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Marine Bivalve Shellfish

Conservation Priorities for the Delaware Estuary

Partnership for the Delaware Estuary

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Introduction

The purpose of this study was to identify current and future protection, enhancement and restoration activities that might be implemented to boost bivalve shellfish populations in the Delaware Estuary and to prioritize the best areas for implementing these tactics. Only native species of marine and estuarine bivalves are included in this analysis (excludes tidal freshwater mussels and exotic species). This characterization of bivalve restoration priorities should be considered a first step in an iterative process whereby priorities are updated in the future as conditions change and new information comes to light regarding needs and tactics for the various marine bivalve species.

Prioritizing marine bivalve shellfish restoration is important so that limited resources are invested strategically to maximize net benefits to both people and the environment. The prioritization framework applied in this study was designed to focus on ecologically significant species, which includes commercially valuable oysters. Both historical information and future (climate) projections were considered so that priorities are informed by our current understanding of ecological trajectories of change in the system.

American oysters (*Crassostrea virginica*) are the kingpin of the commercial shellfishery in the Delaware Estuary. Oysters are also valued as a cultural and historical iconic species that resonates with the public. Oyster reefs benefit water quality, provide fish habitat and can help buffer coastal flooding. ***Strategic shell planting is the top recommended conservation tactic for oysters***. Shell planting has been a proven success in Delaware Bay by boosting recruitment, sustaining a positive shell budget, and enhancing overall productivity.

Ribbed mussels (*Geukensia demissa)* are of major ecological importance in the Delaware Estuary. This salt marsh species is valued for its role in salt marsh food webs and biogeochemical cycles (Jordan and Valieda 1979) as well as its filtration of large water volumes (Kreeger and Bushek 2008). ***Marsh protection and enhancement is the top recommended conservation tactic for ribbed mussels***. Many other marine species exist in the Delaware Estuary, but either they are not abundant or restoration opportunities are limited. Priorities for native species of freshwater bivalves were not considered for the purposes of this report; however, they are also part of a watershed-wide conservation and restoration strategy being developed by the Partnership for the Delaware Estuary.

The strategies and recommended bivalve restoration priorities in this report inventory an array of conservation strategies for oysters and ribbed mussels in the Delaware Estuary. Traditional tactics are presented in this paper as well as new and experimental options to restore shellfish. General recommendations are furnished for each conservation activity in this inventory section, but should not be considered as formal project designs. Projects should obtain the proper permits, permissions, and the details should be drafted by those with appropriate expertise. Finally, various policy impediments and other implementation considerations are summarized because some activities might not be possible under current management and regulatory constraints.

Bivalve Species in the Delaware Estuary

The Delaware River Basin contains over 60 species of bivalve mollusks, including 2 non-native clams (Kreeger & Kraeuter, 2010). Of these, only about a dozen are estuarine natives, and only two are considered to be "ecologically significant." The American oyster, *Crossostrea virginica*, is a well recognized conservation and restoration target for its commercial and ecological values (Beck, et al., 2009), and is especially notable in the Delaware Estuary for its historical importance and current socioeconomic importance to an economically depressed region (Ford, 1997). The ribbed mussel (*Geukensia demissa*) is a lesser known animal that is the functional dominant in Mid-Atlantic salt marshes (Kuenzler, 1961; Lent, 1969; Jordan, 1982) and recent estimates indicate that it filters more water in the Delaware Estuary than any other native bivalve species (Kreeger & Gatenby, 2007), including oysters. These two species are amenable to restoration and protection because they form aggregations that form relatively stable dense beds or reefs, which can be managed and enhanced. Most of the other Delaware Bay marine bivalves exist in more spatially diffuse or ephemeral populations (eg. *Mya arenaria*, *Ensis directus*, clams), and there is insufficient information to characterize their abundance. Table 1 lists the marine bivalve molluscs thought to live in the Delaware Estuary.

Table 1: Marine bivalve molluscs of the Delaware Estuary that were considered initially, from which oysters and ribbed mussels were selected.

Common	Scientific Name	Bay Zone	Salinity Zone
Oyster	*Crassostrea virginica*	Subtidal	Mesohaline, Polyhaline
Ribbed (Marsh) Mussel	*Geukensia demissa*	Intertidal	Polyhaline Mesohaline
Northern Quahog (Hard Clam)	*Mercenaria mercenaria*	Subtidal	Mesohaline Polyhaline
Blue Mussel	*Mytilus edulis*	Intertidal/Subtidal	Polyhaline
Atlantic Rangia	*Rangia cuneata*	Subtidal	Oligohaline
Hooked Mussel	*Ischadium recurvum*	Subtidal	Mesohaline, Oligohaline
Softshell Clam	*Mya arenaria*	Subtidal	Polyhaline, Mesohaline
Stout Tagelus (Stout razor clam)	*Tagelus plebeius*	Intertidal	Polyhaline
Atlantic Jackknife Clam (Razor Clam)	*Ensis directus*	Intertidal/subtidal	Polyhaline, Mesohaline

Overview of Conservation Strategies

Bivalve populations can be enhanced via diverse protection, restoration and management actions. The following list inventories the array of conservation strategies which can be used to enhance marine bivalves.

Conservation

Harvest Guidelines

From the late 1800s to the early 1900s, natural oyster populations were overfished and manipulated in order to sustain high harvest quotas (Ford, 1997). Since the 1950s, oyster beds in New Jersey have been actively managed through an ‘area management plan,’ which resulted in a relatively stable oyster population for the past 60 years (Fegley et al., 2003; Fegley et al., 1994; Kreeger & Kraeuter, 2010). Harvest quotas are adjusted based on stock conditions, and typically limited to only 2-3% of the adult population. Due to the long track record of successful stock maintenance and the adaptive and proactive management structure, the Delaware Bay oyster fishery was declared “sustainable” by the Stock Assessment Review Committee (SARC), which includes three external reviewers. Most of the system’s oyster beds are situated in New Jersey waters that have been well monitored. We know less about bivalve populations within the State of Delaware, but collaborative participation in the annual New Jersey Delaware Bay Oyster Stock Assessment Workshop (SAW) indicates similar status and trends (pers. comm. Richard Wong and Rick Coles, DNREC, Feb 9, 2011). Our recommendations for protection and restoration projects in this report reflect this general state of knowledge, and more refined recommendations for Delaware can be developed as new information is gathered.

Ribbed mussels are not commercially or recreationally harvested, and so no harvest guidelines are recommended.

Recommendation. Any change to oyster harvest guidelines should be made in concert with the SARC and vested parties, and with careful consideration of the socio-historical and economic importance of oysters.

Special Management Areas

Special management areas (SMAs) are manipulation-free sanctuaries for aquatic life, designed to preserve aquatic biodiversity and native ecology (Edgar, Russ, & Babcock, 2007). In the Delaware Estuary, no formal SMAs have been established to restrict oyster harvesting, although certain waters do not allow harvest because of shellfish sanitation concerns. Ribbed mussels live in protected salt marshes, and so these areas function similar to SMAs for wetland species.

This report recommends three adaptive management techniques for oysters within the existing oyster management paradigm. First, special oyster management areas (SOMAs) should be identified and established in the Estuary. Areas for potential SOMAs include marginal beds which are shallow and unsuitable for oyster boats to navigate. The management specifics would vary by site, but each SOMA would be set aside from harvest for periods of time (e.g., 2-5 years) by the Stock Assessment Review Committee. Additionally, SOMAs should be considered for areas where no reefs currently exist but where future reefs might become established, such as the area around the C&D Canal (see Area 4). Second, this report recommends that more monitoring and study take place on the upper oyster beds (Liston Range, Hope Creek, Fishing Creek), where oysters are moved to replenish other beds down bay following harvest and natural mortality. The upper beds are important areas for potential climate change adaptation, but we know little about recruitment, growth rates, mortality rates, shell budgets and other population maintenance features for those subpopulations. Third, special management consideration should be given to tributary rivers, which are closed to harvest and which present potentially expanding habitat opportunities as sea levels rise and tributary embayments widen.

This report recommends two management techniques for the ribbed mussel: habitat preservation and scientific study. Fortunately, the primary habitat for ribbed mussels is salt marshes, which are protected wetlands under the Clean Water Act. Despite these protections, however, salt marshes (and ribbed mussels) are still being lost due to erosion and sea level rise. These habitats could be further 'protected' if tactics are installed to prevent or slow salt marsh loss. Implementation of erosion control projects would buy more time for the inland migration of these habitats, thereby helping to preserve ribbed mussels and their numerous ecosystem benefits (Kreeger and Kraeuter 2010).

