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AN ECOSYSTEM SERVICES APPROACH

A PRACTITIONERS GUIDE TO THE

Design & Monitoring of Shellfish Restoration Projects

NOAA

The mission of The Nature Conservancy is to preserve the plants, animals and natural communities that represent the diversity of life on Earth by protecting the lands and waters they need to survive.

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I. Preface

Bivalve shellfish restoration projects are becoming increasingly common in the United States, spurred by increased public awareness of their important ecological role in coastal waters and increases in funding (primarily federal) available for such efforts. Community groups, school classes and others interested in promoting healthier coastal ecosystems are joining forces with government agencies at the local, state and federal level to help restore these important components of coastal ecosystems. This increased interest in restoration is due, in part, to the dramatic declines in shellfish fisheries that were once the mainstay of many coastal communities. This is also likely due to greater public awareness of the imperiled state of coastal environments in general, and a desire to restore the ecosystems such as oyster reefs, marshes, seagrass beds and mangroves that contribute to an overall healthier environment. The elements of shellfish restoration may appear complex, especially for those who are unfamiliar with bivalve ecology or the basic tenets of restoration science. As a result, it may be difficult to know where to begin.

This guide was written to help restoration practitioners design and monitor shellfish restoration projects that restore not only the populations of target shellfish species – primarily clams, oysters, scallops – but also the 'ecosystem services' associated with healthy populations of these organisms. As a primer for conservationists, resource managers and others interested in understanding basic approaches to the design and implementation of shellfish restoration projects, this publication provides advice on:

1. **Making the case for shellfish restoration**
2. **Identifying candidate species and an appropriate restoration strategy (or strategies)**
3. **Choosing sites for restoration projects**
4. **Monitoring project outcomes**
5. **Creating effective partnerships for restoration projects**

II. Introduction: The case for shellfish restoration

A Lost Resource

Bivalve shellfish have historically been a prominent component of benthic, or bottom dwelling, communities of temperate and subtropical estuaries and coastal baysBivalves also have been and continue to be an important food source for people throughout the world, serving as both as a delicacy and a staple. In coastal communities throughout the U.S., shellfish are cultural icons, reflecting traditions and a way of life dating back generations. It is not surprising therefore that until very recently resource management agencies have focused almost exclusively on maximizing short-term returns from commercial and recreational bivalve harvest.

Once considered nearly inexhaustible, many shellfish populations around the world have declined precipitously – some to commercial extinction - over the past two hundred years. These declines are due in large part to over-exploitation as well as from the related overall decline in the condition of estuaries (Gross and Smyth 1946; Cook et al 2000; Jackson et al 2001; Edgar and Samson 2004; Kirby 2004). In recent decades the translocation of shellfish parasites and diseases between coastal areas has contributed to further losses and has exacerbated the effect of habitat loss (Kennedy et at 1996).

While bivalve fisheries in many places have produced substantial landings, traditional management efforts for shellfish have generally failed to sustain shellfish populations or the fisheries that depended on them. Few bivalve fisheries, if any, have been managed with any evidence of long-term sustainability, both in the U.S. and in many other parts of the world. Oysters and mussels in particular have posed a unique challenge to fishery managers since fishing activities for these species, unlike most fish and other mobile organisms, tends to simultaneously remove their habitat. Various approaches for countering fishery declines have been implemented, ranging from hatchery based put-and-take fisheries to introductions of non-native species, often with mixed results. By managing bivalves and their habitats almost exclusively for recreational and commercial fishing, many facets of their ecology that contribute to maintaining the overall condition of our coastal bays and estuaries have been ignored.

Engineers at Work

With the decline of shellfish populations we have lost more than the fisheries and economic activity associated with fishing. A growing body of research in recent decades has illuminated the profoundly important ecological roles that shellfish play in coastal ecosystems. These roles include filtering water as bivalves feed on suspended algae, providing structured habitat for other species, and protecting shorelines from erosion by stabilizing sediments and dampening waves. In fact, many bivalve shellfish have been labeled 'ecosystem engineers' (Jones et al 1994; Lenihan 1999) in recognition of the multiple roles they play in shaping the environments in which they live. Restoring shellfish populations to our coastal waters, therefore, represents a powerful way to restore the integrity and resilience of these ecosystems.

The Water Filter

Shellfish are suspension-feeders that strain microscopic algae (*phytoplankton*) that grow suspended in surrounding waters. In some coastal systems shellfish, through their feeding activity and resultant deposition of organic material onto the bottom sediments, were abundant enough to influence or control the overall abundance of phytoplankton growing in the overlying waters. This control was accomplished both by direct removal of suspended material and by controlling the rate that nutrients were exchanged between the sediments and overlying waters (Officer et al 1982; Dame 1996; Newell 2004). For example, it is widely touted that in the late 19th century oysters were so abundant in the Chesapeake Bay that they likely filtered a volume of water equivalent to the entire volume of the Bay in less than a week (Newell 1988). This feeding activity contributed to greater water clarity and allowed seagrasses to thrive in more areas of the estuary than is observed today (Newell and Koch 2004).

Similar ecological impacts have been attributed to other species of bivalves as well. Hard clams in Long Island's Great South Bay were likely abundant enough, until about two decades ago, to prevent outbreaks "brown tides" caused by planktonic algae that cloud the water and prevent light from reaching seagrasses growing in the bay. As these algae die, sink to the bottom and decay, they also rob the Bay of oxygen (Kassner 1993; Cerrato et al 2004). The uptake of nutrients and localized impacts on water quality documented for blue mussels, Mytilus edulis, using flume experiments (Asmus and Asmus 1991) and field observations in European estuaries suggest that robust populations of mussels are capable of consuming a considerable fraction of the phytoplankton from overlying waters (Haamer and Rodhe 2000).

Ecosystem modeling and mesocosm studies have indicated that restoring shellfish populations to even a modest fraction of their historic abundance could improve water quality and aid in the recovery of seagrasses (Newell and Koch 2004; Ulanowicz and Tuttle 1992). Field studies have also revealed positive feedback mechanisms from shellfish populations that promote greater seagrass productivity (Peterson and Heck 1999).

The Habitat Provider

In addition to their impacts as filter feeders, some species of bivalve shellfish such as oysters and mussels form reefs or complex structures that provide refuge or hard substrate for other species of marine plants and animals to colonize. For example, the eastern oyster Crassostrea virginica, forms three-dimensional reefs as generations of oysters settle and grow attached to one another (Zimmerman et al 1989; Hargis and Haven 1999; Steimle and Zetlin 2000). Reefs can occur subtidally, often associated with edges of channels, as well as in intertidal habitats, keeping pace with sea-level rise (DeAlteris 1988; McCormick-Ray 1998 and 2005; Hargis and Haven 1999). These reefs represent a temperate analog to coral reefs that occur in more tropical environments. Both kinds of reefs are "biogenic", being formed by the accumulation of colonial animals, and both provide complex physical structure and surface area used by scores of other species as a temporary or permanent habitat. A single square meter of oyster reef may provide 50 square meters of surface area in its cracks, crevices, and convolutions, providing attachment points and shelter for an array of plants and animals (Bahr and Lanier 1981). Given the variety of species and complex interactions of species associated with oyster reefs, they have been suggested as "essential fish habitat," which is an important distinction for fisheries management in the U.S. (Coen et al. 1999). Unfortunately, many of the reefs that were once so prevalent have been mined away through fishing and dredging activities, and their remnant 'footprints' have been silted over in the past century (Rothschild et al. 1994, Hargis and Haven 1999).

The Shoreline Protector

In some regions, intertidal oyster reefs and, likely, mussel beds serve as natural breakwaters that can stabilize shorelines and reduce the amount of suspended sediment in the adjacent waters. This reduction in suspended sediment improves water clarity and protects shellfish, seagrasses and other species. Shellfish restoration, therefore, offers a way to recapture this important ecosystem service (Meyer et al 1997) in some locations.

Given the increased understanding of the various roles that shellfish play in nearshore ecosystems, there is increasing interest in re-establishing robust and self-sustaining native shellfish populations as a component of coastal ecosystems. Indeed, the restoration of shellfish is increasingly invoked as a key strategy for rehabilitating and conserving marine and estuarine systems because of these anticipated ecosystem services. However, surprisingly little effort has been made to document the degree to which these ecosystem services are provided through restoration activities in actual practice.

As more restoration efforts are initiated, it is important to document and publicize the broader ecological and economic returns from restoration activities to garner the long term support necessary for large scale restoration efforts.

To balance the many services provided by shellfish and the objectives of multiple stakeholders and agencies, we must incorporate into our restoration and management goals the many ecological linkages between shellfish and the surrounding sediments, waters, and other species within coastal systems (Coen and Luckenbach 2000; Peterson et al 2003). Despite an incomplete knowledge of these linkages it is reasonable to conclude that the ultimate goals of restoration – whether for economic or ecological gain – depend to some degree on increasing the abundance and overall biomass of a targeted shellfish population (Coen and Luckenbach 2000; French McCay et al 2003; Newell 2004).

Of course, not all shellfish provide the same kinds or degree of ecosystem services and there are many ways that shellfish biomass can be increased without returning all of the desired ecosystem services or even cause additional environmental stress. Intensive shellfish aquaculture, for example, may provide filtration benefits but may not provide much in the way of habitat (Newell 2004) and the extensive use of nets, docks, cages, and mechanical harvesters can create significant environmental stress. Non-native species that are brought in to new environments may indeed exert a top-down control on phytoplankton biomass (Cloern 1982) but can also compete with native species, negatively affect food webs (Kimmerer et al 1994; Strayer et al 1999), and bring in new diseases and other undesirable species (NRC 2004).

III. How shellfish work

To restore any species, it is important to understand its life cycle, and how various life stages interact with and are influenced by their surrounding environment. Applying this information to shellfish restoration projects will aide practitioners in selecting appropriate sites, understanding and abating threats and measuring progress.

Basic Life Cycle

Most bivalve shellfish have separate sexes (i.e., they are dioecious) and many change sex during their lifetime (i.e., they are hermaphroditic). For example, the eastern oyster begins life as a male and becomes female as it ages and grows larger (see Kennedy 1996 for thorough review). The typical bivalve shellfish lifecycle involves a planktonic (free-floating) larval stage, and a sedentary benthic (bottom dwelling) juvenile and adult stage (Figure 1).

Eggs and sperm are released into overlying waters where fertilization occurs. The eggs hatch and rather quickly develop into a larval stage called a 'veliger' that spends days (scallops) to weeks (oysters) drifting with currents, feeding and growing while suspended in the water. The larval stage bears little resemblance to the adult stages, and is well adapted for this planktonic phase in their life cycle. While their swimming ability is generally limited, they are equipped with tiny hairs called 'setae' that they use to control their depth in the water column. Beyond a basic ability to control their depth, they are largely at the mercy of wind and tidal driven currents that transport them horizontally and this larval stage is essentially the only period during the bivalve life cycle that allows any significant horizontal movement from one location to another. Juvenile and adult clams can burrow into sediments with their muscular foot, scallops can 'swim' by clapping their valves together, and mussels can even jockey for position within a mussel bed by manipulating the tiny byssal threads used for attachment to surfaces. However, the distances traveled are much shorter by comparison than the distances traveled as larvae. The actual distance that shellfish larvae travel depends on many factors, including behavior that affects their placement within currents moving in various directions, and the overall pattern and strength of local currents and tides.

> ***Significance for Restoration Project Design:*** *a general knowledge of local tidal current patterns can be useful for predicting where larvae might be transported to—or from—and in turn can help with selection of a restoration* site.

