Contemporary Approaches for Small-Scale Oyster Reef Restoration to Address Substrate *Versus* Recruitment Limitation: A Review and Comments Relevant for the Olympia Oyster, *Ostrea lurida* Carpenter 1864

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CONTEMPORARY APPROACHES FOR SMALL-SCALE OYSTER REEF RESTORATION TO ADDRESS SUBSTRATE *VERSUS* RECRUITMENT LIMITATION: A REVIEW AND COMMENTS RELEVANT FOR THE OLYMPIA OYSTER, *OSTREA LURIDA* CARPENTER 1864

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ABSTRACT Reefs and beds formed by oysters such as the Eastern oyster, *Crassostrea virginica* and the Olympia oyster, *Ostrea lurida* Carpenter 1864† were dominant features in many estuaries throughout their native ranges. Many of these estuaries no longer have healthy, productive reefs because of impacts from destructive fishing, sediment accumulation, pollution, and parasites. Once valued primarily as a fishery resource, increasing attention is being focused today on the array of other ecosystem services that oysters and the reefs they form provide in United States coastal bays and estuaries. Since the early 1990s efforts to restore subtidal and intertidal oyster reefs have increased significantly, with particular interest in small-scale community-based projects initiated most often by nongovernmental organizations (NGOs). To date, such projects have been undertaken in at least 15 US states, for both species of dominant native oysters along the United States coast. Community-based restoration practitioners have used a broad range of nonmutually exclusive approaches, including: (1) oyster gardening of hatchery-produced oysters; (2) deployment of juvenile to adult shellfish (''broodstock'') within designated areas for stock enhancement; and (3) substrate enhancement using natural or recycled man-made materials loose or in ''bags'' designed to enhance local settlement success. Many of these approaches are inspired by fishery-enhancement efforts of the past, though are implemented with different outcomes in mind (ecological services *vs.* fishery outcomes). This paper was originally presented at the first West Coast Restoration Workshop in 2006 in San Rafael, California and is intended to summarize potential approaches for small-scale restoration projects, including some emerging methods, and highlight the logistical benefits and limitations of these approaches. Because the majority of the past efforts have been with *C. viriginica*, we use those examples initially to highlight efforts with the intent of enlightening current west coast United States efforts with *Ostrea lurida*. We also discuss site-specific characteristics including ''recruitment bottlenecks'' and ''substrate limitation'' as criteria for identifying the most appropriate approaches to use for small-scale restoration projects. Many of the included ''lessons-learned'' from the smaller-scale restoration projects being implemented today can be used to inform not only large-scale estuary wide efforts to restore *C. virginica*, but also the relatively nascent efforts directed at restoring the United States west coast's native Olympia oyster, *Ostrea lurida*.

INTRODUCTION

Review of Oyster Declines on East/Gulf Coasts and Shift Towards Restoration for Ecosystem Services

Prior to the 1990s, coastal resource managers focused their efforts on management and enhancement of the Eastern oyster, *Crassostrea virginica*, primarily for fisheries production (e.g., Luckenbach et al. 1999, Coen & Luckenbach 2000, Peterson et al. 2003a, Coen et al. 2007a). Despite this focus, *C. virginica* fisheries declined precipitously over the course of the 20th century, especially in the northern portions of its historic range (e.g., Canadian maritime provinces to North Carolina) (see reviews by Rothschild et al. 1994, Kirby 2004, NRC 2004, Kirby & Miller 2005, Ruesink et al. 2005, Beck et al. in review). Similarly, *Ostrea lurida* (spp.) populations on the west coast of the United States have undergone even greater declines with decimating harvesting impacts traceable to the late 1800s and finally their near extinction as observable ecosystems perhaps back to the 1930s to 1950s (reviewed in Couch & Hassler 1989, Baker 1995, Cook et al. 1998, Peter-Contesse & Peabody 2005).

Overfishing and loss of reef structure, defined here as ''clean, three-dimensional substrate with significant vertical relief'' are commonly cited reasons for the decline of most reef-forming oyster species, along with degraded water quality and impacts of oyster parasites in recent decades (see Haven et al. 1978, Rothschild et al 1994, Lenihan & Peterson 1998, Lenihan 1999, Lenihan et al. 1999, Hargis & Haven 1999, Luckenbach et al. 1999, Lenihan et al. 1999, North Carolina Division of Marine Fisheries 2001, Newell 2004, NRC 2004, Luckenbach et al. 2005, Beck et al. in review). Populations in the more southerly portion of *C. virginica*'s range are believed to be diminished, although a substantial fishery still exists in portions of the southeastern United States, such as South Carolina, and most states bordering the Gulf of Mexico (e.g., Kirby 2004, NRC 2004, Kirby & Miller 2005, NMFS landings website data through 2005, Lotze et al. 2006, ASMFC 2007, Beck et al. in review).

Oyster studies are increasingly focusing attention on a broader suite of ''ecosystem services'' from these ''ecosystem engineers'' (e.g., Dame 1996, Coen et al. 1999b, Peterson et al. 2003a, Peterson et al. 2003b, Coen et al. 2007a, Grabowski & Peterson 2007) such as water filtration (reviewed by Newell 2004, Newell et al. 2005, Grizzle et al. 2006, Grizzle et al. 2008), biogenic reef habitat for other species (e.g., Coen et al. 1999b, Coen et al. 1999a, Peterson et al. 2003a, ASMFC 2007), and shoreline stabilization (e.g., Meyer et al. 1997, Coen & Bolton-Warberg 2005, Piazza et al. 2005) associated with *C. virginica* and their reefs. However, compared with the extensive literature related to management for fisheries enhancement or production, a paucity of data exists in the primary literature about

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†The taxonomy of the Olympia oyster has been in dispute since Harry (1985) proposed synonymy of *Ostrea lurida* Carpenter 1864 and *Ostrea conchaphila* Carpenter 1857. Polson et al. (2009) provide molecular evidence that the Olympia oyster refers to the nominal species, *Ostrea lurida* Carpenter 1864. In view of their genetic data, and for consistency, the original taxon, *Ostrea lurida*, is used throughout this volume to refer to the Olympia oyster, which is distributed from approximately Baja California (Mexico) to southeast Alaska

these other services (e.g., Luckenbach et al. 2005, Coen et al. 2007a, Grabowski & Peterson 2007). Indeed, in the updated compendium on the biology of the eastern oyster, *C. virginca*, Kennedy et al. (1996) made little reference to these additional services (but see Kennedy 1989), despite extensive work by Wells, Dame, Ulanowicz, Newell, Bahr, and others from the 1960s through the 1980s on their role in filtering vast quantities of water (summarized in Dame 1996, Dame et al. 2001, Cressman et al. 2003, Nelson et al. 2004, Grizzle et al. 2006, Grizzle et al. 2008) and other important functions (e.g., Coen et al. 1999b, Coen & Luckenbach 2000, Breitburg et al. 2000, Newell 2004, ASMFC 2007, Nestlerode et al. 2007).

Despite the ongoing emphasis on fisheries production by many resource management agencies, there is a greater public awareness today of the loss of "ecosystem services" (e.g., Coen et al. 1999a, Coen et al. 1999b, Lenihan et al. 2001, Newell 2004, NRC 2004, Ruesink et al. 2005, ASMFC 2007) associated with declines or loss of oyster populations. This has inspired a significant investment of public and private funding for community restoration of these beneficial "ecosystem services" provided in their respective native ecosystems (e.g., Brumbaugh et al. 2000a, Brumbaugh et al. 2000b, Hadley & Coen 2002, Brumbaugh et al. 2006, Hadley et al. in press), fueled in part by creation of new programs such as the National Oceanic and Atmospheric Administration Community-based Restoration Program (NOAA-CRP). Indeed, a review of the National Estuarine Restoration Inventory (NERI) reveals scores of *C. virginica* restoration projects initiated since 1995. These projects were frequently designed with nonfishery ecosystem services in mind (https://neri.noaa.gov/, accessed February 22, 2007) and total more than 318 hectares (see Table 1).

Unfortunately, limited effort has been made to document outcomes of most small-scale projects (summarized in Coen & Luckenbach 2000, Luckenbach et al. 2005, Coen et al. 2007a, Hadley et al. in press). One impediment has been a lack of standardized monitoring approaches and, until recently, few projects developed with rigorous experimental designs to facilitate comparisons (Coen et al. 2007b, see also http://www.oyster-restoration.org/). Critical for all shellfish restoration projects, however, are explicit goals and appropriate metrics for their assessment (Coen & Luckenbach 2000, Luckenbach et al. 2005, Coen et al. 2007a, in review). Using inappropriate metrics to assess restoration progress in any system can be problematic. However, as Palmer et al. (1997) noted for freshwater systems and others for salt marshes (e.g., Zedler & Calloway 2000) the importance of correctly choosing restoration endpoints. For example, Craft et al. (1999) emphasized that habitat restoration success should not be solely dependent on the growth/survival of just a single targeted species. Using our work and that of our colleagues in 2004 (Coen et al. 2007b) we previously identified six potential restoration goals and ranked the value of current approaches, sampling and monitoring methods, and associated metrics for each (Coen et al. 2007b). Also of critical importance is the use of natural "reference" sites (Coen & Luckenbach 2000, Walters & Coen 2006, Coen et al. 2007b, in review) when available. By explicitly focusing on and using common goals, metrics, and traditional and novel (e.g., Grizzle et al. 2006, Grizzle et al. 2008, Coen et al. 2007b) methods, we hope to be able to assess the functioning and development of both intertidal and subtidal oyster reef habitats (e.g., Powers et al. for NC, in review), including recommending potential collaborative efforts across a broad spatial scale (e.g., state-wide, regional, basin wide, among basins).

In this paper, we review the most common restoration techniques used in small-scale oyster restoration projects as defined by the restoration categories in the National Estuarine Restoration Inventory (NERI). These techniques are not mutually exclusive and in many instances they are used in concert to address restoration goals. Based on direct experience and communication with practitioners and colleagues involved in various restoration efforts, we summarize some generally applicable lessons derived from these projects and then offer recommendations for optimal project design and management.

