolina using 0.25 m^2 quadrats. Photo courtesy of Loren Coen, Marine Resources Research Institute, South Carolina Department of Natural Resources.

Figure 11. Assessing the size and condition of oysters along the shoreline by sampling with quadrats. Photo courtesy of Loren Coen, Marine Resources Research Institute, South Carolina Department of Natural Resources.

data on population trends. A disadvantage to dredges is that they gather organisms while moving over the bottom, but may not collect organisms consistently throughout a single dredge haul, potentially biasing the samples (Powell et al. 2002; Mann et al. 2004).

Patent tongs - Patent tongs sample oysters on and below the oyster reef surface. The tongs are hinged so they open while being lowered and close as they are elevated. The tongs are attached to a cable used to lower and raise them in and out of the water. Data collected from patent tong surveys can provide estimates of oysters by size and volume (Mann and Evans 1998; Mann et al. 2004).

High-resolution remote sensing - High-resolution remote sensing methods are also used to assess intertidal oyster reefs (Chauvaud et al. 1998; Cracknell 1999; Smith et al. 2001; Wilson et al. 2000; Vincent et al. 2002; Finkbeiner et al. 2003; Corbley 2004). Multiple image processing, photography, spectral clustering, and digital texture analysis are used to determine the boundaries and spatial characteristics of oyster reefs, and provide rapid and accurate means to qualify and quantify changes in marine habitat. Restoration practitioners may also use digital and analog aerial photography to gather baseline information on the restoration site, including reef and adjacent land activities, and to assess the structure and acreage of the oyster reef over time following restoration. Assessment of habitat acreage can help determine whether oyster recruitment and establishment are successful. Figure 12 shows an aerial photograph of intertidal oyster reef distribution at a specific study site in South Carolina.

PHYSICAL

Bathymetry/Topography

Bathymetry which is the science of measuring the depths of the oceans, and mapping the corresponding topography, or physical features of those depths. Both reef bathymetry and topography create zones that support various organisms or life history stages by providing shelter, feeding grounds, breeding areas or substrates for attachment. Topography of intertidal oyster reef has a distinct three-dimensional structure consisting of a core and a veneer. The core consists of living oyster shell, shell fragments, sand, silt, or clays (Bahr and Lanier 1981; Hargis 1999). The veneer (i.e., a thin layer of shell matieral permanently bonded to the core) consists of living oysters, shells of recently dead oysters, biological associates, and other depositional materials. Materials that consist of the core and veneer characterize the rough and hard reef texture and provide a place of attachment for sessile organisms. The presence of these organisms may also contribute to the unique texture of the oyster reef. The reefs provide vertical relief and structural heterogeneity (e.g., the height and width of the oyster shells that form reefs) that attracts many grazers, browsers, and predators as well as sustains many transient fish species (Lenihan 1999; Harding and Mann 1999) such as:

Figure 12. Aerial photograph of intertidal oyster reef construction in Inlet Creek, South Carolina, part of a six-year study by the Oyster Recovery Partnership (ORP). Photo courtesy of George Steele and Loren Coen, South Carolina Department of Natural Resources.

Striped bass (*Morone saxatilis*)
Redfish (*Sebastes marinus*)
Snook (*Centropomus spp.)*
Rockfish (genus *Sebastes*)
Snappers (genus *Lutjanus*)
Bluefish (*Pomatomus saltatrix*), and
Weakfish (*Cynoscion regalis*)

These transient nekton (i.e., swimming organisms that move independent of water currents, including most fish, mammals, turtles, sea snakes, and aquatic birds) also function as mobile links between the oyster reefs and other sub-systems in the estuarine ecosystem. Other features of the reef that contribute to its structural heterogeneity are the interstices between shells and shell fragments that provide places where the sediment particles and reef wastes from upper levels may be sequestered. In addition, many micro-organism and small macro-organism species colonize shell surfaces and interstitial spaces in reefs and utilize reef waste for sustenance (Hargis and Haven 1999). Particulate material dropping away from reef heights can also settle onto the adjacent estuary bottom or be swept away from the reef by currents. Increased reef elevation due to shell added to the core and by new spatfall and growth in the veneer keeps the living oysters away from the bottom (Hargis and Haven 1999).

Reef topography also increases the overall surface significantly, thereby providing a place for growing oysters. On subtidal oyster reefs, vertical height affects animal abundance and utilization (Breitburg 1999; Harding and Mann 1999; Harding and Mann 2001a, b; Harding and Mann 2003), as well as growth and survival rates for individual oysters by maximizing circulation benefits (Lenihan et al. 1999; Peterson et al. 2003). The vertical structure of oyster reefs physically elevates oysters off the bottom and allows oysters to avoid anoxic conditions (Lenihan and Peterson 1998) or being smothered during sedimentation (Coen et al. 1999a and b). The size of the reef's vertical relief can also influence water quality. For example, if the reef is large, the number of oysters is greater and therefore reef filtration rates may be greater (Hargis and Haven 1999).

Several researchers indicated that some oyster harvest practices (e.g., dredging) can also affect the reef's topography by reducing the height of oyster reefs. Negative impacts to subtidal oyster reefs that may result from dredging include (Lenihan and Peterson 1998; Lenihan et al. 1999):

- Damage to the reef's structure increasing susceptibility to future storm damage
- Remove live and dead oysters decreasing the possible number of spawning adults (spawning stock biomass) and suitable areas available for settlement by oyster larvae
- Lower depth in the water column exposing newly settled oysters to lower oxygen and increased sediment, and
- Reduce interstitial spaces in the reef that provide a place of refuge and foraging areas for juvenile fish (see Street et al. 2004)

Along the Neuse River in North Carolina, researchers determined that dredging practices caused the reduction in the height of oyster reefs (Lenihan 1999; Lenihan and Thayer 1999; Lenihan and Peterson 1998). As a result of reduced reef height, water flow speeds were also reduced, causing an increase in sedimentation. In addition, the quality of suspended food materials for oysters was also reduced (Lenihan 1999; Lenihan and Thayer 1999). This explained why oyster growth on reefs disturbed by harvesting was slow, their health was relatively poor, and mortality rates were higher. However, this is one of many studies in which results vary depending on factors such as the reef's location, water quality, and frequency of physical disturbance to the reef. In some cases, these factors may be primarily responsible for oyster reef decline in a given area rather than changes in oyster reef topography.

Sampling and Monitoring Methods

Chain transects - Evaluations on intertidal reef topography involve assessment of surface rugosity (i.e., texture of the reef's surface) (Coen et al. 2004; McCormick 1994). The chain transect method and random point heights may be used to assess surface rugosity (McCormick 1994). The chain transect method involves placing a lightweight chain on the reef along the measuring tape, and recording the number of chain links of each sessile organism or the relative substrates. This method provides a better estimate of vertical complexity and thus allows for a better understanding of the habitat quality of the oyster reefs (Coen et al. 2004; McCormick 1994).

Remote Sensing - Reef footprints (i.e., historical structure), distribution and abundance patterns, and the effect of channels on the reef structure may be characterized using low-altitude aerial imagery and geographical information system (GIS)-based mapping (Grizzle and Castagna 2000; Grizzle et al. 2002; Grizzle et al. 2003). Patterns seen using aerial imagery can indicate how water movements influence reef development and whether the patterns changed over time (Grizzle and Castagna 2000). The same information gathered using aerial imagery and GIS mapping may also be obtained from historical maps of many locations along the U.S. East coast. Some of these maps are more than 100 years old and are available from various sources such as the Virginia Institute of Marine Sciences (e.g., see www.vims.edu, "oyster restoration map atlas") and NOAA historic maps and charts(e.g., http://nauticalcharts.noaa.gov/csdl/ctp/abstract.htm). The maps can then be compared to identify changes in reef patterns and channels.

Underwater hydroacoustic technology - Underwater hydroacoustic technology with reflected sound energy may also be used to identify surface objects, texture, size, fragmentation, and density disturbances, as well as classify bottom coverage (Dealteris 1988; Simons et al. 1992; Wilson et al. 1999; Smith et al. 2001). This technique involves a precision survey echo sounder operating at 200 kilohertz (kHz), and a side-scan sonar system operating at 100 kHz. Researchers have also used side-scan sonar and acoustic seabed classification systems to assess oyster reef structures, a fathometer to assess bottom relief, and a global positioning system (GPS) to determine accurate position (Simons et al. 1992). Data collected on the quality and quantity of oyster shell resources can then be integrated into a GIS to assess oyster habitat (Jefferson et al. 1991; Smith et al. 2001). Using this method, practitioners may be able to evaluate changes in subtidal oyster reef topographic features and bottom coverage over time following restoration efforts.

It is worth noting that aerial imagery, GIS-based mapping, acoustic profiling (i.e., seabed classification) and side-scan sonar are costly and involve high-tech methods, and therefore may not be accessible to all laypersons. Data collected using these methods, however, may be available from experts who have used such technology to assess reefs within or near the restoration site.

Sediment

Grain size

Intertidal oyster reefs are often associated with fine, soft sediment with low wave energy (Figure 13), whereas subtidal reefs are often associated with coarser sediments in high wave energy that generally contain oyster shell hash (Dame 1996; Hargis and Haven 1999). Variation in sediment type, to a large extent, may be locally related to wind fetch that is partially related to long-term removal of oyster reefs as buffer structures. As sediments and water flow are correlated,

Figure 13. Oyster reefs growing in muddy, fine grain sediment are harvested to evaluate impacts and recovery of multiple intertidal fishery practices; project followed recovery for 2 or 3 years. Photo courtesy of Loren Coen, Marine Resources Research Institute, South Carolina Department of Natural Resources.

sediment gradients are generally found in coastal waters and the intertidal zone.

Sedimentation

Although oysters have the ability to filter sediments (Newell 1988), large amounts of sediments can affect the reef. The primary concern is when the sediment becomes unstable due to human disturbances or by other means. The disturbed sediments (increased sedimentation) can affect oyster reefs by clogging oyster filtering structures, resuspending and burying newly settled oyster larvae, and covering substrates preventing attachment by adult oysters (Dame 1996).

Exposure to polluted sediments through increased sedimentation may cause stress that can reduce an oyster's ability to resist diseases and parasites, causing mortality of embryos and larvae, and a reduction in spat (i.e., immature bivalve mollusc) growth and setting (LeGore 1975; Umezawa et al. 1976; Mahoney and Noyes 1982; Marcus 1989; Encomio and Chu 2000; Geffard et al. 2001; Geffard et al. 2003). As a result of oyster larvae exposure to polluted sediments, oyster reef development and growth processes may be limited. Although oysters growing on three-dimensional reefs extend out of the sediment and up into the water column, it is important for practitioners and environmental managers to consider assessing the quality of sediments, as they store nutrients to support the benthic community as well as pollutants that may negatively affect oyster reef communities.

Basin for materials

Oyster reef sediments can act as both a nutrient basin and source, providing food for benthic organisms and serving as a reservoir for different dissolved constituents (Lenihan and Micheli 2000; Newell 2004). Inputs from industrial chemical or agricultural (fertilizers) sources may also be absorbed by reef sediments. Finer sediments, however, can contain higher nutrient and pollutant levels because they are not as porous as coarser sediments, and thus can retain pollutants longer (Lenihan and Micheli 2000). During nutrient cycling through the ecosystem, some percentage of nutrients is deposited in bottom sediments. If sediments are disturbed by means of dredging or boating activities, nutrients may be placed back into the water column where they may stimulate the growth of phytoplankton, and contribute to increased turbidity levels and depletion of oxygen.

Sampling and Monitoring Methods

Corers - Many types of coring devices and sediment traps can be used to collect underwater sediment samples. They are generally operated by driving the instrument into the bottom sediment and extracting the sediment sample from the corer tube. Two of these sampling devices are hand corers and piston corers (Miller and Bingham 1987; United States Army Corps of Engineers 1996; Radtke 1997).

Hand corers or also known as push corers are hollow tubes that are pushed into sediment to obtain samples. The corer is driven into the sediment to the point marked on the instrument and then removed and stored. Once retrieved, the corer can be divided so that separate samples from different depths of sediment can be distinguished (Radtke 1997).

Piston corers can use either gravity or hydrostatic pressure to function. As the instrument penetrates the sediments, an internal piston remains at the level of the sediment/water interface to prevent sediment compression (United States Army Corps of Engineers 1996).

Grain size and nutrient analysis - Sediment can also be characterized by analyzing grain size through dry sieving, and using pipettes (McManus 1988) as well as a laser coulter counter (Volety et al. 2002). Percent carbon and oxygen present in sediment samples are determined using acid dissolution, while the percent organics is determined via ignition. To conduct carbon and nitrogen isotope analyses, sediment samples are dried and acidified with 10 percent hydrochloric acid to eliminate all carbonates. The samples are then dried again and analyzed for carbon and nitrogen (Volety et al. 2002). Data collected from nutrient analyses of sediment samples can indicate whether nutrient levels have increased or decreased significantly over time. An increase in nutrient levels, for example, may be an indication of agricultural runoff, causing increased algal growth and thus reduced oxygen levels. Nutrient concentration is just one of many physical parameters that should be monitored to determine whether a selected site is suitable for restoration or whether restoration progress is limited as a result of changes in nutrient concentration and additional physical parameters.

Sedimentation rate - Sediment traps (Figure 14) are also used for sampling sediments (Soutar et al. 1977; Asper 1987; Hayakawa et al. 2001). The traps are deployed from the side of a boat at different depths and collect particles settling in the water column in order to determine the sediment types and sedimentation rate. The size of the particles collected depends on the mesh size of the trap; particles smaller than the mesh size of the trap escape back into the water.

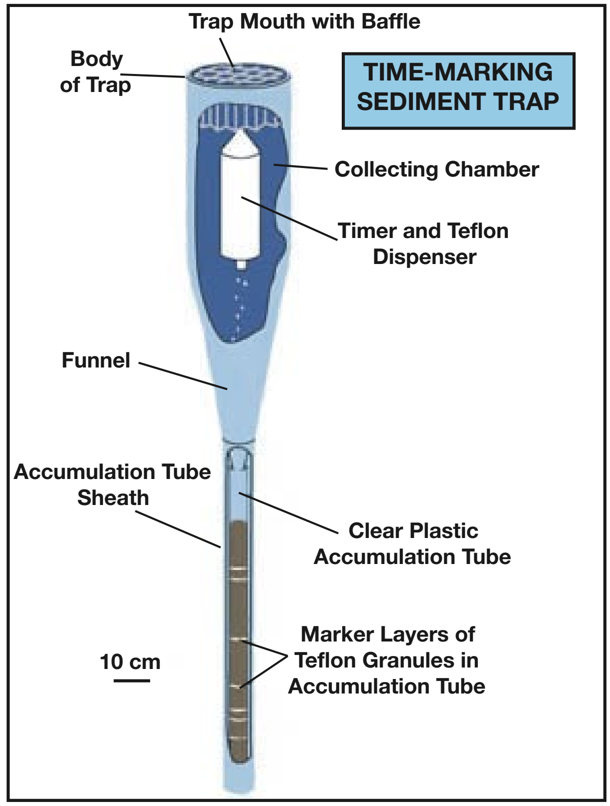

Figure 14. Diagram of a sediment trap. Photo courtesy of United States Geological Survey, Earth Surface Process Division. http://climchange.cr.usgs.gov/info/lacs/sedtraps.htm

Turbidity/Light Availability

Although oysters filter water and improve its quality, an increase in turbidity can influence oyster reef growth and survival. An increase in suspended sediment in the water column may be caused by high energy tides, waves, agriculture, forestry, mining, dredging of sediment (Cairns 1990), boat propellers, as well as other factors, can also smother oyster larvae and disturb the filter feeding process of oysters. High and persistent levels of sedimentation cause permanent changes in oyster reef community structure (e.g., reduced diversity, density, biomass, growth, and rates of reproduction in oysters), cause increased mortality rates, and alter local food webs (Cairns 1990). Generally, mortality from direct burial or smothering caused by harvesting or sediment dredging is an issue only for organisms with restricted mobility (e.g., attached eggs, juveniles, burrowing infauna, oysters) (Lunz 1938; Barnes et al. 1991). Normal sediment movement as a direct result of increased harvesting is less than 10-30 centimeters, a depth not considered to cause mortality to small infauna (Barnes et al. 1991).