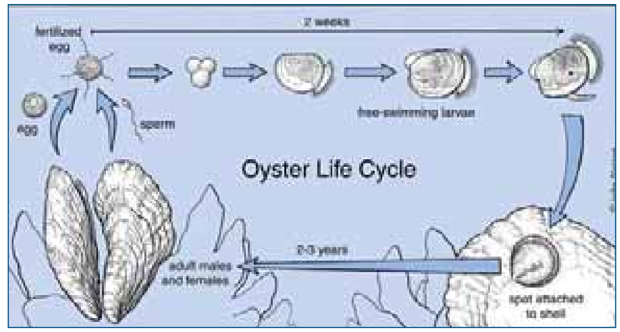


FIGURE 1: Basic lifecycle diagram for the eastern oyster, *Crassostrea virginica*. Image reprinted courtesy of John Norton and MD Sea Grant. http://www.mdsg.umd.edu/oysters/garden/seed.html

Settlement and Substrate Selection

When shellfish larvae have grown large enough (days to weeks) they begin the benthic portion of the life cycle and settle to the bottom. At this point, they select an appropriate habitat in response to both chemical and physical cues from the environment. Cues can include substances exuded by adult shellfish of the same species or vegetation associated with their preferred habitat, and physical characteristics such as surface roughness (Rodriguez et al 1993). Upon settlement the larvae undergo metamorphosis and transform into juvenile stages that more closely resemble the adults. Since most bivalve species have only a limited ability, if any, to move after settlement, it is critical that larvae select the habitat that provides the best chance of growth and survival to adult stages.

> ***Significance for Restoration Project Design:*** *It is important to know what kind of settlement substrate – or bottom material – is preferred by the species under restoration. Providing the correct kind of material can help to attract and protect young shellfish that settle and accumulate there. Ideally, the substrate material can also serve as a refuge that protects newly settled shellfish from predators.*

* Exceptions to Every Rule:

Given the marvelous diversity of bivalve shellfish, it is not surprising that there are several variations on this generalized life cycle. Some species, such as the Olympia oyster, *Ostrea choncaphila*, fertilize and brood their eggs in the female oyster's mantle cavity, rather than broadcasting them directly into the overlying waters. The larvae of some species of freshwater mussels attach to the gills of fish and are then transported upstream as 'hitchhikers' rather than drifting with currents as plankton. Scallops use tiny hook-like hairs to attach to settle first onto underwater grasses and seaweeds prior to settling directly on the bottom.

IV. Getting to the bottom of it all: Restoration by design

Perhaps the most fundamental step for successful shellfish restoration is to carefully consider and define restoration goals for a specific project (Coen and Luckenbach 2000; Shumway and Kraeuter 2003; Luckenbach et al 2005). Given the commercial and social significance of many bivalve species, fishery production has been for decades the primary and often sole motivating factor in shellfish enhancement projects. The literature describing techniques for enhancing commercial and recreational production of shellfish is extensive (MacKenzie 1989; Kennedy et al 1996; Arnol et al 2002) and has typically focused on increasing short-term fisheries production. In contrast, until very recently few restoration initiatives have defined as their primary goal the rebuilding of natural capital – reefs and robust spawning populations capable of sustaining both fisheries and the health of coastal ecosystems (Breitburg et al 2000). Given the multifaceted ecological roles played by bivalves in coastal systems, ecosystem restoration is becoming a primary motivating force for at least small scale restoration projects (Brumbaugh et al 2000a & b; Hadley and Coen 2002). With these issues in mind, we offer in this guide a suite of 'Better Management Practices" to help practitioners design and monitor shellfish restoration projects with ecosystem services in mind, i.e., to document and enhance the services provided by shellfish ecosystems.

Systematic identification, design and monitoring of shellfish restoration using The Nature Conservancy's "5-S Approach"

The need for systematic approaches within a given region for the identification, design and monitoring of conservation, management, and restoration projects is widely recognized (e.g., Groves 2003; Groves et al. 2002; Margules & Pressey 2000; Pressey et al 1993; U.S. Commission on Ocean Policy 2004). The Nature Conservancy uses such an approach, called 'Conservation by Design' (TNC 2000), to identify biodiversity conservation objectives at regional (Ecoregional) scales. As a systematic approach to defining restoration needs and identifying strategies for shellfish restoration projects, Conservation by Design has four discrete steps: **(1)** identifying priorities, i.e., compiling data and information to identify representative sites that account for the full range of biodiversity across regional ecosystems (Beck and Odaya 2001, Beck 2003), **(2)** developing site and multi-site strategies for preserving or restoring those sites to fullest functionality, **(3)** implementation of those strategies, **(4)** measuring the effect of implementation. This guide assumes that shellfish restoration is a conservation strategy that has been identified through some form of regional-scale assessment, and the balance of our discussion will focus on the restoration strategies that are applicable at individual sites or multiple sites within an ecoregion.

Once a biodiversity conservation approach – e.g., shellfish restoration – has been identified through an Ecoregional Assessment, the specific actions to take at the site and multi-site scale must be defined, implemented and monitored for their outcomes. To accomplish these tasks, TNC employs a "5-S" methodology to identify the System, Stresses and Sources of stress to the system, Strategies for abating stresses, and Success measures to determine whether a conservation or restoration objective has been achieved. For the purposes of this guide the System is the bivalve shellfish ecosystem – more specifically oysters, clams, scallops and mussels and the other associated species. It is recognized that these are connected to other types of Systems (e.g., marshes and seagrass meadows) within estuaries or coastal lagoons.

The second and third "S" when embarking on a shellfish restoration project is to identify the Stress and Sources of Stress affecting the abundance of shellfish at a given site. Here we combine these somewhat within three broad categories – fisheries mortality, habitat limitation and recruitment limitation. At many sites, all three types of stress are present. Later we will discuss potential Strategies and appropriate Success measures (or indicators) to track the outcome of restoration activities.

Sources of Stress: Fishing mortality, habitat loss, recruitment limitation

The Sources of stress affecting shellfish populations can include fishing, channel dredging and destruction of habitat, and degraded water quality (i.e., anoxia, sedimentation, harmful algal blooms). Depending on the source of stress it is helpful to view restoration activities within a 'hierarchy of intervention actions' that represent the range of potential strategies to be considered when designing a project (Shumway and Kraueter 2003).

Stress Category 1: Fisheries Mortality encompasses a group of stresses that can depress and hold population biomass below levels necessary to return economic or ecological benefits. There are many stresses within this category such as excessive take

Box 1: Considerations for Site Selection

- Identify areas where reefs or target shellfish populations historically existed. Data on historic distributions can be obtained from published accounts, fishing records, and navigation charts or other bottom surveys. It is predicted that these sites are the most likely to be able to further support shellfish.
- Evaluate bottom conditions to determine if the bottom will support addition of shell or other materials used for habitat enhancement. It may be necessary to restore the bottom for example by removing excess sediments or other debris such as wood waste from logging operations.
- Determine whether this area is a "sink" for larvae being transported in from other areas. Populations have a higher chance of recovering most rapidly in areas that are "sinks" for larvae (Crowder et al 2000). Deployment of spat collectors - devices used to attract larvae to settle - or sampling the bottom within areas that are known for supporting shellfish can help to gauge the level of 'recruitment' likely for a given restoration site.
- Assess the current velocity. Shellfish growth is generally higher where currents are greater, delivering food and oxygenated water and carrying away waste by-products.
- Determine what threats exist in areas formerly populated by shellfish. Examples include sources of sedimentation (e.g., erosive banks, poorly buffered shorelines), stormwater or other point sources of pollution.
- Determine whether the overlying waters are well oxygenated. Small, poorly flushed coves may become sub-oxic or anoxic, particularly in the summer when the water is warmest. This can affect shellfish directly (e.g., reduce recruitment and survival, Breitburg 1992) and indirectly (e.g., fish and crabs escaping areas of low oxygen may converge on reefs or nearby shellfish populations and alter community structure through predation or competition, Lenihan et al 2001).
- Consider locating restoration projects within small, replicable sub-estuaries. Such areas are sometimes referred to as "trap estuaries" (Pritchard 1953), denoting areas with a high degree of retention of water circulation, which can help promote recruitment of shellfish larvae and other colonizing species. These small systems can serve as testing grounds for measuring potential ecosystem service impacts to water clarity and quality.
- Consider placement of restoration projects in areas where illegal impacts can be deterred. For example projects can be placed where shellfish harvest is banned for human health reasons. Such areas represent de-facto sanctuaries. Other areas may lend themselves to enforcement such as areas where there have been well established lease or ownership rights or areas near bridges, research stations and nature preserves where there are potential partners to monitor the project. These are also likely to be urban areas where community support and involvement in restoration for strictly environmental reasons may be garnered (Brumbaugh 2000b).
- Consider using submerged lands that are privately leased or owned to maintain investments in restoration on project sites. Submerged lands are available for lease and ownership in all coastal states (Marsh et al 2002; Beck et al 2005). Many of these lands have traditionally been used to grant exclusive access for shellfishing. They can however also be used to protect investments in restoration and allow groups greater stewardship opportunities for the natural resources that they have enhanced at sites.

Box 2: Addressing Genetic Consequences of Stock Enhancement Programs

Because there are potential genetic consequences when using stock enhancement as a strategy to restore shellfish populations, there are several fundamental guidelines for reducing these potential risks (Allen and Hilbish 2000):

- Transplant wild broodstock animals collected from local sources. Shellfish that are collected in the immediate vicinity or purchased from fishermen working nearby can be transplanted at higher densities to improve the likelihood of reproductive (fertilization) success. This is a way to tap into the local gene pool and minimizes the chances of "genetic bottlenecking".

- Use locally collected broodstock for spawning in hatchery-based stock enhancement. It may be necessary to collect wild shellfish for artificial propagation if little natural settlement is occurring in local waters, and when importing large numbers of shellfish from another location would produce undesirable results (e.g., would diminish the ecosystem services or fishery stock in a given location). Collecting broodstock from an area close to your project can reduce the loss of local genetic characteristics (Peter-Contesse and Peabody 2005).

- Use pair-wise crossings of animals in the hatchery to maximize 'effective population size' (Ne) and to minimize "genetic bottlenecking". Maximizing the number of animals spawned in the hatchery (i.e., getting close to Ne) and using pair-wise crosses can maximize the chances of maintaining genetic diversity in a broodstock enhancement program.

- Characterize the genetics of broodstock (for wild and hatchery-origin stocks) to aid in the tracking of progeny in the field. This is an expensive and time consuming process (both the genetic characterization and the identification of offspring in field samples), but allows for 'proof of restoration impact' and also for monitoring of genetic changes over time. Efforts to use genetic markers to track the offspring of oysters transplanted to selected Chesapeake Bay restoration reefs are underway and are intended to provide a quantitative basis for improving future restoration projects (Mann 2004; Millbury et al 2004).

and destructive fishing practices that impact habitat directly, or removal of species as bycatch. In some instances, restoration may be as "simple" as reducing fishing pressure or modifying other activities such as dredging and filling (see Habitat Limitation below) that damages or removes shellfish (Abadie and Poirrier 2000; Maguire et al. 2002). The reduction of fishing mortality can promote an increase in the numbers of adult shellfish that help to bolster the spawning population over time, assuming that habitat (e.g., bottom characteristics and water quality) remains abundant and in good condition to allow young shellfish to accumulate and grow. As an example of this approach, Jordan and Coakley (2004) have postulated based on results of a population dynamics modeling exercise that eliminating fishing pressure on the Chesapeake Bay's remaining oyster populations would allow for a 10-fold expansion of the population in less than ten years.

Of course, the political will necessary to amend fishing regulations can be challenging to build. It should also be noted that reductions in fishing effort need not involve absolute closures or prohibitions of fishing activity. Rather, reductions may be achievable through some combination of controls on overall harvest numbers, size limits, locations, or timing of harvest depending on the overall status of the population. Fundamentally, restoration efforts that are intended to enhance the total value of ecological services must first and foremost reduce stresses that are affecting the population and not just consider how to maximize landings.

