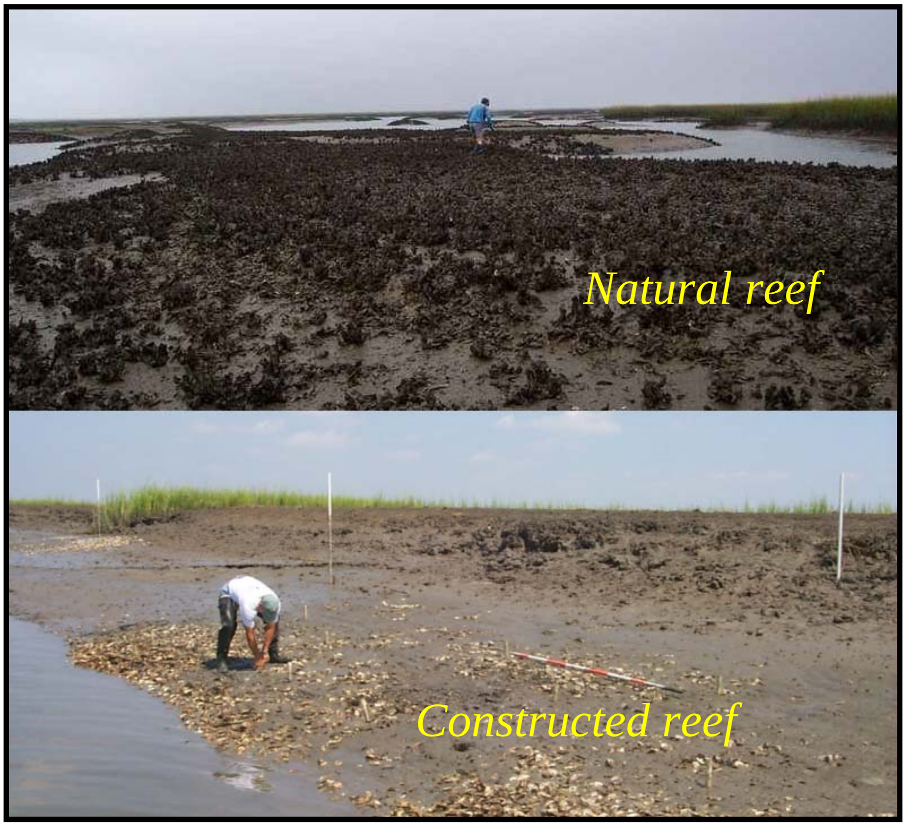
A South Carolina Sea Grant Report of

A 2004 Workshop to Examine and Evaluate Oyster Restoration Metrics to Assess Ecological Function, Sustainability and Success: Results and Related Information



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Oyster Reef Restoration: Learning from Combined Experiences

The decline of the Eastern oyster, *Crassostrea virginica*, once a dominant feature of most Atlantic and Gulf coast estuaries, has led to large- and small-scale restoration efforts throughout the oyster's range (Kirby 2004, National Research Council 2004). Successes and failures in reef restoration have varied throughout the region. Understanding why different restoration projects succeed or fail is critical to the future optimal use of limited resources (e.g., shells, manpower) and the deployment of cost-effective, successful reef restoration projects. Communicating the results of ongoing oyster reef construction and assessment efforts also is vital (Coen and Luckenbach 2000). Leading oyster reef restoration practitioners from throughout the Gulf of Mexico and eastern U.S. coastal states met to discuss restoration goals, site selection parameters, metrics to assess success, and associated monitoring methods at a South Carolina Sea Grant sponsored workshop held in Myrtle Beach in May, 2004. This document summarizes the results of that workshop, providing a concise and non-technical explanation of the current state of knowledge regarding the why, where, what, and how of oyster reef restoration. We also expand on the workshop results to include information and approaches developed since 2004.

Restoration Project Goals

Workshop participants identified six major goals of oyster reef restoration projects: habitat creation, shoreline stabilization, water quality improvement, harvesting enrichment, broodstock enhancement, and educational outreach. Any restoration project can include one or more of these goals.

Habitat creation: Oyster reefs provide habitat for fish and invertebrates (e.g., crabs and shrimps) that require structural complexity for foraging, nesting and refuge from predators (reviewed in ASMFC 2007). Fish associated with oyster reefs range from residents that use the reef as a primary habitat to transient species that are wide ranging and may forage on or near the reef (Breitburg 1999, Coen et al. 1999b, ASMFC 2007). Some fish species, such as oyster toad fish, gobies, and blennies, attach eggs to the undersides of oyster shells, relying on reef architecture or microhabitat for reproductive success. Crabs commonly are found in greater densities on oyster reefs than on surrounding open-bottom habitat where vulnerability to predation is greater and prey resources are less abundant (Glancy et al. 2003, Grabowski 2004, Tolley and Volety 2005, Hosack et al. 2006). Bivalves including clams and mussels also may utilize reefs as a refuge from predators (e.g., Grabowski 2002, 2004) enabling populations within reefs to act as a source for mudflat and marsh populations that may be depleted more easily by predators.