Small-scale Oyster Reef Restoration Techniques

Thayer et al. (2005) and the related NERI database describes three separate restoration techniques for "oyster reef/shell bottom" habitat: (1) reef construction using natural materials; (2) oyster gardening; and (3) stock enhancement. Based on this framework for organizing and analyzing restoration projects, we will describe some of the benefits and limitations of each technique throughout the remainder of this paper. Many projects involve more than one technique and, when considering which technique(s) to use, we believe it is helpful to consider the underlying threats or limitations to the functioning of the target oyster species in a given location, especially focusing on "*habitat (or substrate) limitation*" and/or "*recruitment limitation*" (cf. Olafsson et al. 1994).

Techniques for Addressing Habitat (Substrate) Limitation

There is a general recognition that oyster reef habitats have declined markedly in many bays and estuaries—destructive fishing, dredging for creation of ship channels, and physical damage from boat wakes are factors that directly affect the physical three-dimensional structure of oyster reefs (e.g., reviewed in Luckenbach et al. 1999, Lenihan 1999, Coen & Luckenbach 2000, ASMFC 2007) that has been show to be so critical for subtidal oyster reefs (e.g., Lenihan & Peterson 1998, Breitburg 1999, Lenihan 1999). Sedimentation, algal blooms, water pollution, temperatures, and freezing and low dissolved oxygen (e.g., anoxia) all have also reduced the availability of appropriate sites/substrates for oyster settlement and postsettlement survival (e.g., Lenihan et al. 1999, Mann & Evans 2004, Kirby & Miller 2005; Smith et al. 2005, ASMFC 2007, Taylor & Bushek 2008).

Oyster shell is a biogenic substrate that allows oysters to build reefs by providing a hard substrate for the attachment of oyster larvae generation after generation. A recent paper by Powell et al. (2006) for example, suggests that shell is rapidly lost in Delaware Bay as oyster populations decline and fail to renew/regenerate this potentially labile resource. They suggest that shell durability, disarticulation, and subsequent valve dispersal explain only part of the process. A diverse community of boring organisms ("bioeroders"), especially in higher salinities, shell dissolution, dredge impacts, subsidence, and sedimentation are significant factors regulating the rate of oyster bed regeneration (e.g., Gutiérrez et al. 2003, Powell et al. 2006 and references therein).

Despite the decrease in area or overall habitat (substate) quality in many areas, these areas may have extant populations

TABLE 1.

Distribution and area of restoration projects in the National Estuarine Restoration Inventory (NERI). Note that more than one restoration approach may be used for a given project, so row totals under the "Method" heading may exceed the number shown in the table.

US Region & State	Projects by Habitat Type Oyster reef/ shell bottom	Restoration Method: Reef Construction	Oyster Gardening	Stock Enhancement	Reef Area Restored Acres (% of total)
Target Species: Eastern Oyster, *Crassostrea virginica*					
Mid-Atlantic					**722.26 (91.8)**
MA	1	1	0	0	
CT	1	0	0	1	
NY	2	0	0	2	
NJ	2	2	2	0	
DE	1	0	1	1	
MD	48	43	13	3	
VA	48	47	6	0	
South Atlantic					**10.04 (1.2)**
NC	9	7	0	1	
SC	4	4	2	0	
GA	2	2	0	0	
FL	2	2	0	0	
Gulf of Mexico					**31.29 (4.0)**
FL	22	16	3	2	
AL	7	3	3	1	
MS	3	3	0	0	
LA	3	3	0	0	
TX	2	1	0	0	
Total C.v.	**157**	**134**	**30**	**11**	**763.59 (97)**
Target Species: Olympia oyster, *Ostrea lurida*					
Pacific Coast					**23.5 (3.0)**
WA	3	0	1	2	
CA	7	6	1	1	

that are reproductively viable and capable of producing large numbers of offspring (larvae) on a consistent basis. Projects to restore or enhance reef habitat can be small-scale (e.g., shell bags, cement "reef balls," or vertical stakes deployed and placed by volunteers or larger equipment) to large-scale (e.g., many hectares and metric tons of material deployed by barge and crane or water cannon). The NERI database includes projects at both ends of this spectrum. Whereas most projects have primarily involved deployments of loose shell or shell retained in small mesh bags, other novel or "alternative materials" such as limestone or marl (e.g., NC, NJ, LA, SC) and modified cement "reef balls" (Tampa Bay, Ft. Myers, FL; Dauphin Island, AL; coastal SC) are being tested currently at a number of sites. We describe these efforts in greater detail in the next section.

Construction Using Natural Materials

There are significant benefits that accrue from reef habitat construction. First, this technique recognizes one fundamental habitat requirement of the target species. Second, even in the absence of live oysters, the addition of shell substrate provides habitat for a diverse array of other species even in the early stages of oyster population development (e.g., Lehnert & Allen 2002, Luckenbach et al. 2005, Tolley & Volety 2005, Coen et al. 2007a). Third, there is evidence that intact (cemented), intertidal oyster reefs serve as "natural breakwaters" and provide a means of reducing shoreline erosion without resorting to other engineering solutions that harden (e.g., bulkheads, rip-rap) the shoreline (e.g., Meyer et al. 1997, Coen & Bolton-Warberg 2005, Piazza et al. 2005).

Physical habitat restoration for shellfish most often involves the placement of fresh or fossil dredged or mined oyster or clam shell (whole or fragments) or other materials (e.g., limestone marl, cement) directly on the bottom. Planting subtidal reefs with some (meters) vertical relief in some estuaries with low dissolved oxygen problems is a key objective of this restoration approach (e.g., Lenihan 1999, Thayer et al. 2005, Brumbaugh et al. 2006, Coen et al. 2007b), and reef construction using "natural materials" was the most common restoration technique in NERI ($n = 134$ projects), accounting for >69% of all projects in the midAtlantic region, 11% in the south Atlantic region, and 19% in the Gulf of Mexico. There are many factors that contribute to this geographic pattern, and projects in the Chesapeake Bay region represent most ($n = 90$) of all reef restoration projects listed. The existence of well-defined goals for restoration of the Chesapeake Bay system overall (EPA

Chesapeake Bay Program 2000) likely contributes to this high concentration of projects that community organizations have pursued in the Chesapeake Bay region since the mid1990s. This observed concentration potentially also reflects the relative magnitude of reef (resource and habitat) loss in Atlantic estuaries, paralleling the sequential exploitation and collapse of oyster fisheries within the oyster's Atlantic and Gulf of Mexico range (e.g., Luckenbach et al. 1999, Jackson et al. 2001, Kirby 2004, NRC 2004, Kurlansky 2006).

State resource agencies and (in some states) private leaseholders have for many decades actively planted oyster shell (''cultch'') on managed oyster beds to help maintain oyster fisheries productivity (e.g., Kennedy 1989, Louisiana Department of Wildlife and Fisheries 2004, Street et al. 2005, ASMFC 2007). Historically, shell has been obtained from local shucking houses (e.g., Chatry et al 1986, Dugas et al. 1991, Haven et al. 1987, Putman 1995, Brumbaugh 2000, Louisiana Department of Wildlife and Fisheries 2004, Street et al. 2005, Powell et al. 2006). Recently, however, the availability of oyster shell has become quite limited in many states, particularly in states where landings have declined significantly. Most of these states now maintain their replanting programs by importing ''shell-stock'' (i.e., unprocessed animals) from other states (e.g., Gulf of Mexico). Other sources such as fossil shell (oyster or clam) deposits dredged in subtidal areas or from quarries (e.g., Florida) have also been used to meet the increasing substrate demand, but permitting constraints have limited this practice because this material can be a critical habitat in itself (discussed in Luckenbach et al. 1999, NRC 2004, Thayer et al. 2005, ASMFC 2007).

Many have voiced concerns about the risks of bringing in large amounts of shell from a different region (discussed in Bushek et al. 2004, Powell et al. 2006, Miller et al. 2007), largely centered around questions related to pathogens or exotic ''hitchhikers'' that could be introduced when shell is returned to the water (see also Grosholz & Ruiz 1995, Burreson et al. 2000). Public health agency concerns tend to be related sampling and closures caused by human pathogens, whereas resource management agencies are more often concerned with shellfish pathogens, sustainable harvesting, and related species enhancement/restoration. In addition to reintroducing or moving diseases or strains that may or may not exist locally (e.g., Reece et al. 2001), new diseases or other nonnative species (e.g., Bushek et al. 2004, Lafferty et al. 2004), including cysts or other stages of harmful algal species (and HABs) may be introduced with live individuals (Walton & Ruiz 1995, Hégaret et al. 2008, A. Lewitus NOAA, pers. comm.). Specific concerns have been voiced also by other state agencies involved with public health and coastal zone management (SCDHEC and OCRM), as well as by the public and from Sea Grant extension personnel (e.g., C. Sawyer, pers. comm.) over oyster-gardening, especially in closed waters.

Shell Recycling and Procurement

Researchers at South Carolina Department of Natural Resources' (SCDNR), Marine Resources Research Institute (Hadley & Coen 2002, Thayer et al. 2005, Brumbaugh et al. 2006, Hadley et al. in press) have begun directed community-based restoration efforts across South Carolina's entire coast, modeled after successful programs in the Chesapeake Bay. Their efforts and the Office of Fisheries Management in SCDNR include a program that encourages local oyster consumers to recycle their oyster shells rather, than send them to the landfill as trash, employing them for decorative purposes (imitation ''tabby'' or in cement walkways or walls) or as fill for driveways and roads. A large percentage of the oysters used for this restoration effort and larger-scale South Carolina and North Carolina efforts come from Gulf of Mexico populations. This out-of-state shell is being recycled initially on a small scale (~15,000 bushels/year) through the establishment of recycling stations, and a conscious effort is being made to quarantine the nonlocal shell, based on concerns that the shell may harbor nonnative pathogens or strains and exotic hitchhikers. Using the results of Bushek et al. (2004), shell (from either whelk or oyster) is quarantined for a minimum of 1–3 mo before being used for planting. Shell recycling programs are also becoming widespread (e.g., North Carolina, Florida, New Hampshire) in an effort to maximize the retention of shell for restoration projects in coastal areas (summarized in Box 1, see later).