Stress Category 2: Habitat limitation is a stress that occurs when there is no longer a sufficient amount of habitat to support all life history stages of the population and, as a result, the population cannot be sustained over long periods of time. Relevant subcategories of stress include habitat modification, degradation, and loss. For example, physical degradation of three-dimensional oyster reefs throughout much of the eastern oyster's range is considered a limiting factor for populations throughout its range. Since the 1800s, the three-dimensional reef habitat has been destroyed leaving only rubble 'footprints' of oyster reefs (Rothschild et al 1994; Hargis and Havens 1999). The reduction of vertical relief has relegated oysters to living lower in the water column where dissolved oxygen levels cause stress that increases their susceptibility to diseases (Lenihan and Peterson 1998). As another example, the global decline of seagrasses as a result of nutrient over-enrichment and disease (Orth and Moore 1983, Green and Short 2003, Short and Wyllie-Echeverria 1996, Duarte 2002) likely limits populations of shellfish species such as hard clams and scallops that recruit first as juveniles to these beds of vegetation (Pohle et al 1991; Heck and Crowder 1991; Irlandi et al 1995, 1999).

To abate the stress of habitat limitation, therefore, it may be necessary to develop and implement strategies that involve direct manipulation of the habitat available to juvenile or adult shellfish. Habitat manipulation, such as placement of shells on the bottom or restoration of seagrass beds, represents a much higher degree of intervention than just regulating harvest alone and care should be taken to select the appropriate sites for habitat enhancement (See Box 1 for some considerations).

Stress Category 3: Recruitment limitation occurs when an insufficient number of offspring are added to the population on an ongoing basis to offset losses of larger, older members of the population. Several factors can contribute to this condition, including an overabundance of predators, excessive fishing pressure that reduces the number of spawners in the population, degraded water quality that affects survival of larvae, and diseases or parasites that affect the ability of adults to spawn successfully. Given the depleted status of many shellfish populations, an insufficient abundance – and density - of spawning age animals in the population is not uncommon. The overall abundance and size of adults in the population will determine the maximum number of eggs and larvae produced, and the density (i.e., proximity to one another) affects the relative fertilization success, since bivalves release eggs and sperm cells directly into the water.

Strategies for Restoration: *Options based on stresses*

There is an array of strategies available for abating the stresses outlined in the previous section. Each project is unique and appropriate strategies must be based on knowledge of the target species, geography, social and political framework. The Strategies outlined below give examples of approaches that have been proven broadly applicable at many sites.

Strategies to address Fishing Mortality

No-take areas or sanctuaries: A basic intervention strategy to reduce stress associated with excessive fishing mortality is to set aside areas where fishing is curtailed – essentially, 'no take' reserves for shellfish. By eliminating fisheries mortality, the presumption is that shellfish will live longer, grow to larger sizes, and occur at higher densities thereby producing more offspring (Rice et al 1989; Breitburg et al 2000). 'No take' reserves are also useful for reducing impacts from fishing gear on the bottom, which can alter the distribution of shelly habitat and affect overall biodiversity (Hewitt et al 2005). This approach may be employed with all kinds of bivalve shellfish.

Reducing effort and incidental take: While it is often preferable to restrict harvest entirely at sites and this will result in the greatest likelihood in restoring natural shellfish

Box 3: Coping with Predation

All life stages of bivalve shellfish are susceptible to some degree of predation, from larvae (Breitburg et al 1995) to adult (Virnstein 1977). Losses to predators can significantly reduce the effectiveness of stock enhancement programs and should be factored into restoration planning. Predation is a part of the natural functioning of ecosystems. Nonetheless it is often desirable to reduce these levels as naturally as possible initially in order to successfully establish new shellfish reefs and beds:

- **Broodstock Size:** Predation mortality tends to decrease with increasing shellfish size (Bisker and Castagna, 1989; Eggleston 1990). For oysters, a minimum size of 40 mm is recommended as field and laboratory studies have shown that blue crabs can readily consume smaller oysters (e.g., Krantz and Chamberlain 1978). Clams may fair well at a somewhat smaller size than oysters, but in general the larger the bivalve, the less susceptible it is to predation. Minimizing, rather than eliminating, losses of animals added for broodstock enhancement is a reasonable objective, since even the largest shellfish are vulnerable to some level of predation.

- **Time of Year:** Generally, it may be most advantageous to transplant broodstock immediately prior to the spawning season as it is desirable to have individuals spawn successfully prior to significant predation. Factors such as (1) predator abundance and activity (Bishop et al. 2005), (2) recruitment of other competing species (Osman et al 1989) and (3) physiological stress of temperature extremes (high or low) are factors that may determine how far in advance of spawning season you might want to transplant broodstock.

- **Consider Spatial Arrangement**: It may be possible to minimize predation by siting the project away from sources of predators. For example, blue crabs are a significant predator on juvenile oysters, and they are abundant in marshes and sea grass beds. Crabs may move between these different ecosystems as they forage (Micheli and Peterson 1999) so restoring an oyster reef some distance away from marsh edges or seagrass beds may minimize the likelihood of crab predation on young oysters (Grabowski et al 2005).

- **Predator Control:** Numerous studies have been undertaken to evaluate methods for controlling predators affecting aquaculture production. Typically, these methods involve exclusion devices (cages or nets) or predator removal regimens. Exclusion devices require maintenance and likely require additional permits. Direct predator control in the field is expensive, time consuming and may not be consistent with restoration goals in the long term. A more ecosystem-based approach may be to sustain or increase the abundance of other associated species such as toadfish that prey on crabs and other bivalve predators (Bisker and Castagna 1989). Curbing fishing pressure or providing habitat for such species in association with restoration projects, predation on stocked shellfish may be reduced.

- **Increase the Number of Animals Stocked:** It may be possible to adjust the stocking density to compensate for anticipated levels of predation. Increasing the number of shellfish added to a sanctuary site may compensate for losses to predators assuming that the increased number of shellfish does not attract additional predators or cause density-dependent problems such as competition between shellfish for food or space.

- **Use Substrate as a Predator Deterant:** Placing a thin layer of shell or other material on the bottom, or even on top of the shellfish themselves, may reduce the ability of predators to find and consume shellfish added to a restoration site.

capital, even just reducing or redirecting effort can still be helpful. In places where many non-native shellfish are present (e.g., Puget Sound) it may be possible to direct harvest to these species to avoid fishery pressure in areas of restoration with native species. Where there are practices that are too efficient at removing shellfish (e.g. dredging), less efficient methods could be mandated (e.g., tonging or diving).

Strategies to address Habitat Loss

When the overall abundance of shellfish in a system is limited by the availability of suitable habitat, it may be desirable to enhance or alter the bottom to promote greater recruitment of young bivalves and to enhance their survival. This is a 'passive' approach to restoration, and assumes that adequate spawning and larval supply is occurring at a given location. When restoring habitat for shellfish, as with many kinds of wildlife, it is important to consider the placement of the restoration project in the context of the larger landscape (Scott et al 2001). For example, an oyster reef placed in the vicinity of areas that periodically experience low oxygen conditions may result in mobile organisms – fish and crabs – seeking refuge on the reef and causing elevated rates of predation on the shellfish being restored, or on other organisms residing on the reef (Lenihan et al 2001). Similarly, the placement of oyster reefs near vegetated areas such as marsh edges or seagrass beds may encourage greater use by mobile organisms such as crabs and fish (Grabowski et al 2005). While this may expose the shellfish on the reef to predation by crabs and other predators, this may be acceptable if the intent of the project is to convey benefits such as shoreline stabilization or habitat corridors for mobile organisms. These and other considerations relevant to site selection are addressed in Text Box 1.

Restoration of seagrass habitat is an activity that can be useful – if not a prerequisite for restoring scallops and to some extent hard clams as well. Seagrasses are an important settlement habitat for scallops, which settle onto seagrass blades before dropping to the bottom as they grow to larger sizes (Pohle et al 1991). Being off the bottom presumably helps to protect the youngest scallops from predators that might be foraging below. The physical complexity of seagrass habitat is also thought to reduce the ability of predators to prey on scallops within the beds (Irlandi et al. 1995, 1999; Talman et al 2004).

Construction of 3-dimensional reefs has become a widely used approach for enhancing the recruitment of and survival of oysters and their associated reef community, particularly from Pamlico Sound northward along the east coast of the U.S. Materials used for reef creation should provide a significant degree of 'interstitial space' within the reef matrix. This complexity increases survival of young oysters (Bartol and Mann 1997) and provides refuge from predation for other species that inhabit the reef (Breitburg 1999; Posey et al 1999). Typically, oyster shells are the preferred material for use in oyster reef projects since they most closely emulate the natural reef matrix and interstitial space in a natural reef when they are piled on the bottom (O'Beirn et al 2000). Limestone marl rock has been successfully used to create settlement habitat for oysters in Louisiana (Haywood et al 1999; Soniat and Burton 2005). TNC and the North Carolina Department of Marine Fisheries are also using this material to create spawner sanctuary reefs in Pamlico Sound with much success (Figure 2 and Case Study 2).

Construction of intertidal 'fringing reefs' may be a more appropriate approach for restoring oysters in the southern portion of its range, particularly along the southeastern U.S. coastline. This approaches focuses on providing substrate for settlement and 3-dimensional 'relief' in the intertidal zone. For oysters growing in the intertidal zone, the significance of shell orientation (i.e., vertical vs. horizontal) is still poorly understood, but may play a role in growth and survival. Intertidal oysters tend to grow vertically, which may be a means of reducing exposure to solar radiation and, by extension, moderating temperature (Bahr and Lanier 1981). Restoration efforts should strive to provide vertical relief on both large scales (reefs) and micro-scales (individual oyster shells).

Broad scale placement of shell or shell fragments at high density on the bottom has been shown to increase recruitment of hard clams (Kraeuter et al 2003) and this kind of patchy habitat also serves to increase biodiversity (Hewitt et al 2005).

Shells for projects can be obtained from oyster processing facilities or from shell recycling programs (Hadley and Coen 2002). South Carolina has a well-developed program that enables people to return shells from oyster roasts for use in reef restoration projects:

www.dnr.state.sc.us/marine/regs/sfrecycling.html.

One cautionary note, however, is that shells should be allowed to 'age' or dry out on land for a period of at least one month prior to deployment in the water to minimize the likelihood of transmitting any oyster parasites or pathogens that may be found in residual tissues (Bushek et al 2004).

Strategies to address Recruitment Limitation

Populations that are extremely depleted may in some cases gradually rebound on their own without supplementation of "broodstock," or reproductively capable adults. However, in some cases the population has declined below a point of recovery, when recruitment of offspring will not overcome the mortality of adults in the population ("Allee effect," Gascoigne and Lipcius 2004). In this instance, it may be necessary to artificially increase the abundance and density of adults in the population through "stock enhancement". This differs from stocking clams, oysters or scallops in support of 'put-and-take' fisheries since (1) the stocked animals are never re-harvested, and (2) the stock enhancement strategy (location, density, genetic composition) is specifically intended to encourage maximum reproductive contribution to the population.

Broodstock Enhancement: To address recruitment limitation, it may be necessary to add shellfish to the population to increase the production of offspring. Stocking adult shellfish in relatively high densities is likely to improve the chances of successful spawning and reproductive success. This strategy may be useful for 'jump starting' populations from a range of bivalve species including scallops (Peterson et al 1996), oysters (Brumbaugh et al 2000a & b; Southworth and Mann 1999) and clams (Stewart and Creese 2002). There are a number of factors that should be considered with broodstock enhancement efforts, ranging from genetic considerations to predation on transplanted bivalves. Additional information about these topics is provided in Text Boxes 2 and 3.

For many shellfish species, both availability of habitat and recruitment are limiting factors, and a combination of restoration strategies involving both habitat manipulation and stock enhancement is required to restore the shellfish population (Caddy and Defeo 2003). Clearly this represents the highest degree of intervention, and increases the complexity of the project. Mann and Evans (2004) have summarized some of the significant factors that can affect the success of restoration involving both habitat rehabilitation and stock enhancement and advocate taking a population dynamics approach to planning such activities. In particular, they recommend that restoration efforts be informed by demographic modeling that takes into account egg production, losses of larvae to advection, and factors contributing to recruitment success (e.g., habitat availability). To accomplish this requires fairly specific knowledge of the system undergoing restoration, including (i) temperature and salinity, which can be determined from regional water quality monitoring programs, (ii) circulation patterns, which can be inferred from drifter studies and (iii) risk of predation (see Box 3).