Shoreline stabilization: Oyster reefs are hard structures on typically unconsolidated or mobile bottom sediments that can extend above the sediment surface in subtidal areas or fringe marshes in the low intertidal zone (Luckenbach et al. 1999, ASMFC 2007). In subtidal systems, reefs provide vertical relief in otherwise featureless benthic environments that can reduce fetch and the wind-driven resuspension of particulate matter (Lenihan 1999, Luckenbach et al. 1999). Oyster reefs near salt marshes absorb wave energy and promote colonization and persistence of the salt marsh habitat (Meyer et al. 1997). The reduction in sediment input from shoreline erosion and subtidal resuspension can increase light penetration and promote growth of submerged aquatic vegetation (SAV) or benthic microalgae that further stabilize unconsolidated sediments. Restored reefs can be placed near SAV and/or intertidal marshes to enhance the value of the vegetated habitat and control erosion (e.g., mediating boat wake effects that can cause marsh banks to erode into tidal creeks) (Newell and Koch 2004, Piazza et al. 2005).

Water quality improvement: Filter feeding bivalves can affect significantly water quality and phytoplankton dynamics (Frechette et al. 1989, Dame 1996). Extensive oyster populations have a substantial filtering capacity and may remove significant phytoplankton biomass from the water column (Cressman et al. 2003, Nelson et al. 2004). The result is a reduction in the biological oxygen demand from the microbial decomposition of algal cells that otherwise would settle to the sediment (Dame 1996). Bivalve filtration may have improved the water quality in several basin-wide ecosystems (Gerritsen et al. 1994, Dame 1996, Newell 2004), but bivalve control of phytoplankton has been questioned (Pomeroy et al. 2006). Ecosystem rehabilitation typically relies on a reduction of nutrient inputs (e.g., nitrogen, phosphorus) that result in eutrophication, but filter feeding bivalves such as oysters may be equally important for improving water clarity and quality by removing algae and sediments suspended in the water column.

Harvesting enrichment: Fisheries enhancement often is the goal of many restoration projects, especially in states experiencing a decline in the oyster fishery. Economic incentives to maintain an oyster fishery remain even in states with drastically reduced yields. Oyster reef restoration often is undertaken to create marketable-size oysters that are available to both recreational and commercial harvesters. An unanticipated conflict to creating reefs for harvesting is the frequent observation that harvesting can affect negatively the ecological success of the reef (e.g., breaking up clusters to retrieve marketable oysters) (Lenihan and Peterson 2004).

Brood stock enhancement: Creating oyster reefs in refuge areas where oyster harvesting is not allowed can protect brood stock and larger individuals with disease resistance. Creation of oyster reefs off limits to harvesting can enhance oyster populations in surrounding harvested areas that are many times the size of the refuge itself (Breitburg et al. 2000). Off limit reefs provide protection for larger individuals that have the greatest fecundity and some resistance to disease potentially increasing the fitness and survival of recruits to the harvestable population (Coen and Luckenbach 2000). Oyster reef sanctuaries develop into mature and structurally complex habitats with many associated benefits for fish and decapod crustaceans (Coen et al. 1999b, ASMFC 2007).

Educational outreach: Community-based restoration projects provide educational benefits through programs that foster a more scientifically and environmentally informed public (Brumbaugh 2006a and 2006b). In some areas, coastal residents of all ages become involved in the construction and monitoring of local reefs (e.g., SCORE, http://score.dnr.sc.gov/). Waterfront property owners are informed about the ecological benefits of filter feeding bivalves to water quality and overall coastal ecosystem health. Small scale reef restoration projects may be implemented successfully with private citizen involvement.

Site Selection Parameters

Researchers involved in oyster reef restoration efforts listed factors considered when deciding where to construct reefs (Table1). Site selection parameters were ranked by each investigator and individual ranks were summarized for the final listing in

Table 1. A summary of individual researcher (n = 25) ranked site selection parameters.		
Physical Parameters		
Subtidal	**Rank**	**Intertidal**
Reef Depth	1	Primary Substrate
Primary Substrate	2	Average Salinity
Substrate Firmness	3	Substrate Firmness
Water Quality	4	Siltation/Sedimentation
Average Salinity	5	Height Relative to MLW
Elevation off Bottom	6	Water Quality
Siltation/Sedimentation	7	Runoff
Flow Rate	8	Flow Rate
Reef Orientation	9	Bank Slope
Channel Depth (lowest tide)	10	Width of Intertidal Zone
Runoff	11	Erosion Potential
Erosion Potential	12	Fetch
Fetch (wind exposure)	13	Channel Width and Depth
Width of Intertidal Zone	14	Reef Orientation
Biological Parameters		
Disease	1	Typical Recruitment
Typical Recruitment	2	Disease
Predation	3	Fouling Communities
Proximity to Oysters	4	Food Quantity and Quality
Food Quantity and Quality	5	Predation
Fouling Communities	6	Proximity to Oysters

Table 1. Some researchers recommend establishing restored reefs in areas where oyster populations existed historically. However, changes in current patterns, dissolved oxygen, etc. may enable establishing reefs in areas previously unoccupied. Historical reef locations typically can be determined from navigation charts, bottom surveys, or published fishing records. Additionally, a number of models have been developed to predict feasible site locations for oyster reef establishment (Cake 1983, Soniat and Brody 1988). Descriptions of selected physical and biological site parameters are provided separately, where appropriate, for subtidal and intertidal habitats.

Selected Physical Parameters

Proximity to oysters: A ready supply of oyster larvae is critical for the survival and development of restored reefs. Broadcast breeders, oysters will dispense millions of larvae into the water column to be carried by local currents until an appropriate settlement site is located. Where living oysters occur, larval oysters typically will settle gregariously onto hard substrata within the same general area. Settlement behavior may be mediated chemically (Crisp 1967, Turner et al. 1994, Zimmer-Faust and Tamburri 1994). Restored reefs established within the natural circulation pattern of existing reefs can provide needed larval recruits to the restored site (Southworth and Mann 1988).