Shell Bags

One of the most common techniques for small-scale reef construction is deployment of shell contained in polyethylene mesh bags (e.g., diamond-oriented tubular mesh) cut from >300-m rolls (formerly produced by ADPI) into 1.37-m lengths and then slipped over 20.3 cm diameter schedule 40 PVC of 0.6–0.9 m in length. The shellbags contain 0.5–0.75 US bushels of loose Gulf, South Carolina oysters or whelk shell. This technique was derived from earlier applications (e.g., at the University of Maryland's CES Horn Point Laboratory) used to transport preset (with spat) shell to the field sites intended for eventual harvest. Typically, for projects with resource restoration as the ultimate objective (e.g., 3-y rotating harvest reserves in Maryland), mesh bags are opened and the shells are emptied onto constructed shell reefs or reef footprints.

In projects designed primarily for the restoration of other ecosystem services, the objective is to create a stable, three-dimensional substrate (cf. Bartol & Mann 1997, Taylor & Bushek 2008, Hadley et al. in press) that allows for recruitment of juvenile oysters (''spat''), whereas minimizing shell loss or sinking from waves and currents generated by natural and anthropogenic sources (e.g., Hadley & Coen 2002, Coen & Bolton-Warberg 2005, Thayer et al. 2005, Brumbaugh et al. 2006, Coen et al. 2007b, Taylor & Bushek 2008). In many ways this approach mimics the bagging of sand for storm and related erosion control (Hadley et al. in press).

The small mesh size (31.9 cm) of the 0.6–0.9 m long bags allows for relatively easy (if volunteer intensive) transport and deployment at a variety of field sites (e.g., Hadley & Coen 2002, Thayer et al. 2005, Hadley et al. in press). Volunteers ranging in age from 8–80 have been involved with such efforts in South Carolina and other Gulf of Mexico, east (most states) and west coast (e.g., California) programs. Because of the intertidal nature of many oyster reefs in South Carolina, Georgia, North Carolina, and Florida (Coen et al. 1999a, ASMFC 2007) we modified the approach and left the shell in the mesh bag to aid in initial shell retention also. In South Carolina for example, bags are generally deployed side-by-side on the shore to create replicated reef footprints, generally in a matrix of 25 × 4 columns and rows, respectively (e.g., see Hadley et al. in press, also http://score.dnr.sc.gov/index.php). Shell bags have now

Box 1. Overview of Shell Recycling Programs.

Oyster reef habitat restoration and fishery enhancement typically involves the placement of large quantities of shell on current or historic "footprints" of oyster reefs to provide substrate for attachment of juvenile (recruiting) oysters. Purchasing oyster shells for reef restoration projects from shucking houses can be expensive and can be difficult to obtain. This is particularly the case for projects that are community-based, small scale or in locations that are not intended to support commercial fisheries production. As a result, many community groups have developed oyster shell recycling programs as a means of securing a sufficient quantity of shells for restoration projects.

Whereas many shell-recycling programs typically begin as community-driven efforts designed primarily to increase public awareness of local water quality issues and habitat restoration needs, they are proving to be quite effective at catalyzing larger efforts (even state-wide) to restore and protect oyster reef habitat. Some states, most notably South Carolina (http://saltwaterfishing.sc.gov/oyster.html) and North Carolina (http://www.ncfisheries.net/shellfish/recycle1.htm), have made shell recycling a mainstream part of their restoration/management efforts. A summary of shell recycling programs is provided here, with the larger and more highly developed programs highlighted first, followed by some projects that are in the "start-up" phase. By highlighting programs in various stages of development it is possible to illustrate some of the common management approaches and techniques, as well as messages used to communicate about oyster reef habitat restoration and conservation generally, and shell recycling in particular.

Mature Programs

SOUTH CAROLINA: Shell recycling in South Carolina is managed through SC Department of Natural Resources (SCDNR), and is an outgrowth of SCORE (South Carolina Oyster Restoration & Enhancement). Currently there are over 16 shell-recycling stations set up in coastal counties throughout the state to facilitate the collection of shell from volunteers, restaurants, and community groups. Funds to support this statewide program are generated through sales of the saltwater fishing licenses, and shells are used primarily for restoration of recreation-only public oyster grounds (usually fringing intertidal areas) that are subsequently available for hand-harvest. Information about the program, including maps and directions to recycling stations are found on the SCDNR web site: http://saltwaterfishing.sc.gov/oyster.html

SCORE has a dedicated website with information about reef restoration, monitoring methods, an extensive bibliography of oyster literature, tools for public relations and outreach, and links to many other sites of relevance to oyster restoration practitioners: http://score.dnr.sc.gov/

NORTH CAROLINA: The Nature Conservancy of North Carolina, through support from a TNC-NOAA Community-based Restoration Program, initiated a shell-recycling program on the Outer Banks in 2004. Since that time, the North Carolina Division of Marine Fisheries (DMF) added new staff and funding to support this shell recycling program on a state-wide basis. DMF has excellent information on their web site describing their new state-managed shell recycling program, as well as their oyster reef sanctuary program. North Carolina Shell Recycling: http://www.ncfisheries.net/shellfish/recycle1.htm North Carolina Oyster Reef Sanctuary Program: http://www.ncfisheries.net/shellfish/sanctuary1.htm

Start-up Programs

ALABAMA: Several groups are working on oyster restoration and gardening at DISL and Auburn University supported by Mobile Bay National Estuary Program, MS-AL Sea Grant and the Auburn University Marine Extension and Research Center. http://www.aces.edu/dept/fisheries/aumerc/research/oyster-restoration.php, http://www.mobilebaynep.com/oystergardening/Oyster%20Gardening.htm

GEORGIA: University of Georgia is using shell recycling as a way to engage volunteers and to collect substrate for small projects and research. http://www.marex.uga.edu/shellfish/oysterrest.html

LOUISIANA: The Gulf of Mexico Foundation and NOAA CRP are supporting a project in Louisiana that includes oyster shell recycling as one component of a larger project to restore sanctuary reefs in Vermillion Bay. The Louisiana Wetlands Association is spearheading this effort to create reefs using a variety of materials, including crushed concrete, limestone marl and oyster shells. http://gulfmex.org/crp/5005.html

NEW HAMPSHIRE: A shell recycling program is under development at the University of New Hampshire's Jackson Estuarine Research Laboratory. This program is intended mostly as a means of collecting sufficient shell to support small-scale restoration projects. http://www.oyster.unh.edu/shell_recycling.html

VIRGINIA: A regional shell-recycling program is being developed for various areas in Hampton Roads and Gloucester, VA. Shells are being collected from local restaurants for local restoration projects and there are public drop-off locations for individuals wishing to deliver shells from home consumption. http://www.cbf.org/site/PageServer?pagename=oysters_va_shellrecycling

Recycling Programs: Some Common Themes

- Recycling programs can generate significant quantities of shell and can be leveraged to support large restoration projects;
- Shell recycling often starts with a community organization or nonprofit organization as the lead organizer;
- Successful recycling programs often begin at a very local (i.e., town or county) level;
- Volunteer labor is often used in the early stages of program development for collection and transport of shells to centralized storage sites;
- Typical of many community-driven efforts, volunteers tend to be retirees or school students fulfilling community-service requirements;
- The state, county or local government are often willing to provide the minimal storage space necessary for collecting recycled shells—often a remote corner of a parking lot at a state park or municipal government depot is sufficient;
- Restaurants are a primary source of shell initially, but as awareness builds there is an increasing fraction derived from individuals or community-level events (e.g., backyard oyster roasts and community fundraisers);
- Recycling programs are adopted and supported by state management agencies when it becomes clear that (a) there is strong public support for the effort; (b) a significant volume of shell can be collected to enhance or augment traditional shellfish management activities; and (c) state-managed recycling programs can be leveraged for additional federal restoration funds (e.g., NOAA's Community-based Restoration Program);
- Public awareness is an ongoing need and community partners such as nonprofit conservation groups, research institutions and local governments are important conduits for information even after a recycling program becomes state-wide "mainstream" activity.

Recommendations for Shell Recycling Programs:

- **DO** separate shell from trash (plastic forks, napkins, lemon rinds, etc.). Shell mixed with trash is not suitable for recycling. Provide separate containers for shell at oyster roasts can make it easier to keep trash separate from shell at oyster roasts.
- **DO** keep shell in porous containers to reduce odors. Fish baskets or plastic barrels with large drain holes drilled in the bottom and sides are good containers.
- **DO** bring your shell to the nearest shell-recycling center.
- **DO NOT** transfer live oysters from an oyster roast or other unknown source into open waters. This is especially important if the oysters you purchased were harvested outside the state, because it is often illegal to place them overboard without permits. Placing imported oysters overboard can create public health problems and may harm local oysters or other animals.
- **DO NOT** put freshly shucked shell overboard, recycled shell should be dried on land for 4–6 mo to minimize the risk of introducing oyster pathogens to local waters (Bushek et al. 2004).

been used extensively for intertidal and subtidal community restoration programs in northeastern United States (New Hampshire, Maryland, Virginia, New Jersey), the southeastern United States (e.g., North Carolina, South Carolina, Georgia), the Gulf of Mexico (e.g., Florida, Alabama, Mississippi) and the west coast of the United States (e.g., California, see papers in this volume and Fig. 1 here).

Loose Shell Deployments

Unconsolidated shell deployments are often used in fishery enhancement efforts, as well as ecosystem restoration efforts in subtidal waters where the placement of shell bags is problematic or impractical because of the scale of the effort (e.g., tens of thousands of bags required). This approach is also been used extensively in Chesapeake Bay. Intertidal deployments of loose shell are also used in areas with lower boat traffic and on shorelines with low slope; loose shell tends to be highly unstable on slopes greater than 15° to 20° in vertical relief, and in areas with moderate to heavy boat traffic (e.g., Grizzle et al. 2002, Coen & Bolton-Warberg 2005, Thayer et al. 2005, Wall et al. 2005).