More study is recommended to understand the life history, ecology and habitat requirements of ribbed mussels so that desired outcomes from shellfish enhancement efforts can be maximized. SMAs designed to maximize ribbed mussel populations could be created in or along salt marshes where mussel protection, restoration or scientific study occurs.

Recommendations. Establish three types of SOMAS (for oysters) described above, protect and enhance salt marshes (for ribbed mussels), and support scientific study of conservation outcomes from ribbed mussel enhancement projects.

Culture/Propagation

Hatchery/Seed Production/Population Augmentation

Figure 1: Example of a freshwater mussel hatchery at Cheyney University used to grow animals for restoration.

Hatcheries can be used to boost shellfish populations for harvest, but they can also be used to support restoration (Fig. 1). Successful shellfish hatcheries have been established in Maryland and Virginia to support Chesapeake Bay restoration sites. Hundreds of millions of spat-on-shell are produced at Horn Point Laboratory's Shellfish Cultivation Facility, and later transplanted to restoration sites (CES, 2010).

In Delaware Bay, hatchery production for oysters could be used to rehabilitate areas where stocks are reduced, especially when natural recruitment is low. Rutgers has maintained a research oyster hatchery on Delaware Bay and recently opened an aquaculture facility on the Cape May canal with hatchery capabilities that approximate those at Horn Point. Several small commercial hatcheries also exist along the Atlantic Coast, and the University of Delaware maintains a small research hatchery in Lewes. All of these could be used to help boost shellfish populations in Delaware Bay.

Hatcheries can also be used to breed disease-resistant oysters that are more resilient to salinity rise from climate change (see Area 4). Hatchery methods for ribbed mussels are lacking. Therefore, we recommend that ribbed mussel seed production methods be developed for shellfish-based living shorelines (see living shoreline section). Ribbed mussel hatcheries could also provide seed to watershed organizations for educational and shellfish gardening projects (see below).

Recommendations. Boost oyster and ribbed mussel populations with seed produced in underutilized Delaware Bay hatcheries, and invest in needed R&D for ribbed mussel hatchery and outplantng protocol development.

Spat Collection & Relaying

Relaying is the process of transplanting live bivalves to a new location. Oyster relaying has been used as a management technique for centuries with spat and adult relaying occurring in the Delaware Bay on the upper seed beds. Oyster relaying was also used in Mississippi to restore damaged reefs from hurricane Katrina. In the lower portion of the Delaware Bay, spat (baby oyster) recruitment is high, but most spat do not survive because mortality from predation and sedimentation is also high in the higher salinities. A proven tactic is to put shell out to catch spat, and then move it to lower disease zones to mature. This strategy was successfully used as part of the Delaware Bay shellplanting project where spat were collected on shell placed in the NJ Cape Shore area (PDE, 2007).

In most years Delaware Bay has no shortage of oyster larvae but recruitment on the natural seedbeds is patchy in space and time; therefore, catching and relaying natural spat on planted shell in the lower bay is a tactic that can boost recruitment and is much cheaper than using hatcheries. However, this method is spatially limited by bottom quality and spat recruitment conditions and it also requires large equipment and significant logistical effort. Methods for collecting natural recruitment of ribbed mussels have yet to be developed.

Recommendation. Continue to encourage the oyster industry to use lower bay spat collection and relaying as a mechanism to replenish and expand the populations they harvest. Also, support research into methods for collecting natural recruitment of ribbed mussels.

Gardening

Gardening refers to any small scale activity which grows shellfish on a temporary non-reef structure. Shellfish gardens are typically small and used to promote conservation through community participation by schools, parks, businesses, watershed groups, and waterfront property owners (VDEQ, 2010). Oyster gardening has been used in areas such as the Chesapeake Bay, the Delaware Inland Bays, and the Gulf of Mexico (Fig. 2).

Figure 2: Independent oyster gardener in the Inland Bays Estuary. (Sally Boswell, DE Center for the Inland Bays)

In Delaware Bay, the major constraint on oyster gardening is the human health risk associated with consumption of oysters grown in poor quality waters. New Jersey recently banned gardening of any commercial species in tributaries and other closed waters because of sanitation concerns. A similar ban in Maryland was recently reversed because concerns were addressed through public education and policy enforcement (Delando 2011). The New Jersey ban does not apply to ribbed mussel gardening because they are not a commercial species.

Recommendation. Shellfish gardening methods should be developed for ribbed mussels as New Jersey continues to weigh the risks of oyster gardening to the shellfish industry versus the benefits such activities may provide through education and outreach, shellfish population enhancement, and vested public interest in shellfish populations.

Extensive Aquaculture

Extensive aquaculture refers to cultivation that exerts relatively limited control of the cultivated organism. The oyster fishery is arguably a form of extensive aquaculture given the level of manipulation to the population that exists today, which includes transplanting oysters from upper to lower seedbeds, planting shell to improve bottom habitats for oyster recruitment and relaying spat from the lower bay. Traditional cultivation of oysters on leased grounds is a clear example of extensive aquaculture.

Recommendation. Extensive aquaculture should be permitted and encouraged where supported by the market rather than discouraged. Although aquaculture is not an enhancement priority, it will have enhancement benefits, so a "do not hinder" approach is recommended.

Intensive Aquaculture

Intensive aquaculture involves much more control of the organisms life cycle and may include hatchery production, a nursery phase and cage or bag culture during grow out. It can be more costly and energy-intensive than extensive aquaculture, but more predictable and controlled.

Recommendation. (similar for Extensive Aquaculture above) do not hinder as long as siting for intensive aquaculture is selected to ensure any environmental effects are negligible or beneficial.

Stock Enhancement

Promote Disease Resistance

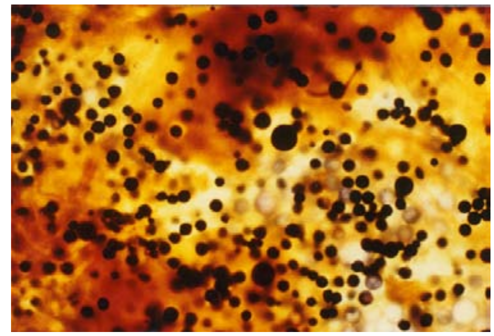

Figure 3: Black spots show Dermo infested oyster tissue.

Oyster diseases called MSX and Dermo are two primary factors limiting oyster populations in Delaware Bay. Salinity largely determines disease levels and distribution; hence the management of freshwater inputs from the upper watershed is a high priority for oyster health (Fig. 3). Adaptive management can be used to enhance disease resistance by developing disease-resistant stocks through aquaculture and oyster gardening. In Delaware Bay, data from the Haskin Shellfish Research Laboratory indicate that the native oyster population has become MSX resistant through natural selection (Hofmann et al., 2009). Unfortunately, resistance to Dermo has yet to be developed despite extensive experimental breeding programs. For this reason, there is a critical need to support more research on Dermo disease.

Recommendation. Continue supporting research on Dermo, including oyster monitoring.

Reef Creation/Enhancement

Designed Shellfish Reef

Figure 4: Example of a reefball structure used to catch natural oyster spat. (reefball.org)

In traditional shellplanting projects, a lot of shell is lost due to being swept away or buried in mud. Vertical reefs can be used to prevent lost shell and they can create more surface area in the water column to attract spat. For example, HESCO concertainer units are giant metal cages used to hold shell for recruitment in the Gulf of Mexico (HESCO, 2010). The spat settle on the trapped shell and eventually cover over the cage. Additional options exist for creating vertical reefs, such as tripod panels. Concrete can be used instead of expensive shell to build vertical reefs.

For shallow areas, a variety of commercial reef construction products are also now available. One example of a reef product is a "reef ball", which is made of limestone or concrete, and ranges in dimensions from the size of a basketball to over 5ft tall (Fig. 4). "Reef-Blok" and "Wave Attentuation Devices" are other commercial products that have been shown to be effective in areas along the Gulf of Mexico (The Reef Ball Foundation, 2011). Shallow shellfish reefs must not conflict with navigation routes or interfere with oyster fishing dredges. These hard structures will need testing in pilot projects to determine their long-term effects and suitability within the Delaware Estuary.