Reef depth: Shallow (1-5 m) and sufficiently elevated subtidal reefs experience less stress from hypoxic conditions and greater resistance to diseases such as *Perkinsus marinus* or Dermo (e.g., Lenihan and Peterson 1998).

Subtidal oyster reefs commonly occur less than five meters below the water surface. Oysters on intertidal reefs can incur unique physiological challenges exposed to high summer and low winter temperatures (e.g., Bahr and Lanier 1981).

Primary substrate: When selecting a substrate type on which to build oyster reefs, most workshop participants indicated shell followed by sand were preferred. Substrates consisting of greater silt/clay percentages were avoided if possible. Sedimentation, siltation, and burial were considered a problem for most reef restoration efforts, and initial selection of a site with firm substrates important for minimizing the probability of future reef burial (e.g., Soniat and Brody 1988).

Water quality

***Dissolved oxygen*:** Reduced levels of dissolved oxygen, DO (< 2 mg L^{-1}), cause mortality in oysters and the more sedentary reef-associated organisms including amphipods, shrimps, and small crabs (Breitburg 1992, Lenihan and Peterson 1998, Lenihan et al. 1999). Hypoxia (< 4 mg L^{-1}) will result in fish moving off of reefs to more oxygenated water (Breitburg 1992). DO may vary with tides and time of day.

***Salinity*:** Low salinities may reduce the negative effects of disease and predation. The oyster pathogens, *P. marinus* and *Haplosporidium nelsoni* (=MSX) are intolerant of salinities <10 ppt (Ford and Tripp 1996). Restoration sites located in close proximity to freshwater inflows can affect potential oyster predators and other reef-associated species (e.g., Wells 1961, Tolley et al. 2005). The possible benefits of sites neighboring freshwater inflows may be counter-balanced by increased oyster mortality either directly via osmotic stress or indirectly from sedimentation (Wilber 1992, Livingston et al. 1999, La Peyre et al. 2003). Prolonged salinities <5 ppt can reduce oyster feeding, growth, reproduction, and availability of suitable substrata for larval settlement (Cake 1983). Negative effects on associated taxa also can reduce the habitat value of created reefs (e.g., Tolley et al. 2005, Tolley et al. in press).

Flow rate: Sites with greater current flow (Fig. 1) are associated with greater oyster survival and faster growth (Lenihan et al. 1996). Currents deliver food and remove silt and waste from the reef (Dame in press). Flows ranging from 156-260 cm/sec are

Figure 1. Methods for measuring flow rates around reefs. The SonTek instrument (above) provides instantaneous rates while the dissolution of dental plaster cylinders (below) can integrate flow rates over longer time periods (photos from L. Coen).

associated with enhanced growth (Sellers and Stanley 1984). Oysters reared in the lab under reduced (<4 cm/sec) flow rates have slower growth and greater mortality compared to oysters reared under increased (7-20 cm/sec) flow rates (Lenihan et al. 1996).

Elevation off bottom

***Subtidal vertical height*:** Constructing subtidal reefs with a reasonable vertical relief above the sediment surface can reduce negative effects of sedimentation and enhances local flow rates (Lenihan and Peterson 1998). The presence of tall oyster culms interspersed with low areas, often termed rugosity, also can enhance fish and decapod use of reef habitat (e.g., Coen and Luckenbach 2000, Tolley and Volety 2005). The minimum, suggested topography for subtidal reefs is 1 m (Lenihan and Peterson 1998), but a minimum has yet to be established for intertidal reefs.

Height relative to mean low water/width of intertidal zone: Intertidal oyster reef temperature ranges can vary dramatically when reefs are exposed during low tides (Coen et al. 1999a). Exposure can influence oyster reproductive periodicity, disease susceptibility, and responses to anthropogenic stress (Kennedy et al. 1996, Coen et al. 1999b). Intertidal placement of restored reef shell material relative to MLW will determine aerial exposure and the likelihood of survival. Intertidal oysters in the South Atlantic occur predominantly from just below the mean low water level to about 1 m above mean low water (Bahr and Lanier 1981, Stanley and Sellers 1986).

Siltation/sedimentation: In areas receiving high sediment loads oyster beds typically will experience burial. Sedimentary forces also shape the perimeter size and features of the reef. The risk of sedimentation is greater at the reef's lowest tidal elevation where water currents are slowest and particulate matter settles out of the water column (Lenihan 1999).

Selected Biological Parameters

Disease: Oyster disease (Fig. 2) usually refers to the presence of either *P. marinus* or *H. nelsoni*. Dermo has been reported to occur from the Gulf of Mexico to Maine and MSX from Florida to Maine (Ford and Tripp 1986, Bobo et al. 1997). Infection by these pathogens can induce mortality and reduce growth rates, thus areas in which disease prevalence is high may be avoided as potential restoration sites (Kennedy et al. 1995).