Cost is a significant logistical consideration for restoration projects involving deployment of loose shell. Material costs now can range from \$1 to \$5 per US bushel of shell and adding transportation to loading site and planting contractor costs, these can easily double the earlier mentioned costs, depending on distance for barge transport, and reef vertical relief, with mounded (1–3 m often), three-dimensional reefs typical of restoration projects in the Chesapeake costing up to \$100,000 per acre or more (USACE 2005).

Reef Construction Using "Alternative" Materials

Creativity for identifying economical sources of alternative substrate is on the rise. Although shell continues to be favored for reef restoration efforts, largely because of the interstitial spaces that the shell creates (e.g., Lenihan 1999, Coen & Luckenbach 2000, Louisiana Dept of Wildlife and Fisheries 2004, ASMFC 2007 and citations therein), its scarcity is requiring restoration practitioners and management agencies to identify viable alternatives (Luckenbach et al. 1999). Alternative materials have included crushed limestone and marl, concrete, *Rangia*, *Spisula*, scallops, and other bivalve species (e.g., Haven et al. 1987, Soniat et al. 1991, Haywood and Soniat 1992, Soniat & Burton 2005, ASMFC 2007, Coen et al. 2007b). Less natural materials include derelict recycled crab pots (e.g., South Carolina), and clam cages (e.g., Georgia, South Carolina), man-made cement "reef balls" (e.g., Alabama, Florida), recycled crushed concrete (e.g., Alabama, Louisiana, Florida), coal fly ash (e.g., Texas, Virginia; O'Beirn et al. 2000), and even broken porcelain fixtures (e.g., see Chatry et al. 1986, Dugas et al. 1991, Haven et al. 1987, Putman 1995, Brumbaugh 2000, Louisiana Department of Wildlife and Fisheries 2004, Street et al. 2005, Powell et al. 2006, ASMFC 2007).

In South Carolina, as an outgrowth of planting material by aquaculture permits, research is being conducted to compare shell bags, loose shell, and vertical stakes (K. Walters et al. in prep.) with and without concrete coatings to enhance "surface rugosity" and "attractiveness" as a settlement substrate (Fig. 2 here and O'Beirn 1996). These are generally biodegradable (e.g., untreated wood, bamboo, other material easily bored into by boring organisms), can be moved or stripped of their attached oysters and if unattended eventually fall over adding the initial substrate for reef initiation (K. Walters, Coastal Carolina Univ., unpublished data). Others have used purchased grooved spat-tubes (often referred to as "French collectors," see Michener & Kenny 1991 for details) cut into 1-m lengths for assessing recruitment and conducting small-scale restoration efforts.

Figure 1. Small scale reef creation can be accomplished with shell bags deployed by hand (A & B) as well as with loose shell deployed mechanically from barges, similar to fishery enhancement efforts (C & D).

More highly engineered approaches to creating oyster reef habitat are emerging as well, particularly for incorporating a ''restoration'' component to shoreline stabilization efforts in areas with high wave energy. ''Reef BLK'' cages containing oyster shells were deployed along a section of the Gulf Intracoastal Waterway in Texas to reduce shoreline erosion along a preserve owned by The Nature Conservancy (see Fig. 3). Oyster settlement and survival has exceeded expectations, with >1,000 oysters m^{-2} on the surfaces of the structure (J. Laing, TNC unpubl. data). Although such approaches may not represent oyster restoration in the strictest sense, it is noteworthy that the coastal engineering industry is working to incorporate ecosystem services associated with oyster reefs into such engineering solutions.

Logistical Considerations for Implementation

There are basically three logistical constraints that need to be addressed for reef construction and related restoration efforts:

First, loose shell and other natural materials used for reef restoration projects are considered ''fill'' material in a number of states (e.g., Georgia, California) and some form of permit is almost always required for conducting restoration projects in coastal waters, although resource agencies generally have few or no hoops to jump through (M. Berrigan FL, pers. comm., L. Coen pers. obs.). Permitting can be minimized when state or other agencies oversee or coordinate efforts (e.g., the South Carolina Oyster Restoration and Enhancement [SCORE] program in SC, see below also). For certain activities, a Nationwide Permit through the United States Army Corps of Engineers has been used to cover many ''traditional'' shellfish cultivation activities, and many states have allowed restoration activities to be addressed through this permit. We encourage individuals, NGOs, and other entities to talk with their relevant local, state and federal regulatory agencies upfront to discuss any potential hoops and hurdles, long before the on-the-ground restoration efforts are planned as many states. Several presentations were given at this workshop from agency representatives from Californis, Oregan, and Washington. States typically have very different permitting requirements, and practitioners can find the permitting process to be cumbersome and time consuming. For example, state and federal permitting for reef restoration efforts can require more than a year in some states (A. Power UGA, pers. comm.). However, restoration projects that pair non-governmental community-based practitioners with state management agencies often fare better. In South Carolina, the SCORE program managed by SC Department of Natural Resources has expedited the permitting process using signs, dedicated collecting permits and other streamlined processes (e.g., maps from GIS provided to other permitting agencies in the state). Its reefs fall under research efforts and hence are more easily approved. Similarly, restoration efforts in Virginia and Maryland often been organized through partnerships between management agencies and community groups.

Second, freshly shucked shells may be a vector for oyster pathogens and should be allowed to dry on land for an appropriate length of time to decrease this risk. Bushek et al. (2004) recommended that freshly shucked shells be stored on land for a period of at least 1–3 mo (function of location and time of year) prior to deployment to reduce the risk of disease transmission to newly restored sites. Storage of shells for significant lengths of time, particularly in urban areas, can be a significant challenge. Movement of shellfish from areas with HABs can also transfer these blooms to areas without them (e.g., Hégaret et al. 2008).

Finally, third there is increasing evidence that reef architecture such as depth of the planted shell layer and three-dimensionality of reef structure can affect the health of oysters and, ultimately, the outcome of the project (e.g., Bartol & Mann 1997, Lenihan et al. 1999, Luckenbach et al. 1999, ASMFC 2007).

Figure 2. Oyster gardening technology includes various floating cages, suspended cages, or off-bottom trays.

Figure 3. The Nature Conservancy used an approach that combined a static structural approach to reducing wave energy with efforts to enhance oyster reef habitat in Texas. The ''Reef Bloc'' structures dissipate wave energy from frequent tug and barge traffic in the Gulf Intracoastal Waterway, and have developed a substantial population of oysters after just 18 mo (photos: Jared Laing, TNC).

Techniques for addressing Recruitment Limitation

Many Eastern oyster populations are currently exhibiting low or limited rates of natural recruitment relative to historic levels, although reference data are scarce. Estuaries where populations are at historic lows and where ''recruitment bottlenecks'' are prevalent include Chesapeake Bay (Mann & Evans 2004), portions of Delaware Bay (Bushek, pers. comm.), and Great Bay New Hampshire (Odell et al. 2006 and references therein). In such recruitment limited systems, two broad techniques identified in the NERI database are often used in restoration projects: oyster gardening and/or stock enhancement.

Oyster Gardening

Oyster gardening is the practice of cultivating oysters, most often produced from hatchery stocks, using small-scale aquaculture techniques such as floating cages, suspended cages or off-bottom racks (see Fig. 2). In oyster gardening, the grow-out of oysters is accomplished in a diffuse fashion, often in the care of volunteers, school classes, or civic groups who maintain the aquaculture structures at multiple locations (e.g., private docks, private or municipal marinas, or boat landings) for a significant period of time. Often, the objective is to grow the oysters large enough to pass thresholds for mortality from predation after transplanting (e.g., Brumbaugh et al. 2000b). We use this objective and the characteristic of diffuse (i.e., remote) grow-out locations to distinguish oyster gardening from other forms of ''stock enhancement'' discussed in the next section. Most projects using oyster gardening were located in the midAtlantic region (22 of 30 total), which reflects a trend of recruitment limitation in the midAtlantic and northward portions of *C. virginica*'s range.

Oyster gardening is an effective public relations tool and a way to engage large numbers of people directly in the management and restoration of oysters and associated reef habitat. The large volunteer element also provides tremendous leverage — volunteer hours are frequently used as in-kind match for public funding sources (see Leslie et al. 2004). From an ecological perspective, oyster gardening enables the grow-out of large numbers of shellfish that may serve to increase spawning stocks over time (Brumbaugh et al. 2000b). For example, with the help of more than 1,800 volunteers, the Chesapeake Bay Foundation's ''Oyster Corps'' has produced more than 1.5 million juvenile (seed) oysters for 36 restoration projects over the course of 10 y (S. Reynolds, pers. comm.).

Oyster gardening programs require the active management of a large volunteer base, which is time consuming and often outside the realm of expertise or capabilities of most research or management agencies. It also requires access to technical expertise on oyster cultivation and hatchery-based production of oysters for grow-out. Lastly, it requires a means of transferring oysters produced through the program to restoration sites. Partnerships between nongovernmental community organizations, research institutions, and public management agencies are often used to bridge the various gaps in capacity or expertise. An excellent example is the partnership between the Chesapeake Bay Foundation, Maryland Department of Natural Resources and University of Maryland's Horn Point Hatchery.

Oyster gardening technology can take many forms, including: (1) floating rafts (often called "oyster floats"), (2) suspended cages, or (3) trays deployed in shallow waters (Fig. 2). Volunteers provide the labor pool necessary to maintain these structures over the course of a grow-out period—frequently one year or less (Brumbaugh et al. 2000b). Some states are reluctant to allow oyster gardening in areas that do not allow direct harvesting (i.e., Prohibited or Restricted harvesting classifications) because of concerns about water quality and human health (e.g., Alabama). However, a few states have created permits or other processes for facilitating restoration in closed areas. For example, Virginia has worked closely with stakeholders to develop a "Non-commercial oyster gardening permit" that helps to track oyster gardening activities and ensure a clear line of communication between agencies and volunteers (Brumbaugh et al. 2000b). Ultimately, enabling restoration in such areas demonstrates a shift toward more ecosystem-based management of shellfish.