Recommendation. In order to test artificial reefs, pilots should first be developed as part of living shoreline projects or in areas of tributaries, and later potentially expanded to other shallow marginal areas

Living Shorelines – Intertidal Zones

Living shorelines are shoreline stabilization projects that can be used to offset wave energy and sea level rise effects while also enhancing ecological values. They range in complexity from modest biological modifications in low energy areas to hard structures in high energy areas. The Delaware Estuary Living Shorelines Initiative (DELSI), piloted in New Jersey salt marshes, was intended to stabilize eroding tidal marsh shorelines in low to moderate energy areas, partly by the binding action of ribbed mussels and plants within coir biolog and shell bag treatments. Although more monitoring is needed to document long-term out comes, this method appears to bolster the resilience of marsh plants by stabilizing erosion while also encouraging recruitment of shellfish communities. In addition to these benefits, fish and wildlife use the mussel-rich edges of salt marshes, and mussels promote good water quality through their filter-feeding. At a pilot site in the Maurice River, DELSI was also successfully employed over an existing revetment to restore ribbed mussel salt marsh habitat and improve habitat for fish, shrimp, and crabs (Fig. 5).

Figure 5: A five month time series of a Delaware Estuary Living Shoreline site at Matts Landing, NJ.

The Partnership for the Delaware Estuary and Rutgers University are currently examining the suitability of other types of living shorelines for addressing erosion and other issues across the Delaware Estuary, many of which include bivalve shellfish as part of their design. In the future, oyster-based living shorelines might become more widespread as global warming enhances the winter survivorship of oysters in the intertidal zone.

Living shorelines designed to promote ribbed mussels, such as DELSI, can yield diverse benefits. Not only are mussels promoted within the treatment, but extensive marsh acreage can be protected landward of the treatment, which is also habitat for mussels and other fauna. Since mussels have been estimated to filter more water than other native bivalve species across the Delaware River Basin (Kreeger & Bushek, 2008), protection of ribbed mussel populations (such as by protecting their habitat) is imperative.

Recommendation. Expand shellfish-based living shorelines as a tactic to both promote bivalves and to stabilize coastal habitats such as tidal wetlands.

Living Shoreline – Subtidal Breakwater

Near shore oyster breakwaters in shallow subtidal areas may help to stem shoreline erosion and prevent flooding for coastal properties, especially when combined with intertidal living shorelines and hybrid arrangements. (Potential options for near shore oyster breakwaters in Delaware Bay include places where historic reefs existed in shallow nearshore areas and places where the current habitat is marginal for tonging or dredging (too shallow or rocky).

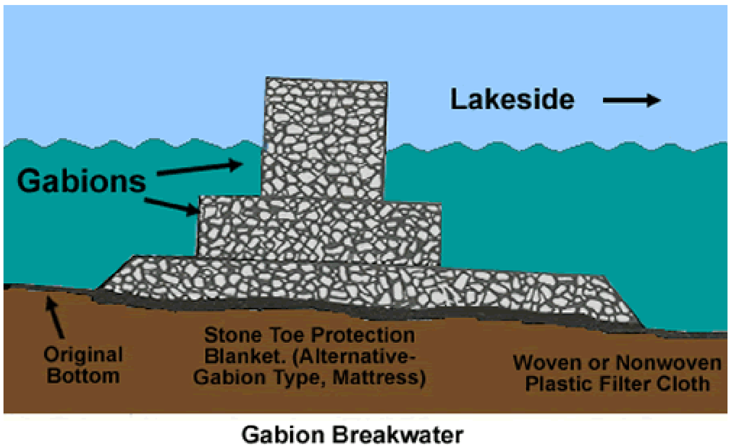

Figure 6: Example of a gabion breakwater from an Army Corps of Engineers project. (http://www.iwr.usace.army.mil/docs/MMDL/FLD/Feature.asp?ID=35)

Breakwaters are rapidly being built in some areas of the US including Alabama and Louisiana to reduce wave energy, protect vulnerable coastlines, and provide greater habitat for protective oyster reefs to form (Piazza, 2005). Reef balls, reef block, or other materials can be used to create near shore reefs as breakwaters (Fig.6). Some of these materials are not readily poached and so they might help address any shellfish safety concerns. Success of this tactic depends on wave energy, bottom type, navigation conflicts, and the fit with area management goals.

Recommendation. Pilot oyster breakwater projects should be completed, which could be expanded or replicated if successful. Pilot projects might be more easily permitted within the State of Delaware than in New Jersey, allowing for demonstration sites to build awareness.

Shell Planting

Figure 7: Shell is being released from the boat on to a Delaware Bay shellplanting site.

Shellplanting to enhance oyster production has been the most effective tactic for boosting oyster production in the Delaware Estuary; e.g., the Delaware Bay Oyster Restoration Project (PDE, 2007). Funding and project management for shellplanting has been overseen by an Oyster Restoration Task Force comprised of agency, industry, non-profit and academic partners from Delaware and New Jersey. Sites for shellplanting are selected based upon existing or historic oyster setting patterns, reef habitats and the most recent monitoring data. When oyster larvae are most abundant in the water (late June, early July), targeted reefs are planted with clam and oyster shell (fig. 7). This provides hard substrate to which oyster larvae attach themselves. The new recruits (spat) remain on these beds. Since 2005, the Delaware Bay Oyster Restoration Project has yielded a substantial increase in recruitment (Powell et al., 2011).

Of the twelve conservation strategies covered above, shell planting is the top priority for oysters due to its proven success and excellent value for money. It has been the main goal of the Delaware Bay Oyster Restoration Task Force, which is led by Dr. Eric Powell (Rutgers University). In 2010, the Delaware Bay Shellplanting Program received the Coastal America Award, one of the nation's top honors for success in environmental restoration. Unfortunately, the shell planting program operated by the task force has not been able to be sustained fully due to funding. In the past 10 years, shellplanting has been supported by either limited-duration projects or from a voluntary industry-supported "cultch fund." Sustained significant funding for shell planting is critically needed. Eventually, oyster productivity is expected to increase due to a projected longer growing season, increased disease resistance, and continued water quality improvements. Until then however, the task force estimates that an annual shell planting budget of $1 million is needed to sustain a positive shell budget, stabilize and enhance oyster stocks, and ensure a continued commercial shellfishery. A minimum of $200,000 per year is needed just to make it cost effective for operating the boats and machinery for shellplanting. While significant, this level of sustained funding is estimated to provide several fold returns in commercial benefits while also significantly enhancing the ecological integrity of the Delaware Estuary. It is also well below funding projections aimed at restoring oysters in other great American estuaries.

Recommendations. Develop sustained funding of $1 million annually for shellplanting in Delaware Bay and engage the Delaware Bay Oyster Task Force to implement operations. Facilitate continued operation of the industry's voluntary cultch fund.

Shellfish Implementation Considerations

Implementation challenges for shellfish restoration tactics include: policy impediments, management paradigms, industry perspectives, and both short term and long term funding. Our prioritization approach assumed that these constraints might be overcome as new research, education, and resources change perspectives more conducive to ecosystem-based shellfish restoration. Nevertheless, the priorities recommended herein are tempered by current funding realities and management priorities. As a general rule of thumb, we discern between short-term priorities that are based on current paradigms and long-term priorities that potentially reflect evolved paradigms.

Commercial Species Bias

Generally shellfish restoration attention is directed at the American oyster because of its commercial importance. This bias towards commercial bivalve species is seen both nationally and internationally, as reflected by funding priorities (e.g., NOAA Restoration Center) and attention by national non-profit groups (Beck et al., 2009). About 60 species of bivalves in the Delaware Estuary (Kreeger & Kraeuter 2010), and many of these are regarded as "ecosystem engineers" because they build or transform benthic habitats, alter aquatic food webs, and provide diverse water quality benefits via filter-feeding.

Certainly, the oyster merits top consideration in the Delaware Estuary because it builds complex reef habitats and because of its historical, socioeconomic, and ecological importance (PDE, 2007; Kraeuter & Kreeger, 2010). Efforts in the last ten years to restore oyster beds with shellplanting have been remarkably successful. On economic grounds alone, oyster restoration should continue to be a management priority because the industry sustains jobs, and because it provides a focal point for public interest in the system's health and well being. However, to achieve ecosystem improvement without commercial benefits, shellfish restoration should extend to species such as the Ribbed Mussel.

The Partnership for the Delaware Estuary has been recommending a watershed-based shellfish restoration strategy for several years, using non-commercial species of bivalves in addition to oysters (Kreeger & Gatenby, 2007; D. Kreeger, 2007; Kreeger & Bushek; 2008; Kreeger & Brumbaugh, 2009). In other areas of the country, shellfish restoration is gradually expanding to include non-commercial species. The draft Executive Order for the Chesapeake Bay, for example, includes provisions to investigate the utility of restored beds of freshwater mussels for intercepting pollutants before they reach the receiving water of the bay and for restored beds of estuarine species such as ribbed mussels for remediating water quality in the receiving waters (FLCCB, 2010).