Typical recruitment: One or more years of oyster recruitment monitoring should precede any reef restoration work to ensure that the availability of oyster recruits to the selected site is sufficient (e.g., Coen and Luckenbach 2000). Circulation patterns should be

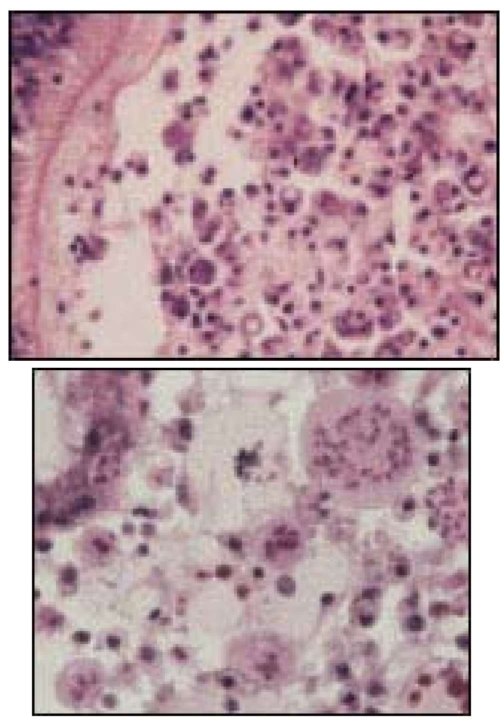

Figure 2. Histological sections of oyster tissue infected with Dermo (above) and MSX (below) (photos from VIMS).

examined during the summer spawning season when planktonic larvae are available for recruitment (e.g., Southworth and Mann 1998).

Food quantity and quality: Oysters filter phytoplankton, resuspended benthic diatoms and other organic particles from the water column (Kennedy et al. 1996). An adequate food supply is necessary for oyster growth and survival. The measurement of water column chlorophyll *a* concentrations (Fig. 3) can be used to assess both the availability of adequate food and the potential filtering effects of reefs (Judge et al. 1993, Dame 1996, Grizzle et al. 2006). Concentrations >30 mg m^{-3} are reported as suitable for rapid oyster growth (Battista 1999). Studies on the ability of reefs to remove measurable phytoplankton amounts from the water column are being conducted as one possible method for evaluating oyster reef restoration success (see below).

Predation: Various predators can have a significant effect on both oysters and reef-associated taxa (Fig. 4). Typical predatory taxa can include starfish, gastropods, and

Figure 3. Manifold used as part of a field instrument designed to measure *in situ* changes in chlorophyll *a* concentrations (photos from L. Coen).

Figure 4. Mussel shell damage examples (above) inflicted by mud crabs (below) in a SC intertidal oyster reef. Crabs can consume >50% of the mussels <40 mm in length in less than 2 weeks (photos from K. Walters).

flatworms in more brackish waters (White and Wilson 1996, Newell et al. 2000). Numerous predators that typically live in higher salinity environments (e.g., oyster drills) are likely to have limited effects on reefs in areas with frequent low salinities. In the Southeastern US, mud (*Panopeus herbstii*) and blue crabs (*Calinectes sapidus*) can cause significant mortality on both oyster and reef-associated fauna (Bisker and Costagna 1987, Meyer 1994, Grabowski 2004, Sonnier 2006).

Larval settlement/recruitment: Deployment of settlement plates, shell strings, vertical tubes, and containers with various materials can be used to indicate larval supply, including oysters, which could colonize cultch material placed on the sediment during the initial stage of a restoration projects (Bartol and Mann 1997, Luckenbach et al. 1999, Brumbaugh 2000). Barnacles, tunicates, and other bivalves such as mussels may attach to oyster shell and limit space available for settlement of oyster larvae (Luckenbach et al. 2005).

Reef Restoration Success Metrics and Associated Methods

Workshop participants matched reef restoration goals identified above with relevant success metrics (Table 2). The selection of specific metrics and methods was based on the ability to measure and easily obtain results in both intertidal and subtidal habitats. Any restoration project should select the most appropriate metrics and methods based on identified project goals and specific site characteristics.

Monitoring restoration projects can provide information on reef development and also may identify reefs that do not satisfy specific restoration goals as possible targets for future adaptive management. For example, monitoring may indicate a site has insufficient larval supply, in which case brood stock enhancement may help establish the reef. Monitoring also may indicate the loss of original shell substrate for larvae to settle on either through physical (e.g., wave action, sedimentation) or biological processes (e.g., boring sponges, competition for settlement space) necessitating the addition of new shell material periodically until the reef becomes established.

Table 2. Metrics associated with each of the major oyster reef restoration goals.

	OYSTER REEF RESTORATION GOAL					
Metric	**Habitat**	**Shoreline**	**WQ**	**Harvesting**	**Broodstock**	**Education**
Reef Condition						
Density	X	X	X	X	X	X
Size Frequency	X	X	X	X	X	?
Associated Fauna	X		X			X
Reef Size	X	X	X	X	X	
Reef Architecture	X	X	?	X		X
Landscape						
Fragmentation	X	X	?	X	X	
Salinity	X		X	X	X	X
DO	X sub		X	X	X	X
Chl			X			
TSS/Turbidity			X			X
Temperature	X		X		X	

Density: Oyster density, or the number of live oysters per unit area (usually adjusted to per m^2), is a common metric measured to assess reef restoration success. Density can be measured by excavating a sample of known dimensions to a specific depth (e.g., 10-15 cm) using either a quadrat or a core and then counting all the live and/or dead oysters (Fig. 5). Samples can be collected from different reef elevations including the reef crest, slope and base to better understand the spatial variation in oyster abundance. Density can be estimated on subtidal reefs using videography or calibrated dredge samples. Additional data including size frequency distributions and survival rates also can be collected from density samples.

Figure 5. Examples of quadrat sampled to a known depth (above) and oyster shell length (below) measured using digital calipers (photos from D. Meyer and L. Coen).