Stock Enhancement

Most bivalves are broadcast spawners, with their reproduction most successful when shellfish occur in very dense aggregations. It is reasonable to assume that increasing shellfish densities within a define area has the potential of increasing fertilization success and associated larval production rates (at least locally), whereas potentially increasing subsequent recruitment to a given area, especially in retention estuaries (e.g., Southworth & Mann 1998, Brumbaugh et al. 2000a). Broadly speaking, we consider stock enhancement to include any means of rapidly increasing oyster density within a defined area through the addition of live broodstock or juvenile (seed) oysters. Often this is accomplished through deployment of large numbers of hatchery produced "spat" on shell, within areas designated as "spawner sanctuaries" (i.e., sites designated and managed for services other than shellfish harvest). This approach is being used in a number of states including Virginia and North Carolina (as well as in New York for clams and scallops).

Although a primary objective of stock enhancement is to overcome recruitment limitations (bottlenecks), stock enhancement projects are also used as a means of reef creation (e.g., Tolley & Volety 2005, Rodney & Paynter 2006). As with other techniques outlined here, it can be used to gain support from commercial and recreational fisheries, when associated with a harvest outcome or related management objective(s). For example, a hybrid system of stocked "harvest reserves" has been established in Maryland that allows for a limited harvest after some defined period of time (typically three years) whereas allowing other ecosystem services to accrue in the interim (see the Oyster Recovery Partnership at http://www.oysterrecovery.org/reserves.html).

In some instances there is a nursery phase that involves the deployment of young oysters within a nursery area and subsequent redeployment to a more permanent sanctuary site. The creation of "spawner sanctuaries" has emerged as one of the most commonly used tools for increasing broodstock densities and, increasingly, sanctuaries are stocked to more rapidly increase the density of broodstock within the sanctuary area (Brumbaugh et al. 2000a; Southworth & Mann 1998).

Logistical Considerations for Implementation

As with substrate enhancement efforts, there are 3 logistical constraints that need to be addressed related to restoration efforts:

First, a demographic approach can be used to set restoration objectives and to identify the most important impediments to population recovery (e.g., low broodstock density resulting in decreased fertilization success and larval production, see Mann & Evans 1998, Mann & Evans 2004). Efforts to increase local broodstock densities have shown promise as a means of overcoming recruitment bottlenecks. Southworth & Mann (1998) noted a dramatic increase in juvenile oyster settlement in the Great Wicomico River subsequent to the transplanting of large broodstock oysters on a sanctuary reef in the river. Brumbaugh et al. (2000a) noted similar order-of-magnitude increases in juvenile oyster settlement in the Lynnhaven and Elizabeth Rivers in VA after stock enhancement efforts there. Although the evidence that spawning by stocked oysters contributed to these subsequent increases remains equivocal, there is at least strong anecdotal evidence that stock enhancement is a potentially valuable approach in areas where recruitment may be limiting. Molecular techniques to assess the contribution of stocked oysters, coupled with spatially explicit hydrodynamic models provide opportunities to more quantitatively assess the effects of stock enhancement efforts (Milbury et al. 2004, Sisson et al. 2005).

Second, creation or designation of spawner sanctuaries for stock enhancement is often through local or state regulation that sets the area aside for a specific purpose, and is a strategy being applied to oyster reef restoration (e.g., Maryland, North Carolina, Virginia), as well as clam and scallop restoration (e.g., New York, Rhode Island). Spawner sanctuaries can be designated on both submerged or intertidal bottoms, and be managed directly by the public management agency, or by a private conservation organization on bottom leased from public management agencies (e.g., Washington State conservation leasing program: http://www.dnr.wa.gov/htdocs/aqr/conservation_leasing/index.html) or bottom that is privately owned in fee simple title (e.g., TNC projects in Virginia and New York). Although spawner sanctuaries are typically managed as "no take" zones for shellfish, they are frequently promoted as sites for recreational angling (e.g., North Carolina Division of Marine Fisheries: http://www.ncfisheries.net/shellfish/sanctuary1.htm).

Finally, conservation of genetic stocks of Olympia oysters have been identified as a priority for management agencies from California, Oregon, and Washington (e.g., Cook et al. 1998, M.D. Camara this special issue and associated papers/presentations at the 2006 workshop, http://www.nmfs.noaa.gov/habitat/restoration/publications/westcoastoysters2006/2006OysterProceedings_web_regular.pdf), but given the long history of moving seed oysters along the coast for commercial fisheries enhancement, the management of genetic stocks is just beginning to emerge as a consideration in *C. virginica* restoration. Significant effort has been directed at developing disease resistant strains of *C. virginica* for aquaculture production, and there is interest in using such directed strains as tools for restoration both to overcome parasite-driven mortality and to identify progeny of stocked oysters (e.g., Allen et al. 2003, Milbury et al. 2004).

Combining Techniques

Oyster populations in some estuaries suffer from habitat (substrate) and recruitment limitations, and this is particularly true in Chesapeake Bay. Most of the restored acreage recorded in the NERI (Table 1) represents reef construction projects in Chesapeake Bay, and particularly in the southern Virginia portion of the Bay. Although stock enhancement and oyster gardening have been included as elements of some of the projects in this estuary, most of the restoration projects were designed to address only habitat limitation without regard to recruitment limitation that might also be a factor in a given location. Subsequently, the low overall recruitment rates and slow accumulations of oysters on many of these project sites (Table 2) has provoked a considerable debate within the region about the relative "success" or "failure" of restoration efforts initiated in the mid-1990s, and raised questions about the viability of a habitat-limitation based approach to *C virginica* restoration (e.g., NRC 2004). Increasingly, however, efforts to integrate stock enhancement activities are being incorporated into integrated into restoration plans (e.g., USACE 2005), reflecting a broader consensus that restoration efforts must address both habitat and recruitment limitations simultaneously rather than in sequence.

CONCLUSIONS AND RECOMMENDATIONS

Despite a diverse and extensive literature on *C. virginica* throughout its range (Canada to Gulf of Mexico-Brazil), there are relatively few attempts to generate United States datasets that have statistically-comparable methodologies for meta-analyses, nor are there appropriate ecological data on reefs prior to their decline in areas with subtidal or intertidal reefs. Approaches for monitoring and restoring these two very different reef habitats can be quite different as well (e.g., Luckenbach et al. 1999, Luckenbach et al. 2005, ASMFC 2007, Coen et al. 2007b, Nestlerode et al. 2007). Hence we have inadequate "reference" data or sites to assess restoration "success" to some historically-healthy reef condition (e.g., Thayer et al. 2003, Thayer et al. 2005, Brumbaugh et al. 2006, ASMFC 2007). In a strange twist of fate, the current EIS for introducing a nonnative oyster (*C. ariakensis*) into the Chesapeake has galvanized funding and the political will to invest in large-scale, collaborative efforts that can develop and evaluate the ecosystem services that oysters provide, along with efforts to restore those services lost through its (*C. virginica*) demise (Coen et al. pers. obs., recent NSA dedicated session and JSR volume). These new data and associated modeling efforts would never have been supported and integrated without it being compelled by the EIS process.

There is still much to learn about restoration and management of *C. virginica*. Efforts for restoring the Olympia oyster (e.g.,

TABLE 2.

Range of mean oyster population densities (oysters · m^{-2}) of eastern oysters at various restoration sites from Virginia to Texas in 2004 and 2005.

Location	Reef Characteristics	2004 (oysters m^{-2})	2005 (oysters m^{-2})	Survey Method	Source
Virginia (Chesapeake Bay)	Subtidal and intertidal unconsolidated shell reefs	0–966 (n = 60 sites)	0–804 (n = 54 sites)	Diver deployed quadrats (0.25 m^{-2})	Virginia Marine Resources Commission (unpubl.)
North Carolina (Pamlico Sound)	subtidal limestone marl (Class B rip-rap) reefs	na	118–360 (n = 2 sites)	Diver deployed quadrats (0.0625 m^{-2})	TNC (unpubl.)
South Carolina	intertidal shell bag reefs	na	584–10,857 (n = 20 sites)	na	SC DNR / SCORE
Florida (Indian River Lagoon)	intertidal reefs	na	0–74.5 (n = 6 sites)	na	W. Arnold & M. Parker, FFWRI
Florida (Gulf coast)	intertidal reefs	108–3,568 (n = 9 sites)	na	Quadrats (0.25 m^{-2})	G. Tolley & A. Volety, FGCU
Gulf Intracoastal Waterway, TX	"reef block" cages containing loose shell	na	1,014 (n = 1 site)	Quadrats (0.16 m^{-2})	J. Laing, TNC unpubl. data

Peter-Contesse & Peabody 2005, Hosack et al. 2006) have additional challenges and potentially even more hurdles. In comparison with the Eastern oyster, restoration and related efforts for the Olympia oyster, *Ostrea lurida (*e.g., Peter-Contesse & Peabody 2005, this volume) seem far more complex, in that there is: (1) little detailed historical information of any kind from its pre-exploited days (pre1890s); (2) few "reference reefs" or abundant extant natural populations along its former broad-range to use for either (a) captive breeding/remote setting, or (b) simply studying them for the ecological roles they might serve (e.g., Peter-Contesse & Peabody 2005, Ruesink et al. 2005, pers. comm., M. Camara pers. comm.); and (3) the Olympia oyster has a very different life history and associated unknowns (e.g., impacts from interactions with *C. gigas*, small size and fecundity relative to *Crassostrea* spp., small effective population sizes, "best" stocks to use for each bay or region, internal brooding, novel diseases, to name just a few issues of significance to restoration). Recent work on *C. ariakensis* in North Carolina has highlighted a poorly-studied, native oyster, the crested oyster, *Ostreola* (*Ostrea) equestris* (e.g., Burreson et al. 2004, Bishop et al. 2006, Carnegie et al. in prep.). This work discovered both a new *Bonamia* sp. and collected data on an endemic *Bonamia* sp. that may impact *C. ariakensis'* introduction, with *O. equestris* potentially acting as an unexpected parasite reservoir (Bishop et al. 2006, Carnegie et al. 2006, Carnegie et al. in review, pers. comm., see http://www.bayjournal.com/article.cfm?article=1234).