In addition to sedimentation, oyster reef communities are affected by excess nutrients in sediments from runoff that promotes algae growth and increases turbidity. Resulting algal blooms can cause local depletion in oxygen available for organisms such as oyster larvae and fish (Cheney et al. 2001). Studies have shown that hypoxic and anoxic conditions affected eastern oyster larval settlement, juvenile growth, and juvenile survival (Baker and Mann 1992). Results showed that oyster settlement was reduced significantly ($P < 0.05$) in hypoxic treatments and practically no settlement occurred in anoxic treatments. Thus, hypoxic and anoxic waters can have potentially harmful effects on oyster settlement and recruitment (Baker and Mann 1992).

Sampling and Monitoring Methods

Turbidimeter - A turbidimeter measures water turbidity by passing a beam of light through the sample and measuring the quantity of light scattered by particulate matter (Rogers et al. 2001). The turbidity measurements are then displayed in nephelometer turbidity units (NTUs) (Rogers et al. 2001).

Secchi disc - Water Clarity can also be determined using a secchi disc (Figure 15) to measure the depth of light penetration in the water column (Lee 1979; Parsons et al. 1984; Steel and Neuhausser 2002). It is a circular-shaped instrument with alternating black and white quadrants, attached to a rope or another type of extension line and lowered into the water column from the shore, pier, or boat until the disc is no longer visible. As light travels through the water column, some of it is absorbed by phytoplankton and dissolved material. The remaining light reflects off the secchi disc and travels back through the water column where more is absorbed. As the disc is slowly lowered in the water, it gradually becomes harder to see, as increasing amounts of light are absorbed. The depth at which the disc can no longer be seen is the depth where light is being absorbed as it passes down and back up through the water column. This is recorded as the secchi disc depth (in meters). This procedure can be performed multiple times (three times on average) in the same location to determine the average water clarity value (Steel and Neuhausser 2002).

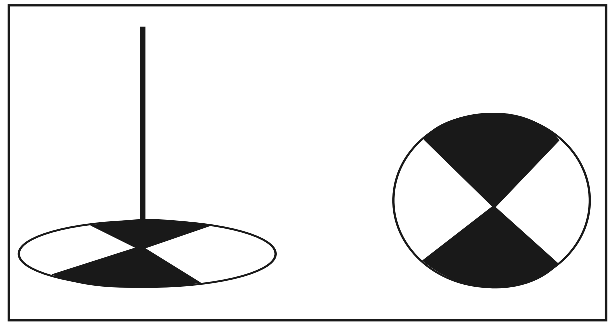

Figure 15. Diagram shows a secchi disc. Diagram courtesy of Felicity Burrows, NOAA National Centers for Coastal and Ocean Science.

HYDROLOGICAL

Tides/Hydroperiod and Currents

Local tides and currents have a major influence on the dispersal of oyster larvae (Carriker 1951; Pritchard 1953; Wood and Hargis 1971; Mann 1988; Ruzecki and Hargis 1989; Southworth and Mann 1998). Larvae place themselves in ebb and tidal currents (vertical motion) so they can be distributed throughout estuaries (Cake 1983). Oyster larvae spend about two to three weeks drifting with tidal currents, feeding on algae, and preparing to attach permanently to the bottom where they spend the rest of their lives, adding to the reef's vertical relief and complexity (Ruzecki and Hargis 1989; Southworth and Mann 1998).

As oyster reefs develop over time, oyster shells occasionally alter tidal currents and increase deposition of particulates, preventing sediment build-up on reefs which can ultimately reduce oxygen levels. Reduced tidal currents with increased sedimentation (e.g., as a result of dredging) can have an indirect effect on oysters as well. If tidal currents are too low and sediment builds up on the reef, oyster recruitment may be reduced because oysters are not able to successfully attach to substrates covered largely by silt (Visel et al. 1989).

Tides and currents also play a significant role in oyster reef functioning by delivering particulate food and carrying away inorganic byproducts of metabolism. They also act as a flushing system, preventing feces and biodeposit build-up on or burial of the reef (Lund 1957; Haven and Morales-Alamo 1968). Biodeposits[5] are generally utilized by detritus feeders. In turn, detritus feeders provide sustenance to higher trophic levels. A robust community of detrital feeders may be considered part of the holistic oyster reef community; otherwise a large amount of accumulated oyster feces may result (Haven and Morales-Alamo 1968). Biodeposits not utilized by detritus feeders are transported away from the oyster reef to help prevent oysters from being inundated with their own feces and pseudofeces[6]. If feces and pseudofeces accumulate on reefs, oysters may not be able to filter feed. Sewage effluents can also be distributed by tidal currents, affecting growth and development of the oyster reef by increasing nutrients in the water column and promoting the growth of algae, which in turn reduces oxygen levels.

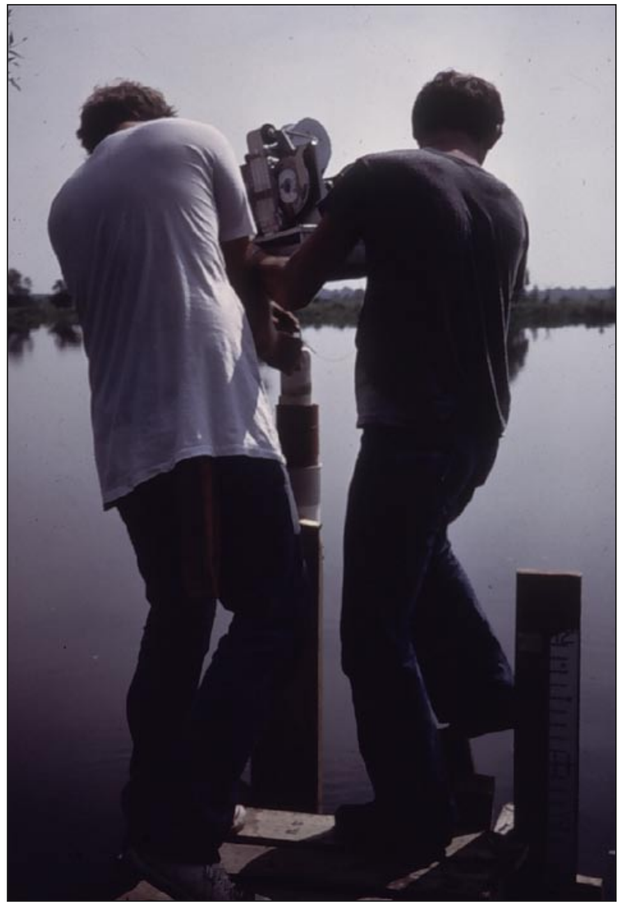

Figure 16. Tide gauge. Photo courtesy of Commander Gerald B. Mills, NOAA Corps. Publication of the NOAA Central Library. http://www.photolib.noaa.gov/historic/c&gs/images/big/theb2373.jpg

Sampling and Monitoring Methods

Tide gauges - Tide gauges (Figure 16) are mechanical devices usually placed on piers or pilings to record water levels (IOC 1985; Carter et al. 1989; Emery and Aubrey 1991; Giardina et al. 2000). The tide gauge consists of a data logger that reads and stores data from different sensors and a modem that communicates with a computer (IOC 1985). The water level sensor should be even from a stable bench mark and calibrated at regular intervals to ensure accurate water level measurements.

Acoustic Doppler flow meters - Acoustic Doppler flow meters can be used to evaluate tidal flow by measuring velocity and particles moving through the water. Acoustic signals are transmitted from the instrument, then reflected off of particles and collected by a receiver. The signals received are then analyzed for frequency changes. The mean value of the frequency changes can directly relate to the average velocity of the particles moving through the water.

Drifters - Drifters (Figure 17) (Southworth and Mann 1998) have been used along with focused plankton sampling around restored reefs to monitor the distribution and abundance of oyster larvae around a restored reef. These devices are available in a variety of sizes and are easily deployed from a small vessel. Regular monitoring of the drifter and recording of the drifter's location in the estuary with handheld GPS devices throughout the tidal cycle provides a quantitative method for evaluating larval dispersal.

[5] Nutrient-rich feces and pseudofeces easily assimilated by organisms.

[6] Substance discarded by suspension feeders or deposit feeders as potential food.

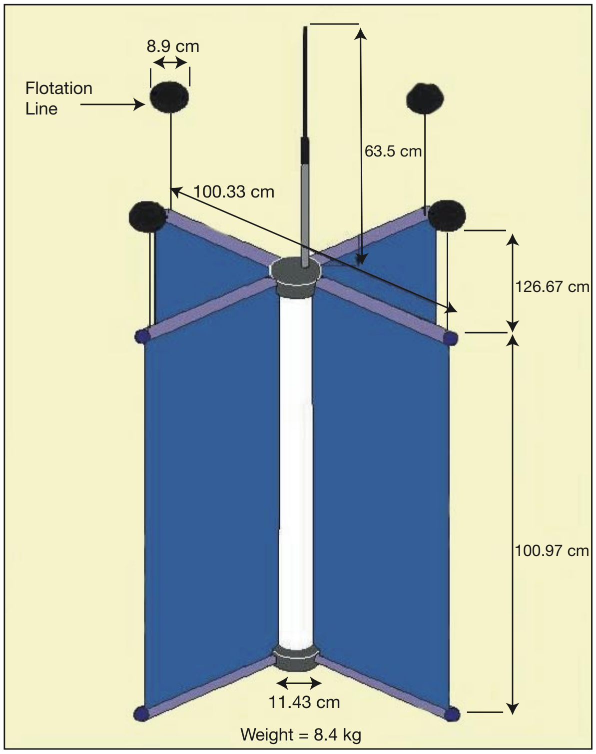

Figure 17. Diagram represents a drifter used for assessing tides and currents. Its main components consist of a waterproof tubular body, sails, spherical floats, and a data collection/transmitter package. Diagram courtesy of NOAA Ocean Explorer. http://oceanexplorer.noaa.gov/technology/tools/drifters/media/fig2.html

Dye studies - Dye studies have been used to evaluate oyster larval dispersal with tidal cycles. This method, currently being performed by Mann and other investigators at the Virginia Institute of Marine Science (see www.vims.edu/vsc), along with focused hydrographic modeling, is an extremely powerful predictive tool and valuable for restoration work.

Harmonic analysis - Harmonic analysis is a relatively straight forward method used to assess hydroperiod in various wetland types (Nuttle 1997). It allows quantitative sampling by gauging the breadth and timing of the main periodic element in a time series of water levels (Nuttle 1997). Quantitative measures of hydroperiod display the relationships between hydroperiod and functioning of oyster reef communities.

Water Sources

Large amounts of water inflow (e.g., from rivers, lakes, and industrial plant discharges) or runoff in proximity to oyster reef communities should be taken into consideration when developing a restoration plan, as this can influence the successful restoration of a naturally sustainable oyster reef habitat. If the source of inflow is not incorporated in the decision making process, monitoring parameters may be poorly selected. By knowing the source of water input, the practitioner will be more equipped to handle impacts to the habitat and select appropriate parameters to track restoration progress over time.

Water quality is a significant parameter that affects oyster reef communities. The source of water inflow can influence nutrient concentrations, oxygen levels, toxins, and ultimately the condition of the oyster reef. The chemical concentration and physical characteristics of water around oyster reefs can be influenced by various environmental factors including:

- Climate
- Tides
- Surface water, and
- Human inputs (e.g., upstream land use) (see "Human Impacts to Oyster Reefs" section)

Upstream land uses, for example, that may result in runoff from agricultural, industrial, or municipal water sources and reduce water quality and adversely affect the condition of the oyster reef and animal community (Scott et al. 1996; Zoun 2003). Oyster embryos and larvae are more sensitive to toxic chemicals than adults and juvenile oysters (Funderburk et al. 1991). Chronic effects on oysters are seen when oysters are exposed to the chemical TBT and petroleum hydrocarbons (Funderburk et al. 1991). Juvenile oysters, however, may experience acute toxicity and sublethal effects when exposed to chlorinated pesticides and polychlorinated biphenyls (PCBs). Heavy metals and polynuclear aromatic hydrocarbons (PAHs) can also cause acute toxicity, resulting in oyster mortality and sublethal stress on all life stages of oysters. In addition, such toxic chemicals can inhibit reproductive development, release of gametes, fertilization, larval development, and growth of juvenile oysters (Wendt et al. 1990; Sanger and Holland 2002).

Runoff from sewage can promote fecal coliform presence which further degrades water quality and negatively affects oyster health. If the health of the oysters deteriorates, the animal community they support may also be affected (i.e., species numbers and diversity may be reduced) (Rodriguez 1986; Zoun 2003). By evaluating oyster reef water sources and their potential impacts, restoration practitioners can design an effective restoration plan with monitoring parameters to measure water quality.

Upstream land source

While oysters are filter feeders, they cannot readily filter substances in high concentrations. In some cases, oysters become infected with diseases or simply decline in health because of exposure to high chemical concentrations. The Chesapeake Bay oyster population has decreased significantly because of municipal and industrial waste discharged into the Bay (Chen and Roesijadi 1994). The chemical pollutants that primarily threatened oysters were:

- Trace heavy metals (e.g., arsenic, cadmium, chromium, copper, mercury, tin, and zinc)
- Organic compounds (e.g., pesticides, phthalate ester, Polycyclic Aromatic Hydrocarbons (PAHs)), and
- PCBs

High levels of both trace metals and organic compounds were found in the sediment of the Bay (Chen and Roesijadi 1994). Because oysters are sedentary bottom dwellers, they are exposed to high concentrations of these toxins (Chen and Roesijadi 1994) which can result in their decline and reduce their ability to function. Thus, monitoring and recording the source of oyster reef water supply and adjacent land use is a priority.

Runoff from land activities has proven to be a significant factor in the reduction of oyster populations. Many researchers have studied the impacts of land use activities on coastal area reefs (Marcus 1989). Such land use activities included recreational marinas, an industrial point source wastewater discharge, and agricultural non-point source pesticide runoff. Results showed that recreational marinas displayed the lowest pollutant levels in oysters with no harmful biological effects. The industrial point source activity showed the highest pollutant levels in oysters and significantly detrimental biological effects. The agricultural runoff activity showed moderate pollutant levels in oysters, but significantly harmful biological effects.

A good reference for monitoring water sources is the *Standard Methods for the Examination of Water and Wastewater* which covers all aspects of water and wastewater analysis techniques. This is a joint publication of the American Public Health Association, American Water Works Association, and Water Environment Federation (see Clesceri et al. 1998). The U.S. Environmental Protection Agency has also developed a methods manual for assessing water quality (see USEPA 1983).

Water Temperature

Temperature may influence the oyster distribution and their physiological rate processes such as feeding and growth rates (Dame 1996). The optimal temperature range for oyster growth is between 14 and 28°C (Shumway 1996), although oyster tolerance to temperature change varies among species type, life stage, and geographical location. For example, oyster larvae cannot tolerate a wide range of temperatures as compared to adult oysters. Eastern oyster larval growth may be harmed once water temperatures increase above 30˚C (Hidu et al.1974; Roegner and Mann 1995; Dekshenieks et al. 1996; Kennedy et. al. 1996). Extremely high temperatures may cause mortality in both larvae and adult oysters. Within the Indian River Bay, Delaware, evidence of oyster mortality was seen after water temperatures increased above 35˚C (Tinsman and Maurer 1974). In other locations, however, eastern oysters generally respond (i.e., reduction in growth rate, feeding process, or mortality) to temperatures above 35˚C. As oysters respond to significant increases in temperatures, they respond similarly when temperatures drop significantly below optimum temperatures (i.e., approximately below 20˚C) (Cake 1983; Dekshenieks et al. 1993).