Size Frequency: The size frequency distribution of an oyster population is determined by measuring the shell height of each individual oyster within a collected sample - usually the same sample used to determine oyster density (Fig. 5)). Additional dimensions can be measured to account for irregular oyster shapes (e.g., SC oysters can be very long and thin). A digital caliper system enables more than one investigator to collect measurements simultaneously as data are relayed to a database or spreadsheet for later analysis (Coen pers. comm.). The individual height measurements (±1.0 mm) are then grouped into size classes and can be used to estimate size (age) class changes over time.

Associated Oyster Reef Fauna: Oyster reef-associated fauna include both resident (Fig. 6) and transient species (Fig. 7) that are sampled by different methods.

Residents Species: Residents typically include decapods, molluscs, and infaunal organisms that can be sampled by

Figure 6. Examples of sampling tray full of oyster shell (top) to be planted within a reef, sieving and collecting fauna from a sampled quadrat (middle), and organisms retrieved from a sample (bottom) (photos from M. Luckenbach and P. Ross).

excavating quadrats, implanting sampling trays or using small lift nets in the reef matrix (Wells 1961, Coen et al. 1999b, Glancy et al. 2003, Grabowski 2004, Tolley et al. 2005, Rodney and Paytner 2006). Collected organisms are then separated from shell and mud on a 1.0 or 0.5 mm mesh sieve, identified to species or lowest possible taxonomic level and counted (Coen et al. in press). Biomass or wet mass of numerically abundant residents (e.g., *Geukensia demissa*) or of speciose smaller invertebrates difficult to identify (e.g., polychaetes, amphipods) often are measured as an alternative to enumerating all individuals (Luckenbach et al. 2005). The sampling of resident species is one of the most time consuming metrics to be collected from reefs requiring both the technical expertise to identify individuals to species and the time to process what are often large numbers of individuals. Data from resident taxa were viewed uniformly by workshop participants as one of the most valuable to collect to address the wider ecological questions associated with oyster reefs.

Figure 7. Sampling technique examples for transient species: lift-net (above) sampling in progress (photo from L. Coen); Breder trap (middle) to sample reef fishes (photo from M. Posey and T. Alphin); small (1 m^2) lift net (below) sampled on ebbing tide (photo from A. Volety and G. Tolley).

***Transients Species*:** Transient species are individuals that move onto and off of reefs usually over a predictable time interval (e.g., 6 h for intertidal reefs). Many transient species utilize reefs as a source of food (e.g., blue crabs) or shelter (e.g., gobies). The transient fish and crustacea are sampled with a variety of techniques including lift nets, drop nets, seines, minnow traps, Breder traps, crab traps, shell trays, gill nets, throw traps, trawls, diver observations, and videography (Zimmerman et al. 1989, Winer et al. 1996, ASMFC 2007, Coen et al. 1999a, 1999b, Posey et al. 1999, Lehnert and Allen 2002, Nestlerode 2004). In circumstances where reefs are located within spatially distinct tidal creeks the entire creek may be block-netted in order to sample transient species (Allen et al. 2007). Sampling is the most problematic aspect of determining transient species numbers. Many netting techniques induce species escape behaviors and suffer from the haphazard loss of individuals. Lift nets also are impractical for subtidal reefs in depths greater that 1-2 m. The use of traps can provide information on the relative abundance of selective taxa, especially when many sites simultaneously are sampled. However, trap data should be interpreted with care as there are situations when biases make even relative comparisons among reefs difficult. Perhaps the most efficient collection method in intertidal systems is the lift net, deployed surrounding the reef and lying on the sediment until drawn over the reef at high tide, but the labor required and long wait periods - set-up at low tide, pulled up at high tide, sampled the next successive low tide - makes any study using lift nets a challenge (Wenner et al. 1996, Meyer and Townsend 2000). Irregardless of the difficulties, transient species data can provide a unique ecosystem and/or landscape scale perspective highlighting the additional value of oyster reefs.

Reef Size: Increased reef area is important for oyster production and associated faunal diversity and can create a buffer against physical disturbances. Typically, reef size is measured as the total footprint of the reef (m^2) and may include an estimate of the percent cover of oysters (Fig. 8). The perimeter of intertidal reefs can be measured by walking the edge of the reef with surveying equipment. Indirect and direct methods for mapping subtidal reefs include digital side-scan sonar, towed video and diver sampled quadrats (Grizzle et al. 2005, 2007). Images can be processed to determine bottom types and the percent coverage of oyster clusters and shells. Data can be integrated into a Geographical Information System (GIS) and changes followed over time (Jefferson et al. 1991, Smith et al. 2001).

Figure 8. Intertidal reefs can be delineated using GPS survey system (e.g., Trimble) (top). Surveys can measure changes in reef size over time (middle and bottom) (photos from L. Coen).

Reef Architecture: The architecture of a reef includes materials used for construction that also may consist of one component as a base and another as veneer on top, the size (footprint), height (relative to the bottom), shape (circumference vs. area), slope (bank slope for intertidal), percent coverage of live oyster, available edge (Fig. 9), and surface rugosity or roughness (Bartol and Mann 1997, Bartol et al. 1999, Lenihan 1999, O'Beirn et al. 2000). An important habitat component of reef architecture is the amount of interstitial space, which is the area in between shells that serves as refuge and nesting sites for associated fauna (Bartol and Mann 1997, Coen et al. 1999b, Coen and Luckenbach 2000). Reefs with greater vertical relief can reduce the negative effects of spatial-temporal

Figure 9. Examples of constructed reefs with reduced (above) and increased (below) edge or architecture (photos from L. Coen).

variability that determines spat set and adult survival (Lenihan and Peterson 1998, Lenihan 1999). Vertical relief also can ameliorate the negative effects of near bottom hypoxic and sedimentation events and increase oyster growth and survival.