Critical for all shellfish restoration efforts are explicit goals and appropriate metrics for their assessment. This has been a major flaw for many restoration efforts in general and probably for most, if not all *C. virginica* restoration efforts. In fact, we as researchers have promised many restored "services," but there have been few attempts to demonstrate these empirically (e.g., Coen & Luckenbach 2000, Luckenbach et al. 2005, Grizzle et al. 2006, Coen et al. 2007a, Grizzle et al. 2008). On the east coast of the United States, longer-term, temporal patterns are only just beginning to be assessed for restoration efforts that are now reaching 5–10 y of age (Powers et al. in press), and larger-scale ecosystem impacts have yet to be assessed in any rigorous manner. Despite these limitations, we can offer the following recommendations for advancing *O. lurida* restoration efforts, based on progress to date with *C. virginica* on the east coast of the United States:

- ***Address limitations in data on historic distribution and abundance***
  1. Set clear goals to illustrate whether projects are for environmental "enhancement" or are truly "restoration" in that they are replacing reefs that were historically present at a given site. Goals should be defined at multiple levels (project, estuarine, state, regional) to provide context for monitoring and interpretation of results;
  2. Define site selection criteria early (slope, sediment characteristics, flow regime, etc.) to enable comparisons across projects over time; and
  3. Establish monitoring and mapping programs in conjunction with restoration projects. These should be seamless and robust to enable comparisons across projects, should monitor effects beyond just the target species, and should readily enable managers to track progress over time;
- ***Reconcile the potentially conflicting goals of fishery enhancement (the traditional objective) and ecological restoration (the "new" objective);***
  1. Recognize that it may not be possible to manage effectively for both a fishery and ecosystem services in the same physical location.
  2. It is not yet clear how much ecological restoration is needed to provide significant fishery benefits outside the restoration zone (e.g., "spillover" effect), so use caution when advancing this as a potential outcome (lest fisheries landings become the only yardstick for determining "success" or "failure" of projects);
  3. Similarly, it remains to be seen whether areas that are enhanced strictly for fisheries production provide the full array of ecosystem services desired from an oyster reefs as ecosystems; and
  4. Develop a long-term management strategy at the outset so that restoration gains are protected. Although there is currently no fishery for Olympia oysters, restoration efforts could spark an interest in reviving a fishery over time. Setting benchmarks for restored populations and ecosystem structure at the beginning of restoration efforts will minimize user conflicts.

- ***Set public expectations early by educating the public about the scale of the problem (i.e., declines are enormous for both C. virginica and O. lurida across their respective ranges) and the magnitude of restoration response-necessary to address the problem.***
  1. place restoration efforts in context (speaks to point about setting goals) – be sure public, decision makers and granting agencies understand this requires a large and long-term commitment and a substantial investment;
  2. monitoring should be embraced as part of adaptive management approach – restoration approaches will likely evolve over time as data are collected that improve design of individual projects and inform larger restoration goals; and
  3. use restoration to educate the public about linkages between watersheds and water quality and to propel initiatives requiring broad public support (e.g., Macfarlane 1996). For example, impacts of degraded water quality on restoration projects in Virginia were used to illuminate the need for sewage treatment plant upgrades to reduce nitrogen loading in Chesapeake Bay (Lawrence Latane, Richmond Times-Dispatch, 10 September 2003). Also, progress with oyster restoration in the Lynnhaven has spurred interest in upgrades to stormwater and sewage infrastructure, as well as changes in personal behavior (e.g., a "*Scoop the Poop*" pet waste disposal campaign) to improve water quality in the river http://www.lynnhavenrivernow.org/poop.html).

By far, the most important lesson we can impart is that restoration efforts should be designed in a scientifically-sound manner, with sufficient data collected on restored and 'reference' (control) sites to learn what does and does not work well. The research, management and restoration community is just beginning to build the case for managing and conserving oyster reefs created by any species for biodiversity conservation. Significant effort will be required to develop a consensus in management and the general public that oyster reef habitat is a critical element necessary for conserving diverse species assemblages in temperate coastal waters, analogous to how coral reefs in tropical systems are now viewed, and solid comparable data from restoration projects would accelerate this effort.

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LITERATURE CITED

Allen, S. K., D. Schulte & R. D. Brumbaugh. 2003. Terraforming Chesapeake Bay. *Virginia Marine Resources Bulletin* 35:2–8.

ASMFC. 2007. The Importance of Habitat Created by Shellfish and Shell Beds Along the Atlantic Coast of the US, prepared by L. D. Coen and R. Grizzle, with contributions by J. Lowery and K. T. Paynter, Jr., estimated. 106 pp.

Baker, P. 1995. Review of ecology and fishery of the Olympia oyster, *Ostrea lurida* with annotated bibliography. *J. Shellfish Res.* 14:501–518.

Bartol, I. K. & R. Mann. 1997. Small-scale settlement patterns of the oyster *Crassostrea virginica* on a constructed intertidal reef. *Bull. Mar. Sci.* 61:881–897.

Beck, M., R. Brumbaugh, L. Airoldi, A. Carranza, L. Coen, C. Crawford, O. Defeo, G. Edgar, B. Hancock., M. Kay, H. Lenihan, M. Luckenbach, C. Toropova & G. Zhang, in review. Shellfish reefs at risk globally and recommendations for ecosystem revitalization. Submitted to *Proc. Nat. Acad. Science*.

Bishop, M. J., R. B. Carnegie, N. A. Stokes, C. H. Peterson & E. M. Burreson. 2006. Complications of a non-native oyster introduction: facilitation of a local parasite. *Mar. Ecol. Prog. Ser.* 325:145–152.

Breitburg, D. L. 1999. Are three-dimensional structure and healthy oyster populations the keys to an ecologically interesting and important fish community? In: M. Luckenbach, R. Mann & J. A. Wesson, editors. Oyster reef habitat restoration: a synopsis and synthesis of approaches. Gloucester Point, VA: VIMS Press. pp. 239–250.

Breitburg, D., L. D. Coen, M. W. Luckenbach, R. Mann, M. Posey & J. A. Wesson. 2000. Oyster reef restoration: convergence of harvest and conservation strategies. *J. Shellfish Res.* 19:371–377.

Brumbaugh, R. D., L. A. Sorabella, C. Oliveras Garcia, W. J. Goldsborough & J. A. Wesson. 2000a. Making a case for community-based restoration: An example from Hampton Roads, Virginia, USA. *J. Shellfish Res.* 19:467–472.

Brumbaugh, R. D., L. A. Sorabella, C. Johnson & W. J. Goldsborough. 2000b. Small-scale aquaculture as a tool for oyster restoration in Chesapeake Bay. *Mar. Tech. Soc.* 34:79–86.

Brumbaugh, R. D. 2000. An analysis of limestone marl as a settlement substrate for oysters in Chesapeake Bay. Report to the Virginia Marine Resources Commission. Chesapeake Bay Foundation, Norfolk VA. 12 pp.

Brumbaugh, R. D., M. W. Beck, L. D. Coen, L. Craig & P. Hicks. 2006. A Practitioners' Guide to the design and monitoring of shellfish restoration projects: an ecosystem services approach. The Nature Conservancy, Arlington, VA., MRD Educational Report No. 22. 28 pp.

Burreson, E. M., N. A. Stokes & C. S. Friedman. 2000. Increased virulence in an introduced pathogen: *Haplosporidium nelsoni* (MSX) in the eastern oyster *Crassostrea virginica*. *J. Aquat. Anim. Health* 12:1–8.

Burreson, E. M., N. A. Stokes, R. B. Carnegie & M. J. Bishop. 2004. *Bonamia* sp. (Haplosporidia) found in non-native oysters *Crassostrea ariakensis* in Bogue Sound, North Carolina. *J. Aquat. Anim. Health* 16:1–9.

Bushek, D., D. Richardson, M. Y. Bobo & L. D. Coen. 2004. Short-term shell pile quarantine reduces the abundance of *Perkinsus marinus* remaining in tissues attached to oyster shell. *J. Shellfish Res.* 23:369–373.

Byers, J. E., K. Cuddington, C. G. Jones, T. S. Talley, A. Hastings, J. G. Lambrinos, J. A. Crooks & W. G. Wilson. 2006. Using ecosystem engineers to restore ecological systems. *Trends Ecol. Evol.* 21:493–500.

Chatry, M., C. Dugas & G. Laiche. 1986. Comparison of oyster settling rates on clamshell and crushed limestone. *Louisiana Wildlife and Fisheries Commission Technical Bulletin* 1986. pp. 54–60.

Coen, L. D., D. M. Knott, E. L. Wenner, N. H. Hadley & A. H. Ringwood. 1999a. Intertidal oyster reef studies in South Carolina: design, sampling and experimental focus for evaluating habitat value and function. In: M. W. Luckenbach, R. Mann, J. A. Wesson, editors, Oyster Reef habitat restoration: a synopsis and synthesis of approaches. Virginia Institute of Marine Science Press, Gloucester Point, Virginia. pp. 131–156.

Coen, L. D., M. W. Luckenbach & D. L. Breitburg. 1999b. The role of oyster reefs as essential fish habitat: a review of current knowledge and some new perspectives., In: L. R. Benaka, editor. Fish habitat: essential fish habitat and rehabilitation. American Fisheries Society. Symposium 22, Bethesda, Maryland. pp. 438–454.

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

Coen, L. D. & M. Bolton-Warberg. 2005. An examination of the impacts of various harvesting/ management strategies and boat wakes on oyster bed condition, recovery rates, shoreline erosion and restoration. A marine recreational fisheries stamp program final Report. 96 pp.

Coen, L. D., R. D. Brumbaugh, D. Bushek, R. Grizzle, M. W. Luckenbach, M. H. Posey, S. P. Powers & G. Tolley. 2007a. AS WE SEE IT. A broader view of ecosystem services related to oyster restoration. *Mar. Ecol. Prog. Ser.* 341:303–307.

Coen, L., K. Walters, D. Wilber & N. Hadley. 2007b. 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, sea grant publication. 27 pp.