Figure 2: Limestone marl has successfully been used to create oyster reefs in North Carolina's Pamlico Sound (Ashley Harraman, TNC; Rob Brumbaugh, TNC)

V. Monitoring for Ecosystem Services

Aquatic ecosystem restoration, in general, is a relatively new field and unfortunately many restoration projects undertaken to date have been poorly monitored and documented (Bernhardt et al. 2005). Without adequate documentation, it is not possible to know the ecological impact and whether the goals or objectives of a project have been met. Conversely, a well designed monitoring plan provides opportunities for adaptive management – essentially mid-course corrections – that enables practitioners to achieve project goals and, importantly, to improve future projects. Ultimately, well documented projects increase the knowledge base that can be used to improve the outcome of projects over time and increase the public support and funding available for additional restoration. This publication provides a starting point and a broad overview of methods that are available for monitoring shellfish projects. More comprehensive guides to monitoring methods are available to practitioners seeking to expand on this introduction (e.g., Thayer et al. 2005).

The methods applied to monitoring will depend on the particular Success Measures (one of TNC's "5-S's") or indicators identified to help quantify project outcomes. Of course, success measures chosen for a shellfish restoration project depend on the original goals of the project (Coen and Luckenbach 2000). In general, success measures relevant to ecological services fall into four broad categories:

1. **recruitment and growth of the shellfish population undergoing restoration**
2. **provision of habitat for other associated species**
3. **direct and indirect effects on local water quality**
4. **shoreline protection**

The scale at which each of these services is measurable will depend on the particular ecosystem service being measured, as well as on the system within which the project is being undertaken (Figure 3). For example, it may be possible to discern an increase in recruitment at relatively large distances from the reef or bed being restored, depending on the water circulation patterns that govern, in part, the distance their larvae are able to travel. Conversely, measuring the service of habitat enhancement may best be accomplished directly at the site being restored with appropriate replication and comparison to reference sites.

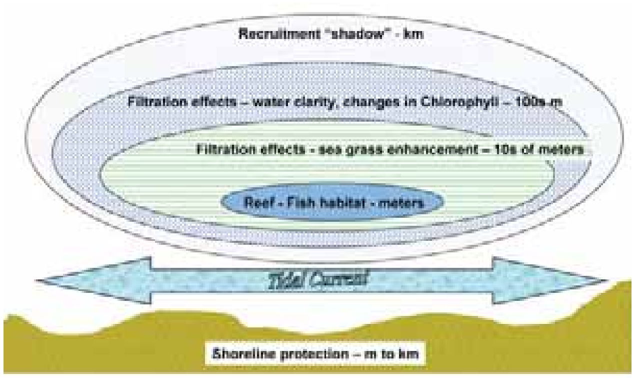


Figure 3: Theoretical array of ecosystem services to measure around restoration project sites

For any measure of success, management agencies and funders are increasingly interested in documenting the relative change in metrics that occurs as a result of restoration activities. The basic design for such monitoring, known as Before-After-Control-Impact (BACI), has been well established in the ecological literature (e.g., Underwood 1991, Schroeter et al 1993 and 2001). In our case the better acronym is BACR to include actions from Restoration rather than ecological impacts (e.g., sewage outfalls). BACR is relatively easy to implement. Though it may appear obvious, the most difficult quantity is forethought; as control and restoration sites need to be monitored before any treatments are established. Moreover, it is best to monitor these areas several times before and after shellfish are restored. Incorporating BACR designs into restoration planning will be important for describing the net return on restoration investment and for developing predictive models for scaling restoration up to ecosystem scales.

Measuring Recruitment to the Shellfish Population

Clearly, to generate ecosystem services the shellfish population under restoration must expand to the point that it becomes self-sustaining. Basic measures such as abundance, density (number per unit area) and size frequency of the shellfish should be monitored over time to determine whether the population and biomass is growing, declining or staying relatively unchanged. Studies of wetland restoration projects have revealed that it can take a decade or longer for a restored site to resemble a natural reference marsh site (reviewed by Callaway 2005). Similarly, the accumulation of fish biomass within marine protected areas can occur over various timescales from years to decades (Russ et al 2005). The reestablishment of shellfish populations and their ecosystem services will likely require similar timescales. Baseline monitoring of shellfish abundance and size should be repeated annually for a minimum of 5 years.

Quadrat samples can be used to provide quantitative estimates of shellfish abundance in both the intertidal zone and in the subtidal zone. On oyster reefs, samples are obtained from various elevations (e.g., reef crest, slope, base) to gauge the variation in recruitment with depth. Usually $0.25m^2$ quadrats, excavated to a depth of 10 – 15 cm, provide a reasonable sample volume for estimating population parameters (Bartol and Mann 1997) (Figure 4). For each sample, count all live oysters and articulated shells (dubbed "boxes," articulated shells are a measure of recent mortality), and measure all live shellfish (or a minimum random sample of 50 individuals for large sample sizes) to the nearest mm. These data will help to characterize the changes in the population density and size classes of animals (and, by inference, age classes) over time. If the reef material is not conducive to sampling with quadrats or if non-destructive sampling is preferred, trays filled with reef substrate (e.g., shells, marl limestone, etc.) can be embedded in the reef surface at random locations and retrieved repeatedly or at the end of the recruitment season. Similar data for clams infaunal bivalves (i.e., organisms living within the sediment) can be collected by divers placing quadrats at random intervals along transects or within a grid on the bottom. Excavate all clams and place within mesh bags for counting and measuring at the surface.

Benthic grab samplers can also be used to quantify clams and other organisms living within the sediment. These devices are used to collect sediments from a relatively small area of the bottom and bring it to the surface where the contents can be evaluated. An advantage of this method is that it provides a quantitative (area-based) measure of abundance. A disadvantage is that only a relatively small area is sampled (unless a very large sampler is used, which requires a crane and larger vessel to deploy). These samplers also tend to be specific to the kinds of sediments they sample most effectively. For example, heavily weighted Ponar-style grab samplers are effective for sampling in gravel, sand or consolidated sediments, while lighter Van Veen- and Ekman-style samplers are more suited for softer sediments.

Artificial settlement substrates or settlement collectors provide a simple and inexpensive means of gauging relative settlement patterns across an array of sites. Artificial settlement substrates can be used to help with siting reefs and beds as well as identifying the habitat value that these species provide to a much wider component of coastal biodiversity. From a conservation point of view, the return of naturally, diverse assemblages of species to re-established shellfish habitats and ecosystems should always be a primary goal. In general, restoration is often approached with a "more biomass is better" perspective (French-McKay et al 2003; also, with caveats, Newell 2004), only recently have investigators attempted to discern the relationship between species diversity and biomass or abundance measures (Coen and Luckenbach 2000; Luckenbach et al 2005). Some studies have documented the fauna - resident and transient fish and invertebrates – that inhabit shellfish reefs (Breitberg 1995; Wenner et al 1996; Coen et al 1999; Harding and Mann 2001). Such studies are often designed in ways that allow for effective comparisons with adjoining habitat such as salt marshes and vegetated or unvegetated bottom (Glancy et al 2003).

Figure 4: For oyster reefs constructed from unconsolidated materials such as shells or small pieces of rock, samples can be collected from quadrats to determine the number of live shellfish and other organisms on the reef. (Rob Brumbaugh, TNC; Lisa Drake, U.S. Coast Guard Academy)

if settlers are being attracted to restoration sites, a key condition for success. Collectors can be deployed from docks or shorelines or by boat using buoys and small anchors to hold the gear in place for a prescribed period of time. Ceramic tiles or other materials that are readily colonized by marine invertebrates can be used to determine the timing and magnitude of settlement of oysters (Michener and Kenny 1991; Roegner and Mann 1995; Bartol and Mann 1997). Mesh bags containing nylon monofilament mesh (e.g., gill net material) can be used to gauge the timing and magnitude of scallop settlement. There are sampling artifacts associated with nearly any type of artificial substrate – e.g., differences in predation rates, fouling, and competition for space. These data can be used to infer relative magnitudes of abundance and general distribution patterns but should not be assumed to represent actual settlement rates on the bottom.

Measuring Habitat Value for Associated Species

A common and rarely monitored goal for the restoration of shellfish (and seagrasses and marshes) is re-establishment of

Various approaches exist to qualitatively or quantitatively monitor or sample the organisms associated with shellfish restoration projects and shallow intertidal environments. These methods include lift nets (Wenner et al 1996), drop nets and enclosures (Minello et al 2003), haul seines and gill nets (Harding and Mann 2001), sampling trays embedded in reefs or beds (O'Beirn et al 2000; Coen and Luckenbach 2000; Luckenbach et al. 2005), video surveys, and diver surveys/fish counts. Different approaches will lend themselves to projects under different conditions. Video surveys and diver surveys are most appropriate for documenting larger or highly mobile species where water clarity is reasonably good, while nets, sampling trays and other enclosures are more useful for quantifying smaller or more cryptic organisms.

A common misconception that explains why species and community change are rarely monitored in restoration projects is that they are perceived to be time consuming to measure in the field and difficult to analyze. For example, it can be difficult in the field to measure abundances of all species in a community.

These issues can be minimized, because often it may be possible to measure and analyze changes in biodiversity and communities by measuring just presence/absence. These measures (either presence/absence or abundance) can be analyzed with statistics that are remarkably robust at detecting community change. These statistics are known as Analyses of Similarity (Anosim) and are part of an easy to use statistics package, Primer (www.pml.ac.uk/primer/). These measures and statistics are widely used (see Primer website). Presence-absence data can also be used to document differences in overall biodiversity between different kinds of habitats, or reefs in different locations (i.e., Beta diversity, see http://cnx.rice.edu/content/m12147/latest/)

Measuring Direct and Indirect Effects on Water Quality

Laboratory and field studies have documented the capacity of filter-feeding shellfish to reduce concentrations of suspended particulates in overlying waters (Verwey 1952; Haven and Morales-Alamo 1971; Asmus and Asmus 1991; Dame 1996). Typically, these studies measure changes in Total Suspended Solids (TSS) and chlorophyll_a (Chl_a) in water before and after it has passed over shellfish beds (Haamer and Rhode 2000; Cressman et al 2003; Nelson et al 2004). More work is needed to develop methods that are robust and capable of measuring subtle changes in these parameters on appropriate spatial and temporal scales. A combination of flow-through fluorometry and analysis of whole water samples is one approach being tested as a means of providing such high resolution information to document filtration effects of shellfish populations (Ray Grizzle, University of New Hampshire, personal communication).

Simpler approaches to monitoring water clarity using Secchi disks are also worth considering, although they are less likely to detect subtle changes in clarity that might be attributable to the filtering of nearby shellfish. This method provides a relative measure of water clarity and light transmission within the water column, but is more subjective than the methods described above because the depth that the disk disappears from view can depend on variety of factors in addition to water clarity, including time of day, ambient light levels and water surface conditions. Different observers, too, can report different readings for the same time and location, so it can be more effective for the data to be collected by the same observer over time. Despite the subjectivity of this method, Secchi disk measurements can be a cost-effective and useful metric and have been used to infer the changes in water clarity attributable to increases in shellfish populations over time (Abadie and Poirrier 2000). Instructions for the use and interpretation of Secchi disks are available in "Volunteer Estuaries Monitoring: A Methods Manual" at:

http://www.epa.gov/owow/estuaries/monitor/.

Lastly, an indirect and somewhat anecdotal means of gauging the effect of shellfish restoration on water clarity is to monitor changes in seagrass presence and abundance in areas adjacent to your project site. There is increasing evidence that shellfish can enhance the productivity of seagrass beds through both filtration of water as well as by changes in sediments resulting from the deposition of organic matter and waste by-products (Peterson and Heck, 1999; Newell and Koch 2004). Examining aerial photos is one approach to monitoring changes to seagrass beds over time. Other methods include recording shoot densities and grass canopy height within quadrats placed at random intervals along transects (McKenzie and Campbell 2002; Short et al 2004, see: http://www.seagrassnet.org/global.html). Care should be taken when attributing observed changes in seagrass abundance to nearby shellfish restoration activities, however, since there are many other factors such as rainfall, suspended sediments and temperature are also major factors affecting the health and productivity of seagrass beds. As with the shellfish restoration site itself, having a reference site for comparison and collecting baseline data as part of the 'Before' stage of a BACR monitoring plan can help with interpreting your observations.