Water temperature changes also influence the rate at which water is pumped through the oyster's gill system. For eastern oysters, water temperatures between 20 and 32˚C are favorable for pumping rates to provide requirements for oxygen, food, and waste disposal (Collier 1954; Loosanoff 1958). If temperatures drop below 7˚C, pumping may be reduced significantly. The ability of oyster to filter feed is affiliated with the pumping rates. Feeding begins when the oyster pumps water containing particles through the gill system. Food particles present in the water are then consumed; particles that cannot be consumed are excreted as pseudofeces. The remaining water is then released back into the water column (Haven and Morales-Alamo 1966). Thus, pumping rates will ultimately affect feeding rates, which in turn affects oyster growth.

Oyster reproduction is another biological process influenced by temperature. In the mid-Atlantic coastal waters, eastern oysters spawned when temperatures were above 20˚C. Adult oysters in 35˚C water temperature, however, experienced increased rates in gametogenesis and spawning (Quick 1971). In Galveston Bay, Texas, oysters spawned after temperatures exceeded 25˚C (Hopkins 1931) while mass spawnings occurred in Apalachicola Bay, Florida, when temperatures exceeded 26˚C (Ingle 1951). In the Gulf of Mexico, spawning occurred when temperatures were near 25˚C. As mentioned earlier, an oyster's biological response to temperature change will vary depending on species type, life stage as well as geographical location.

Measuring and Monitoring Methods

Water temperature can be measured using a thermometer below the water surface. A maximum/minimum thermometer can be left at the site to record the warmest and coldest water temperatures since the last readings were recorded at the study site (Rogers et al. 2001).

Some commercial instruments may be used to measure temperature, although no one type of commercial instrument can be recommended here. The basic procedure when using any one commercial instrument is to place the sensor probe into the water while the temperature reading is displayed.

CHEMICAL

Dissolved Oxygen

Dissolved oxygen (DO) plays a role in oyster survival and growth. In some cases, low dissolved oxygen has resulted in oyster mortalities and a subsequent reduction in reef size. Air exposure causes eastern oysters to close their shells tightly, almost completely isolating themselves from the air. There are reports of oysters being buried in anaerobic dredge spoil for a month yet were still alive (Galstoff 1964). Within the oyster shell, the tissues of the oyster may become hypoxic and significantly acidic as a result of accumulated carbon dioxide (CO_2) (Dwyer and

Burnett 1996). Some researchers have found that oyster metabolism may be vulnerable to hypoxia and the production of reactive oxygen intermediates by oyster hemocytes, considered one of the main defense mechanisms against pathogens, may be inhibited due to low dissolved oxygen (Boyd and Burnett 1999). Also, in cases when oxygen levels have decreased near lethal levels, oyster reef fishes, xanthid, and blue crabs migrate to areas on the reef with higher oxygen concentrations (Breitburg 1992).

In Bon Secour Bay, Alabama, a continuous decrease of oxygen levels caused a significant decline in oysters and reduced reef structure (Rikard et al. 2000). Along Puget Sound, Washington and Tomales Bay, California, an increased rate of oyster mortalities was also seen as a result of long periods of low dissolved oxygen (Cheney et al. 2001). During the evenings, there was a long period of neap tides with low and slow-moving water which resulted in daily and successive reductions in dissolved oxygen levels and caused oyster decline. Dissolved oxygen reductions also resulted in macroalgae blooms and high phytoplankton densities which altered oyster communities. As previously mentioned, oyster reductions throughout the Neuse River in North Carolina were a result of low dissolved oxygen. In addition, the number of fishes and invertebrates occupying oyster reefs were also reduced (Lenihan and Thayer 1999). These examples show that dissolved oxygen plays a role in oyster survival and should be taken in consideration when monitoring restoration success over time.

Sampling and Monitoring Methods

There are several methods used to measure dissolved oxygen including, dissolved oxygen meters, and commercial fiber optic oxygen sensor. The titration-based drop count technique can also be used that calculates dissolved oxygen concentrations by adding an indicator to the sample, then use the dropper to add the titrant until the color changes. Practitioners must record the number of drops it takes to change the color of the water sample. Each drop equals 1 mg/1 of dissolved oxygen. A dissolved oxygen meter consists of a sensor and the meter (Hargreaves and Tucker 2002). The fiber optic oxygen sensor consists of an optical fiber with a sensor tip containing a thin layer of oxygen-sensitive fluorescent dye. Once the sensor is placed into the water sample, the optical fiber stimulates the dye to release fluorescent light that travels to a photo detector. Oxygen diffusing into the sensor tip reacts with the fluorescent dye, reducing the intensity of light emission to indicate the oxygen concentration (Hargreaves and Tucker 2002).

Salinity

Oyster reefs can be found along a salinity gradient ranging from freshwater to marine salinity (12-28 ppt or higher in some cases) (Dame 1996). Depending on location, salinity is influenced by freshwater runoff, river input, and precipitation. Such changes in salinity levels may influence oyster spawning activities. Most spawning activities occur when salinities are above 10 ppt. However, the optimal salinity level for oyster growth and development is 12 to 28 ppt; optimum salinity ranges for gonadal development is from 15 to 25 ppt (Lough 1974; Dame 1996). If salinity levels drop below 10 ppt, then spat set may be hindered. Extreme salinity fluctuations affect the survival, growth, and distribution of oysters that form reefs as well as the abundance and distribution of other macroinvertebrates. Within a ten-mile area of the Newport River estuary in North Carolina, there was a steady decline of organisms in oyster communities when salinity levels were significantly high (Wells 1961). Most bivalves respond instantly to changes in the environment by closing their shells and isolating themselves from the external salinity environment. This isolation helps to reduce the rate of associated changes in the cell volume and allows the oyster to self-regulate osmotic pressure. Rapid changes in salinity may also cause reduced physiological rates of feeding and respiration (Hawkins and Bayne 1992; Dame 1996).

During severe storms, salinity changes occuring in estuaries may promote oyster diseases (Powell et al. 1995). Dermo disease increases during periods of high salinity. During periods of low rainfall, Dermo disease may occur as salinity increases, thus causing oyster mortality (Powell 1994). The effect of environmental changes such as salinity on the eastern oyster population was investigated using computer simulation models (Dekshenieks et al. 2000). The simulations revealed that salinity is the primary factor controlling the spatial degree of oyster distribution. Such studies show that salinity plays an important role in the spat and survival of oysters and should be measured and closely monitored during restoration efforts.

Measuring and Monitoring Methods

Among many commercial instruments used to measure salinity is the hand-held refractometer. This instrument measures how much the light rays are refracted (i.e., bent) as they pass through seawater (Rogers et al. 2001). Salinity is measured on a calibrated refractometer by placing a few drops of the seawater under a transparent slide, and reading the salinity value by looking through the eye piece (Rogers et al. 2001).

A hydrometer measures salinity by comparing the density of the seawater samples to fresh water samples. The glass tube hydrometer is placed in a cylinder of sampled seawater to measure how high it floats in the cylinder - the higher it floats, the greater the salinity. The number on the hydrometer scale at the water surface and the water temperature are used together to determine the salinity; values are referenced on tables that accompany the hydrometer (Rogers et al. 2001).

In the absence of digital recording equipment, salinity can be determined from water samples collected from just above the bottom and at the water surface with a Niskin bottle. The Niskin bottle has stoppers on both ends that are held in place by springs. The bottle is prepared by cocking open both ends of the bottle, then attached to a support (winch) line and lowered to the preferred depth. A small weight known as a messenger is attached to the line and released to trigger the stoppers and seal the bottle. The sample of the water from that depth is contained in the bottle.

FUNCTIONAL CHARACTERISTICS OF OYSTER REEFS

Oyster reefs perform important functions, such as:

Biological

- Provide places for oysters to recruit and grow
- Provide habitats for plants, fish, and invertebrates
- Provide breeding, feeding, and nursery grounds for fish, crustaceans, other invertebrates, and birds species
- Supports carrying capacity
- Biomass production
- Create a place of refuge against larger predators
- Provide a place on which sessile organisms attach

Physical

- Protect coastal areas from erosion, and
- Stabilize sediments and filter particles in the water column

Chemical

- Trap and rapidly recycle essential nutrients in coastal environments

By performing these functions, reefs are able to support important local and commercial fisheries as well as maintain the diversity and abundance of flora and fauna. If the health of the reef is degraded in any way, it can affect habitat function, such as its ability to filter suspended sediments and enhance the cycling of nutrients in the estuary (Dame et al. 1989), and provide nursery and breeding grounds for organisms (Anderson and Connell 1999; Harding and Mann 2001a, b; Harding and Mann 2003). Understanding how oyster reefs function as communities can help the practitioner select suitable parameters to track restoration efforts and achieve a naturally sustainable habitat.

This section concentrates on the biological, physical, and chemical functions performed by oyster reefs. Also provided are several methods to sample, measure, and monitor the functional parameters affiliated with oyster reef characteristics. Oyster reefs, for example, may be used as breeding and feeding grounds by many species of animals other than oysters (Harding and Mann 2001a). These functions are measured by identifying and counting the numbers and types of animals observed in the habitat and quantifying diet and/or size. Not all functional characteristics described in this chapter, however, are expected to be measured. This information simply illustrates the importance of oyster reef habitat, and the methods discussed herein are examples of the numerous methods that can be used. Sources are cited throughout the text to guide readers to additional information.

BIOLOGICAL

Provides Habitat

Oyster reefs provide habitat for many animals (such as oysters which are keystone[7] species) that contribute to the reef's composition. The formation of three-dimensional intertidal reefs results after years of successive settlement and survival of larval oysters that attach to adult oyster shells (Morales-Alamo and Mann 1990; Bartol and Mann 1997; Bartol et al. 1999). The complex structure of the reefs provides surface and interstitial heterogeneity that can ultimately support oyster settlement and survival as well as many other organisms. Types of organisms may also vary between intertidal and subtidal areas because organisms in intertidal areas must be able to adapt to frequently air-exposed conditions, whereas at subtidal depths, organisms must adapt to areas usually submerged by water. Some studies suggest that microscale variations in tidal elevation and substrate depth can significantly affect settlement processes and therefore should be considered when constructing reefs (Bartol and Mann 1997; Bartol et al. 1999).

[7] Essential to the functioning of the ecosystem.

Oyster reefs also support a complex trophic structure and biodiversity by providing food and shelter for many species other than oysters including crustaceans, benthic invertebrates, and many valuable commercial and recreational fisheries (Zimmerman et al. 1989; Coen et al. 1999b; Harding and Mann 1999, 2001a; Lehnert and Allen 2002). Crustaceans such as crabs occupy the crevices inside the oyster reef and may be significant predators on juvenile oysters (Eggleston 1990a, b). Benthic invertebrates like grass shrimp (*Palaemonetes spp.)* are commonly found occupying the bottom areas. Fish use the oyster reef in various ways by laying eggs (see "Providing Breeding and Nursery Grounds" section) and finding protection for juveniles in oyster shells.

Benthic-pelagic coupling reaches its zenith with the dense assemblages of oysters that form oyster reefs (Dame et al. 2002). Oysters can directly and indirectly control the availability of resources to other species by causing physical state changes in abiotic and biotic materials (Jones et al. 1994). Thus, oyster reefs passively and actively move particulate and dissolved materials between themselves and the water column, and thus, both directly and indirectly influence their ecosystems by processing their phytoplankton food and building hard structured reefs. The loss of this keystone species can dramatically alter the ecosystem (Dame 1996). These attributes are exemplified by the role of oyster reefs in processing and recycling carbon, nitrogen, and phosphorus in coastal ecosystems (discussed further in "Supporting Nutrient Cycling" section).

Habitat use and natural sustainability of the habitat should be monitored regularly since any deterioration in the habitat's condition will likely affect animal abundance and survival. Some of the animal species that live amongst oyster reefs include:

Oysters
Fiddler crabs (genus *Uca*) (Figure 18)
Blue crab (*Callinectes sapidus)*
Grass shrimp (*Hippolyte* spp.*)*
Mussels (*Mytilus edulis*)
Rockfish (genus *Sebastes*)
Oyster toadfish (*Opsanus tau)*, and
Sea squirts (*Molgula manhattensis)*

Common vegetative species that live on oyster reefs, including seaweeds and algae, are food sources for many species of fish and crustaceans. These vegetative species include:

Spiny seaweed (*Acanthophora spicifera*) (Kilar and McLachlan 1986), and
Algae (*Carpophyllum scalare* Suhr*, Anatheca dentata* [Suhr] Papenfuss*, Ceramium obsoletum,* and *C. agardh)*

Measuring and Monitoring Methods

Vegetation - Oyster reef vegetation is measured by evaluating its cover, distribution, and abundance. Quadrats provide reference frames to estimate abundance, cover, and biomass of flora. They can be placed randomly or at a fixed position. Species abundance is estimated by calculating the mean of samples collected from each study area. Monitoring frequency for vegetation growth is based on a species

Figure 18. Male fiddler crab, *Uca pugilator*, sporting its large claw as it attempts to hide under the glasswort, *Salicornia sp*. Photo courtesy of NOAA National Estuarine Research Reserve Collection. Publication of the NOAA Central Library. http://www.photolib.noaa.gov/nerr/images/big/nerr0324.jpg

growth rate and time of year. Practitioners may therefore want to consider tracking change in vegetation species richness and percent cover over time.

Vegetation can also be measured and recorded as visual information using fixed viewpoint photography (Moore 2001). Taking regularly scheduled photographs at a specific location allows the recording of changes that occur in the habitat's physical structure. This also shows whether visual photographs taken of these changes in smaller areas are a good representation of larger areas (Moore 2001). A single lens reflex camera with a 50 mm lens, a 35 mm or 28 mm wide angle lens, and a fixed focal length will ensure repeatability of the view angle each time a photo is taken (Moore 2001). Photos can then be compared to determine whether vegetation has increased or decreased over time.

Provides Breeding and Nursery Grounds

Reefs provide breeding and nursery grounds for many species such as crustaceans, fishes, and birds. For instance, mussels commonly attach and spawn in areas adjacent to oyster reefs. Oyster toadfish (*Opsanus tau)* also attach their eggs to the underside of articulated empty oyster shells while striped blennies (*Chasmodes bosquianus*), gobies (e.g., *Gobiosoma bosc, G. ginsburgi*), and skilletfish (e.g., *Gobiesox strumosus)* lay their eggs in dead oyster shell beds (Breitburg 1999; Coen et al. 1999a). In estuaries, eastern oyster shell-covered bottoms also supported juvenile seabass (e.g., *Centropristis striata*), groupers (*Epinephelus* spp.) (Figure 19), snappers (e.g., *Lutjanus* spp.*),* and crustaceans (Lehnert and Allen 2002). Other recreationally and commercially valuable finfishes that commonly use oyster reefs as nursery grounds (Harding and Mann 1999; Harding and Mann 2001a, b; Harding and Mann 2003) include:

Figure 19. Nassau grouper (*Epinephelus striatus*). Photo courtesy of NOAA OAR/National Undersea Research Program. Publication of the NOAA Central Library. http://www.photolib.noaa.gov/nurp/images/big/nur00526.jpg

Striped bass (*Morone saxatilis*)
Bluefish (*Pomatomus saltatrix*), and
Weakfish (*Cynoscion regalis*)

Provides Feeding Grounds

Reefs provide feeding grounds for many mobile and sessile species but only a few examples are discussed here. Juvenile crustaceans (e.g., crabs) feed on invertebrates and molluscs that are present in oyster reef crevices and sediments near oyster reefs. Recreationally and commercially important fish, especially apex predators (i.e., predators at the top of the food chain) such as striped bass, bluefish, and weakfish, commonly feed on crustaceans, shrimps, marine worms, and other fish species (Harding and Mann 1999). Smaller fish such as naked gobies (*Gobiosoma bosc*), and in some cases striped blennies consume oyster larvae and as a result, may influence recruitment success within oyster reef communities (Harding 1999).