Landscape Fragmentation: Reefs may be fragmented in space existing as one large or several small reefs (Fig. 10). Similar to reef architecture, where oyster growth and habitat use by transient and resident species may differ based on the amount of edge available (see above), the natural function of reefs may be dependent on landscape-scale patterns and the ability of species to move among a suite of reefs. Restored reefs can be designed to maximize the landscape-scale footprint for a given volume of shell or substrate material, but little is know about the importance of habitat fragmentation to the dynamics of reef systems.

Water Quality Parameters

Salinity, DO, Temperature: Continuous information on water quality can be

Figure 10. Examples of different reef landscapes for the same amount of shell (photos from M. Posey and T. Alphin).

obtained by deploying automated instrument packages (e.g., YSI, Hydrolab) near restoration sites. An alternative method is the use of field kits for water quality monitoring that can be used by research personnel or community volunteers. Salinity commonly is measured using a handheld refractometer where a few drops of seawater are placed on the instrument's glass stage and the salinity read through an eyepiece (Fig. 11). Inexpensive methods for measuring DO include colorimetric determination (Fig. 11), dissolved oxygen meter and a fiber optic oxygen sensor.

***TSS/Turbidity*:** The amount of suspended material in the water column may indicate potential siltation problems and/or food availability (phytoplankton). Turbidity readings measure the transmission of light through water that is limited by the presence of suspended matter including plankton, sand, silt, and clay. Perhaps the simplest method for determining turbidity is with a secchi disc (Fig. 11). The alternating black and white quadrants on the disk are lowered into the water until no longer visible and the depth of visible light penetration recorded. Greater secchi disc depths indicate greater water clarity and less suspended material. Turbidity also can be measured in the field using a turbidity tube (Fig. 11). In the laboratory, total suspended sediments (TSS) can be measured using a variety of gravimetric approaches including filtration and differential weighing. Additional approaches including a turbidimeter that passes a beam of light through the sample and measures the quantity of light scattered by particulate matter can be used to measure suspended sediments. Turbidity measurements can be reported as mg/L, Nephelometer Turbidity Units (NTUs) or Jackson Turbidity Units (JTUs).

Figure 11. Examples using a refractometer for salinity determination (top), colorimetric DO reading (middle), secchi disk for water clarity (bottom left), and TSS sample collection (bottom right) (photos from L. Coen and SCORE).

Novel Reef Restoration Success Metrics and Associated Methods

A number of novel methodologies for assessing oyster reef restoration success were presented and discussed at the workshop.

Oyster Disease: Measuring the presence, prevalence and intensity the diseases Dermo and MSX can help discern causes of mortality and provide information on disease tolerant populations (Ford and Tripp 1996, Bobo et al. 1997, Burreson and Ford 2004, Lafferty et al. 2004). Oysters (20-25/sample) are collected and examined for the presence and concentration of pathogens (Fig. 12). Sampling fewer oysters typically does not provide enough information to differentiate differences among sites and the variability in disease prevalence easily may obscure even seasonal patterns. To assess seasonal trends samples need to be collected at least 4 – 6 times per year. As new diseases are detected additional sampling may be required to evaluate impacts on oyster reefs (Bishop et al. 2006).

Figure 12. Working up oyster tissue samples for disease (Dermo and MSX) analyses (photos from David Bushek).

Figure 13. Example of settlement plate (top) being photographed to enumerate attached larvae and tray of oyster shells (bottom) used to collect samples of settling oysters within natural reefs (photos from L. Coen).

Oyster Recruitment: Larval availability can be assessed by deploying settlement collectors (e.g., shell strings, trays filled with shell or artificial surfaces including tubes or flat plates) near natural and restored reef locations for known periods (Fig. 13). The horizontal and vertical positioning of settlement collectors can be adjusted to assess spatial variation in larval availability. Periodic plankton tows, although very labor intensive, also may be used to measure larval availability. Variation in recruitment, post-settlement survival and growth can occur over differing time intervals (O'Beirn 1996, Giotta 1999). Data typically are reported as the number of recruits/unit area/time interval. Direct settlement on natural reefs also should be measured for comparisons to collector data. Currently the use of different collection devices makes direct comparisons across regions difficult.

Oyster Growth/Survival: Oyster reef functions are dependent on successful growth and survival of the oysters that make up the reef. Individual oyster growth rates typically are measured by placing a number of small oysters in mesh bags and sequentially assessing survival and changes in shell height over a given time interval (Fig. 13). Mesh