Measuring the Value of Oyster Reefs as Shoreline Protection

Aerial photography and GIS/image analysis approaches have also been used to provide landscape scale analysis of intertidal oyster reef habitat (Grizzle et al 2002). While oyster reefs are subject to erosive forces from boat wakes and wave action (Grizzle et al. 2002) they can also, by dampening and absorbing wave energy, be an effective means of stabilizing erosive shorelines (Meyer et al 1997). Stakes planted along the shoreline at restoration sites provide a baseline for measuring shoreline migration relative to reference sites. The change in vegetative cover behind fringing reefs is also a useful metric for assessing performance relative to reference sites and can be measured by estimating the percent cover of vegetation or shoot density (number of stems per square meter) in quadrat samples within the marsh.

V. Putting it all together

Build an Effective Partnership

There are many stakeholders that care, for various reasons, about activities – including restoration – that affect the waterways near where they live, work or recreate. Engaging these stakeholders is an important step in the development of a project as the right mix of partners can be a tremendous help in designing and implementing a successful restoration project and ensuring a sustainable result (Brumbaugh 2000a). Different organizations or agencies possess different strengths, resources or capabilities, so building an effective coalition of partners is perhaps the best way to facilitate a project. The exact mix of partners and their roles in the project will vary from project to project. Here are some general considerations for what various different agencies or stakeholders have to offer:

Local, state and federal agencies have legal jurisdiction and can help facilitate or even take the lead on securing permits needed for habitat enhancement. The necessary permits will vary depending on the location, type of restoration activity being proposed, project scale and other factors. Agency partners also typically possess the long term data sets that can help with site selection and setting restoration targets.

Fishing industry representatives have both knowledge and infrastructure to help with projects. Involving industry stakeholders not only helps to ensure buy in and support, but can prove invaluable for tackling tasks like hauling and deploying shells on restoration sites, or transporting and transplanting clams or oysters.

Non-profit organizations have various strengths that can aid in the development and implementation of a project. Small locally-focused organizations that have close ties to a community and may be instrumental at securing permission to use coastal property as either a staging area or a restoration site. Recruiting volunteers for hands-on components of a project is another forte of local non-profit organizations. Land trusts serve as a catalyst by securing and holding leased areas used for restoration. Larger organizations may have the capacity to help research and write proposals or even provide matching funds.

Academic partners can provide the technical expertise as well as the facilities and equipment (e.g., boats, labs, instrumentation) to support the monitoring necessary for measuring project outcomes. Involving academic partners early in the process is also a good way to solicit input on the design to ensure that meaningful data can be collected to document results of a project. For academic partners, the benefits of being involved with restoration include community service, increased visibility, opportunities for students to hone research skills, and having a platform for inquiry based education.

Volunteers are vital connections to the local community and can provide many services that would otherwise have to be contracted

or undertaken by partners. Time contributed by volunteers can be used as in-kind leverage for many grant programs, providing a tremendous leveraging opportunity. For federal grants, such as those available through NOAA's Community-based Restoration Program (http://www.nmfs.noaa.gov/habitat/restoration), volunteer time is valued at rates equivalent to contractors or staff hired to perform similar tasks. Volunteers with appropriate training and oversight can also conduct some of the routine monitoring of restored shellfish and associated communities (Brumbaugh 2000b; Hadley and Coen 2002). It helps to have an academic or research institution involved for advice and oversight to ensure appropriate methods are used for gathering the data and analyzing the project outcomes.

Securing Permits

Soliciting input from local, state and federal agencies early on in the design process will be helpful for identifying which permits, if any, are needed for a shellfish restoration project. Generally speaking, anything that involves placing material such as oyster shells or shell material on the bottom will involve a state or federal permit under the Federal Clean Water Act. Often the authority for evaluating projects and issuing permits under the Clean Water Act has been delegated to a state agency, although federal oversight is still in force as well. Likewise, placing shell or other structures (e.g., aquaculture cages, predator control nets, etc.) is likely also regulated by the Federal Rivers and Harbors Act through the U.S. Army Corps of Engineers. In any event, it is important to investigate permitting requirements early in the design process to identify which actions are regulated, how long it might require to secure permits, and what kind of environmental monitoring requirements might accompany a permitted activity.

Raising Awareness

An often overlooked part of restoration projects is the media outreach strategy. This is an invaluable part of any restoration project because it helps to ensure that the project is supported by those who live, work and recreate in the vicinity of the project. Again, a diverse partnership can be helpful for providing access to media contacts and assistance in preparing and distributing press releases. Such partnerships also make for attractive stories, which can increase the chances of having the media highlight your project. Restoration projects are tremendous vehicles for calling attention to not only to specific places and objectives (e.g., restoring shellfish to your local waterway), but they are also invaluable opportunities for drawing attention to larger, related issues of habitat conservation, water quality, and coastal management. Integrating these themes into your press releases and communication with the media is a great way to raise public awareness of these other broad topics.

Footing the Bill

While funding for habitat restoration has been increasing (Bernhardt et al. 2005), finding the right funding source or combination of sources is still a time consuming process. All of these partners can help to bring funding or in-kind donations to support the project, and it is important not to overlook the monetary value of their contributions (e.g., capturing volunteer hours as in-kind match to use as leverage for grant funds). Most funders of restoration activities, whether they are public agencies or private foundations, are interested in seeing their funds leveraged as much as possible. Look for ways to leverage partner's contributions, whether this is a direct financial contribution or an in-kind service. As mentioned in the previous section, volunteer-time is an important and valuable source of in-kind match that can be used in many instances.

Case Study 1

Hard clam restoration in Great South Bay, New York

< The Nature Conservancy is using its ownership stake in Great South Bay to bring stakeholders together to restore the entire ecosystem.

Private ownership provides a platform for ecosystem-based conservation, restoration and partnership

Project Synopsis:

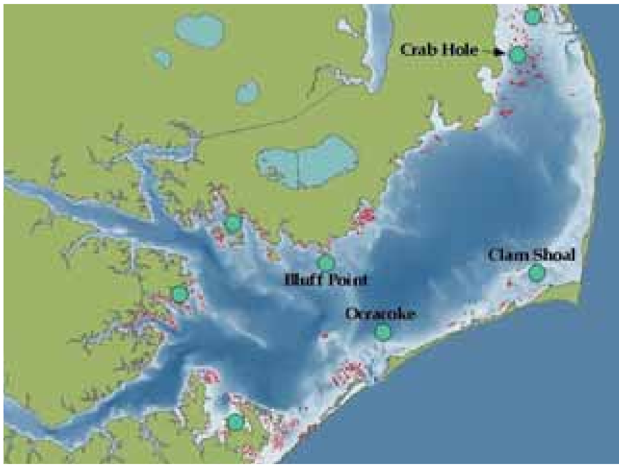
Great South Bay, a shallow tidal lagoon inside Long Island's south shore, was once known as the "clam factory". In the 1970s, fishermen pulled more than 700,000 bushels of wild hard clams (Mercenaria mercenaria) from the sandy bottom of the Bay, and supplied more than 50 percent of the annual catch in the U.S. However, the fishery was not sustainable and as clam populations declined in the late 20th century, the harvest dwindled to just 1 percent of the peak level seen in the 1970s. In addition to local economic losses, profound changes to the ecosystem have become apparent as well. Without enough clams to filter the bay's waters, brown tides caused by microscopic algae became prevalent The blooms killed additional shellfish and prevented sunlight from reaching underwater grasses that provide a refuge for young fish, crabs and other organisms.

Since 2002, The Nature Conservancy has acquired 13,000 acres of submerged lands in Great South Bay from the Bluepoints Oyster Company, representing about 20 percent of the bottom of the Bay. The Conservancy's Conservation by Design planning process has guided the formation of the Bluepoints Bottomlands Council, a group of stakeholders, local state and federal agencies and scientists, that is committed to creating and implementing a plan "to restore Great South Bay to a thriving, healthy, naturally productive, self-sustaining estuary that supports native shellfish, seagrass, and other essential ecosystem components." TNC and its partners have embarked on a restoration plan that has the following elements:

- Establish a network of spawner sanctuaries to allow clams to accumulate, grow and reproduce, thereby supplying offspring to other parts of the Bay.
- Stock approximately one million adult clams per year for several years to increase the overall level of clam reproduction in the Bay.
- Measure survival and reproduction of clams transplanted into sanctuaries.
- Maximize survival of clams in sanctuary areas through ecosystem-based approaches to managing predators.
- Identify nutrient sources and understand their broad ecological effects on the ecosystem.

The restoration activities on the Bluepoints property are being closely monitored by The Nature Conservancy and its partners. Results to date have increased our understanding of clam reproduction in the Bay, and are leading to improvements in transplanting approaches. The broad involvement of stakeholders is intended to foster greater sense of community stewardship of the estuary and its resources, and should ensure that future harvest management and enforcement efforts are consistent with long-term sustainability of a more functional ecosystem.

Carl LoBue, a scientist with The Nature Conservancy, stocks adult hard clams to a sanctuary located on TNC's 'Bluepoints Property' in Great South Bay. *Stacy Goldyn-Moller, TNC*



Case Study 2:

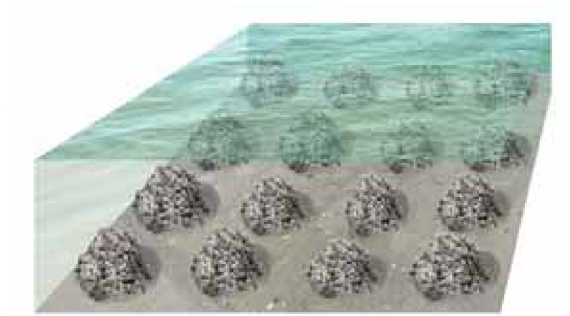
Eastern oyster restoration in Pamlico Sound, North Carolina

< Oyster sanctuaries in North Carolina. *The Nature Conservancy*

Pamlico Sound oyster reef projects demonstrate strategies for large scale restoration

Project Synopsis:

Like so many coastal embayments from Nova Scotia to the Gulf of Mexico, the Sounds behind North Carolina's Outer Banks once supported tremendous populations of the eastern oyster, Crassostrea virginica. Extensive areas of oyster reef habitat were formed by these populations and supported diverse assemblages of fish, crustaceans and other marine life. Tragically, the oyster population and extensive oyster reef structure in North Carolina has declined to only a small fraction of what it once was, and with it the fisheries that shaped coastal communities until well into the 20th century.



Limestone marl is used to restore oyster reef structure within sanctuaries. *NC Division of Marine Fisheries*

In 2001 The Nature Conservancy, in partnership with the NOAA Community-based Restoration Program and the NC Division of Marine Fisheries, began working to develop and refine new approaches for restoring the eastern oyster (Crassostrea virginica) to Sounds of coastal North Carolina. Since then, TNC and its partners have taken the following actions since to address the decline of native oyster populations in the Sound:

Careful monitoring is key to understanding the effects of restoration. *Rob Brumbaugh, TNC*

- Created multiple spawner sanctuaries to allow oysters to accumulate, grow to large sizes, reproduce and supply larvae to other parts of the Sound.
- Constructed large three-dimensional oyster reefs within sanctuary areas using Class-B rip-rap marl (limestone rocks about the size of basket balls). The reef structure mimics historic shape of reef habitat that once occurred in the Sound.
- Monitored the settlement, growth and survival of oysters on newly constructed reefs and documented the use of restored reefs by other species.