Intertidal reefs are also important habitat and foraging grounds for shorebirds. These birds commonly feed on small fish such as naked gobies and striped blennies in shallow waters near oyster reefs. Oysters that are exposed on intertidal flats provide food for some shorebirds such as the American oystercatcher (*Haematopus palliates)* (Figure 20). Near Fisherman's Island, Virginia, some researchers

Figure 20. American oyster catcher, (*Haematopus palliates*). Photo courtesy of NOAA National Estuarine Research Reserve Collection. Publication of the NOAA Central Library. http://www.photolib.noaa.gov/nerr/images/big/nerr0086.jpg

observed the roosting and foraging behavior of the American oystercatcher within and adjacent to thirteen reefs consisting of surf clam shell, oyster shell, and coal ash pellets (Crockett et al. 1998). The American oystercatcher was seen resting and feeding mainly on reefs composed of oyster shell (Crockett et al. 1998). As a result, oyster reefs serve as important resting and feeding areas for birds (Crockett et al. 1998). If oyster reefs are degraded in any way, bird communities occupying the reefs within a specific area may be forced to migrate to other areas where environmental conditions are suitable and food is available.

Sampling and Monitoring Methods

Invertebrates - Reef invertebrate species may be quantified using quadrats and transects (Nestlerode 2004). Quadrats are used to identify invertebrate species cover and density on oyster reefs (Grizzle and Castagna 1996; Harris and Paynter 2001; Murray et al. 2002). Species diversity is estimated by calculating the mean of two to three samples collected from each study area. To keep track of organisms counted in quadrats, some organisms, if not to small, can be marked as they are counted and the results recorded on a data sheet. Quadrats can be fixed so that a sample area can be measured repeatedly. Transects are also used to collect field data by recording the number of organisms and species in each sampling unit along the line or by collecting samples of species along a line or within a habitat (Michener et al. 1995; Haws et al. 1995).

Fish - Fish should be sampled both during the day and night to accurately assess habitat use. Their numbers are relatively greater at night, but sampling near shallow water or intertidal oyster reefs in the dark may be dangerous, so caution must be taken when sampling at night. Many fish species show diurnal variability in habitat use (Harding and Mann 2001a). If sampling is performed only during the day, then the number, size, and type of organisms in a habitat may be gravely underestimated.

Different types of nets can be used to sample fish and other nekton in oyster communities, including seines, lift nets, and gill nets. Seine nets may be appropriate in intertidal habitats, and are composed of a bunt (bag or loose netting) with long ropes to pull the seine out the water. The nets have floats to keep the top part of the net afloat and weights to keep the bottom of the net submerged to prevent the fish from escaping from the invisible net-enclosed area. Fish caught within the net are then identified and counted (Crabtree and Dean 1982; USEPA 1993).

Lift nets may be more appropriate for subtidal habitats. These nets consist of a bag-shaped structure with the opening facing upwards while the bottom of the bag remains submerged. Fish that swim over the opening of the bag are then enclosed as persons holding the net lift it out of the water (Wenner et al. 1996).

Advantages to the use of a lift net are:

- The habitat in the area to be sampled will experience minimal damage

- The size and shape of the net system can fit a variety of habitats
- No permanent structures, other than a shallow perimeter trench, are present to act as attractants, and
- It is inexpensive to purchase and maintain gear (Wenner et al. 1996)

Both intertidal and subtidal reef habitats may be sampled with gill nets with predetermined mesh sizes (Figure 21). Nekton are captured when they swim into the invisible mesh net and struggle to escape. As they struggle, they become entangled within the net. Practitioners then separate the fish from the nets so that they can be identified, counted, and analyzed to determine diet, age, and fecundity (Nielson and Johnson 1983; Harding and Mann 1999; Harding and Mann 2001a, b; Harding and Mann 2003).

In habitats with low turbidity, visual surveys may be used to identify and assess fish species during daylight hours. Underwater visual census is used for estimating fish abundance via snorkeling, scuba diving, or video cameras when visibility conditions permit. Organisms are counted using quadrats, transects, or fixed point counts (Samoilys and Carlos 2000). Transects are marked to define the boundaries of the study area. Fixed point counts entail counting from a specific point while rotating in the quadrat (Samoilys and Carlos 2000).

Figure 21. Using nets to collect samples of fish and other marine organisms along oyster reefs, as part of Fisherman Island Project, Virginia's Eastern Shore. Photo courtesy of Mark Luckenbach, Eastern Shore Laboratory, Virginia Institute of Marine Science.

Fish may also be captured on both natural (reference) and created oyster reefs to compare the number, type, and size of the fish between the two reef types. Species type, abundance, density, and diversity are recorded in a given area for both natural and created reefs (Harding and Mann 1999; Harding and Mann 2001a). Quantitative measurements of fish abundance and large mobile crustaceans on oyster reefs and on nearby sedimentary habitat can be analyzed. Densities can be compared for each species by size on oyster reefs and sedimentary bottom to estimate how oyster reef restoration on sedimentary bottom may increase fisheries abundance. Published information on growth rates of each species and empirical data on age-specific survivorship can also be analyzed for change in species and abundance over time. The per-unit-area enhancement of fish production and large mobile crustaceans expected from the addition of oyster reef habitat can then be calculated (Peterson et al. 2003).

Another method to assess the use of restored oyster reefs by numerous organisms, particularly finfishes, is the Essential Fish Habitat (EFH)[8] system. This system measures certain parameters in four levels:

- Level 1 - presence/absence data
- Level 2 - distribution and abundance
- Level 3 - the functional relationship between species and habitat: reproduction, growth, survival, and
- Level 4 - habitat-specific fish production

This four-level system can provide the practitioner with basic parameters to monitor the functional ecological relationship between oyster reefs and trophic communities that they support (Benaka 1999; Harding and Mann 2001a, b; Harding and Mann 2003). In addition,

[8] Under the Magnuson-Stevens Fisheries Conservation and Management Act, Essential Fisheries Habitat (EFH) is defined as waters and substrate necessary to fish for spawning, breeding, feeding, or growth to maturity, and is applied in regulating coastal fisheries.

this system can be used to show whether the habitat is important (i.e., a significant role in supporting animals) or essential (i.e., the primary role in supporting animals) (Harding and Mann 2001a).

Invertebrates - Aerial surveys and direct counts can be used to monitor birds along coastal and estuarine habitats. Aerial surveys inventory migrant shorebirds (Erwin et al. 1991) and monitor wintering populations (Morrison and Ross 1989). Surveys are used to estimate relative abundance of migratory and wintering populations, and to assess population trends of migratory shorebirds. Direct counts are used to estimate shorebird density. Data collected on the number of birds in a habitat can be recorded on audio tape and then copied onto data sheets. In some cases, video cameras and aerial photography are used with aerial surveys (Dolbeer et al. 1997). Aerial photographs provide precise estimates of birds and visual records of the structure of oyster reef habitats.

Crustaceans - Crustacean recruitment, particularly crabs, can be quantified using settlement trays filled with either air-dried oyster shells or artificial seagrass. This allows the practitioner to determine the preferred habitat type for the different life stages of crabs (Etherington et al. 1996). Seagrasses should be assessed because they are considered an associated habitat of oyster reefs and influence reef communities. Some researchers have placed trays on unstructured seafloor to assess recruitment of blue crab megalopae (i.e., the postlarval stage of a crab). The effects of patch shape (square versus thin) and patch location ("edge" versus "center") on density were also quantified. Using this method, researchers were able to show that blue crabs relied on both seagrass and oyster reefs as a place for settlement and refuge; thus both habitat types function as an interconnected community (Etherington et al. 1996).

The abundance of mud crabs (*Panopeus herbstii* and *Eurypanopeus depressus*) on intertidal oyster reefs can be determined with regard to surface oyster reef shell cover, surface oyster cluster volume, subsurface shell content, substrate sand and silt composition, and oyster reef elevation (Meyer 1994) using quadrats during low tide. Quadrats allow researchers to effectively assess crab abundance at selected areas throughout the study site in order to obtain a good representation of the number of crab species (Meyer 1994) within the restoration site.

Provides Substrate Attachment

Oyster reefs form when substrates, including both living and dead oysters, accumulate and serve as a base for organisms (Wells 1961; Bahr and Lanier 1981; Rheinhardt and Mann 1990) such as:

- Mussels (Figure 22)
- Serupilid worms
- Bryozoans
- Hydroids
- Barnacles
- Macroalgae, and
- Spawn of oyster

Crustose algae and other macroalgae, for instance, are found attached to oyster shell substrate especially in shallow shoreline areas. Figure 23 shows clusters of oysters and sponges attached to shells. Oyster shells also support mussels and barnacles, which in turn provide protection and food for:

- Juvenile dungeness crab (*Cancer magister)*
- Shore crabs (*Hemigrapsus spp.)*
- Tube building gammarid amphipods (e.g., *Amphithoe* and *Corophium)*
- Caprellid amphipods
- Tanaids, and
- Annelids (Dumbauld 2002)

Figure 22. A small oyster reef with mussels attach to it in the Choptank River, Maryland. Photo courtesy of Mary Hollinger, NOAA National Oceanographic Data Center. Publication of the NOAA Central Library. http://www.photolib.noaa.gov/coastline/images/big/line0797.jpg

Reefs also support recruitment of oysters, thereby contributing to the increase in size of the reef's structure. Along Fisherman's Island, Virginia, intertidal reefs were constructed using oyster shell (O'Beirn et al. 2000). Oyster recruitment and settlement occurred on oyster shell reefs at various tidal heights (high-, mid-, and low- intertidal), allowing continuous growth of the reef and supporting various organisms.

Provides Refuge from Predation

Oyster reefs provide refuge from predation for numerous species such as:

- Newly metamorphosed and young oysters (Eggleston 1990a, b; Baker and Mann 1998)
- Resident predators, such as rock crabs (e.g., *Nectocarcinus intigrifrons)* and gobies, and
- Transient predators, such as blue crabs and pinfish (*Lagodon rhomboides*)

Small fishes and other organisms such as xanthid crabs also hide within spaces in the reef to avoid being preyed on by predators that feed on the reef surface (Meyer 1994; Anderson and Connell 1999; Coen et al. 1999a). Benthic organisms hide from crustaceans such as blue crabs within interstitial spaces formed between oyster shells as well.

Figure 23. Oyster shell with fouling sponges attached. Photo courtesy of South Carolina Department of Natural Resources.

Supports Carrying Capacity/Biomass Production

Carrying capacity may be defined as the maximum living oyster reef biomass that can be supported in a particular ecosystem (see Dame and Prins 1998). While it is considered both a structural and functional characteristic of oyster reefs and their environment, carrying capacity is discussed here as a function of oyster reefs. In an ecosystem dominated by oyster reefs, carrying capacity is a function of water mass turnover time, phytoplankton production time, and oyster clearance time (Dame and Prins 1998). Massive bivalve suspension-feeder systems are usually found in ecosystems with relatively short water mass residence times (less than 40 days) and short phytoplankton production times (less than 4 days) (Dame and Prins 1998).

When considering an ecosystem for oyster reef restoration, the three turnover time characteristics aforementioned should be determined for

Figure 24. Small-scale experiments to assess the impact of boat wakes[9] on newly planted Gulf shell in Inlet Creek in April 2000. Photo courtesy of Loren Coen, Marine Resources Research Institute, South Carolina Department of Natural Resources.

the target sites. This determination requires estimates of the total water mass flushing rates (flushing is important for removing excess materials); total phytoplankton biomass (usually Chl *a*) in the water near the reef because excess growth of phytoplankton can contribute to reduce oxygen levels affecting oyster growth; and total or expected total oyster biomass in the ecosystem.

PHYSICAL

Reduces Shoreline Erosion

Oyster reefs serve as barriers that protect shorelines from erosion by reducing wave energy entering coastal habitats such as marshes. As the waves approach the shoreline, the physical structure of oyster reefs reduces the force of the waves and helps protect the shoreline from erosion (Figure 24). Once oyster reefs slow wave energy, they are able to stabilize sediments, reduce vegetation loss, conserve other habitats, and promote animal use of the habitat without the threat of being swept away by waves (Hargis 1999; Hargis and Haven 1999; Meyer and Townsend 2000).

Filters Water and Stabilizes Sediments

Oysters pump and filter volumes of water in order to consume sufficient phytoplankton as food. This process takes place when water is pumped through the gills, allowing potential food particles to be trapped by the mucus of oysters and then transported to the mouth by its frontal cilia where it is either consumed or discarded. Other particles too large or too small to be utilized by oysters are rejected as pseudofeces (Dame 1996). Oysters also help maintain water quality in estuarine environments by filtering suspended solids and nutrients (discussed further in “Supporting Nutrient Cycling” section) as well as altering hydrology

[9] The wave of water resulting from passage of a boat’s hull through the water. The wave generated, depending on size and speed of the vessel, can be large and affect oyster reefs.

patterns which further assist particulate removal. Oysters reduce particulate inorganic material and organic material suspended in the water column (Dame et al. 1984; Newell 1988). During the filtration process, sediments settle out of the water column and onto the bottom (Meyer and Townsend 2000; Mugg et al. 2001). If oysters are infected by disease or otherwise degraded, their ability to stabilize sediments may be reduced, allowing increased sedimentation which can ultimately affect algae productivity and oyster feeding and development.

Measuring and Monitoring Methods

For on-site evaluation of oyster filtration capacity, a flow-through plastic tunnel[10] is a feasible method of determining significant changes in tidal water materials passing over an oyster reef (Dame et al. 1984). The reef reduces the amount of particulate organic carbon and chlorophyll *a* (Chl *a*) while increasing the amount of ammonia in the water column. Observations can help determine the magnitude of particulate organic carbon removal and filtration ability of the oyster reef.

Laboratory observations of individual or groups of oysters may provide an efficient, reliable method to evaluate changes in filtration rates and feeding ability in relation to environmental conditions. Laboratory studies also provide an opportunity to examine filtration response across gradients of environmental conditions and combinations of conditions that are difficult or impossible to observe in the habitat.

CHEMICAL

Supports Nutrient Cycling

Oysters play a role in nutrient cycling of carbon, phosphorus, and nitrogen (Figure 25). The animals on the reefs remove large quantities of suspended organic particulate material (phytoplankton) from the water column. The organic matter is processed by the animals and microbes inhabiting the reef with inorganic matter that is readily utilized by the phytoplankton being released into the water column (Dame 1996; Newell 2004). In most instances, the net result is that the community of organisms living on oyster reefs short-circuits the typical pelagic food web and moves carbon, nitrogen, and phosphorus through these ecosystems at much faster rates (Dame 1996).

As a consequence of these material flows, both negative and positive feedback loops are established that increase the complexity, productivity, and stability of estuarine ecosystems. Nutrient processing by oysters for example, can increase nutrient levels in nutrient-limited areas and may help regulate primary production (Dame 1996). Essentially, oyster reefs increase the functional and structural sustainability of their ecosystems (Dame 1996). An oyster's ability to cycle nutrients was seen along intertidal oyster reefs in Bly Creek, South Carolina. Researchers demonstrated that oysters were able to process carbon at high rates and return inorganic nitrogen and phosphorus to the water column, while the returned inorganic nitrogen was taken up by phytoplankton (Dame et al. 1989).