Traditional Management Perspectives

Oysters have been commercially harvested from the Delaware Estuary for hundreds of years, and the main stock in Delaware Bay has been manipulated in so many ways that it is impossible to reconstruct historic conditions. Seed was imported from other areas to augment natural recruitment. Oysters have been (and continue to be) physically moved from less favorable growing areas to more favorable areas. With more than 100 years of active management, much knowledge has been gained about how to best maximize production and sustain the resource, especially in the post-disease (1990's-present) era which represents a new steady state. Oyster management in Delaware Bay is widely regarded as highly successful model that supports a "sustainable fishery," bucking trends elsewhere.

This model is adaptive management based on a strong monitoring program and continued scientific input. This system has the challenge of managing a resource and its supportive ecosystem while adapting to human induced changes such as channel deepening, pollution, managed freshwater controls, and now climate change with sea-level rise. The current adaptive management strategy should be supported and enhanced in order to handle these encroaching threats. Adaptive management is challenging because it requires a strong science and monitoring program to maintain.

Policy Constraints

State and federal policies can impede or directly prohibit bivalve shellfish restoration, and these policies will need to be adapted before some types of projects can be implemented. Important examples include: 1) state bans on restoration of edible species to protect human health, 2) regulatory constraints on wetland restoration, 3) aversion to habitat trade-offs restoration, and 4) difficulty of permitting for non-traditional tactics.

Restoration bans. In 2010, the State of New Jersey enacted a ban on the restoration or gardening of commercial shellfish species in coastal and inner harbor waters that are classified as contaminated (NJDEP, 2011). This action immediately forced the suspension and removal of oyster restoration project in the New Jersey / New York Harbor, attracting significant press attention (e.g., NJ/NY Baykeeper 2010, Salmon 2010). This policy was designed to protect human health because of fears that restoration and oyster gardening would attract poachers. Illegal harvest in closed waters could make people sick if the oysters were eaten or perhaps sold illegally, posing a liability risk for state or private project sponsors. Bad press for the shellfish industry could pose an economic risk to jobs and $790 million the shellfish industry annually contributes to New Jersey's economy. While on the surface this prohibition policy seems rational, it is not necessarily based on science. Hard clams (edible species) currently occupy some of the same areas that were banned for oyster projects.

In many other areas of the United States, these risks are addressed as part of restoration efforts through a mix of education, enforcement and policy actions. The National Shellfish Sanitation Program of the U.S. Food and Drug Administration recognizes the importance of protecting human health but recommended increased enforcement of oyster reefs in closed waters (USDA, 2011).

Notably, the State of Maryland recently overturned their similar ban on shellfish gardening while enacting stringent new policies to minimize risks (PRFC, 2011), thus enabling oyster restoration to commence in both Maryland and Virginia in the Potomac River. Maryland has a dedicated Shellfish Program under its Department of Natural Resources (MDNR, 2009) and numerous groups are now promoting oyster gardening to the public (e.g., MD Sea Grant 2011) with a tax credit for participants (COM, 2011). Other states already have well developed oyster gardening programs such as Virginia (TOGEB, 2011; VDEQ, 2011; VMRC, 2011), and the DE Inland Bays. To date, it does not appear that anyone has gotten sick from any shellfish restoration project in closed waters, suggesting that appropriate education and safeguards can be developed to protect human health and industry.

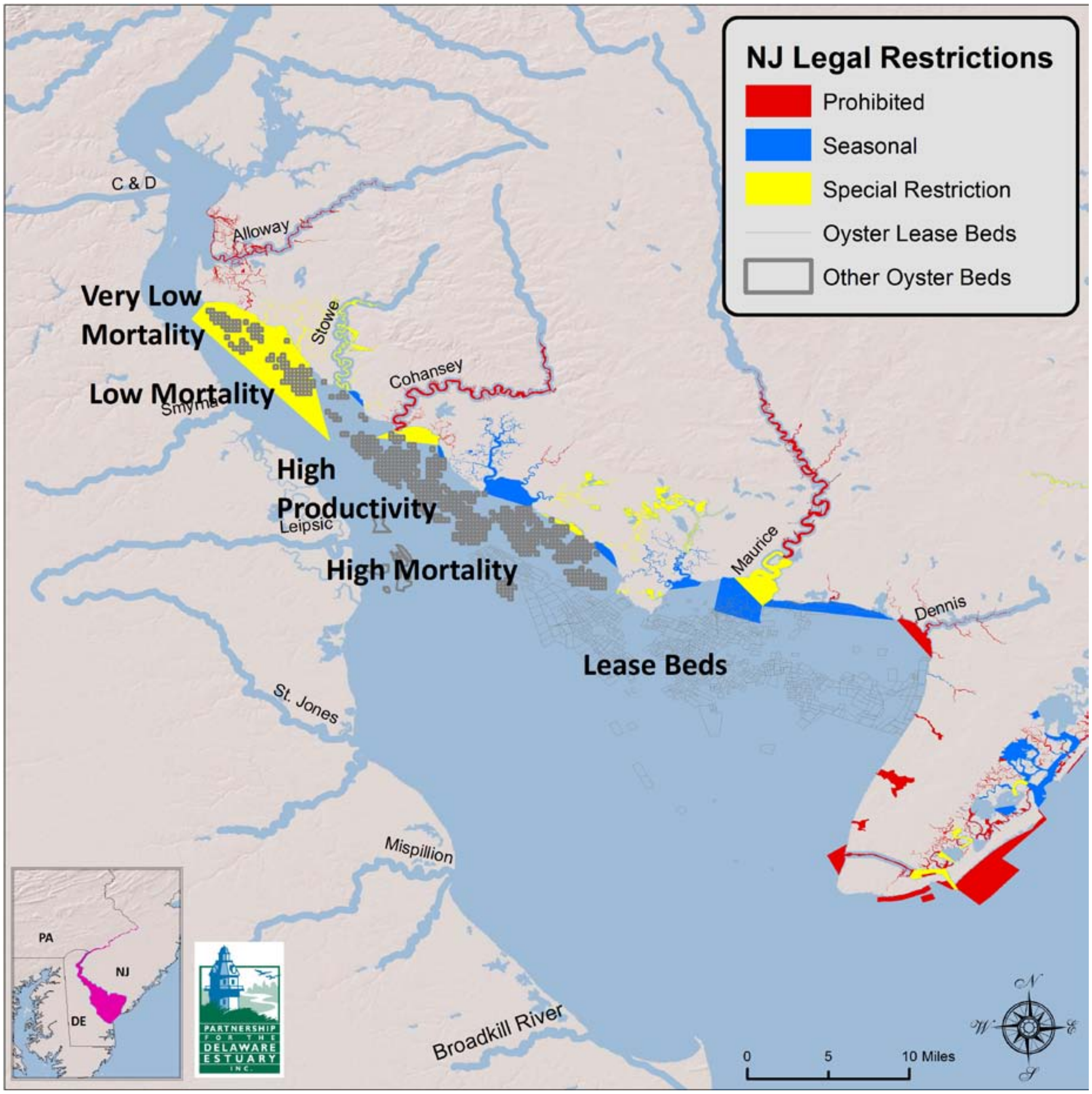

Figure 8: The map shows New Jersey legal restrictions on oyster harvest, because of sanitation concerns.

Regulatory constraints. Management structures for coastal habitats were adopted similar to management of static upland regions (Fig. 8). However, coastal landscapes are dynamic and the pace of transitions among various types of habitats (wetlands, barrier islands, mud flats, channels) is likely to increase with escalating rates of sea level rise. For example, New Jersey tidelands maps from 1972 are still used to determine land ownership and habitat locations, but many of these habitats have since morphed into something different. Outdated charts and maps hamper shellfish restoration especially in tidal wetlands and their associated shellfish communities. Proactive "restoration for the future" will need to recognize the dynamic nature of coastal and estuarine landscapes, predict the most sustainable locations for projects, and gain approval (possibly as exemptions or new rules) to break from past management practices.