The monitoring data collected on reefs constructed since 2001 verifies what had been hypothesized by researchers – that oyster growth and survival is enhanced by the three-dimensional reef structure, and that a diverse array of species will use restored reefs. Validation of these concepts has been a key to inspiring state and federal agencies to look to larger scale application of this strategy in the Sound. To facilitate this work, additional questions remain to be addressed: What spatial configuration of reef sanctuaries is optimal for achieving Sound-wide benefits? What size and spacing of reefs within sanctuaries provides the optimal biodiversity and habitat benefits? Restoration at larger scales, along with continued monitoring, will help to address these questions and provide lessons to export for shellfish restoration in other locations.

Case Study 3

Native oyster restoration in Puget Sound, Washington

< Betsy Peabody, Executive Director of PSRF, measures oyster size and abundance along transect in Liberty Bay. *Kay McGraw, NOAA*

A systematic approach leads to development of restoration strategy

Project Synopsis:

At one time, Puget Sound was home to large populations of the Olympia oyster, *Ostreola chonchaphila*, the only oyster native to the region. Overharvest and pollution led to dramatic declines in Olympia oyster populations between the mid-1800s to the early-1900s, to the point where the commercial shellfish industry now depends on non-native oysters introduced to the region in the early 20th century.

With support from the NOAA Community-based Restoration Program and other funders The Puget Sound Restoration Fund (PSRF) and Washington Department of Fish and Wildlife (WDFW) set out in 2004 to revitalize the native Olympia oyster on a site in Liberty Bay, a small embayment in Puget Sound that once had a robust native oyster population. A systematic approach has been used to determine the best strategies to pursue for restoration.

- Baseline surveys were conducted to identify any existing native oysters in Liberty Bay, and to determine how much habitat was available for settlement of new oysters
- The abundance and population structure of the local oyster population was assessed using quadrat samples (i.e., noting how many larger, older oysters exist relative to smaller, younger oysters).
- The timing and extent of oyster reproduction was measured by sampling oysters at various times and examining gonads to look for signs of eggs and sperm cells.
- Additional reef habitat was constructed adjacent to existing oyster reefs using oyster shells purchased from commercial shellfish companies. Shells were deposited in layers thick enough to ensure an adequate settlement habitat was created on the bottom of the Bay.

The baseline surveys conducted by PSRF and WDFW informed the later steps in this project. Multiple size classes of Olympia oysters were present at the site, indicating that oyster settlement was occurring on a regular basis in Liberty Bay. However, surveys also revealed that clean shell habitat for oysters was in short supply. Armed with this information, PSRF and WDFW along with their additional project partners, Suquamish Tribe, U.S. Navy and Hood Canal Oyster Company, focused their subsequent restoration efforts on construction of new oyster reef habitat. Plots of clean shell were created adjacent to existing reefs and monitored for settlement of juvenile oysters. An expansion is planned to take advantage of the more than 10 acres of tidelands identified as suitable for restoration. Next steps also include monitoring of other fish or invertebrates that use the restored habitat, and evaluating the potential impacts of predators, including an introduced snail, on the project's overall outcome.

Oyster shells are sprayed from the deck of a bardge to create new oyster habitat in liberty Bay. *Tristan Peter-Contesse, PSRF*

VII. Hope for the future

Temperate marine and estuarine ecosystems are places of significant biodiversity and threat. The lands around these systems have been the centers of human habitation with landscapes that have been dramatically altered by human activities, so it is not entirely surprising to find them in poor condition throughout much of the world. From a societal standpoint, returning these systems to a more desirable prior condition (NRC 1992) will require a significant commitment of funding and other resources, coupled with a management paradigm that recognizes the value of ecosystem services provided by various habitats and other components of these systems (Breitburg et al 2000). From a scientific standpoint, this will require a more interdisciplinary approach to understanding how the various components of marine and estuarine ecosystems interact to allow species or habitats targeted for restoration to persist (Peterson and Lipcius 2004).

Given their multi-faceted role within nearshore marine systems, the conservation and restoration of bivalves is emerging as a priority for state and federal agencies as well as the conservation community in general. Benefits to commercial and recreational fishery stakeholders make these groups a natural ally in this endeavor, but the broad suite of ecological benefits should attract even greater public support. While the perceived benefits of restoration seem clear, and some effort has been placed on describing the general attributes and community structure of shellfish ecosystems, the approaches to documenting ecosystem benefits from restoration are still very much in their infancy. Modeling exercises have been used to explore the theoretical relationships between bivalve population size and certain ecological functions, but there have been few tests of these relationships in the field to validate assumptions or findings.

Shellfish landings have served as a primary metric used to gauge the impact of restoration efforts (NRC 2004). While fisheries production is certainly a valuable service, it is important to recognize that it may be years or decades for some shellfish ecosystems to recover to the point of sustaining higher shellfish fishery yields. For restoration to gain the momentum needed to achieve the gains in biomass necessary to deliver the many ecosystem services we deem important, we must redouble our efforts to measure and document the ecological, not just the economic, performance of projects at every scale. Restoration practitioners should seek to elevate ecosystem services such as provision of habitat and water quality as priorities for shellfish projects and should strengthen collaborations with research scientists to refine monitoring approaches to adequately document these services. Results should be communicated broadly within scientific, management and public forums to develop a broader base of support for shellfish restoration and protection. Communicating more directly with the public, through effective media outreach, is also an important component of restoration as this helps to build support for your restoration project specifically, but also for improved long-term coastal management overall.

Finally, it is important to note that shellfish restoration is still very much in its infancy and there is much room for further innovation and improvement to the approaches identified here. To that end, we hope this document helps to spur new restoration projects that, with effective monitoring, will advance the field of restoration and help to build support for expanded restoration activities in the future.

Literature Cited

Abadie, S.W. and M.A. Poirrier. 2000. Increased density of large *Rangia* clams in Lake Pontchartrain after the cessation of she dredging. J. Shellfish Res. 19(1): 481-485.

Allen, S.K. Jr. and T.J. Hilbish. 2000. Genetic Considerations for Hatchery-Based Restoration of Oyster Reefs. A Summary from the September 21-22, 2000 Workshop held at Virginia Institute of Marine Science, Gloucester Point, VA. 10 pp.

Arnol, W.S., D.C. Marelli, M. Parker, P. Hoffman, M. Frischer, and J. Scarpa. 2002.Enhancing hard clam (*Mercenaria spp.*) population density in the Indian River Lagoon, Florida: A comparison of strategies to maintain the commercial fishery. J. Shellfish Res. 21(2): 659-672.

Asmus, R.M. and H. Asmus. 1991 Mussel beds: Limiting or promoting phytoplankton? J. Exp. Mar. Biol. Ecol. 148: 215-232.

Bahr, L.M. and W.P. Lanier. 1981. The ecology of intertidal oyster reefs of the South Atlantic coast: A community profile. U.S. Fish and Wildlife Service, Office of Biological Services, Washington DC. FWS/OBS-81/15. 105 pp.

Bartol, I.K. and R. Mann. 1997. Small-scale settlement patterns of the oyster *Crassostrea virginica* on a constructed intertidal reef. Bull. Mar. Sci. 61(3): 881-897.

Beck, M. W. 2003. The sea around: marine regional planning in C. Groves, editor. Drafting a conservation blueprint: a practitioners' guide to planning for biodiversity. Island Press, Washington, DC.

Beck, M. W., and M. Odaya. 2001. Ecoregional planning in marine environments: identifying priority sites for conservation in the northern Gulf of Mexico. Aquatic Conservation 11: 235-242.

Beck, M.W., K.M. Fletcher, and L.Z. Hale. 2005. Towards Conservation of Submerged Lands: The Law and Policy of Conservation Leasing and Ownership. Rhode Island Sea Grant, Narragansett, RI. 45 pp.

Bernhardt, E.S., MA. Palmer, J.D. Allan, G. Alexander, K.Barnas, S. Brooks, J.Carr, S.Clayton, C.Dahm, J. Follstad-Shah, D. Galat, S.Gloss, P.Goodwin, D.Hart, B.Hassett, R. Jenkinson, S.Katz, G.M. Kondolf, P.S. Lake, R. Lave, J.L. Meyer, T.K. O'Donnell, L.Pagano, B. Powell and E. Sudduth. 2005. Synthesizing U.S. River Restoration Efforts. Science 308: 636-637.

Bishop, M.J., J.A. Rivera, E.A. Irlandi, W.G. Ambrose Jr. and C.H. Peterson. 2005. Spatio-Temporal patterns in the mortality of bay scallop recruits in North Carolina: investigation of a life history anomaly. J. Exp. Mar. Biol. Ecol. 315: 127-146.

Bisker, R. and M. Castagna. 1989. Biological control of crab predation on hard clams *Mercenaria mercenaria* (Linnaeus, 1758) by the toadfish *Opsanus tau* (Linnaeus) in tray cultures. J. Shellfish Res. 8: 33-36.

Breitburg, D.L. 1992. Episodic hypoxia in Chesapeake Bay: Interacting effects of recruitment, behavior, and physical disturbance. Ecol. Monographs 62: 525-546.

Breitburg, D.L. 1999. Are three-dimensional structure and healthy oyster populations the keys to an ecologically interesting and important fish community? In: M.W. Luckenbach, R. Mann and J.A. Wesson, Eds. Oyster reef habitat restoration: A synopsis and synthesis of approaches. Virginia Institute of Marine Science Press, Gloucester Point, Virginia.

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

Breitburg, D.L., M.A. Palmer and T. Loher. 1995. Larval distributions and the spatial patterns of settlement of an oyster reef fish: responses to flow and structure. Mar. Ecol. Prog. Ser. 125: 45-60.

Brumbaugh, R.D., L. Sorabella, C.O. Garcia, W.J. Goldsborough and J. Wesson. 2000a. Making a case for community-based oyster restoration: An example from Hampton Roads, Virginia, U.S.A. J. Shellfish Res. 19: 467-472.

Brumbaugh, R.D., L.A. Sorabella, C. Johnson, and W.J. Goldsborough. 2000b. Small-scale aquaculture as a tool for oyster restoration in Chesapeake Bay. J. Marine Technology 34: 79-86.

Bushek, D., D. Richardson, M.Y. Bobo and L.D. Coen. 2004. Quarantine of oyster shell cultch reduces the abundance of *Perkensus marinus.* J. Shellfish Res. 23: 369-373.

Caddy, J.F. and O. Defeo. 2003. Enhancing or restoring the productivity of natural populations of shellfish and other marine invbrate resources. FAO Fisheries Technical Paper 448. Food and Agriculture Organization of the United Nations. 159 pp.

Callaway, J.C. 2005. The challenge of restoring functioning salt marsh ecosystems. J. Coastal Research 40: 24-36.

Cerrato, R.M., D.A. Caron, D.J. Lonsdale, J.M. Rose and R.A. Schaffner. 2004. Effect of the northern quahog *Mercenaria mercenaria* on the development of blooms of the brown tide alga *Aureococcus anophagefferens*. Mar. Ecol Prog. Ser. 281: 93-108.

Cloern, J.E. 1982. Does the benthos control phytoplankton biomass in South San Francisco Bay? Mar. Ecol Prog. Ser. 9:191-202.

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

Coen, L.D., M.W. Luckenbach, and D.L. Breitburg. 1999. The role of oyster reefs as Essential Fish Habitat: A review of current knowledge and some new perspectives. Am. Fish. Soc. Symp. 22: 438-454.

Cook, A.E., J.Anne Shaffer, B.R. Dumbauld and B.E. Kauffman. 2000. A plan for rebuilding stocks of Olympia oysters (*Ostreola conchaphila*, Carpenter 1857) in Washington state. J. Shellfish Res. 19: 409-412.

Cressman, K.A., M.H. Posey, M.A. Mallin, L.A. Leonard and T.D. Alphin. 2003. Effects of oyster reefs on water quality in a tidal creek estuary. J. Shellfish Res. 22(3): 73-762.

Crowder, L.C., S.J. Lyman, W.F. Figuiera and J. Priddy. 2000. Source-sink dynamics and the problem of siting marine reserves. Bull. Mar. Sci. 66: 799-820.

Dame, R.F. 1996. Ecology of Bivalves: An Ecosystem Approach. CRC Press, Boca Raton, FL 254 pp.