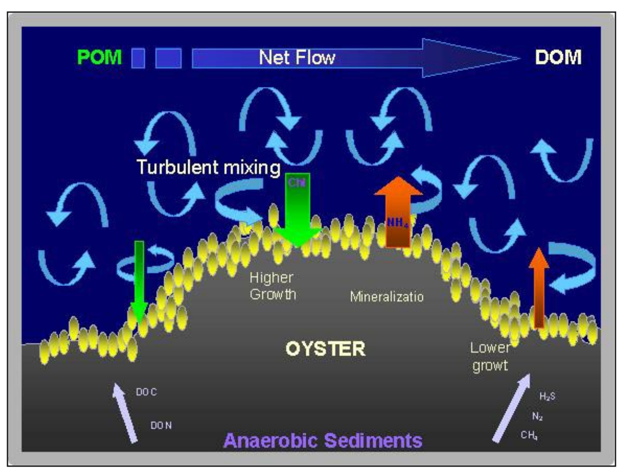

Figure 25. Diagram of nutrient processing in oysters. Diagram courtesy of Richard Dame, Marine Science Department, Coastal Carolina University, South Carolina.

[10]The tunnel method has been successfully used in the United States, as well as The Netherlands, France, and Germany.

Reef Food Webs

Organisms living on the reef may not short-circuit the pelagic food web in all habitats, such as places that were or still are dominated by benthic communities, thereby resulting in benthic-pelagic coupling by filter feeders. In this case, oyster reefs do not short circuit the process but help to restore its naturally functioning state (Dame 1996).

Sampling and Monitoring Methods

There are various methods to measure nutrient concentrations, which in turn can be used to calculate nutrient flux with assistance from experts. These methods include the automated gas segmented continuous flow colorimetric method which measures nitrite and nitrate (Zhang et al. 1997), and the automated colorimetric method which measures orthophosphate (Zimmerman and Keefe 1997).

Nitrate levels can be determined using the automated colorimetric method by (1) reducing the nitrite in a buffer solution, (2) determining nitrite by treating the sample with a dye, and (3) measuring absorbance proportional to the concentration of nitrite + nitrate in the sample. Nitrate is then determined by subtracting the nitrite values (see Zhang et al. 1997).

There are a number of high-tech methods to measure nutrient flux rates as well as oxygen levels such as the automated benthic chamber device. This device is deployed on a line from a vessel, uses one chamber, and contains a sealed waterproof computer as all operations are completely programmable. As the device is lowered into the water, nutrient flux measurements are taken at various intervals. The dissolved oxygen concentrations can also be electronically monitored and stored by the computer (see Grenz et al. 1991; Nicholson et al. 1999).

PARAMETERS FOR MONITORING STRUCTURAL/FUNCTIONAL CHARACTERISTICS OF OYSTER REEFS

The following matrices present parameters for restoration monitoring of the structural and functional characteristics of oyster reefs. These matrices are not exhaustive, but represent those elements most commonly used in such restoration monitoring strategies. These parameters have been recommended by experts in oyster reef restoration as well as in the literature on oyster reef restoration and ecological monitoring. The closed circle (●) denotes a parameter that should be considered in monitoring restoration performance. Parameters with an open circle (❍) may be considered, depending on specific restoration goals.

Parameters to Monitor the Structural Characteristics of Oyster Reefs

Structural Characteristics

Parameters to Monitor	Biological		Physical		Hydrological				Chemical
	Habitat created by animals	Habitat created by plants	Sediment grain size	Topography / Bathymetry	Current velocity	Tides / Hydroperiod	Water sources	Wave energy	pH, salinity, toxics, redox, dissolved oxygen
Geographical									
Acreage of habitat types	●	●							
Biological									
Plants									
Species, composition, and % cover of									
Algae		❍							
Phytoplankton diversity and abundance		❍							
Animals									
Vertical relief	●			●					
Hydrological									
Physical									
Shear force at sediment surface					❍			❍	
Upstream land use							❍		
Water column current velocity					❍				
Tides/Current/Water level fluctuation over time						●	●		
Temperature						●	●		
Chemical									
Dissolved oxygen									●
Nitrogen and phosphorus									❍
pH									❍
Salinity						●	●		●
Toxics									❍
Soil/Sediment									
Physical									
Geomorphology (slope, basin cross section)				●		●			
Organic content			❍			❍			
Sedimentation rate and quality			❍	❍	❍	❍			
Chemical									
Pore water nitrogen and phosphorus									❍

Parameters to Monitor the Functional Characteristics of Oyster Reefs

Parameters to Monitor	Biological: Provides breeding grounds	Provides feeding grounds	Provides nursery areas	Provides refuge from predation	Provides substrate for attachment	Supports a complex trophic structure	Supports biomass production	Supports biodiversity	Physical: Alters turbidity	Reduces erosion potential	Reduces wave energy	Chemical: Modifies chemical water quality	Supports nutrient cycling
Geographical													
Acreage of habitat types	●	●	●	●	●	●	●	●	●	●	●	●	●
Biological													
Plants													
Species, composition, and % cover of:													
Algae	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍
Interspersion of habitat types	❍	❍	❍	❍		❍	❍	❍	❍	❍	❍	❍	❍
Phytoplankton diversity and abundance		❍				❍	❍	❍	❍			❍	❍
Animals													
Species, composition, and abundance of:													
Birds	❍	❍	❍	❍		❍	❍	❍					
Fish	❍	❍	❍	❍		❍	❍	❍					
Invasives	❍	●	●	●			●	●	●				
Invertebrates	❍	❍	❍	❍		❍	❍	❍					
Vertical relief of reef	●	●	●	●	●	●			●	●	●		
Hydrological													
Physical													
PAR							●		●				
Secchi disc depth							●		●				

Parameters to Monitor the Functional Characteristics of Oyster Reefs (cont.)

Parameters to Monitor	Biological: Provides breeding grounds	Provides feeding grounds	Provides nursery areas	Provides refuge from predation	Provides substrate for attachment	Supports a complex trophic structure	Supports biomass production	Supports biodiversity	Physical: Alters turbidity	Reduces erosion potential	Reduces wave energy	Chemical: Modifies chemical water quality	Supports nutrient cycling
Hydrologic													
Physical (cont.)													
Trash		❍							❍				
Upstream land use									❍			❍	
Water column current velocity									❍	❍			
Water level fluctuation over time	●	●	●	●					●	●			●
Chemical													
Dissolved oxygen	❍		❍			❍		❍				❍	❍
Nitrogen and phosphorus	❍		❍				❍	❍	❍			❍	❍
Toxics	❍	❍										❍	
Soil/Sediment													
Physical													
Basin elevations	❍	❍	❍	❍	❍			❍					
Geomorphology (slope, basin cross section)	●	●	●	●	●			●	●	●		●	
Sediment grain size (OM[11]/sand/silt/clay/gravel/cobble)					❍		❍	●	❍	❍	❍	❍	❍
Sedimentation rate and quality								❍	❍	❍		❍	❍

[11] Organic matter.

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APPENDIX I: OYSTER REEFS ANNOTATED BIBLIOGRAPHY

This annotated bibliography contains summaries of restoration case studies and basic ecological literature. It is designed to provide restoration practitioners with examples of previous restoration projects as well as overviews of papers from the ecological literature that offer more detail than that covered in the associated chapter. Entries are presented from both peer reviewed and grey literature. They were selected through extensive literature and Internet searches as well as input from reviewers. They are not, however, a complete listing of all of the available literature. Entries are arranged alphabetically. Wherever possible, web addresses or other contact information has been included in the reference to assist readers in easily obtaining the original resource. Summaries preceded by the terms '*Author Abstract*' or *'Publisher Introduction*' or similar descriptors were taken directly from their original source. Summaries without such descriptors were written by the author of the associated chapter.

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Researchers constructed a three-dimensional oyster reef using oyster shell in the Piankatank River, Virginia, and evaluated settlement and mortality patterns of oysters from June 1993 to September 1994. The reef extended from 2.5 m below mean low water (MLW) to 0.75 m above MLW and covered 150 x 30 m. In 1993 twelve intertidal hummocks were sampled along upstream and downstream transects using transects on two mounds (one sheltered from wave currents and one exposed to wave currents) during each period of sampling. On the reefs transects were marked to prevent re-sampling. In 1994, eight hummocks were partitioned into 64 x 20 cm plots using rope and reinforced bars, and experimental sites. Three tidal heights were considered, 25 cm above MLW, MLW, and 90 cm below MLW. Sampling was then conducted at each of these levels. In intertidal and subtidal locations, settlement and mortality occurrences were monitored at the reef surface and within the reef depths interstices of 10 cm. In subtidal locations settlement was greater and showed no difference in settlement intensity between surface and subsurface environments. Along the intertidal-subtidal continuum survival rates for most of the year were highest at MLW. At this location, physical and predatory influences were minimal. The results indicate that both reef tidal elevation and substrate thickness provide microscale refugia for settlement and survival of early oyster life history stages.

Breitburg, D. L., L. D. Coen, M. W. Luckenbach, R. Mann, M. Posey, and J. A. Wesson. 2000. Oyster reef restoration: Convergence of harvest and conservation strategies. *Journal of Shellfish Research* 19:371-377.

This paper focuses on oyster reef restoration, protection, and construction to meet harvest, water quality, and fish habitat goals in order to view an overall image of why oyster reef monitoring, restoration, and management is important ecologically and economically. The restoration actions that are considered useful and described in this document are constructing reefs at different depths and using different base materials; constructing reefs with varying spatial dispersion patterns; positioning constructed reefs in varying proximity to other landscape elements; constructing reefs in areas with different tidal ranges and water quality and harvesting status; and constructing reefs with varying shapes and vertical structure. Good monitoring and restoration efforts are important to ensure that future restoration efforts are improved, and can enhance the basic information needed to recognize the ecology of oysters and their role in estuarine and coastal systems. Additional information on techniques used to monitor and restore oyster reefs are described in this document.

Bushek, D., J. Keesee, B. Jones, M. Neet and D. Porter. 2000. Shellfish health management: A system level perspective for *Perkinsus marinus*. *Journal of Shellfish Research* 19: 642-643.

Author Abstract. This paper provides information on a study conducted on 2 South Carolina estuaries on shellfish health. The paper presents data from three years of spatial seasonal monitoring of *P. marinus* infection intensities in the 2 estuaries. The data include El Niño, La Niña and normal rainfall years and indicate that water residence time and flushing rates, are primary determinants of infection intensity. Landscape-level anthropogenic impacts that alter these hydrological processes (e.g., upland ditching and drainage, channel dredging, jetty construction, etc.) may be more important factors in intensifying oyster mortality from *P. marinus* than pollutants commonly associated with development. Shellfish health management should include, 1) via site selection for planting, cultivating and harvesting oysters, 2) for selecting sanctuaries and reserves, and 3) to identify potential management regulations and mitigation efforts for coastal development.

Clarke, D., D. Meyer, A. Veisholw and M. LaCroix. 1999. Alabama Oyster Reef Restoration. Virginia Institute of Marine Sciences, pp. 102-106. In Luckenbach, M. W., R. Mann, and J. Wesson (eds.), Oyster Reef Habitat Restoration: A Synopsis and Synthesis of Approaches. Virginia Institute of Marine Science, College of William and Mary, VIMS Press, Williamsburg, VA.

In 1952, Alabama originally contained approximately 2,353 hectares of reefs. By 1971, Alabama had 1,240 hectares of public reefs indicating great loss over time. This paper discusses some techniques used to restore the oyster reef habitats. The Marine Resources Division (MRD) conducted a project involving evaluations made on oyster shell planting. Post planting dredge tows were taken from 1984-1988 to assess spat set success. The results of these tows include 625 shells that were examined with 29% spat; 6510 shells, with 1.6% containing spat; 360 shells, with 19% containing spat; 2619 shells, with 0.4% containing spat; and 1929 shells, with 1.55% containing spat.

There were three basic culture techniques examined. These techniques include: cultchless oysters in horizontal suspended bags; cultchless oysters in bags on racks; and remote set oysters in trays on the bottom. Oysters that were placed in horizontally suspended bags achieved harvestable size within sixteen months. These oysters were then grown in a region of Mobile Bay where oyster production is minimal. Results showed that the cultchless oysters grown on racks averaged 71 mm and remote set oysters on the bottom averaged 82 mm after sixteen months. Despite success with this technique, Alabama is no longer utilizing these techniques.

Coen, L. D., E .L. Wenner, D. M. Knott, B. Stender, N. H. Hadley, M.Y. Bobo, D. L. Richardson, M. A. Thompson and R. E. Giotta. 1997. Intertidal oyster reef habitat assessment and restoration: Evaluating habitat use, development and function. *Journal of Shellfish Research* 16: 262.

Author Abstract. This abstract presents a study conducted in South Carolina 1994 where researchers evaluated the role of intertidal oyster reefs in southeastern estuarine ecosystems. This information was then used to formulate strategies for habitat management and restoration and mitigation methods. The authors experimented in constructing replicate experimental reefs to follow habitat recruitment and succession, using transient and resident species. Two sites were studied, each with three replicate experimental reefs of 23 m^2. Environmental data was collected (DO, salinity, pH, turbidity, intertidal and subtidal temperatures), monitoring of oyster diseases (monthly Dermo and MSX) and other life history parameters (SPF growth, spat set, reproduction) on experimental, and adjacent natural reefs. Results at this time showed more than 34 species of fish and decapod crustaceans that were transient were collected, with densities often exceeding 5,600 individuals/23 m^2 reef. Within seven months (May, 1995), large densities of xanthid crab recruits (<1.5-3 mm cw) were observed on both natural and experimental reefs.

Dame, R. F., E. Koepfler, L. Gregory, T. Prins, D. Allen, D. Bushek, C. Corbett, D. Edwards, B. Kjerfve, A. Lewitus, J. Schubauer-Berigan and S. Thomas. 1998. Testing the role of oyster reefs in the structure and function of tidal creeks with a replicated ecosystem scale experiment: System level variability and response to removal of oysters. *Journal of Shellfish Research* 17:1297.

Author Abstract. Data from an ongoing replicated ecosystem level study that addresses the ecological role of oyster reefs in tidal creeks. The geomorphology and hypsometry were determined for eight similar tidal creek systems in North Inlet Estuary, South Carolina, U.S.A. Oyster biomass, which ranged from 2 to 24 g dry wt. m^{-3} of water, was standardized to 8 g dry weight m^{-3}. Afterward, water quality, phytoplankton and bacterial productivity, oyster growth and recruitment, nekton utilization, total creek metabolism and nutrient cycling were monitored in each creek for one year to determine system variability. After the first year of monitoring was complete (Jan. 1998), oyster reefs were removed from four of the eight creeks in a randomized block design. Monitoring continued so that the before and after reef removal data can be compared among control (no reefs removed) and impact (reefs removed) creeks in completely replicated BACI design. Pre-reef removal data indicated high seasonal variability and significant variability among creeks. Relative differences among creeks were stable - creeks generally maintained the same rankings throughout the year. Analysis of subsequent monitoring viewed changes in the behavior of creek attributes before and after oyster reef removal. The BACI design accounts for such overriding effects, enabling only the impacts of removing oysters to be examined, but also enabling differences in system response to major perturbations when oyster reefs are present or absent to be examined.

Dekshenieks, M. M., E. E. Hofmann, J. M. Klinck and E. N. Powell. 2000. Quantifying the effects of environmental change on an oyster population: A modeling study. *Estuaries* 23:593-610.