Much like the laws of energy, habitat is neither created nor destroyed. 'New habitat' is often simply replacing different forms of habitat, which carries its own benefits, tradeoffs, and species of fish or wildlife. This can be observed where lost wetlands turn into mudflats and open-water, and upland forests turn into new wetlands with sea level rise. Industry, homeowners, and conservation groups value each of these land types for their unique benefits, and may oppose each other's efforts to restore or conserve a particular habitat type. The same is true for creating new oyster reefs, replacing another benthic habitat which potentially contains a different fishery or economic use. All habitat tradeoffs will necessarily come at some cost unless the old habitat is greatly deteriorated in condition (e.g. dredge borrow pits, contaminated sites, developed areas in metropolitan centers etc.). Furthermore, the tradeoff must be evaluated in the larger system perspective (e.g., is a substantial increase in one habitat type more valuable than a small fractional loss of another?). With climate change we expect that many habitats will already be on the move and this change presents opportunities to maximize net ecosystem goods and services focusing on habitats that have the greatest natural capital value.

Permitting challenges. Permitting for non-traditional shellfish restoration projects is often more difficult than permitting for hardened structures such as bulkheads, rock revetments, dredging and other manipulations that can degrade ecological integrity. Novel shellfish-based living shorelines and restoration projects can be a tough sell for states that are unaccustomed to these types of projects (Miller, 2010).

Funding

Shellfish projects in the Delaware Estuary have historically been difficult to fund compared to other major coastal and estuarine areas of the United States. This is partly due to a general lack of marketing, lack of political and public will, and poor awareness of the opportunities for shellfish rehabilitation. Many recent funding attempts for shellfish restoration have been made; e.g. ARRA stimulus applications, appropriation requests for oyster shellplanting, and small research project applications. These applications have been prepared by numerous agencies, academia and non-profits, and were submitted to numerous national agencies and programs. With few exceptions, these grant applications for Delaware Estuary shellfish restoration have been unsuccessful. The general perception is that funding for shellfish restoration in the Delaware Estuary is regarded nationally as a lower priority than other areas, despite the proven track record of success here for projects spanning large scale oyster shellplanting (refs), small scale education/restoration (PORTS, 2011)to shellfish-based living shorelines (Whalen et al. 2011).

It remains unclear why funding for shellfish restoration is difficult for the Delaware Estuary; however, some reviews of grant applications appear to suggest that the open nature of commercial oystering is an issue. There is the perception that restored populations would be subjected to harvest pressure. Whether deserved or not, the shellfish restoration community in the Delaware Estuary should recognize that many potential funders may not be interested in supporting a fishery. To attract and diversify the types of funding for bivalve shellfish restoration, potential funders should be educated that project investments can be sustained even in areas with a shellfishery because Delaware Bay has been sustainably managed for over 50 years in spite of two major oyster disease incursions. This is a tribute to the collaborative active involvement of industry, managers and academia to proactively monitor and adaptively manage the commercial species.

Funders also need to be educated about non-oyster shellfish species, which provide a suite of water quality and habitat benefits. These other species, such as the ribbed mussel do not suffer from the diseases that plague oysters. Ribbed mussels can actually help to remove the disease causing pathogens from the water. However, these alternatives to oyster restoration should not be regarded as providing the same benefits as oyster reef restoration, since oyster reefs represent unique habitats within the coastal mosaic. There is no other species that can replace an oyster reef and yield the same benefits, and the best restoration approach should include oyster reefs within a multi-habitat approach that includes coastal marshes, beaches, and mud flats. If restoration goals are solely focused on water quality outcomes or marsh protection, then investments in other species such as ribbed mussels can offer clear benefits.

Target Species: Oysters

Oysters (*Crassostrea virginica*) live on reefs or scattered lumps in the Delaware Estuary, with some beds in the tributaries. Oyster reefs increase habitat complexity, diversity, and abundance of other organisms, as well as provide ecosystem services such as water quality enhancement (Coen et al., 2007). Based on stock assessments for Delaware Bay oyster fisheries in both New Jersey and Delaware along with local knowledge about populations in tributaries and production on leased grounds, we estimate that there are about 4 billion adult oysters alive in the system today; approximately half live in tributaries and marshes and the other half on the main beds in Delaware Bay. Despite these numbers, the 'Shellfish Reefs at Risk' report from the Nature Conservancy reported that the overall condition of the oyster stock in Delaware Bay is poor, having suffered 90-99% losses compared to historic populations (Beck et al., 2009). To put these numbers in perspective, the majority of the oyster losses resulted from the incursion of 2 non-native oyster diseases. All the while, they oyster industry had been very active to enhance stocks and increase production. Since the 1990's (a.k.a. the "post-Dermo era"), oyster stocks have been generally stable.

Figure 9: 1655 Swedish Colonial Map of Delaware Bay with oyster reefs drawn. (J.T. Scharf, 1884)

It is difficult to reconstruct historic oyster stock size, since Delaware Bay oysters were actively manipulated and managed since before the recorded history of the area. Native Americans were said to have travelled great distances to harvest oysters (Weslager, 1944; Weslager, 1972; Ford 1997), and the first known oyster map of the bay dates back to Swedish colonies in 1655 (Fig. 9). By 1719, New Jersey was enacting laws to restrict harvest due to overharvesting (Ford, 1997). To keep up with demand and supplement natural recruitment, oyster seed was imported to the bay by the millions of bushels per year, reaching its peak in the period between 1880 and 1950 (Ford 1997). In its heyday, the oyster fishery in the Delaware Bay supported more millionaires per square mile in Port Norris NJ than anywhere else in the United States (Ford 1997). It is important to recognize that these oyster boom-times were subsidized in large part by the importation of oyster seed from outside the bay, also augmented by manipulation tactics such as transplanting seed and adults within the bay to increase productivity and boost harvests. Shell planting to boost oyster populations began in the 1950s and this practice continues today. Most recently the Oyster Restoration Task Force has worked to raise funds and awareness for shell planting starting in 2005.

In the late 1950s, the first wave of oyster disease (MSX, *Haplosporidium nelson*) hit Delaware Bay (Ford 1997). Importation of oyster seed was stopped out of fear that this practice brought in the disease. The hardest hit disease areas were on the leased grounds in the open bay. The disease mortality was prevalent on the leased grounds in the open bay. Mortality was lower on the up bay seed beds (Fig. 10). These seed beds became the main source of oyster seed and harvest when imports were stopped. The seed beds had never been able to support the seed demand of the lease beds during the boom times, and the situation became more strained as a result of the disease pressure on the lease beds (Ford 1997).

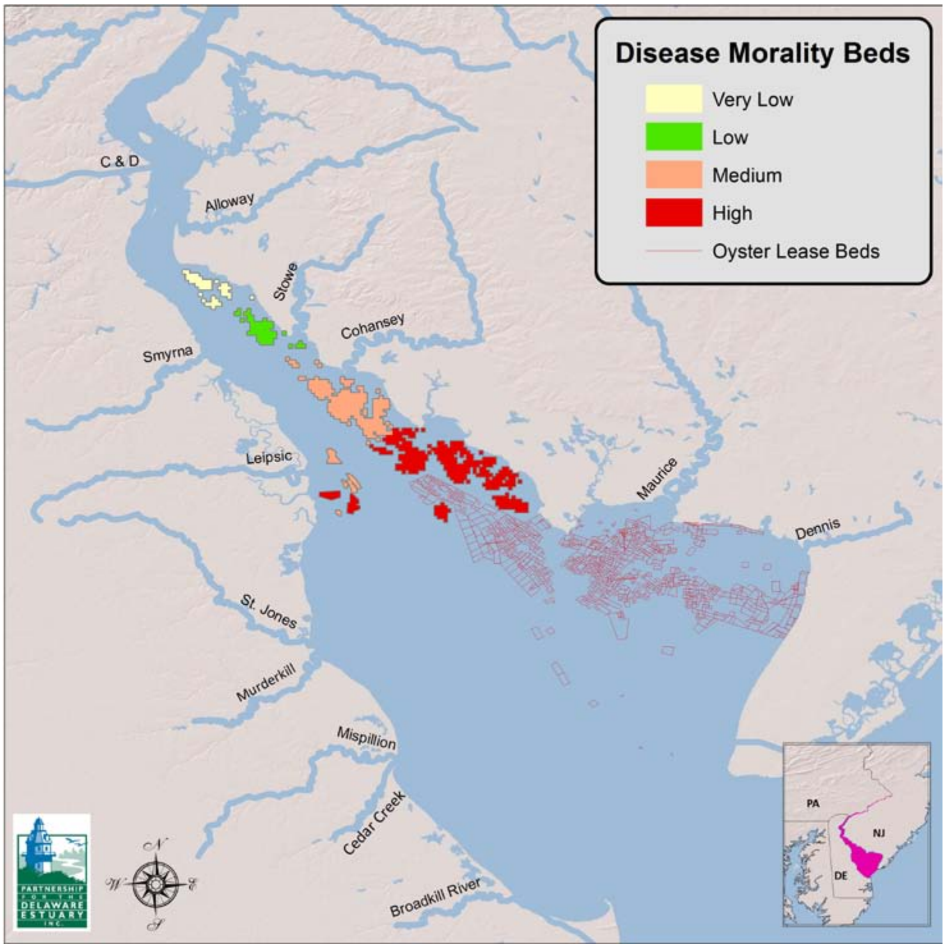

Figure 10: Map shows disease motality for oyster seed beds, and the historic lease beds for New Jersey.