DeAlteris, J.T. 1988. The geomorphic development of wreck shoal, a subtidal oyster reef of the James River, Virginia. Estuaries 11: 240-249.

Duarte, C.M. 2002. The future of seagrass meadows. Environ. Conservation 29: 192-206.

Edgar, G.J. and C.R. Samson 2004. Catastrophic decline in mollusc diversity in eastern Tasmania and its concurrence with shellfish fisheries. Conservation Biology 18: 1579-1588.

Eggleston, D.B. 1990. Foraging behavior of the blue crab *Callinectes sapidus* on juvenile oysters *Crassostrea virginica*: Effects of prey density and size. Bull. Mar. Sci. 46(1): 62-81.

French McCay, D.P., C.H. Peterson, J.T. DeAlteris, J. Catena. 2003. Restoration that targets function as opposed to structure: Replacing lost bivalve production and filtration. Mar. Ecol. Prog. Ser. 264: 197-212.

Gascoigne, J. and R.N. Lipcius. 2004. Allee effects in marine systems. Mar. Ecol. Prog.Ser. 269: 45-59.

Glancy, T.P., T.K. Frazer, C.E. Cichra and W.J. Lindberg. 2003. Comparative patterns of occupancy by decapod crustaceans in sea grass, oyster, and marsh-edge habitats in a northeast Gulf of Mexico estuary. Estuaries 26: 1291-1301.

Grabowski, J.H., A.R. Hughes, D.L. Kimbro and M.A. Dolan. 2005. How habitat setting influences restored oyster reef communities. Ecology 86(7): 1926-1935.

Green, E.P. and F.T. Short. 2003. World atlas of seagrasses. University of California Berkeley, CA.

Grizzle, R.E., J.R. Adams, and L. Walters. 2002. Historical changes in intertidal oyster (*Crassostrea virginica*) reefs in a Florida lagoon potentially related to boating activities. J. Shellfish Res. 21(2): 749-756.

Gross, F. and J.C. Smyth. 1946. The decline of oyster populations. Nature 157: 540-157.

Groves, C.R. 2003. Drafting a conservation blueprint: a practitioners' guide to planning for biodiversity. Washington D.C. Island Press.

Groves, C.R., D.B. Jensen et al. 2002. Planning for biodiversity conservation: putting conservation science into practice. Bioscience 52: 499-512.

Hadley, N.H. and L.D. Coen. 2002. Community-based program engages citizens in oyster reef restoration (South Carolina). Ecological Restoration 20: 297-298.

Haamer, J. and J. Rodhe. 2000. Mussel *Mytilus edulis* (L.) filtering of the Baltic Sea outflow through the Öresund An example of a natural large-scale ecosystem restoration. J. Shellfish Res. 19: 413-421.

Harding, J.M. and R. Mann. 2001. Oyster reefs as fish habitat: Opportunistic use of restored reefs by transient fishes. J. Shellfish Res. 20(3): 951-959.

Hargis, W.J. Jr. and D.S. Haven. 1999. Chesapeake oyster reefs: their importance, destruction and guidelines for restoring them. In: M.W. Luckenbach, R. Mann and J. Wesson, eds. Oyster Reef Habitat Restoration: A Synopsis and Synthesis of Approaches. Virginia Institute of Marine Science Press, Gloucester Point, VA.

Haven, D. and R. Morales-Alamo. 1970. Filtration of particles from suspension by the American oyster, *Crassostrea virginica*. Biol. Bull. 139: 248-264.

Haywood, E.L. T.M. Soniat and R.C. Broadhurst III. 1999. Alternatives to clam and oyster shell as cultch for eastern oysters. In: M.W. Luckenbach, R. Mann and J. Wesson, eds. Oyster Reef Habitat Restoration: A Synopsis and Synthesis of Approaches. Virginia Institute of Marine Science Press, Gloucester Point, VA.

Heck, K.L. Jr, and L.B. Crowder. 1991. Habitat structure and predator-prey interactions in vegetated aquatic systems. Pages 281-295 in S.S. Bell, E.D. McCoy and H.R. Mushinsky, Eds. Habitat structure: the physical arrangement of objects in space. Chapman and Hall, London.

Hewitt, J.E., S.F. Thrush, J.Halliday and C. Duffy. 2005. The importance of small-scale habitat structure for maintaining Beta diversity. Ecology 86(8): 1619-1626.

Irlandi, E.A., W.G. Ambrose Jr., and B.A. Orlando. 1995. Landscape ecology and the marine environment: how spatial configuration of seagrass habitat influences growth and survival of the bay scallop. Oikos 72: 307-313.

Irlandi, E.A., B.A. Orlando, and W.G. Ambrose Jr. 1999. Influence of seagrass habitatPatch size on growth and survival of juvenile bay scallops, *Argopecten irradians Concentiicus* (Say). J. Exp. Mar. Biol. Ecol. 235: 21-43.

Jackson, JBC, and 18 co-authors. 2001. Historical overfishing and the recent collapse of coastal ecosystems. Science. 293: 629-638.

Jones, C.G., J.H.Lawton and M. Shachak. 1994. Organisms as ecosystem engineers. Oikos 69: 373-386.

Jordan, S.J. and J.M. Coakley. 2004. Long-term projections of eastern oyster populations under various management scenarios. J. Shellfish Res. 23: 63-72.

Kassner, J. 1993. Possible effects of reduced hard clam abundance in Great South Bay.On the Water. July/August: 4-5, Cornell Cooperative Extension of Suffolk County, Riverhead, NY.

Kennedy, V.S. 1996. The ecological role of the eastern oyster, *Crassostrea virginica*, with remarks on disease. J. Shellfish Res. 15: 177-183.

Kennedy, V.S., R.I.E. Newell and A.F. Eble, eds. 1996. The Eastern Oyster: Crassostrea virginica. Maryland Sea Grant, College Park, MD 734 p.

Kimmerer, W.J., E. Gartside and J.J. Orsi. 1994. Predation by an introduced clam as the likely cause of substantial declines in zoo plankton of San Francisco Bay. Mar. Ecol. Prog. Ser. 113: 81-93.

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

Kraeuter, J.N., M.J. Kennish, J. Dobarro, S.R. Fegley, G.E. Flimlin, Jr. 2003. Rehabilitation of the Northern quahog (Hard Clam) (*Mercenaria mercenaria*) habitats by shelling – 11 years in Barnegat Bay, New Jersey. J. Shellfish Res. 22(1): 61-67.

Krantz, G.E. and J.V. Chamberlain. 1978. Blue crab predation on cultchless oyster spat. Proc. Nat. Shellfish. Assn. 68: 38-41.

Lenihan, H.S. 1999. Physical-biological coupling on oyster reefs: How habitat structure influences individual performance. Ecol. Monog. 69(3): 251-275.

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

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

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. Coastal Research Special Issue 40: 64-78

MacKenzie, C.L. 1989. A guide for enhancing estuarine molluscan shellfisheries. Marine Fisheries Review 51(3): 1-47.

Maguire, J.A, M. O'Donoghue, S. Jenkins, A. Brand and G.M. Burnell. 2002. Temporal and spatial variability in dredging induced stress in the Great Scallop *Pecten maximus* (L.) J. Shellfish Res. 21(1): 81-86.

Mann, R. and D. Evans 2004. Site selection for oyster habitat rehabilitation in the Virginia portion of the Chesapeake Bay. J. Shellfish Research 23(1): 41-49.

Margules, C.R. and R.L. Pressey. 2000. Systematic conservation planning. Nature 405: 243-253.

Marsh, T.D., M.W. Beck and S.E. Reisewitz. 2002. Leasing and restoration of submerged lands: Strategies for Community-based, watershed-scale conservation. The Nature Conservancy, Arlington, VA. 33 pp.

McCormick-Ray, M.G. 1998. Oyster reefs in 1878 seascape pattern Winslow RevisitedEstuaries 21: 784-800.

McCormick-Ray, J. 2005. Historical oyster reef connections to Chesapeake Bay – a framework for consideration. Est. Coast. Shelf Science 64: 119-134.

McKenzie, L.J. and S.J. Campbell. 2002. Seagrass-Watch: Manual for Community (Citizen) Monitoring of Seagrass Habitat. Western Pacific Edition (QFS, NFC, Cairns). 43 pp.

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

Micheli, F. and C.H. Peterson. 1999. Estuarine vegetated habitats as corridors for predator movements. Conservation Biol. 13: 869-881.

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

Milbury, C.A., D.W. Meritt, R.I.E. Newell and P.M. Gaffney. 2004. Mitochoondrial DNA markers allow monitoring of oyster stock enhancement in the Chesapeake Bay. Marine Biology 145: 351-359.

Minello, T.J., K.W. Able, M.P. Weinstein and C.G. Hays. 2003. Salt marshes as nurseries for nekton: testing hypotheses on density, growth and survival through meta-analysis. Mar. Ecol. Prog. Ser. 246: 39-59.

National Research Council (NRC) 1992. Restoration of Aquatic Systems: Science, Technology and Public Policy. National Academy Press, Washington DC pp 552

National Research Council (NRC). 2004. Non Native Oysters in the Chesapeake Bay. Committee on Nonnative Oysters in the Chesapeake Bay, Ocean Studies Board. National Academies Press, Washington DC.

Nelson, K.A., L.A. Leonard, M.H. Posey, T.D. Alphin and 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.

Newell, R.I.E. 1988. Ecological changes in Chesapeake Bay: Are they the result of overharvesting the American oyster, *Crassostrea virginica*? In, Understanding the Estuary: Proceedings of a Conference, 29-31 March 1988. Chesapeake Research Consortium Publication 129, CBP/TRS 24/88. Baltimore, Maryland.

Newell, R.I.E. 2004. Ecosystem influences of natural and cultivated populations of suspension-feeding bivalve mollusks: A Review. J. Shellfish Res. 23(1): 51-61.

Newell, R.I.E. and E.W. Koch. 2004. Modeling seagrass density and distribution in response to changes in turbidity stemming from bivalve filtration and seagrass sediment stabilization. Estuaries 27: 793-806.

O'Beirn, F., M.W. Luckenbach, J.A. Neslerode and G. 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.

Officer, C.B., T.J. Smayda & R. Mann. 1982. Benthic filter feeding: a natural eutrophication control. Mar. Ecol Prog. Ser. 9: 203-210.

Orth, R.J. and K.A. Moore. 1983. Chesapeake Bay: An unprecedented decline in submerged aquatic vegetation. Science 222: 51-53.

Osman, R.W., R.B. Whitlatch, RN. Zajac. 1989. Effects of resident species on recruitment into a community: larval settlement versus post-settlement mortality in the oyster *Crassostrea virginica*. Mar. Ecol. Prog. Series. 54: 61-73.

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

Peterson, B.J. and K.L. Heck Jr. 1999. The potential for suspension feeding bivalves to increase seagrass productivity. J. Exp. Mar. Biol. & Ecol. 240: 37-52.

Peterson, C.H. and R.N. Lipcius. 2003. Conceptual progress towards predicting quantitative ecosystem benefits of ecological restortions. Mar. Ecol. Prog. Ser. 264: 297-307.

Peterson, C.H., H.C. Summerson and R.A. Leuttich Jr. 1996. Response of bay scallops to spawner transplants: A test of recruitment limitation. Mar. Ecol. Prog. Ser. 132: 93-107.

Peterson, C.H., J. Grabowski, and S.P. Powers. 2003. Estimated enhancement of fish production resulting from restoring oyster reef habitat: quantitative valuation. Mar. Ecol. Prog. Ser. 264: 249-264.

Pohle, D.G., V.M. Bricelj, A. Garcia-Esquivel. 1991. The eelgrass canopy: an above-bottom refuge from benthic predators for juvenile bay scallops *Argopecten irradians*. Mar. Ecol. Prog. Series 74: 47-59.

Posey, M.H., T.D. Alphin, C.M. Powell, and E. Townsend. 1999. Oyster reefs as habitat for fish and decapods. *In*: M.W. Luckenbach, R. Mann and J.A. Wesson, Eds. Oyster reef habitat restoration: A synopsis and synthesis of approaches. Virginia Institute of Marine Science Press, Gloucester Point, Virginia.