Author Abstract. Three models are combined to investigate the effects of changes in environmental conditions on the population structure of the Eastern oyster, *Crassostrea virginica*. The first model, a time-dependent model of the oyster population as described in Powell et al. (1992, 1994, 1995a,b, 1996, 1997) and Hofmann et al. (1992, 1994, 1995), tracks the distribution, development, spawning, and mortality of sessile oyster populations. The second model, a time-dependent larval growth model as described in Dekshenieks et al. (1993), simulates larval growth and mortality. The final

model, a finite element hydrodynamic model, simulates the circulation in Galveston Bay, Texas. The coupled post-settlement-larval model (the oyster model) runs within the finite element grid at locations that include known oyster reef habitats. The oyster model was first forced with 5 yr of mean environmental conditions to provide a reference simulation for Galveston Bay. Additional simulations considered the effects of long-term increases and decreases in freshwater inflow and temperature, as well as decreases in food concentration and total seston on Galveston Bay oyster populations. In general, the simulations show that salinity is the primary environmental factor controlling the spatial extent of oyster distribution within the estuary. Results also indicate a need to consider all environmental factors when attempting to predict the response of oyster populations; it is the superposition of a combination of these factors that determines the state of the population. The results from this study allow predictions to be made concerning the effects of environmental change on the status of oyster populations, both within Galveston Bay and within other estuarine systems supporting oyster populations.

Ellis, M. S., J. Song and E. N. Powell. 1993. Status and trends analysis of oyster reef habitat in Galveston Bay, Texas. *Journal of Shellfish Research* 12:154.

Author Abstract. This study was conducted to test a new technique for determining the status and trends of oysters (*Crassostrea virginica*) populations in Galveston Bay, Texas. An acoustic profiler was used to differentiate substrate type, a fathometer to assess bottom relief and a global positioning system to accurately establish position. The acoustic profiler chart interpreted sediment characteristics and reefall according to the amount of return generated. Researchers were able to distinguish oyster reef from mud, sand, and shell hash. The bathymetry, sediment type, and geographic position data were computerized and processed for use by a Geographic Information System (GIS) to produce the maps. Arc/Info software was used to produce maps covering the majority of Galveston Bay, Trinity Bay, East Bay, and West Bay. The reefs were then compared to those in the late ‘60s and early ‘70s by the Texas Parks and Wildlife Department. See publication for additional information on techniques used. The amount of oyster reef and oyster bottom recorded in this study was higher than that depicted on the TPWD charts.

Harding, J. M. and R. Mann. 2001. Oyster reefs as fish habitat: Opportunistic use of restored reefs by transient fishes. *Journal of Shellfish Research* 20:951-959.

Author Abstract. Under the Magnuson-Stevenson Fisheries Management Act of 1996, current fisheries management practice is focused on the concept of Essential Fish Habitat (EFH). Application of the EFH concept to estuarine habitats relates directly to ongoing oyster reef restoration efforts. Oyster reef restoration typically creates complex habitat in regions where such habitat is limited or absent. While healthy oyster reefs provide structurally and ecologically complex habitat for many other species from all trophic levels including recreationally and commercially valuable transient finfishes, additional data is required to evaluate oyster reef habitats in the context of essential fish habitat. Patterns of transient fish species richness, abundance, and size-specific habitat use were examined along an estuarine habitat gradient from complex reef habitat through simple sand bottom in the Piankatank River, Virginia. There was no clear delineation of habitat use by transient fishes along this cline of estuarine habitat types (oyster reef to sand bar). Atlantic croaker (*Micropogonias undulatus*), Atlantic menhaden (*Brevoortia tyrannus*), bluefish (*Pomatomus saltatrix*), silver perch (*Bairdiella chrysoura*), spot (*Leiostomus

xanthurus), spotted seatrout (*Cynoscion regalis*), striped bass (*Morone saxatilis*), and weakfish (*Cynoscion nebulosus*) were found in all habitat types examined. In general, the smallest fish were found on the sand bar, the site with the least habitat heterogeneity. As habitat complexity increased along the gradient from oyster shell bar through oyster reef, transient fish size and abundance increased. Opportunistic habitat use by this suite of generalists relates variations in habitat quality as related to habitat-specific productivity and suggested that oyster reefs may be important but not essential habitat for these fishes.

Harris, C. S. and K. T. Paynter, Jr.. 2001. The effect of local population density on growth and condition in the eastern oyster *Crassostrea virginica,* pp. 279. Aquaculture 2001: Book of Abstracts. World Aquaculture Society, Louisiana State University, Baton Rouge, LA.

Author Abstract. The restoration of oysters and oyster reefs is an important component in the restoration of the Chesapeake Bay estuary. The impact of oyster stocking density on oyster growth, mortality, condition, and parasite prevalence has not been widely studied. In order to maximize the effectiveness of oyster restoration, it is important to determine how stocking density may affect these parameters. In addition, the effect of increased oyster reef habitat on the surrounding benthic community is important to understand. In the fall of 1999, twelve 0.2 acre experimental plots were constructed in the Patuxent River by placing fossilized oyster shell on a former, but now barren, natural oyster bar. The plots were randomly assigned one of four treatments, including zero oysters/m^2, 124 oysters/m^2, 247 oysters/m^2 or 494 oysters/m^2, in a randomized design. Samples were collected by divers using quadrats from each site in November 1999 and May 2000. In May 2000, shell height of high-density oysters (mean 37(± 1.6 SEM) mm) was not significantly different than that of low density oysters (40 ± 1.4 mm). However, low-density oysters had a mean condition index of 13.2(± 0.65) but the mean condition index of the high density oysters was significantly lower at 11.1 (± 0.62). Condition index is a measure of dry tissue weight unit per pallial volume and is often used as an indicator of oyster health. This may suggest that density may play a role in the health of oysters and that oysters in high densities may be stressed by limiting environmental factors such as food or dissolved oxygen. The results of this study will provide further insight on the importance of local population density in oyster restoration projects.

Jordan, S. J., K. Greenhawk and G. F. Smith. 1995. Maryland oyster geographical information system: Management and scientific applications. *Journal of Shellfish Research* 14:269.

Author Abstract. A microcomputer geographical information system (GIS) has been developed to manage and interpret data from Maryland's oyster monitoring and management programs. The GIS was initiated to portray annual monitoring information geographically, but has been expanded to include physical and chemical habitat data, management-related information, and data from special studies. Complete biological and physical information about an individual oyster bar, a region, or the entire Maryland Chesapeake Bay can be retrieved to a user's specification almost instantaneously, and portrayed in a variety of graphical and tabular formats. The system has proved especially useful in supporting the information needs of the state's Oyster Recovery Action Plan. For example, we have provided managers, scientists, and policy-makers with clear, graphical portrayals of oyster habitat, population and disease status, salinity gradients, and management history with a minimum of effort. As new experimental management efforts develop, the GIS maintained a standard, geographically precise database for documenting and tracking their performance. The use of GIS with biological monitoring data greatly simplifies the spatial aspects of analysis, allowing the analyst to focus on temporal variations: the GIS tested hypotheses about historical changes in the aerial extent of oyster physical habitat, spatfall, and diseases. Besides its utility for management and scientific investigations, the GIS proved to be a valuable educational tool for students and tour groups.

Koles, T. and K. T. Paynter. 1999. Oyster restoration in Maryland: Measuring progress and productivity. National Shell Fisheries Association. *Journal of Shellfish Research* 18:330.

Author Abstract. A study conducted in 1997, in cooperation with the Maryland Department of Natural Resources and the Army Corps of Engineers, in which five sites in both the Choptank and Patuxent Rivers, extending from the mouth of each river to approximately eight miles upstream, were identified for restoration. At each site, fossil oyster shells were deposited in a configuration of two 0.5-acre flat areas and one mound approximately three to four meters high. Some of these areas were then planted with hatchery reared spat (1 million/acre; 247/m^2) while the rest were left unplanted. Divers obtained quadrat samples from each of the flats and mounds and YSI 6000 continuous water quality monitors to measure ambient water temperature, salinity, pH, and dissolved oxygen. The samples were analyzed for oyster size, abundance, mortality, fouling community, and parasite (*Perkinsus marinus*) prevalence and intensity. In both rivers, the oysters appeared to be growing dynamically. Parasitic activity was very low with only a few oysters in each river infected with *P. marinus*. Mortality was also low overall and the unplanted mounds in both rivers recruited higher numbers of natural spat set than the unplanted flat areas nearby. Results were used to evaluate the differences in bottom morphology and differing water characteristics (i.e., salinity) on oyster recruitment, growth, mortality, and disease pressures.

Lenihan, H. S., C. H. Peterson, J. E. Byers, J. H. Grabowski, G. W. Thayer and D. R. Colby. 2001. Cascading of habitat degradation: Oyster reefs invaded by refugee fishes escaping stress. *Ecological Applications* 11: 764-782.

Author Abstract. In this study researchers evaluated the structurally complex, species-rich biogenic reefs created by the eastern oyster, *Crassostrea virginica*, in the Neuse River estuary, North Carolina, USA. Researchers first sampled fishes and invertebrates on natural and restored reefs and on sand bottom to compare fish utilization of these different habitats and to characterize the trophic relations among large reef-associated fishes and benthic invertebrates, and secondly, tested whether bottom-water hypoxia and fishery-caused degradation of reef habitat combine to induce mass emigration of fish that then modify community composition in refuges across an estuarine seascape. Experimentally restored oyster reefs of 1 m tall “degraded” or 2 m tall “natural” reefs were constructed at 3 and 6 m depths. Samples were taken of the hydrographic conditions within the estuary over the summer to monitor onset and duration of bottom-water hypoxia/anoxia, resulting from density stratification and anthropogenic eutrophication. Reduction of reef height caused by oyster dredging exposed the reefs located in deep water to hypoxia/anoxia for >2 wk, killing reef-associated invertebrate prey and forcing mobile fishes into refuge habitats. Refugee fishes gathered at high densities on reefs in oxygenated shallow water, where they depleted epibenthic crustacean prey populations. However, physical disturbances can impact remote, undisturbed refuge habitats by movement and abnormal concentration of refugee organisms that have strong trophic impacts. The results show that reserves placed in proximity to disturbed areas may be impacted indirectly but may serve as an important refuge function on a scale comparable to the mobility of consumers.

Luckenbach, M. W., J. Harding, R. Mann, J. Nestlerode, F. O. Beirn and J. A. Wesson. 1999. Oyster reef restoration in Virginia, USA: Rehabilitating habitats and restoring ecological functions. *Journal of Shellfish Research* 18:720-721.

Author Abstract. Repletion efforts in response to declines in abundance of the eastern oyster, *Crassostrea virginica,* have historically relied upon transplanting of oyster seed and planting of a suitable settlement substrate. These efforts have generally failed to revitalize the fishery because they (1) failed to rehabilitate degraded reef habitat and (2) placed little emphasis upon reestablishing a population age structure capable of sustaining a self-supporting reef. More recently restoration efforts in Virginia have focused on reconstructing 3-dimensional reef habitats and establishing brood stock sanctuaries with an emphasis on restoring lost ecological functions of reefs. Manipulative studies of reef placement, construction material and interstitial space have lead to the development of design criteria for maximizing oyster recruitment, growth, and survival on constructed reefs. Further, we have characterized the successional development of resident macrofaunal communities on restored reefs and have begun to relate that development to specific habitat characteristics. Utilization of these restored reef habitats by transient species has been characterized through extensive field collections and underwater video observations; gut analyses of finfish are beginning to elucidate trophic linkages between the reefs and adjacent habitats. In addition, these structures appear important to the early developmental stages of juvenile fishes, some of which have considerable recreational and commercial importance. These studies are helping us to (1) clarify the ecological functions supported by oyster reef habitat, (2) define design criteria for reconstructing reefs, and (3) establish success criteria for such restoration projects. While destructive fishing of oyster reefs appears inconsistent with meeting these goals, an emerging paradigm is that reef sanctuaries can be used to support desired ecological functions as well as supply recruits to adjacent areas which can be managed from a fisheries perspective.

McCollough, C., S. J. Jordan and M. L. Homer. 2000. Chesapeake Bay oysters: Trends in relative abundance and biomass. *Journal of Shellfish Research* 19:623.

Author Abstract. Oyster populations are distributed patchily over more than 400,000 acres in Chesapeake Bay, so it is not feasible to assess their absolute numbers or biomass. Traditionally, landings data, with their inherent inaccuracies and biases, have been the only consistent means of estimating trends. A long term monitoring program in Maryland has recorded relative numbers and size distributions of oysters, along with other population and disease data annually; 43 fixed sites have been monitored consistently since 1990, with many records from these sites available from earlier years. In 1999, we obtained shell height measurements and dry tissue weights from samples of 10 oysters from each site (selected to represent the range of sizes present). By applying the resulting length: weight equation to size-frequency data from earlier surveys, we computed an index of relative biomass that varied from year to year according to the relative abundance and size distribution of the oyster populations. The index is useful for portraying trends and tracking the performance of restoration efforts. It reflects interannual variations in recruitment and growth, as well as mortality caused by the oyster parasites *Haplosporidium nelsoni* and *Perkinsus marinus.*

Meyer, D. L. 1994. Habitat partitioning between the xanthid crabs *Panopeus herbstii* and *Eurypanopeus depressus* on intertidal oyster reefs in southeastern North Carolina. *Estuaries* 17:674-679.

Author Abstract. The abundances of the xanthid crabs *Panopeus herbstii* and *Eurypanopeus depressus* were examined relative to surface oyster shell cover, surface oyster cluster volume, subsurface shell content, substrate sand and silt composition, and oyster reef elevation. During August 1986 through July 1987, xanthid crabs were collected monthly from twelve 0.25 m^2 x 15 cm deep quadrats, during low tide, from intertidal oyster reefs in Mill Creek, Pender County, North Carolina, USA, with respective quadrat details recorded. The abundance of *P. herbstii*, and to a lesser degree of *E. depressus*, was positively correlated with surface shell cover. The abundance of *E. depressus*, and to a lesser degree *P. herbstii*, was positively correlated with surface cluster volume. The majority of *P. herbstii* inhabited the subsurface stratum of the oyster reef, whereas the majority of *E. depressus* inhabited the cluster stratum. Seasonality (i.e., temperature) appeared to influence the strata habitation of both species, with a higher incidence of cluster habitation during warmer months and a lower incidence during colder months. Crab abundance was not related to other factors examined, such as subsurface shell, substrate sand and silt composition, or elevation within the oyster reef. The analyses show that *P. herbstii* and *E. depressus* have partitioned the intertidal oyster reef habitat, with *E. depressus* exploiting surface shell clusters and *P. herbstii* the subsurface stratum. Refer to publication for additional information on methods used.

Meyer, D. L. and E. C. Townsend. 2000. Faunal utilization of created intertidal eastern oyster (*Crassostrea virginica)* reefs in the southeastern United States. *Estuaries* 23: 34-45.

Author Abstract. Oyster cultch was added to the lower intertidal marsh-sandflat fringe of three previously created *Spartina alterniflora* salt marshes. Colonization of these created reefs by oysters and other select taxa were then examined. The created reefs supported numerous oyster reef-associated faunas at equivalent or greater densities than adjacent natural reefs. Eastern oyster (*Crassostrea virginica*) settlement at one site of created reef exceeded that of the adjacent natural reefs within 9 months of reef creation. Within 2 years, harvestable-size *C. virginica* (>75 mm) were present in the created reefs along with large numbers of *C. virginica* clusters. The created reefs also had a higher number of molluscan, fish, and decapod species than the adjacent natural reefs. After 2 yr the densities of *C. virginica*, striped barnacle (*Balanus amphitrite*), scorched mussel (*Brachidontes exustus*), Atlantic ribbed mussel (*Geukensia demissa*), common mud crab (*Panopeus herbstii*), and flat mud crab (*Eurypanopeus depressus*) within the created reefs was equivalent to adjacent natural reefs. Data collected indicate that created oyster reefs can readily acquire functional ecological attributes of their natural counterparts. Based on the results, reef function and physical and ecological linkages of oyster reefs to other habitats (marsh, submerged aquatic vegetation, and bare bottom) should be taken into consideration when reefs are created in order to provide resources that are able to maintain estuarine systems.