Cook, A. E., J. A. Shaffer & B. Dumbauld. 1998. Olympia oyster stock rebuilding plan for Washington State. *Puget Sound Res.* 98:525–530.

Couch, D. & T. J. Hassler. 1989. Species profiles: life history and environmental requirements of coast fishes and invertebrates. Olympia oyster. Biological report for the United States Army Corps of Engineers and Department of Interior 82 (11.124) TR EL 82-4.

Craft, C., J. Reader, J. N. Sacco & S. W. Broome. 1999. Twenty-five years of ecosystem development of constructed *Spartina alterniflora* (Loisel) marshes. *Ecol. Appl.* 9:1405–1419.

Carnegie, R. B., E. M. Burreson, P. Mike Hine, N. Stokes, C. Audemard, M. J. Bishop & C. H. Peterson. 2006. *Bonamia perspora* n. sp. (Haplosporidia), a parasite of the oyster *Ostreola equestris*, is the first *Bonamia* species known to produce spores. *J. Eukar. Mirobiol.* 53:232–245.

Cressman, K. A., M. H. Posey, M. A. Mallin, L. A. Leonard & T. D. Alphin. 2003. Effects of oyster reefs on water quality in a tidal creek estuary. *J. Shellfish Res.* 22:753–762.

Dame, R. 1996. Ecology of marine bivalves: an ecosystem approach. CRC Marine Science Series, Boca Raton. 254 pp.

Dame, R., D. Bushek & T. Prins. 2001. The role of suspension feeders as ecosystem transformers in shallow coastal environments. In K. Reise, editor. The ecology of sedimentary coasts. Berlin: Springer-Verlag. pp. 11–37.

Dugas, R., R. Leard & M. E. Berrigan. 1991. A partial bibliography of oyster cultch materials and resource management projects Gulf States Mar. Fish. Comm. EPA Chesapeake Bay Program. 2000. Chesapeake 2000 Agreement. http://www.chesapeakebay.net/agreement.htm (accessed March 1, 2007) 12 pp.

EPA Chesapeake Bay Program. 2000. *Chesapeake 2000 Agreement*. EPA Chesapeake Bay Program, Annapolis, MD. 13 pp.

Grabowski, J. H. & C. H. Peterson. 2007. Restoring oyster reefs to recover ecosystem services. In: *Ecosystem Engineers*. K. Cuddington, J. Byers, W. Wilson & A. Hastings, eds. Elsevier Press. pp. 281–298.

Grizzle, R. E., J. R. Adams & L. J. Walters. 2002. Historical changes in intertidal oyster (*Crassostrea virginica*) reefs in a Florida lagoon potentially related to boating activities. *J. Shellfish Res.* 21:749–756.

Grizzle, R. E., J. K. Greene, M. W. Luckenbach & L. D. Coen. 2006. A new *in situ* method for measuring seston uptake by suspension-feeding bivalve molluscs. *J. Shellfish Res.* 25:643–649.

Grizzle, R.E., J.K. Greene & L.D. Coen. 2008. Seston removal by natural and constructed intertidal eastern oyster (*Crassostrea virginica*) reefs: a comparison with previous laboratory studies, and the value of *in situ* methods. Estuaries and Coasts.

Grosholz, E. D. & G. M. Ruiz. 1995. Does spatial heterogeneity and genetic variation in populations of the xanthid crab *Rhithropanopeus harrisii* (Gould) influence the prevalence of an introduced parasitic castrator? *J. Exp. Mar. Biol. Ecol.* 187:129–145.

Gutiérrez, J. L., C. G. Jones, D. L. Strayer & O. O. Iribarne. 2003. Mollusks as ecosystem engineers: the role of shell production in aquatic habitats. *Oikos* 101:79–90.

Hadley, N. H. & L. D. Coen. 2002. Community-based program engages citizens in oyster reef restoration (South Carolina). *Ecol. Res.* 20:297.

Hadley, N., M. Hodges, D. H. Wilber & L. D. Coen. Evaluating intertidal oyster reef development using community-based restoration approaches in South Carolina. *Restor. Ecol.* (in press).

Hargis, W. J., Jr. & D. S. Haven. 1999. Chesapeake oyster reefs, their importance, destruction and guidelines for restoring them. In: M. W. Luckenbach, R. Mann & J. A. Wesson, editors. Oyster reef habitat restoration: a synopsis and synthesis of approaches. Gloucester Point, VA: VIMS Press. pp. 5–23.

Harry, H. W. 1985. Synopsis of the supraspecific classification of living oysters (Bivalvia, Gryphaeidae and Ostreidae). *Veliger* 28:121–158.

Haven, D. S., W. J. Hargis, Jr & P. C. Kendall. 1978. The oyster industry of Virginia: its status, problems and promise. Virginia Sea Grant Special Paper #4. 1,024 pp.

Haven, D. S., J. M. Zeigler, J. T. Dealteris & J. P. Whitcomb. 1987. Comparative attachment, growth, and mortalities of oyster (*Crassostrea virginica*) spat on slate and oyster shell in the James River, Virginia. *J. Shellfish Res.* 6:45–48.

Haywood, E. L. & T. M. Soniat. 1992. The use of cement-stabilized gypsum as cultch for the eastern oyster, *Crassostrea virginica* (Gmelin, 1791). *J. Shellfish Res.* 11:417–420.

Hégaret, H., S. E. Shumway, G. H. Wikfors, S. Pate & J. M. Burkholder. 2008. Potential transport of harmful algae through relocation of bivalve molluscs. *Mar. Ecol. Prog. Ser.* 361:169–179.

Hosack, G. R., B. R. Dumbauld, J. L. Ruesink & D. A. Armstrong. 2006. Habitat associations of estuarine species: comparisons of intertidal mudflat, seagrass (*Zostera marina*), and oyster (*Crassostrea gigas*) habitats. *Estuaries Coasts* 29:1150–1160.

Jackson, J. B. C., M. X. Kirby, W. H. Berger, K. A. Bjorndal, L. W. Botsford, B. J. Bourque, R. H. Bradbury, R. Cooke, J. Erlandson, J. A. Estes, T. P. Hughes, S. Kidwell, C. B. Lange, H. S. Lenihan, J. M. Pandolfi, C. H. Peterson, R. S. Steneck, M. J. Tegner & R. R. Warner. 2001. Historical overfishing and the recent collapse of coastal ecosystems. *Science* 293:629–638.

Kennedy, V. S. 1989. The Chesapeake Bay oyster fishery: traditional management practices. In: J. F. Caddy, Editor. Marine invertebrate fisheries: their assessment and management. John Wiley & Sons, New York. pp. 455–477.

Kennedy, V. S., R. I.E. Newell & A.F. Eble, Eds. 1996. The Eastern Oyster: *Crassostrea virginica*. Maryland Sea Grant, College Park, MD. 734 pp.

Kirby, M. X. 2004. Fishing down the coast: historical expansion and collapse of oyster fisheries along continental margins. *Proc. Natl. Acad. Sci. USA* 101:13096–13099.

Kirby, M. X. & H. M. Miller. 2005. Response of a benthic suspension feeder (*Crassostrea virginica* Gmelin) to three centuries of anthropogenic eutrophication in Chesapeake Bay. *Estuar. Coast. Shelf Sci.* 62:679–689.

Kurlansky, M. 2006. The big oyster: history on the half shell. New York, NY: Ballantine Books, Random House. 320 pp.

Lafferty, K. D., J. W. Porter & S. E. Ford. 2004. Are diseases increasing in the ocean? *Annu. Rev. Ecol. Syst.* 35:31–54.

Lehnert, R. L. & D. M. Allen. 2002. Nekton use of subtidal oyster shell habitats in a southeastern U.S. estuary. *Estuaries* 25:1015–1024.

Lenihan, H. S. & C. H. Peterson. 1998. How habitat degradation through fishery disturbance enhances impacts of hypoxia on oyster reefs. *Ecol. Appl.* 8:128–140.

Lenihan, H. S., C. H. Peterson, J. E. Byers, J. H. Grabowski, G. W. Thayer & D. Colby. 2001. Cascading of habitat degradation: oyster reefs invaded by refugee fishes escaping stress. *Ecol. Appl.* 11:764–782.

Lenihan, H. S., F. Micheli, S. W. Shelton & C. H. Peterson. 1999. The influence of multiple environmental stressors on susceptibility to parasites: an experimental determination with oysters. *Limnol. Oceanogr.* 44:910–924.

Lenihan, H. S. 1999. Physical-biological coupling on oyster reefs: how habitat structure influences individual performance. *Ecol. Monogr.* 69:251–275.

Leslie, L. L., C. E. Velez & S. A. Bonar. 2004. Utilizing volunteers on fisheries projects: benefits, challenges and management techniques. *Fisheries* 29:10–14.

Lotze, H. K., H. S. Leniham, B. J. Bourque, R. H. Bradbury, R. G. Cooke, M. C. Kay, S. M. Kidwell, M. X. Kirby, C. H. Peterson & J. B. C. Jackson. 2006. Depletion, degradation, and recovery potential of estuaries and coastal seas. *Science* 312:1806–1809.

Louisiana Department of Wildlife and Fisheries. 2004. Louisiana's oyster shell recovery pilot project. Final Report for NOAA Award No. NA96FK0188, Socioeconomics research and development section and marine fisheries division. 253 pp.

Luckenbach, M. W., R. Mann & J. A. Wesson, Eds. 1999. Oyster reef habitat restoration. A Synopsis and Synthesis of Approaches. Virginia Institute of Marine Science Press. Virginia Gloucester Point, VA: Institute of Marine Science Press 358 pp.

Luckenbach, M. W., L. D. Coen, P. G. Ross, Jr. & J. A. Stephen. 2005. Oyster reef habitat restoration: relationships between oyster abundance and community development based on two studies in Virginia and South Carolina. *J. Coast. Res.* Special Issue 40: 64–78.

Macfarlane, S. L. 1996. Shellfish as the impetus for embayment management. *Estuaries* 19:311–319.