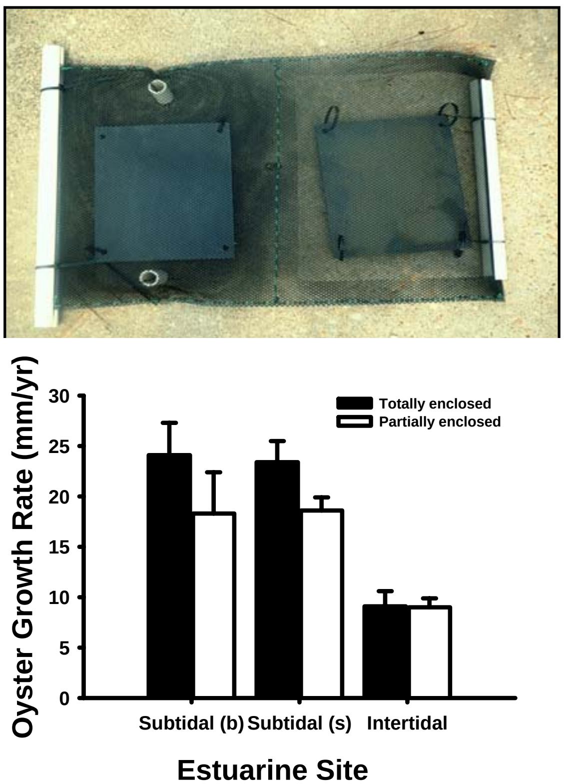

Figure 14. Example of totally and partially mesh-enclosed settlement plates (top) and yearly growth rates (bottom) for oysters reared in enclosures at subtidal (b = on bottom, s = suspended) and intertidal sites (photos and figure from R. Giotta).

bags enable easy recovery and identification of deployed oysters and prevent loss from predation, etc. The mesh does not seem to inhibit natural feeding although in areas of heavy algal growth and/or sedimentation bags periodically may need to be cleaned. Survival can be estimated from changes in density over time, but the causes of oyster mortality (e.g., disease, predation, harvesting) are difficult to infer simply from density changes. Short-term experiments comparing the survival of oysters in full cages to ones in partial cages or open tray can be used to measure mortality attributable to predation directly in the field (Giotta 1999, Newell et al. 2000, Lenihan et al. 2001). The interpretation of caging experiment results may be compromised because of cage effects on flow, sedimentation, and other factors (Giotta 1999).

Seston uptake: A water/seston collection apparatus can be used to measure changes in water column seston concentration attributed to bivalve feeding over an oyster reef (Fig. 15). One can use a simple syringe sampling device and associated current meter (see Judge et al. 1993) or a more integrated, but costly system (e.g., Grizzle et al. 2006) comprised of

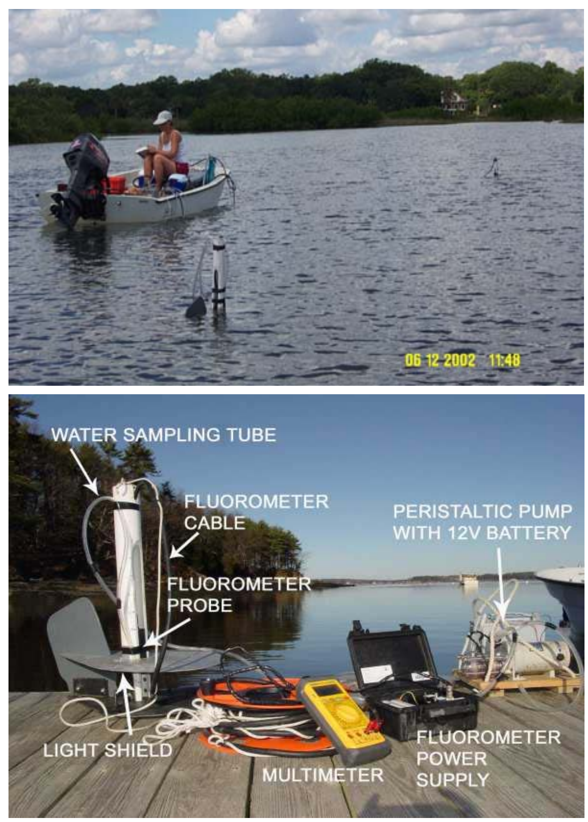

Figure 15. Two *in situ* seston units deployed in the field (top) and single unit on the dock (bottom) (photos from R. Grizzle).

two or more identical units, each consisting of an *in situ* fluorometer, data logger and peristaltic pump sampling water at various heights with Tygon™ tubes attached to the deployed devices and water collected in Whirlpack™ bags. The deployment device allows precise placement of the fluorometer probe and intake ends of the water sampling tubes so that in situ fluorescence (chlorophyll *a*) can be measured at one height and water can be sampled for seston analyses at two heights. The typical sampling setup involves placing the units upstream and downstream of the study area and sampling the water at periodic intervals. Seston uptake is determined instantaneously by the logging fluorometers, and the sampled water can be analyzed for various seston, nutrients and chlorophyll *a* parameters to verify the fluorometry and provide additional data on changes in seston characteristics (e.g., Grizzle et al. 2006).

Flow: The determination of flow rates on or adjacent to subtidal and intertidal submerged reefs is an important parameter for oyster growth and survival (e.g., Lenihan et al. 1996, Grizzle et al. 2006). Flow is important as it can reflect food fluxes available to filter-feeding organisms such as oysters and other reef residing invertebrates. Flow (current speed) can be measured by using either longer-term (e.g., clod cards and other methods that involve dissolution or logging meters) or short-term methods (Fig. 1). The former method has been used to integrate flow over hours to days through changes in size, weight or area (i.e. dissolution) change through time (e.g., Doty 1971, Yund et al. 1991, Judge and Craig, 1997, Giotta 1999, Hart et al. 2002, but see caveats in Porter 2000) or by using logging systems. The latter can include simple free-stream flow measurements in one (e.g., Marsh-McBirney Flow Mate) or multiple dimensions (e.g., SonTek, InterOcean Systems S4, and other manufacturers using acoustic doppler velocimeters/profilers or ADV or ADP methods or electromagnetic approaches, Marsh-McBirney). With logging capabilities these can sample for days to weeks depending on sampling rates and internal memory capabilities

Mussel Growth and Survival: Evaluating the success of reef restoration efforts directly by measuring oyster growth, associated