O'Beirn, F. X., M. W. Luckenbach, J. A. Nestlerode and G. M. Coates. 2000. Toward design criteria in constructed oyster reefs: Oyster recruitment as a function of substrate type and tidal height. *Journal of Shellfish Research* 19: 387-395.

Author Abstract. Restoration of degraded oyster reef habitat generally begins with the addition of substrate that serves as a reef base and site for oyster spat attachment. Remarkably, little is known about how substrate type and reef morphology affect the development of oyster populations on restored reefs. Three-dimensional, intertidal reefs were constructed near Fisherman's Island, Virginia: two reefs in 1995 using surf clam (*Spisula solidissima*) shell and six reefs in 1996 using surf clam shell, oyster shell, and stabilized coal ash. Researchers monitored oyster recruitment and growth quarterly at three tidal heights (intertidal, mean low water, and subtidal) on each reef type since their construction. Oyster recruitment in 1995 exceeded that observed in the two subsequent years. High initial densities on the 1995 reefs decreased and stabilized at a mean of 418 oyster/m^2. Oyster settlement occurred on all reef types and tidal heights in 1996; however, post-settlement mortality on the surf clam shell and coal ash reefs exceeded that on the oyster shell reefs, which remained relatively constant throughout the year (mean = 935 oysters/m^2). Based on the field observations, predation accounts for most of the observed mortality and that the clam shell and coal ash reefs suffer greater predation. Oyster abundance was consistently higher in the intertidal zone on all reefs for each year studied. Based on patterns observed, researchers concluded that the provision of spatial refugia (both intertidal and interstitial) from predation is important for successful oyster reef restoration in this region. Finally, high levels of recruitment can provide a numerical refuge, whereby the oysters provide structure and increase the probability of an oyster population and reef structure.

Oliver, L. M. and S. A. Fisher. 1995. Comparative form and function of oyster *Crassostrea virginica* hemocytes from Chesapeake Bay, Virginia and Apalachicola Bay, FL. *Diseases of Aquatic Organisms* 22:217-225.

Author Abstract. Oysters *Crassostrea virginica* from Chesapeake Bay, Virginia, and Apalachicola Bay, Florida, USA, were collected in March and October 1992 to investigate possible differences in defense-related hemocyte activities between individuals from geographically separate populations. In March, hemolymph drawn from Chesapeake Bay oysters contained an average of 1.08 x 10^6 hemocytes/m hemolymph, significantly lower than the average 1.63 x 10^6 hemocytes/ml hemolymph obtained from Apalachicola Bay oysters. Hemocyte number did not differ significantly in the October comparison. At both times of year, Chesapeake Bay oyster hemolymph samples contained significantly greater proportions of granular hemocytes compared to Apalachicola Bay hemolymph samples. Hemocyte samples from Chesapeake Bay oysters demonstrated a higher percentage of mobile hemocytes and greater particle binding ability than Apalachicola Bay oyster hemocytes when tested in March, but the reverse was found in the October experiments. Chesapeake Bay oyster hemocytes produced significantly more superoxide anion as measured by nitroblue tetrazolium reduction than did Apalachicola Bay oyster hemocytes in both March and October. Oyster hemolymph levels of the protozoan parasite *Perkinsus marinus* did not differ significantly between the two sites at either time of year. These results demonstrate the importance of background studies to characterize site-specific differences in oyster hemocyte defense-related functions.

Posey, M. H., T. D. Alphin, C. M. Powell and E. Townsend. 1995. Use of oyster reefs as habitat for epibenthic fish and decapods, pp. 229- 237. In Luckenbach, M. W., R. Mann, and J. Wesson (eds.), Oyster Reef Habitat Restoration: A Synopsis and Synthesis of Approaches. Virginia Institute of Marine Science, College of William and Mary, VIMS Press, Williamsburg, VA.

Researchers examined the use of intertidal oyster beds by epibenthic decapods and fish in southeastern North Carolina. Sampling of mobile epifauna at low tide was performed using quadrats; and fish and mobile decapods at high tide were sampled using sweep nets. Estimates were made of large fish and decapods that may be able to avoid being caught in sweep nets when the beds were submerged by diver observations. Laboratory mesocosm studies examined the potential use of oyster patches by the grass shrimp, *Palaemonetes pugio* when predators are present. See publication for additional information on methods used. Results showed that fish and decapods were abundant over oyster beds compared to adjacent sandflat areas and were used more by grass shrimp, pinfish, and blue crabs. Laboratory studies indicated significant use of oyster patches by grass shrimp when threatened by predatory fish compared to treatments with no fish or a non-predatory fish. Overall oyster habitats are important for epibenthic decapods and fish. Therefore oyster reef management is required to sustain fisheries around the reefs as well as provide protection for reefs that provide habitats for other species.

Saoud, I. G., D. B. Rouse, R. K. Wallace, J. E. Supan and S. Rikard. 2000. An *in situ* study on the survival and growth of *Crassostrea virginica* juveniles in Bon Secour Bay, Alabama. *Journal of Shellfish Research* 19: 809-814.

Author Abstract. For this study experimental plots were established at a relic oyster reef on the eastern side of Mobile Bay, Alabama between July 1998 and November 1999 to determine whether elevated beds might improve oyster survival and growth. Oysters *(Crassostrea virginica)* were spawned in a hatchery and the spat were allowed to settle on small oyster shell fragments and on whole oyster shell. Two-month-old juveniles (15-18 mm) were deployed in polyethylene oyster bags on bottom and on underwater shell pads 20 cm and 40 cm above bottom. Oysters on whole shells were deployed outside bags in order to evaluate predation. Remote sensing data loggers were used to measure temperature, salinity, and oxygen concentration. Growth (increase in height), survival, and condition of oysters in bags at the three experimental depths were compared. Temperature and salinity varied between 11.8º C - 32.8º C and 4.4 ppt - 29.7 ppt, respectively. The results showed that oysters at the three experimental levels grew to approximately 55 mm during the first year. Total mortality was observed at all three levels during the second summer when oxygen levels dropped to 0 mg L^{-1} for five consecutive days while water temperature was 28º C.

Southworth, M. and R. Mann. 1998. Oyster reef broodstock enhancement as a mechanism for rapid oyster reef replenishment. *Journal of Shellfish Research*. 17:1101-1114.

Author Abstract. Natural oyster populations in the Chesapeake Bay have become severely depleted due to a combination of overfishing and disease. Replenishment programs in the form of artificial reefs are currently in effect throughout most of the Virginia portion of the Chesapeake Bay. Shell Bar reef, built in the Great Wicomico River, Virginia in 1996 was supplemented with reproductively active broodstock oysters from Tangier and Pocomoke Sounds. The Great Wicomico River was historically a high seed producing river, but production has decreased in recent years. Oyster larval concentrations (plankton tows), gonad development, and circulation data were collected in the river throughout the 1997 reproductive season. The broodstock oysters spawned from mid-June through mid-August, with a peak occurring from mid-June through mid-July. Larval concentrations were several orders of magnitude higher than the highest reported in the literature over the past 25 years.

Larvae were significantly more abundant on the flood tidal stage, suggesting some vertical migration with the changing tide, thus aiding in their retention in the system. Settlement of larvae on shellstrings and on bottom substrate, was higher than in recent years. The most abundant settlement occurred near the reef and upriver of the reef. Circulation patterns observed are favorable for local retention of larvae in the system. Reef building, and subsequent transplants of broodstock onto these reefs, can be an effective management option provided the circulation patterns of the system are similar to the Great Wicomico.

University of Maryland Center for Environmental Sciences. Restoration Design for Oyster Beds. Sandy Point Integrated Ecosystem Restoration Project, Chesapeake Bay Biological Laboratory, Solomon, MD.

This paper discusses a restoration design for oyster beds. The restoration methods include planting about five acres of submerged aquatic vegetation (SAV) at two locations and constructing about three acres of oyster bars in an L-shape protecting the SAV. The oyster bars were created at various depths and densities to collect information on relative effectiveness of intensive vs. extensive oyster bed construction. Three high-density oyster mounds were positioned at tactical points along the bar. The oyster mounds were used to enhance oyster reef ability to reduce waves; provide added protection to SAV beds; and provide information concerning oyster density and distribution along the bottom and in the water column and how it influences their performance.

Oyster setting tanks were used to acquire oyster larvae from off-site before being relocated to a protected shallow-water oyster nursery. The spat was kept at that position and allowed to solidify for numerous days/weeks before being transported for final seeding. The survival and growth of the oysters, adjacent and nearby SAV beds, and the abundance, diversity, and distribution of small and large fish and foraging birds were monitored.

Virginia Institute of Marine Sciences (VIMS). 1994. Monitoring Programs for Oyster Beds. Virginia Institute of Marine Science, Gloucester Point, VA. Contact information: Dr. Roger Mann, Department of Fisheries Science, Virginia Institute of Marine Science. http://www.vims.edu/mollusc/monrestoration/monoyster.htm#modern

Data are collected by the VIMS Spatfall Survey and the VIMS Dredge Survey on oyster bed health in Virginia waters. The VIMS Spatfall Survey organized shell strings weekly from May to September at stations within the Chesapeake Bay to provide an annual index of oyster settlement and recruitment. Shell strings were suspended 0.5 m from the bottom to provide settlement substrate for oyster veligers. After retrieval, oyster spat (recently settled oysters) on the undersides of ten shells were counted under a dissecting microscope. The average number of spat per shell was calculated for each time and place.

The VIMS Dredge Survey monitored the status of Virginia's public oyster fishery, encompasses more than 243,000 acres. Oyster bars were sampled throughout the state annually to assess trends in oyster growth, mortality, and recruitment using a dredge. At each location three samples of bottom material were dredged. Half-bushel aliquots (25 quarts) were taken from each sample for processing. Researchers then counted the number of spat, small, and market oysters. Averages of counts per bushel of bottom material were calculated so that comparisons can be made between areas and years in which study was conducted. The Patent Tong survey was then initiated in 1993 to provide more quantitative estimates of oyster standing stock in Virginia tributaries. At each station, a patent tong was used to sample one square meter of bottom. Oysters from each sample were examined. Researchers stated that the surveys used to assist in monitoring oyster health was efficient in providing data that support management and restoration of Virginia's oyster resource.

APPENDIX II: OYSTER REEFS
REVIEW OF TECHNICAL METHODS MANUALS

This Review of Technical Methods Manuals includes a variety of sampling manuals, Quality Assurance/Quality Control (QA/QC) documents, standardized protocols, or other technical resources that may provide practitioners with the level of detail needed when developing a monitoring plan for a coastal restoration project. Examples from both peer reviewed and grey literature are presented. Entries were selected through extensive literature and Internet searches as well as input from reviewers. As with the Annotated Bibliographies, these entries are not, however, a complete list. Entries are arranged alphabetically by author. Wherever possible, web addresses or other contact information is included in the reference to assist readers in easily obtaining the original resource. Summaries preceded by the terms '*Author Abstract'* or *'Publisher Introduction*' or similar descriptors were taken directly from their original source. Summaries without such descriptors were written by the authors of the associated chapters.

Campbell, G. and S. Wildberger. 1992. The Monitor's Handbook. Lamotte Company ENC-016429. P. O. Box 329, Chestertown MD 21620. Contact information: Phone # (410) 778-3100, (800) 344-3100 or Fax # (410) 778-6394. Reference No.1507.

Author Abstract. This handbook provides the background and testing procedures for individuals who want to learn more about their local waterways or are involved in a water monitoring program. Aquatic ecosystems, such as streams, rivers, and lakes, are explained and a pre-monitoring sequence of activities is discussed. The handbook outlines sampling techniques and the equipment involved. Information for each of the water quality factors covered in the book (such as hardness, pH, and coliform bacteria levels) include: how to measure the factors, what the significant levels are, and what the measured levels indicate. Tips are provided for assuring the test results' accuracy for each test method. Quality assurance practices that contain calibration procedures and audits are suggested. Readers can find discussions of data analysis and presentation methods. A glossary, bibliography, and conversion table is included in the document. Appendices provide an overview of management concerns for a volunteer water monitoring program and lists of additional resources. Black and white photographs and drawings are found throughout the book.

Davies, J., J. Baxter, M. Bradley, D. Connor, J. Khan, E. Murray, W. Sanderson, C. Turnbull and M. Vincent. 2001. Marine Monitoring Handbook. UK Marine Science Project, and Scottish Association of Marine Science. Joint Nature conservation Committee, English Nature, Scottish Natural Heritage, Environment and Heritage Services. http://www.jncc.gov.uk/marine/mmh/Introduction.pdf.

The UK Marine Science Project developed this hand book to provide guidelines for recording, monitoring, and reporting characteristics and conditions of marine habitats. However based on location and other environmental conditions methodologies will have to be modified to suit the structural characteristics of the habitat. This manual addresses the fundamentals and procedures for monitoring different parameters in marine habitats, management tools, and benefits and costs for developing a monitoring project. Topics presented in this document include establishing marine monitoring programs highlighting what needs to be measured and methods to use; provides guidance when developing a monitoring program; selecting proper monitoring techniques to attain precision and accuracy; and procedural guidelines for monitoring a specific marine habitat. Detailed information on the tools needed for monitoring marine habitats are described within the marine monitoring handbook.

Halse, S. A., D. J. Cale, E. J. Jasinska and R. J. Shiel. 2002. Monitoring change in aquatic invertebrate biodiversity: Sample size, faunal elements and analytical methods. *Aquatic Ecology* 36:395-410.

Author Abstract. Replication is usually regarded as an integral part of biological sampling, yet the cost of extensive within-wetland replication prohibits its use in broad-scale monitoring of trends in aquatic invertebrate biodiversity. In this paper, we report results of testing an alternative protocol, whereby only two samples are collected from a wetland per monitoring event and then analyzed using ordination to detect any changes in invertebrate biodiversity over time. Simulated data suggested ordination of combined data from the two samples would detect 20% species turnover and be a cost-effective method of monitoring changes in biodiversity, whereas power analyses showed about 10 samples were required to detect 20% change in species richness using ANOVA. Errors will be higher if years with extreme climatic events (e.g., drought), which often have dramatic short-term effects on invertebrate communities, are included in analyses. We also suggest that protocols for monitoring aquatic invertebrate biodiversity should include microinvertebrates. Almost half the species collected from the wetlands in this study were microinvertebrates and their biodiversity was poorly predicted by macroinvertebrate data.

McCobb, T. D. and P. K. Wieskel. 2003. Long-Term Hydrologic Monitoring Protocol for Coastal Ecosystems. United States Geological Survey Open-File Report 02-497. 94 pp. http://water.usgs.gov/pubs/of/2002/ofr02497/

The United States Geological Survey (USGS) and the National Park Service have designed and tested monitoring protocols implemented at Cape Cod National Seashore. The monitoring protocols are divided into two parts. Part one of the protocol discusses the objectives of the monitoring protocol and presents rationale for the recommended sampling program. The second part describes the field, data-analysis, and data-management, and variables that are to be taken into consideration when monitoring (e.g., sea level rise, climate change and urbanization). This protocol provides consistency when monitoring changes in ground-water levels, pond levels, and stream discharge. The monitoring protocol not only establishes a hydrologic sampling network but provides reasoning for measurement methods selected and spatial and temporal sampling frequency. Data collected during the first year of monitoring and hydrologic analyses for selected sites are presented. Long-term hydrologic monitoring procedures performed at the Cape Cod National Seashore may also assist set a template for deciphering findings of other monitoring programs.

Michener, W. K., J. W. Brunt and W. H. Jefferson. 1995. New techniques for monitoring American oyster (*Crassostrea virginica*) recruitment in the intertidal zone, pp. 267-273. In Aiken, D. E., S. L. Waddy, and G. L. Conan, (eds.), Shellfish Life Histories and Shellfishery Models. Selected Papers from a Symposium Held in Moncton, New Brunswick, 25-29 June 1990, ICES, Copenhagen (Denmark). ICES Marine Science Symposia 199. ICES, Copenhagen, Denmark.