Today, oysters in the NJ portion of Delaware Bay are adaptively managed under an Area Management Plan. The plan is managed by the New Jersey Department of Environmental Protection through the Bureau of Shellfisheries, the Haskin Shellfish Research Laboratory (Rutgers University) and the Delaware Bay section of the Shellfish Council. These three entities work through the efforts of the Delaware Bay Section of the New Jersey Shell Fisheries Council, Stock Assessment Review Committee, Oyster Industry Science Committee, and the oystermen. Together, these groups are responsible for making annual decisions regarding planting, transplanting, monitoring disease and condition, setting harvest quotas, and self-regulating enforcement (Powell, Ashton-Alcox, & Bushek, 2011).

On the Delaware side, the Delaware Department of Natural Resources and Environmental Control is the primary coordinating entity. The Oyster Restoration Task Force works with all these groups to help raise support, partly from voluntary industry contributions to a cultch fund for shell planting projects. Any new oyster enhancement projects must work in concert with these existing management groups because projects will be more successful if they have support and advice from the oyster community.

Recommended Oyster Conservation Areas with Tactics

Five conservation strategy areas have been identified, which appear in maps labeled: Area 1 – High Productivity Oyster Beds, Area 2 – Marginal (harvest) Areas, Area 3 – Hybrid Oyster-Mussel Areas, Area 4 – Climate Future Targets, and Area 5 – Ribbed Mussel Target Areas. Each map is accompanied by a table explaining the recommended strategies for each area. The strategies also appear directly on each map.

Area 1: High Productivity Oyster Beds

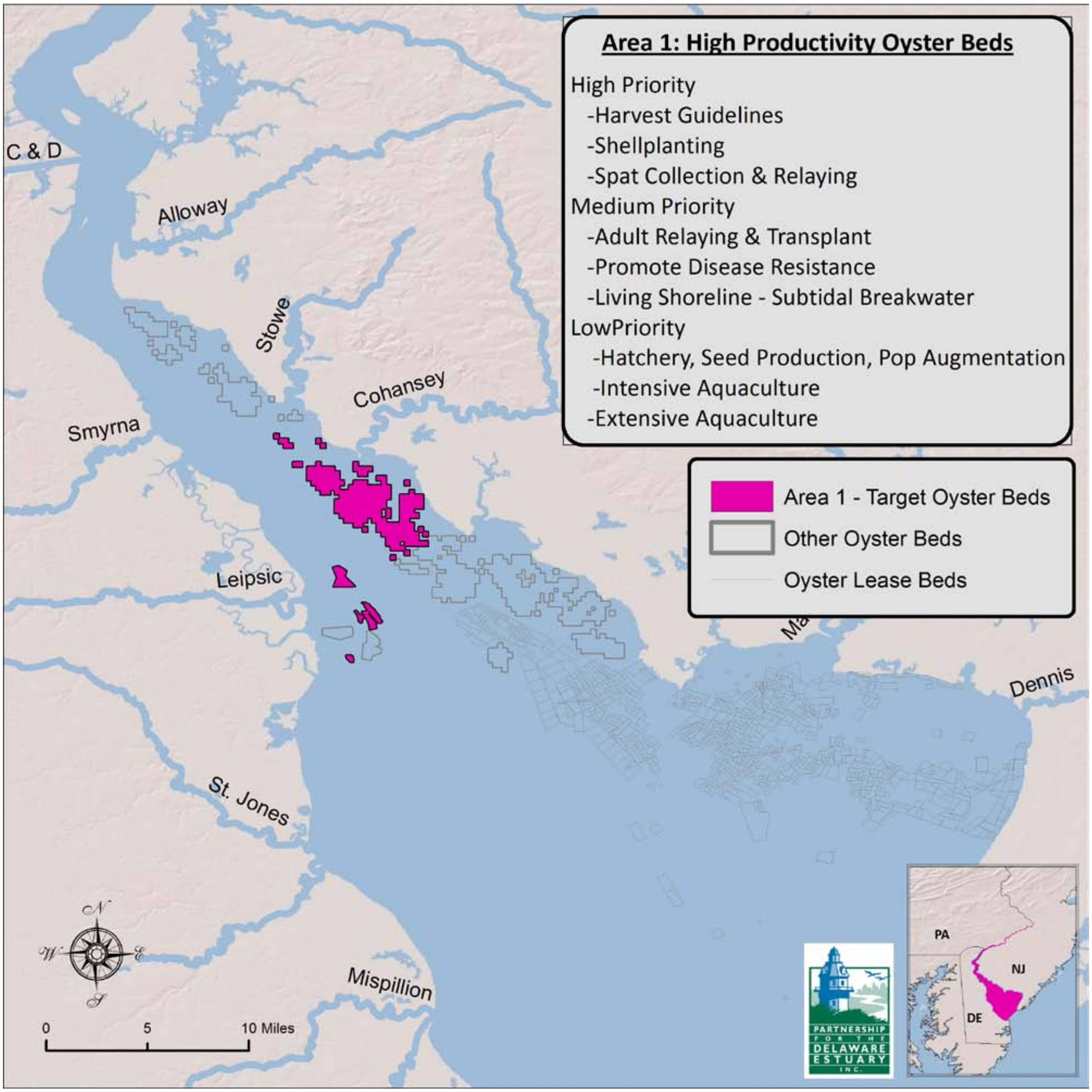

Figure 11: Area 1 - Highest productivity 'middle beds' where nutrition is maximized, recruitment is moderate and disease related mortality is reduced.

The 'central beds' of the oyster seed beds (appearing in pink) have the highest productivity since the onset of oyster diseases. The following beds are included in the 'central beds': Shell Rock, Upper Middle, Middle, Ship John, Cohansey, and Sea Breeze. These 'central beds' achieve the highest productivity because of their strategic position in the system. They are far enough south to take advantage of high food quality and relatively consistent recruitment, and far enough north to escape high disease mortality. While disease is even lower in the upper beds, food quality and recruitment there are lower, resulting in slower growth and sporadic recruitment (Fig. 11) (Bushek, 2010; Powell, Ashton-Alcox, & Bushek, 2011). Strategies proposed in this central region of the Bay aim to keep these beds at a highly productive level, which is imperative to sustaining both a commercial fishery and overall population abundance. Currently, shell planting is a major tactic being employed in this area, in part by funding obtained by the Oyster Restoration Task Force. Other recommended strategies for Area 1 can be found in Table 2.

Table 2: Recommended Tactics for Area 1 - High Productivity Oyster Beds

High Priority		Medium Priority		Low Priority	

HG **Harvest Guidelines** (Top Priority for Present & Future)
Harvest guidelines are aimed at keeping these middle beds highly productive. Harvest guidelines for the bay should continue to rely on annual monitoring surveys, and science-based adaptive management by the Shellfish Advisory Committee.

SP **Shell planting** (Top Priority for Present & Future)
Shell planting maintains and increases extant populations by enhancing natural recruitment and replacing shell lost to natural erosion or harvesting. Target areas should ideally have a good probability of recruitment and relatively high survival and growth. This type of program should be coordinated with the ongoing management of the resource.

SR **Spat Collection & Relaying (aka replants)** (High Priority for Present & Future)
Shell planting in the lower bay where recruitment is high but survival is low can be an effective strategy for collecting young oysters but they must be moved to more productive areas for grow out; e.g., collect spat on shell from Cape Shore and move to Area 1.

AR **Adult Relaying & Transplant**
Adult oysters can be collected from areas of low survivorship or low productivity and transplanted to areas of high productivity and moderately low mortality, such as the central beds. Movement of adults from the very low mortality (upper) beds should be carefully considered, and monitoring and studies are needed to deduce shell and oyster population maintenance on these poorly studied beds. Because recruitment is usually low on the upper beds, planting of spat on shell (either from the hatchery or natural set) should be considered here, possibly using disease resistant stocks. In any case, shell replacement must be considered from source areas.

DR **Promote disease resistance**
Enhancing oysters in medium and high disease zones encourages the breeding of disease resistant oysters. Funding is needed to sustain disease resistance research and monitoring in relation to managing Area 1.