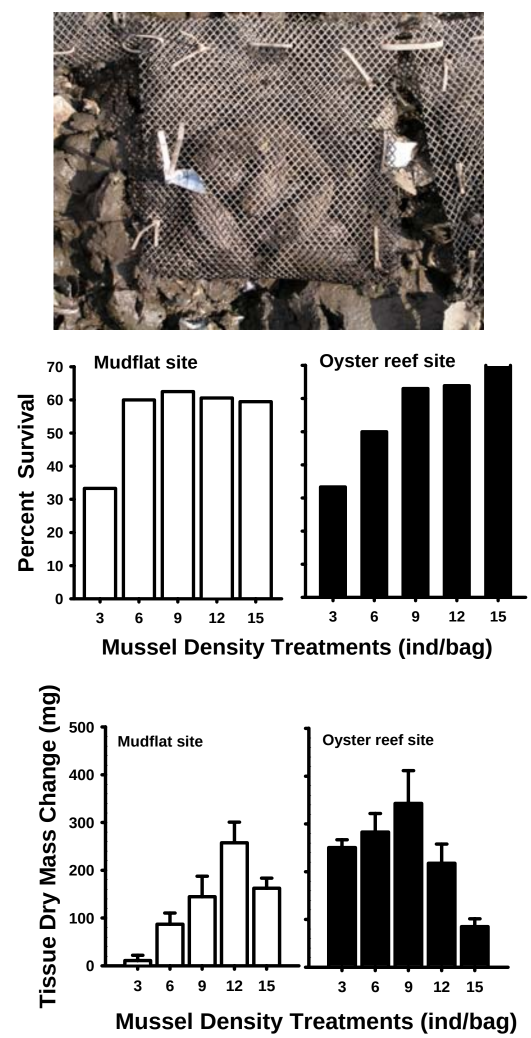

Figure 16. Growth (bottom) and survival (middle) of mussels placed within mesh bags (top) containing different density treatments in reef or mudflat sites. Survival was not different between sites, but tissue growth was density dependent (photos and figures from K. Walters).

species densities or other metrics can be time consuming and frequently physically challenging. The question of whether there is an easier, more cost-effective approach that could be used to assess accurately the success of restored reefs remains a challenge for researchers. One possible approach may be to utilize a common resident of oyster reefs, *Geukensia demissa*, as an indicator species of reef success (Fig. 16). Similar to measurements typically collected for oysters, mussel density, growth, and survival (e.g., Bertness 1980, 1984, Franz 2001) may provide insight into how well a reef is doing.

Faunal Compositional Similarity: The evaluation of oyster reef restoration success depends on the selection of appropriate goals, identification of relevant metrics, and use of robust analytic approaches that enable effective evaluation of significant differences in data collected for each metric. For intertidal oyster reefs, the goal of restoring ecological function often is as important as the production of harvestable oysters, especially since oysters are the habitat. Assessing differences in resident faunal composition between created and natural reefs is one possible metric for evaluating ecological success. A variety of statistical approaches exist to assess the possible convergence in compositional similarity of reef assemblages over time (Table 3). The utility of each statistical approach was evaluated for data collected from a controlled SC reef restoration experiment (Walters and Coen 2006). The negligible limitations, flexible design options, and ability to generate significance tests for small sample sizes made PERMANOVA the favored statistical test. Ongoing development of effective statistical approaches for testing the significance of taxonomic compositional changes among habitats makes the determination of whether restoration projects are successful less dependent on the choice of analytic technique. More critical, biological questions including whether convergence of taxa abundance and composition is a valid indicator of similar ecological function remain to be answered.

Table 3. A summary of analytic approaches that can be used to evaluate the similarity of faunal compositions between natural and restored reefs. (from Walters and Coen, 2006)

	Statistical Approaches			
	MANOVA	ECOSIM	ANOSIM	PERMANOVA
Assumptions	Independence, Normality, Homogeneity*	Taxa pool defined Equal dispersal abilities	"Distribution free"	Observation units exchangeable & independent
Data Analyzed	Abundance, Proportion, Biomass, etc.	Presence/absence and row or column weighted presence/absence	Similarity or distance index (based on abundance, proportion, or biomass)	Similarity or distance index (based on abundance, biomass, or proportion)
Test	F-statistic Range 0 to +∞	C-score (obs .vs. exp.) (Stone & Roberts 1990) Range 0 to $\sum SiSj/((R)(R\text{-}1)/2)$	Global R (Clarke & Warwick 2001) Range -1 to 1	Pseudo F-ratio (Anderson 2005) Range 0 to +∞
Designs	All ANOVA designs (e.g., factorial, blocked, nested, +)	2-cell design (obs. & exp.)	1-way, 2-way, 2 level nested	All ANOVA designs
Limitations	Sufficient replicates for number of dependent variables	Variable Type I & II errors based on row & column constraints & test index	Small sample size restriction Sensitive to group spread (homogeneity) Index dependence (?)	Only balanced designs Sensitive to group spread (homogeneity) Index dependence (?)
Comments	Many taxa and/or "0" observations more difficult to satisfy assumptions	Design limitations Careful selection of test & recognition of errors required	Effective multivariate test for simple experimental designs & sufficient sample sizes	Similar to ANOVA approach w/o limits from assumptions

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Appendix 1: List of 2004 Workshop Attendees

(see Website for additional information: http://www.coastal.edu/marine/sgoyster)

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http://nature.org/success/greatsouthbay.html
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