Author Abstract. Changes in oyster reef size, organism density, and community organization can occur randomly or in relation to controlling biotic and abiotic factors. Non-random spatial discontinuities may be interpreted as ecologically important edges and could provide important insights into habitat quality, settlement, recruitment, competition, predation, and other ecological processes. In this study, vertical settlement tubes were deployed along an estuarine transect to document variable invertebrate recruitment to intertidal oyster reef communities. A Squared Euclidean Distance algorithm with a moving window filter was utilized to identify discontinuities in community recruitment. The sampling and analytical approaches provided useful insights into recruitment patterns which could be related to intra-estuarine physical and chemical variability. These and related techniques can likely be used to address regional and estuary-wide shellfisheries-related problems.

Oregon Watershed Enhancement Board. 1999. Oregon Aquatic Habitat: Restoration and Enhancement Guide. Contact information: 775 Summer street, suite 360, Salem Oregon, 97301, Phone # (503) 986-0178. http://www.oweb.state.or.us/publications/habguide99.shtml

This guide was developed to provide guidance on restoration and enhancement measures that would assist in aquatic ecosystem recovery. The guide is divided into five sections: An overview of Restoration activities, activity guidelines, overview of agency regulatory functions and sources of assistance, grants and assistance, and monitoring and reporting. The purpose of this document is to provide information that will assist in developing effective restoration projects; to define standards and priorities that will be approve by state and receive funding or authorized restoration projects; to identify state and federal regulatory requirements and receive assistance in restoration projects. Additional information on monitoring techniques for salmonid restoration and guidelines and considerations for reporting restoration progress over time are described within the document.

Paynter, K. T. Jr. 2001. Oyster restoration in Maryland: Results from Choptank and Patuxent River experiments, p. 519. Aquaculture 2001: Book of Abstracts, World Aquaculture Society, 143 J.M Parker Coliseum Louisiana State University, Baton Rouge, LA.

Author Abstract. In 1997, this study was conducted in which oysters were planted in the Choptank and Patuxent rivers in Maryland as the initiation of a large scale oyster restoration effort undertaken by the Army Corps of Engineers and the Maryland Department of Natural Resources. Three plots of approximately 1/2 acre in area were prepared by placing fossil shell on the bottom. Two of the three plots were created as flat, rectangular shells beds while the third was constructed as a large mound approximately 10 m in diameter and about 2 m high. Five sites of three plots each were constructed in each river sited from the mouth upstream to the low salinity. In the Choptank, seed was produced from Louisiana brood-stock and in the Patuxent, seed was produced from larvae purchased from Oregon. In 1998, *Perkinsus marinus* prevalence was low throughout the Maryland portion of Chesapeake Bay. In the Patuxent, oyster growth was poor and mortalities were very high due to parasitic activity. However, in the Choptank most stocks planted from the hatchery remained uninfected while natural transplants and local populations acquired significant levels of the disease. Growth and condition index remained vigorous in the planted oysters while the health of natural local populations declined. Researchers concluded that these experiments provide evidence that disease levels may be managed in lower salinity regions like in the central and northern parts of the Maryland's portion of the Chesapeake Bay.

Raposa, K. B. and C. T. Roman. 2001. Monitoring nekton in shallow estuarine habitats. A Protocol for the Long Term Monitoring Program at Cape Cod National Seashore. 39 pp. Narragansett Bay National Estuarine Research Reserve Prudence Island, RI and National Park Service, Graduate School of Oceanography, University of Rhode Island, Narragansett, RI 02882. 39 pp. Contact information: Kenny@gso.uri.edu. http://www.nature.nps.gov/im/monitor/protocoldb.cfm

Author Abstract. Long term monitoring of estuarine nekton has many practical and ecological benefits but efforts are hampered by a lack of standardized sampling procedures. This study develops a protocol for monitoring nekton in shallow (<1m) estuarine habitats for use in the Long Term Coastal Monitoring Program at Cape Cod National Seashore. Sampling in seagrass and salt marsh habitats is emphasized due to the susceptibility of each habitat to anthropogenic stress and to the abundant and rich nekton assemblages that each habitat supports. Extensive sampling with quantitative enclosure traps that estimate nekton density is suggested. These gears have a high capture efficiency in most habitats and are small enough (typically $1m^2$) to permit sampling in specific microhabitats. Other aspects of nekton monitoring are discussed, including seasonal sampling considerations, sample allocation, station selection, sample size estimation, parameter selection, and associated environmental data sampling. Developing and initiating long term nekton monitoring programs will help track natural and human-induced changes in estuarine nekton over time and advance our understanding of the interactions between nekton and the dynamic estuarine environments.

Soniat, T. M., E. N. Powell, E. E. Hofmann and J .M. Klinck. 1998. Understanding the success and failure of oyster populations: The importance of sampled variables and sample timing. *Journal of Shellfish Research* 17: 1149-1165.

Author Abstract. One of the primary obstacles to understanding why some oyster populations are successful and others are not is the complex interaction of environmental variables with oyster physiology and with such population variables as the rates of recruitment and juvenile mortality. A numerical model is useful in investigating how population structure originates out of this complexity. We have monitored a suite of environmental conditions over an environmental gradient to document the importance of short time-scale variations in such variables as food supply, turbidity, and salinity. Then, using a coupled oyster disease population dynamics model, we examine the need for short time-scale monitoring. We evaluate the usefulness of several measures of food supply by comparing field observations and model simulations. Finally, we evaluate the ability of a model to reproduce field observations that derive from a complex interplay of environmental variables and address the problem of the time-history of populations. Our results stress the need to evaluate the complex interactions of environmental variables with a numerical model and, conversely, the need to evaluate the success of modeling against field observations of the results of complex processes. Model simulations of oyster populations only approached field observations when the environmental variables were measured weekly, rather than monthly. Oyster food supply was estimated from measures of total particulate organic matter, phytoplankton biomass estimated from chlorophyll a, and total labile organic matter estimated from a regression between chlorophyll a and total labile carbohydrate, lipid, and protein. Only the third measure provided simulations comparable to field observations. Model simulations also only approached field observations when a multiyear time series was used. The simulations show that the most recent year exerts the strongest influence on oyster population attributes, but that the longer time-history modulates the effect. The results emphasize that year-to-year changes in environment contribute substantially to observed population attributes and that multiyear environmental time series are important in describing the time-history of relatively long- lived species.

Trippel, E. A. 2001. Marine Biodiversity Monitoring: Protocol for Monitoring of Fish Communities. A Report by the Marine Biodiversity Monitoring Committee (Atlantic Maritime Ecological Science Cooperative, Huntsman Marine Science Centre) to the Ecological Monitoring and Assessment Network of Environment Canada. http://www.eman-rese.ca/eman/ecotools/protocols/marine/fishes/intro.html#Rationale

This document presents a monitoring protocol for estimating species diversity of bottom dwelling or demersal fish species inhabiting the Canadian continental shelf regions. Monitoring protocols presented in this document can be used to monitor and evaluate fish communities in regions other than the Canadian continental shelf. Methods used to estimate the abundance of different demersal fish species include random stratified sampling and fixed station sampling. Using these standardized procedures helps to maintain precision. Some factors taken into consideration when monitoring fish communities include depth, temperature, salinity, seasonal shifts and diurnal behavior patterns. Additional information found in this document includes size of area and sampling intensity, sampling gear, sampling procedures, and treatment of data.

U.S. EPA. 1992. Monitoring Guidance for the National Estuary Program. United States Environmental Protection Agency, Office of Water, Office of Wetlands, Washington D.C. EPA Report 842-B-92-004.

This document provides guidance on the design, implementation, and evaluation of the required monitoring programs. It also identifies steps to be taken when developing and implementing estuarine monitoring programs and provides technical basis for discussions on the development of monitoring program objectives, the selection of monitoring program components, and the allocation of sampling effort.

Some of the criteria listed for developing a monitoring program and described in this document include: monitoring program objectives, performance criteria, establish testable hypotheses, selection of statistical methods, alternative sampling designs, use of existing monitoring programs, and evaluate monitoring program performance. Additional information on guidelines for developing a monitoring program is described in this document.

U.S. EPA. 1993. Volunteer Estuary Monitoring. In R. L. Ohrel, Jr., and K. M. Register (eds.), A Methods Manual. U.S. Environmental Protection Agency, Washington, D.C., Office of Water. EPA Report- 842-B-93-004. http://www.epa.gov/owow/estuaries/monitor/

This document presents information and methodologies specific to estuarine water quality. Information presented in the first eight chapters include: understanding estuaries and what makes them unique; impacts to estuarine habitats and human's role in solving the problems; guidance on how to establish and maintain a volunteer monitoring program; guidance for working with volunteers and ensuring that they are well-positioned to collect water quality data safely and effectively; ensuring that the program consistently produces high quality data; and managing the data and making it readily available to data users. Also presented are water quality measures that determine the condition of the estuary: physical (e.g., substrate texture), chemical (e.g., dissolved oxygen) and biological parameters (e.g., plant and animal presence and abundance). The importance of each parameter and methods used to monitor the conditions are described in a gradual process. Proper quality assurance and quality control techniques must also be described in detail to ensure that the data are beneficial to state agencies and other data users.

University of Florida IFAS-Indian River Research and Education Center and South Florida Water Management District. Restoration of the Eastern Oyster, *Crassostrea virginica*, in the St. Lucie Estuary, Contact information: Liberta Scotto, lscotto@gnv.ifas.ufl.edu. http://www.irrec.ifas.ufl.edu/oyster/oysterstory.htm

Two oyster reefs from each of the North and South Forks and the Mid-Estuary of the St. Lucie Estuary (SLE) were monitored to assess their condition. Methods used include: (1) recruitment with various types of "spat" (newly settled oysters) collectors that were placed in the water at oyster reefs sites selected. The collectors were then replaced during the study year and evaluated for spat presence; (2) use of condition index which assessed the oysters physiological condition or overall health; (3) water quality measurements such as temperature, pH, dissolved oxygen, and salinity which were done weekly at replicate sites at each of the oyster reefs in order to relate oyster health to water quality; (4) reproductive potential in which oysters from the Mid-Estuary and the North Fork were collected monthly to evaluate the gonadal state and reproductive potential at different salinity regimes. Histological and image analysis was used to estimate reproductive potential; and (5) *Perkinsus marinus* presence, a protozoan parasite was assessed. Oysters were collected monthly and rated on a Mackin scale for Dermo infection which ranged from 0 (no infection) to 6 (heavy infection). Parameters used in this study to assess oyster health proved effective and contributed to successful restoration of oyster communities by approximately 45%. Additional information on this study can be obtained from the source mentioned above.

Virginia Institute of Marine Sciences (VIMS). 1994. Monitoring Programs for Oyster Beds. Virginia Institute of Marine Science, Gloucester Point, VA. Contact information: Dr. Roger Mann, Dept. of Fisheries Science, Virginia Institute of Marine Science, Virginia U.S.A. http://www.vims.edu/mollusc/monrestoration/monoyster.htm#modern

Data was collected by the VIMS Spatfall Survey and the VIMS Dredge Survey oyster bed health in Virginia waters. The VIMS Spatfall Survey deployed shell strings weekly from May through September at stations throughout the Chesapeake Bay to provide an annual index of oyster settlement and recruitment. Shell strings were suspended 0.5 m from the bottom to provide settlement substrate for oyster veligers. After retrieval, oyster spat (recently settled oysters) on the undersides of 10 shells were counted under a dissecting microscope. The average number of spat per shell was calculated for each time and place.

The VIMS Dredge Survey monitored the status of Virginia's public oyster fishery, comprising over 243,000 acres. Oyster bars were sampled annually and dredge was used to assess trends in oyster growth, mortality, and recruitment. Three samples of bottom material were dredged at each location. Half-bushel aliquots (25 quarts) were taken from each sample for processing. The number of spat, small, and market oysters were counted. Averages counts per bushel of bottom material were calculated for comparisons between areas over periods of time. Patent Tong survey was performed in 1993 to provide quantitative estimates of oyster standing stock in Virginia tributaries. At each station patent tong samples were taken of one square meter of bottom. All of the oysters from each sample were examined. The surveys provided data that support management and restoration of Virginia's oyster resource.

Wenner, E. L. and M. Geist. 2001. The National Estuarine Research Reserves Program to Monitor and Preserve Estuarine Waters. *Coastal Management* 29:1-17.

The National Estuarine Research Reserve (NERR) sites in 1992 coordinated a program that would attempt to identify and track short-term variability and long-term changes in representative estuarine ecosystems and coastal watersheds. Water quality parameters that were monitored include: pH, conductivity, temperature, dissolved oxygen, turbidity, and water level. Standardized protocols were also used at each site so that sampling, processing, and data management techniques were consistent among sites. Statistical techniques are being used to identify periodicity in water quality variables. Periodic regression analysis indicated that diel periodicity in dissolved oxygen is a larger source of variation than tidal periodicity at sites with less tidal amplitude. Authors of this document stress how understanding the functions of estuaries and how they change over time will help predict how these systems respond to change in climate and anthropogenic sources.

Wenner, E., H. R. Beatty and L. Coen. 1996. A method for quantitatively sampling nekton on intertidal oyster reefs. *Journal of Shellfish Research* 15: 769-775.

Author Abstract. We developed a sampling methodology using a 24 m^{-2} super(2) lift net to quantitatively sample intertidal oyster (*Crassostrea virginica*) reefs as a part of a long-term study of their functional ecology. This method can also be used in restoration monitoring of oyster reefs to evaluate reef functionality. The method involved surrounding an area of oyster reef with a buried net at low tide, allowing the water level to rise, raising the net at high tide to trap motile organisms, allowing the water to recede, and collecting the entrapped nekton. Natural and artificially constructed reefs were sampled, monitored and efficiency (mark-recapture) studies were performed to evaluate the method. The advantages of this method are: (1) the habitat in the area to be sampled receives minimal damage; (2) the size and shape of the net system are flexible and can be adapted to fit a variety of habitats; (3) no permanent structures, other than a shallow perimeter trench, are present to act as attractants; and (4) it is relatively inexpensive to purchase and maintain gear. One disadvantage to the method is that it is very labor intensive, typically using three to five people. This method proved more efficient on natural reefs than artificial reefs, and the return rate was slightly better for *Fundulus heteroclitus* than for *Palaemonetes spp.* Seventeen decapod and 24 fish taxa were collected from initial spring, summer, and fall 1995 sampling.

APPENDIX III: LIST OF OYSTER REEF EXPERTS

The experts listed below have provided their contact information so practitioners may contact them with questions pertaining to the restoration or restoration monitoring of this habitat. Contact information is up-to-date as of the printing of this volume. The list below includes only those experts who were 1) contacted by the authors and 2) agreed to submit their contact information. Some of those listed also reviewed the associated habitat chapter. In addition to these resources, practitioners are encouraged to seek out the advice of local experts as well faculty members and researchers at colleges and universities. Engineering, planning, and landscape architecture firms also have experts on staff or contract out the services of botanists, biologists, ecologists, and other experts whose skills are needed in restoration monitoring. These people are in the business of providing assistance in restoration and restoration monitoring and are often extremely knowledgeable in local habitats and how to implement projects on the ground. Finally local, state, and Federal environmental agencies also house many experts who monitor and manage coastal habitats. In addition to the National Oceanic and Atmospheric Administration (NOAA), the Environmental Protection Agency (EPA), the Army Corps of Engineers (ACE), Fish and Wildlife Service (FWS), and the United States Geologic Survey (USGS) are important Federal agencies to contact for assistance in designing restoration and monitoring projects as well as potential sources of funding and permits to conduct work in coastal waterways.

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