LSB **Living Shoreline – Subtidal Breakwater**
A subtidal nearshore oyster breakwater is recommended as a pilot in Area 1. If effective, this could then be expanded to other places. The shallow waters bordering Sea Breeze represent a candidate test location since this is a marginal area where oyster harvesting is reportedly difficult. Subtidal oyster breakwaters might also be constructed as part of a hybrid tactic combined with living shorelines.

HS **Hatchery, Seed Production, Population Augmentation** (Future)
Oysters can be grown in a hatchery and transplanted to the middle beds to increase oyster abundance in the high productivity Area 1. However, this tactic is assigned low priority as long as collection of natural spat remains less expensive and effective.

AI **Intensive Aquaculture**
This could not be conducted in this area without significant changes in the regulations

AE **Extensive Aquaculture**
This could not be conducted in this area without significant changes in the regulations

Area 2: Marginal (Harvest) Area Targets

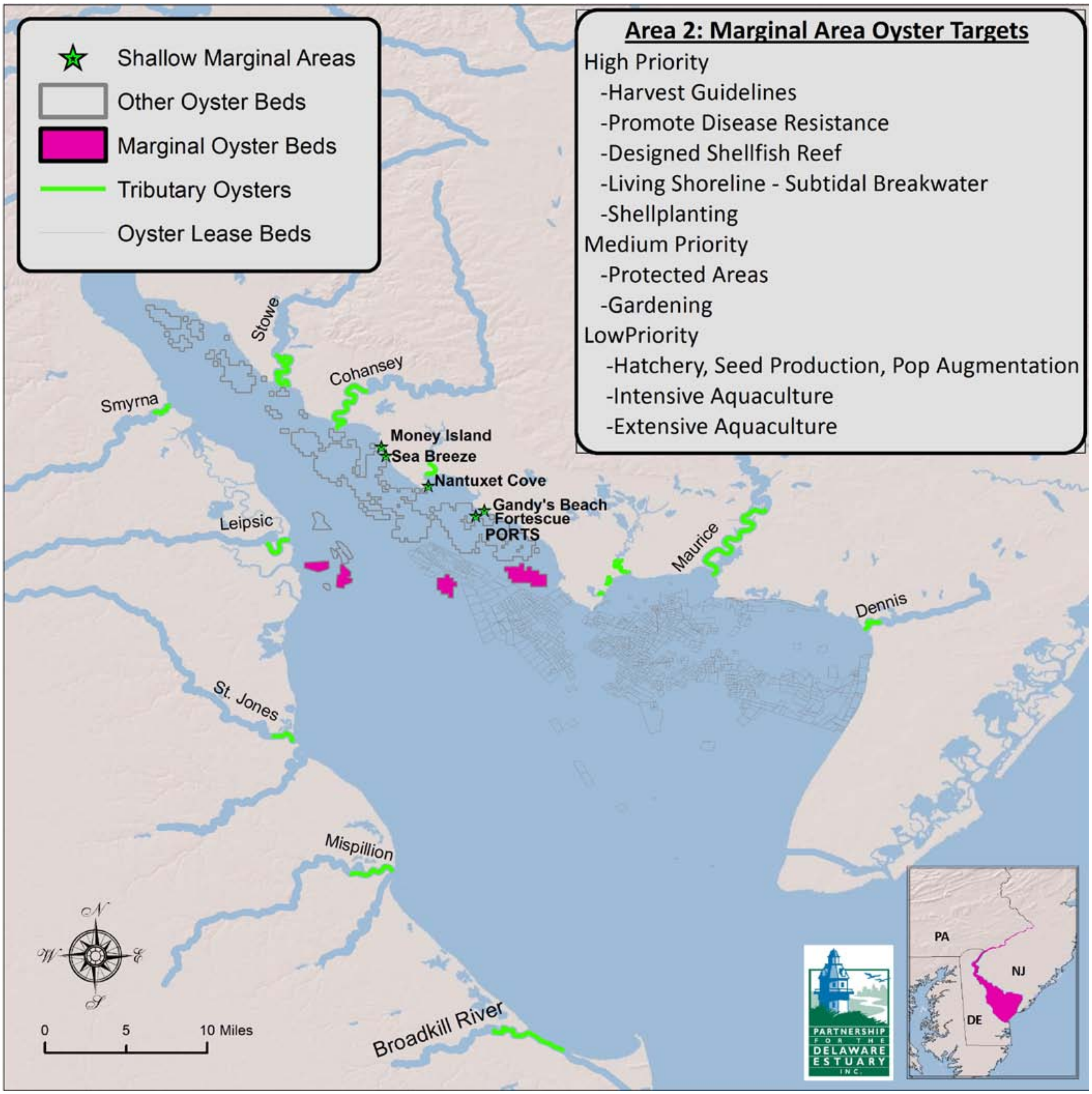

Figure 12: Area 2 - Marginal areas for traditional harvesting activities have been flagged as potential oyster enhancement areas.

Marginal (harvest) areas are defined as areas which are not as good for oyster harvest for one or more of four reasons:

1) the area is too shallow for oyster boats to get into,

2) the bottom is rocky or sparse in shell cover,

3) oysters are in tributaries that are closed to harvest, or

4) the area has high disease pressure.

Since most of these areas are included in area management planning, care must be taken to work with the Stock Assessment Review Committee to implement conservation activities in these locations. Marginal harvest areas have potential to be prime areas for conservation or ecological restoration.

Marginal areas that cannot be effectively dredged for commercial harvests due to depth or bottom conditions (#1 and 2 above) might represent places to install shallow subtidal, nearshore reefs. Potential candidate sites occur along the New Jersey Bayshore between the shore and the eastern border of current seed beds in likely high productivity zones. These areas are denoted as green stars in Figure 12, which include areas near Money Island, Sea Breeze, Nantuxet Cove, Gandy's Beach, and around the PORTS project site. Some of these locations are located in NJDEP prohibited or special restricted waters for shellfish (NJDEP 2011), which could necessitate use of construction tactics that thwart poaching In addition, tongers might still work some of these shallow nearshore marginal areas, and more (local) research would be needed to determine if these users would be affected. Due to the New Jersey shellfish restoration restrictions for edible bivalves, greater opportunity might exist in Delaware waters near the mouth of the Leipsic, St. Jones, or Murderkill Rivers in suitable nearshore marginal areas.

Tributary oysters provide additional opportunities for conservation or restoration projects, and these are highlighted as green lines in Area 2. Freshwater input lowers the salinity in tributaries, and so disease is generally lower there, too. Oysters in the tributaries are not part of the harvested seed beds or leased beds, although in NJ many of these tributaries are within prohibited or special restricted areas. As climate change causes warmer water temperature and saltier conditions, oysters may find increasing refuge in tributaries leading to habitat expansion possibilities.

High disease marginal areas include the beds of Ledge and Egg Island. Although disease pressure is high on these two beds, they still have potential for oyster conservation projects. These chould be managed to provide dual benefits of supporting oyster harvests (because most will die anyway) and increased disease resistance (because this is where disease pressure drives selection fastest as long as they don't all die). One idea is to divide each bed into large and small sections. On a rotational basis of 1-5 years, the larger section would be harvested while the smaller section would be shell planted and withheld from harvest to facilitate natural disease resistance selection during the no harvest period. The Shellfish Advisory Council would make decisions regarding such efforts. Selection might be further expedited if the set aside beds are seeded with disease resistant seed from hatcheries (See Table 3 for strategy recommendations).

Table 3: Recommended tactics for oysters in Area 2 - Marginal Areas

High Priority		Medium Priority		Low Priority	

Harvest Guidelines

A rotational harvest pilot is recommended for the seed beds of Egg Island and Ledge which are marginal because of high disease pressure. Each (pilot) bed would be subdivided into a larger harvest section and a smaller disease resistance promotion section, which could be augmented with shell cleaning, shell planting, or seeding with disease resistant seed. The smaller set side area would be designated for no harvest for 1 to 2.5 years to allow for natural selection. After that time period, harvest would be allowed again. Disease resistance monitoring is essential to deduce success.

Promote disease resistance

The oyster beds identified in this area are within the medium to high mortality areas. Any activities which enhance oysters using disease resistant stocks in these zones should contribute to disease resistance promotion. See harvest guidelines for an example project.

Designed Shellfish Reef

The shallow marginal areas could be potential sites for reef creation or enhancement of existing shellfish, while also meeting additional ecological services.