Pressey, R.L., C.J. Humphries, C.R. Margules, R.I. Van-Wright and P.H. Williams. 1993. Beyond opportunism: key principles for sys tematic reserve selection. Trends in Ecology & Evolution 8(4): 124-128. 1993.

Pritchard, D.W. 1953. Distribution of oyster larvae in relation to hydrographic conditions. Pro. Gulf Carib. Fish. Instit. 3: 123-132.

Rice, M.A., C. Hickox and I. Zehra. 1989. Effects of intensive fishing effort on the population structure of quahogs, *Mercenaria mer cenaria* (Linnaeus 1758), in Narragansett Bay. J. Shellfish Res. 8: 345-354.

Rodriguez, S., F. Patricio Jedi, and N. Investors. 1993. Settlement of benthic marine invertebrates. Mar. Ecol. Prog. Ser. 97: 193-207.

Roegner, G.C. and R. Mann. 1995. Early recruitment and growth of the AmericanOyster *Crassostrea virginica* (Bivalve: Ostreola) with respect to tidal zonation And season. Mar. Ecol. Prog. Ser. 117: 91-101.

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.

Russ, G.R., B. Stockwell and A.C. Alcala. 2005. Inferring vs. measuring rates of recovery in no-take marine reserves. Mar. Ecol. Prog. Series. 292: 1-12.

Schroeter, S.C., J.D. Dixon, J. Kastendiek, R.O. Smith and J.R. Bence. 1993. Detecting the ecological effects of environmental impacts: a case study of kelp forest invertebrates. Ecological Applications 3:3331-350.

Schroeter, S. C., D. C. Reed, D. J. Kushner, J. A. Estes, and D. S. Ono. 2001. The Use of Marine Reserves in Evaluating the Dive Fishery for the Warty Sea Cucumber (*Parastichopus parvimensis*) in California, U.S.A. Canadian Journal of Fisheries and Aquatic Sciences 58:1773-1781.

Scott, T.A. W. Wehtje and M. Wehtje. 2001. The need for strategic planning in passive restoration of wildlife populations.Restoration Ecology 9(3): 262-271.

Short, F.T., L.J. McKenzie, R.G. Coles and J.L. Gaeckle. 2004. SeagrassNet Manual for Scientific Monitoring of Seagrass Habitat – Western Pacific Edition. University of New Hampshire, USA. QDPI, Northern Fisheries Centre, Australia. 71 pp. http://www.seagrassnet.org/SeagrassNet_Man.pdf

Short, F.T. and S. Wyllie-cheverria 1996. Natural and human-induced disturbance of seagrasses. Envir. Conservation 23: 17-27.

Shumway, S.E. and J.H. Kraeuter. 2003. Mulluscan Shellfish Research and Management: Charting a Course for the Future. Final Proceedings from the Workshop: Charleston, SC, January 2000.

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

Southworth, M. and R. Mann. 1998. Oyster reef broodstock enhancement in the Great Wicomico River, Virginia. J. Shellfish Research 17(4): 1101-1114.

Steimle, F.W. and C. Zetlin. 2000. Reef habitats in the Middle Atlantic Bight: Abundance, distribution, associated biological communities, and fishery resource use. Marine Fisheries Review 62: 24-42.

Stewart, M.J. and R.G. Creese. 2002. Transplants of intertidal shellfish for enhancement of depleted populations: Preliminary trials with the New Zealand little neck clam. J. Shellfish Res. 21(1): 21-27.

Strayer, D.L., N.F. Caraco, J.J. Cole et al. 1999. Transformation of freshwater ecosystems by bivalves, a case study of zebra mussels in the Hudson River. BioScience 49: 19-27.

Talman, S.G., A.Norkko, S.F. Thrush and J.E. Hewitt. 2004. Habitat structure and the survival of juvenile scallops *Pecten novaezelandiae*: comparing predation in habitats with varying complexity. Mar. Ecol. Prog. Ser. 269: 18: 97-207.

Thayer, G.W., T.A. McTigue, R.J.Salz, D.H.Merkey, F.M.Burrows and P.F. Gayaldo (eds). 2005. Science-based restoration monitoring of coastal habitats, Volume Two: Tools for Monitoring Coastal Habitats. NOAA Coastal Ocean Program Decision Analysis Series No. 23. NOAA Centers for Coastal Ocean Science, Silver Spring MD 628 pp. plus appendices.

The Nature Conservancy. 2000. Conservation by Design: A Framework for Mission Success. Arlington, Virginia. 12 pp.

Ulanowicz, R.E. and J.H. Tuttle. 1992. The trophic consequences of oyster stock rehabilitation in Chesapeake Bay. Estuaries 15: 298-306.

Underwood, A. J. 1991. Beyond BACI: experimental designs for detecting human environmental impacts on temporal variations in natural populations. Australian Journal of Marine and Freshwater Research 42:569-587.

U.S. Commission on Ocean Policy. 2004. An ocean blueprint for the 21st century: final report of the U.S. Commission on Ocean Policy. Washington, D.C. http://www.oceancommission.gov

Verwey, J. 1952. On the ecology and distribution of cockle and mussel in the Dutch Wadden Sea, their role in sedimentation and the source of their food supply. Arch. Neerl. Zool. 10: 172-239.

Virnstein, R.W. 1977. The importance of predation of crabs and fishes on benthic infauna in Chesapeake Bay. Ecology 58: 1199-1217.

Wenner, E, H.R. Beatty and L.D. Coen. 1996. Method for quantitatively sampling nekton on intertidal oyster reefs. J. Shellfish Res. 115: 769-775.

Zimmerman, R., T.J. Minello, T. Baumer and M. Castiglione. 1989. Oyster reef as habitat for estuarine macrofauna. National Oceanic and Atmospheric Administration Technical Memorandum NMFS-SEFC-249.

Appendix:

Some relevant web sites related to shellfish, restoration and monitoring

EPA's Shellfish Web Site:
http://www.epa.gov/ost/shellfish/

Interstate Shellfish Commission:
http://www.issc.org/

Maryland Seagrant Oyster Page:
http://www.mdsg.umd.edu/oysters/

Virginia Institute of Marine Science shellfish restoration atlas:
http://www.vims.edu/mollusc/oyrestatlas/oramaptoc.htm

Gulf of Maine Restoration Goals:
http://www.gulfofmaine.org/habitatrestoration/

SCORE! South Carolina Oyster Restoration and Enhancement Web Site:
http://www.csc.noaa.gov/scoysters/

South Carolina DNR Shellfish Research:
http://www.dnr.sc.gov/marine/mrri/shellfish/index.htm

Oyster Shell Recycling in South Carolina
http://saltwaterfishing.sc.gov/oyster.html

Restore America's Estuaries Principles of Estuarine Habitat Restoration:
http://www.estuaries.org/assets/documents/Principles.pdf

Society or Ecological Restoration International (Primer on Ecological Restoration):
http://www.ser.org/content/ecological_restoration_primer.asp

NOAA Community-based Restoration Program
http://www.nmfs.noaa.gov/habitat/restoration/

Army Corps of Engineers
http://www.usace.army.mil/

U.S. Fish and Wildlife Service
http://www.fws.gov/coastal/
http://www.fws.gov/partners/

EPA Office of Welands, Oceans and Watersheds:
http://www.epa.gov/owow/

Geological Survey
http://www.usgs.gov/

National Park Service:
http://www.nps.gov/

Natural Resources Conservation Service:
http://www.nrcs.usda.gov/

EPA Volunteer-based Monitoring Web Site:
http://www.epa.gov/owow/estuaries/monitor/

EPA's Principles of Habitat Restoration
http://www.epa.gov/owow/wetlands/restore/principles.html

National Sea Grant:
http://www.nsgo.seagrant.org/

South Carolina oyster reef monitoring workgroup
http://www.coastal.edu/marine/sgoyster/

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Brumbaugh, R.D., M.W. Beck, L. D. Coen, L.Craig and P. Hicks. 2006. A Practitioners´ Guide to the Design and Monitoring of Shellfish Restoration Projects: An Ecosystem Services Approach. The Nature Conservancy, Arlington, VA.

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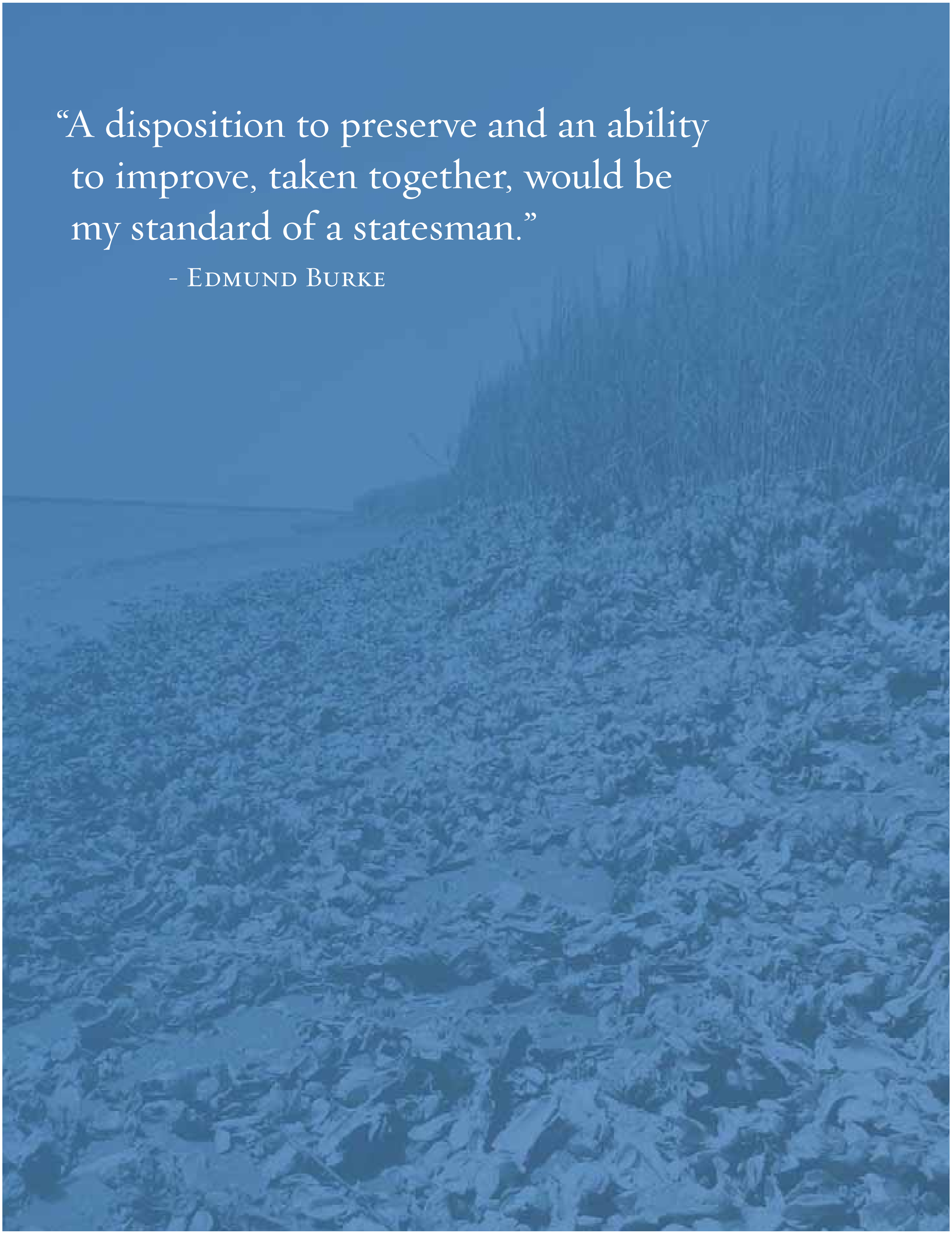

"A disposition to preserve and an ability to improve, taken together, would be my standard of a statesman."

- Edmund Burke