Mann, R. & D. A. Evans. 1998. Estimation of oyster, *Crassostrea virginica*, standing stock, larval production and advective loss in relation to observed recruitment in the James River, Virginia. *J. Shellfish Res.* 17:239–254.

Mann, R. & D. A. Evans. 2004. Site selection for oyster habitat rehabilitation in the Virginia portion of the Chesapeake Bay: A commentary. *J. Shellfish Res.* 23:41–49.

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

Michener, W. K. & P. D. Kenny. 1991. Spatial and temporal patterns of *Crassostrea virginica* (Gmelin) recruitment: relationship to scale and substratum. *J. Exp. Mar. Biol. Ecol.* 154:97–121.

Milbury, C. A., D. W. Meritt, R. I. E. Newell & P. M. Gaffney. 2004. Mitochondrial DNA markers allow monitoring of oyster stock enhancement in Chesapeake Bay. *Mar. Biol.* 145:351–359.

Miller, A. W., G. M. Ruiz, M. S. Minton & R. F. Ambrose. 2007. Differentiating successful and failed molluscan invaders in estuarine ecosystems. *Mar. Ecol. Prog. Ser.* 332:41–51.

Nelson, K. A., L. A. Leonard, M. H. Posey, T. D. Alphin & M. A. Mallin. 2004. Using transplanted oyster beds to improve water quality in small tidal creeks: a pilot study. *J. Exp. Mar. Biol. Ecol.* 298:347–368.

Nestlerode, J. A., M. W. Luckenbach & F. X. O'Beirn. 2007. Settlement and survival of the oyster *Crassostrea virginica* on constructed oyster reef habitats in Chesapeake Bay. *Restor. Ecol.* 15:273–283.

National Research Council (NRC). 2004. Nonnative oysters in the Chesapeake Bay. Washington, DC: National Academies Press. 325 pp.

Newell, R. I. E. 2004. Ecosystem influences of natural and cultivated populations of suspension-feeding bivalve mollusks: A review. *J. Shellfish Res.* 23:51–61.

Newell, R. I. E., T. R. Fisher, R. R. Holyoke & J. C. Cornwell. 2005. Influence of eastern oysters on N and P regeneration in Chesapeake Bay, USA. In: R. Dame & S. Olenin, editors. The comparative roles of suspension feeders in ecosystems. Vol 47 NATO Science Series: IV—Earth and environmental sciences. Netherlands: Springer. pp. 93–120.

North Carolina Division of Marine Fisheries. 2001. North Carolina oyster fishery management plan. North Carolina Department of Environment and Natural Resources, Morehead City, NC, Rev. 1/03. 218 pp.

O'Beirn, F. X. 1996. Recruitment of the eastern oyster in coastal Georgia: patterns and recommendations. *N. Am. J. Fish. Manage.* 16:413–426.

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

Odell, J., A. Eberhardt, D. Burdick & P. Ingraham. 2006. Great Bay estuary compendium New Hampshire Coastal Program and New Hampshore Estuaries Project. 93pp. http://www.nhep.unh.edu/resources/pdf/great_bay_restoration-tnc-06.pdf.

Olafsson, E. B., C. H. Peterson & W. G. Ambrose, Jr. 1994. Does recruitment limitation structure populations and communities of macro-invertebrates in marine soft sediments: the relative significance of pre- and post-settlement processes. *Ocean. Mar. Biol. Ann. Rev.* 32:65–109.

Palmer, M. A., R. F. Ambrose & N. L. Poff. 1997. Ecological theory and community restoration ecology. *Restor. Ecol.* 5:291–300.

Peter-Contesse, T. & B. Peabody. 2005. Reestablishing Olympia oyster populations in Puget Sound, Washington. Washington Sea Grant Publication WSG-AS 05-04. 9 pp.

Peterson, C. H., J. H. Grabowski & S. P. Powers. 2003a. Estimated enhancement of fish production resulting from restoring oyster reef habitat: quantitative valuation. *Mar. Ecol. Prog. Ser.* 264:251–256.

Peterson, C. H., R. T. Kneib & C. Manen. 2003b. Scaling restoration actions in the marine environment to meet quantitative targets of enhanced ecosystem services. *Mar. Ecol. Prog. Ser.* 264:173–175.

Piazza, B. P., P. D. Banks & M. K. La Peyre. 2005. The potential for created oyster shell reefs as a sustainable shoreline protection strategy in Louisiana. *Restor. Ecol.* 13:499–506.

Powell, E. N., J. N. Kraeuter & K. A. Ashton-Alcox. 2006. How long does oyster shell last on an oyster reef? *Estuar. Coast. Shelf Sci.* 69:531–542.

Powers, S. P., C. H. Peterson, J. H. Grabowski & H. S. Lenihan. The realities of native oyster restoration and why the myth of failure intensified a conservation crisis. *Mar. Ecol. Prog. Ser.* (In Press).

Putman, G. 1995. Oyster enhancement and restoration efforts among Gulf and Atlantic coast states. North Carolina Division of Marine Fisheries, North Carolina Department of Environment and Natural Resources, Morehead City, NC. 43 pp.

Reece, K. S., D. Bushek, K. L. Hudson & J. E. Graves. 2001. Geographic distribution of Perkinsus marinus genetic strains along the Atlantic and Gulf coasts of the USA. *Mar. Biol.* 139: 1047–1055.

Rodney, W. S. & K. T. Paynter. 2006. Comparisons of macrofaunal assemblages on restored and non-restored oyster reefs in mesohaline regions of Chesapeake Bay in Maryland. *J. Exp. Mar. Biol. Ecol.* 335:39–51.

Rothschild, B. J., J. S. Ault, P. Goulletquer & M. Héral. 1994. Decline of the Chesapeake Bay oyster population: a century of habitat destruction and overfishing. *Mar. Ecol. Prog. Ser.* 111:29–39.

Ruesink, J. L., H. S. Lenihan, A. C. Trimble, K. W. Heiman, F. Micheli, J. E. Byers & M. C. Kay. 2005. Introduction of non-native oysters: ecosystem effects and restoration implications. *Annu. Rev. Ecol. Evol. Syst.* 36:643–689.

Sisson, G. M., Y. Li, J. Shen & H. V. Wang. 2005. Estimating spatially varying transport times in a shallow water environment using a numerical hydrodynamic model. Estuarine and Coastal Modeling. Proceedings of the Ninth International Conference. Virginia Institute of Marine Science Contribution No. 2728. Gloucester, VA. pp. 216–234.

Smith, G. F., D. G. Bruce, E. B. Roach, A. Hansen, R. I. E. Newell & A. M. McManus. 2005. Habitat conditions of mesohaline oyster bars in the Maryland Chesapeake Bay: An assessment of 40 years of oyster management. *N. Am. J. Fish. Manage.* 25:1569–1590.

Soniat, T. M., R. C. Broadhurst & E. L. Haywood, III. 1991. Alternatives to clamshell as cultch oysters, and the use of gypsum for the production of cultchless oysters. *J. Shellfish Res.* 10:405–410.

Soniat, T. M. & G. M. Burton. 2005. A comparison of the effectiveness of sandstone and limestone as cultch for oysters, *Crassostrea virginica*. *J. Shellfish Res.* 24:483–485.

Southworth, M. & R. Mann. 1998. Oyster reef broodstock enhancement in the Great Wicomico River, Virginia. *J. Shellfish Res.* 17:1101–1114.

Street, M. W., A. S. Deaton, W. S. Chappell & P. D. Mooreside. 2005. North Carolina coastal habitat protection plan. North Carolina Department of Environment and Natural Resources, Division of Marine Fisheries, Morehead City, NC. 656 pp.

Taylor, J. & D. Bushek. 2008. Intertidal oyster reefs can persist and function in a temperate North American Atlantic estuary. *Mar. Ecol. Prog. Ser.* 361:301–306.

Thayer, G. W., T. A. McTigue, R. J. Bellmer, F. M. Burrows, D. H. Merkey, A. D. Nickens, S. J. Lozano, P. F. Gayaldo, P. J. Polmateer & P. T. Pinit. 2003. Science-based restoration monitoring of coastal habitats, Vol. 1: a framework for monitoring plans under the Estuaries and Clean Waters Act of 2000 (Public Law 160-457). NOAA Coastal Ocean Program Decision Analysis Series No. 23. NOAA National Centers for Coastal Ocean Science, Silver Spring, MD. 35pp. plus appendices.

Thayer, G. W., T. A. McTigue, R. J. Salz, D. H. Merkey, F. M. Burrows & P. F. Gayaldo (Eds.). 2005. Science-based restoration monitoring of coastal habitats, Vol. 2.: tools for monitoring coastal habitats. NOAA Coastal Ocean Program Decision Analysis Series No. 23.

NOAA National Centers for Coastal Ocean Science, Silver Spring, Maryland. 628 pp. plus appendices.
Tolley, S. G. & A. K. Volety. 2005. The role of oysters in habitat use of oyster reefs by resident fishes and decapod crustaceans. *J. Shellfish Res*. 24:1007–1012.
United States Army Corps of Engineers (USACE), 2005. Chesapeake Bay oyster recovery phase IV—Lynnhaven River, Virginia. Draft Decision Document Amendment Section 704(b) As Amended. Norfolk District, Norfolk, Virginia,336 pp.
Wall, L., L. Walters, P. Sacks & R. Grizzle. 2005. Recreational boating activity and its impact on the recruitment and survival of the oyster *Crassostrea virginica* on intertidal reefs in Mosquito Lagoon, FL. *J. Shellfish Res*. 24:965–974.
Walters, K. & L. D. Coen. 2006. A comparison of statistical approaches to analyzing community convergence between natural and constructed oyster reefs. *J. Exp. Mar. Biol. Ecol*. 330: 81–95.
Walton, W. & G. Ruiz. 1995. Importation of oysters to Chesapeake Bay as a transfer mechanism for nonindigenous species. Abstract, 1995 Benthic Ecology Meeting, New Jersey.
Zedler, J. B. & J. C. Calloway. 2000. Evaluating the progress of engineered tidal wetlands. *Ecol. Eng*. 15:211–225.