Living Shoreline – Subtidal Breakwater

Shallow marginal areas that are nearshore represent key places to install pilot oyster breakwaters, possibly in conjunction with other tactics as hybrid living shorelines.

Shell planting

Shell planting is recommended on Egg Island, which is a marginal area.

Special Management Areas

Marginal areas in tributaries or in waters that are too shallow for oyster boats to access could become special management areas on a rotating basis (green stars on Figure 12). Many of these locations are in high productivity areas that are also closed or provisional waters for direct market harvest. Establishment of special shellfish management areas will need to balance the considerations of industry, state shellfish sanitation personnel, and the viability of oysters themselves. We also recommend that efforts be made to find the sources of shellfish closures and to have water quality remediated directly.

Gardening

Oyster gardening represents a tactic to be used in some tributaries if state shellfish sanitation concerns can be addressed, possibly following examples from other states. Oyster gardening might become possible in DE before NJ, but until the conflicts between shellfish sanitation policies and ecological restoration goals are resolved this tactic will remain medium to low viability.

Hatchery, Seed Production, Population Augmentation

This tactic is a low priority as long as collection of natural spat and cultivation is effective and less expensive.

Intensive Aquaculture

Some local low salinity areas in the creeks might be used for seed growth areas so that diseases could be avoided until the oysters reach a size that could be transplanted to leased areas.

Extensive Aquaculture

Some shallow areas may benefit from extensive aquaculture, but this should be determined by the market.

Area 3: Hybrid Tactic Zones

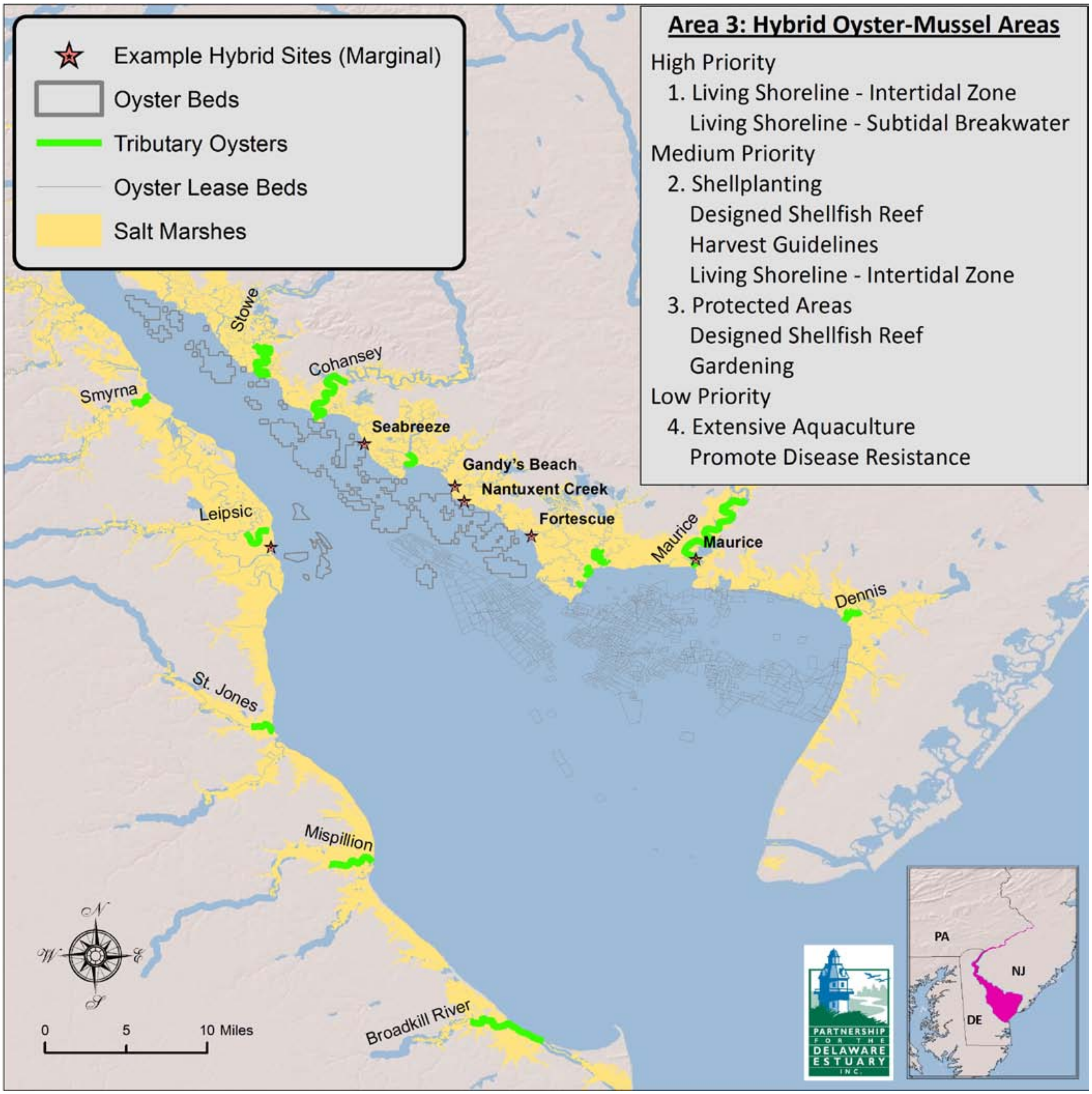

Figure 13: Area 3 - Locations of potential hybrid tactic areas incorporating living shorelines, oyster breakwaters, and tributary oyster beds.

Hybrid tactics provide opportunities to enhance shellfish using two or more conservation strategies, and possibly leading to synergistic outcomes. For example, mussel-based living shorelines (intertidal, low energy) might be paired with oyster-based breakwaters (subtidal, moderate energy) to collectively reduce wave energy and enhance ecological value as a hybrid living shoreline. Similarly, oyster breakwaters near creek mouths might enhance available oyster seed stock (by augmenting larvae) for beds in the tributaries, or vice versa. Red stars in

Figure 13 represent areas potentially suitable for living shorelines with oyster break waters, though many other areas may be suitable for hybrid tactics. Green lines show locations where potential tributary oyster reefs overlap with nearby breakwater/living shoreline hybrids. All of these strategies have the potential to improve near shore oyster reefs. The salt marshes shown in yellow are also key areas for conservation, incorporating another component into the hybrid model (see table 4a – 4d).

Table 4: Recommended tactics for Area 3 - Oyster and Mussel Hybrid Areas

High Priority		**Medium Priority**		**Low Priority**	

Table 4a: High priority pilot using two types of living shorelines. It is recommended to start with a small pilot project and expand if successful.

LS	**Living Shoreline – Intertidal Zone** The red stars indicate areas which are recommended for living shoreline tactics in the salt marshes.
LSB	**Living Shoreline – Subtidal Breakwater** These areas are recommended for subtidal breakwater structures using oysters. Structures such as gabions can be used to contain oyster shell so that they are not readily harvested, possibly addressing shellfish sanitation concerns.

Table 4b: Medium Priority project using four strategies together.

SP	**Shell planting** Shell planting could be employed to boost the oyster beds in a marginal area.
DS	**Designed Shellfish Reef** Construct a shellfish reef in the same marginal area.
HG	**Harvest Guidelines** See Table 5 for a full description of this strategy. Rotate harvests across pilot site in different years, and monitor and compare oyster population success and disease resistance between harvested and unharvested sections of the project site.
LSI	**Living Shoreline – Intertidal Zone** The red stars indicate areas which are recommended for living shoreline tactics in the salt marshes.

Table 4c: Medium priority project using three strategies.

SM	**Special Management Area** Marginal areas that are included in the project would be specially managed under the area management plan, providing ample protection (see Table 5 for more information).
DS	**Designed Shellfish Reef** The marginal oyster population at the pilot site would augmented with reef creation tactics.
G	**Gardening** Oyster plots at the marginal pilot site could be installed and tended using oyster gardening concepts (see Table 5) contingent on shellfish sanitation concerns being addressed.

Table 4d: Low priority project using two of the strategies.

AI **Intensive Aquaculture**

Intensive aquaculture could be used to produce animals from hatchery stock, to provide enough oysters (or ribbed mussels) for outplanting.

DR **Promote disease resistance**

Outplant disease resistant stocks into medium to high mortality disease zones (red stars on map) to enhance disease resistance build-up in the population at the pilot site. More scientific study and discussion is warranted as new information is gained before implementation of this tactic. Tributary oysters might represent an ideal marginal area for outplanting disease tolerant strains of oysters because oysters in those places might develop their own resistance slowly.

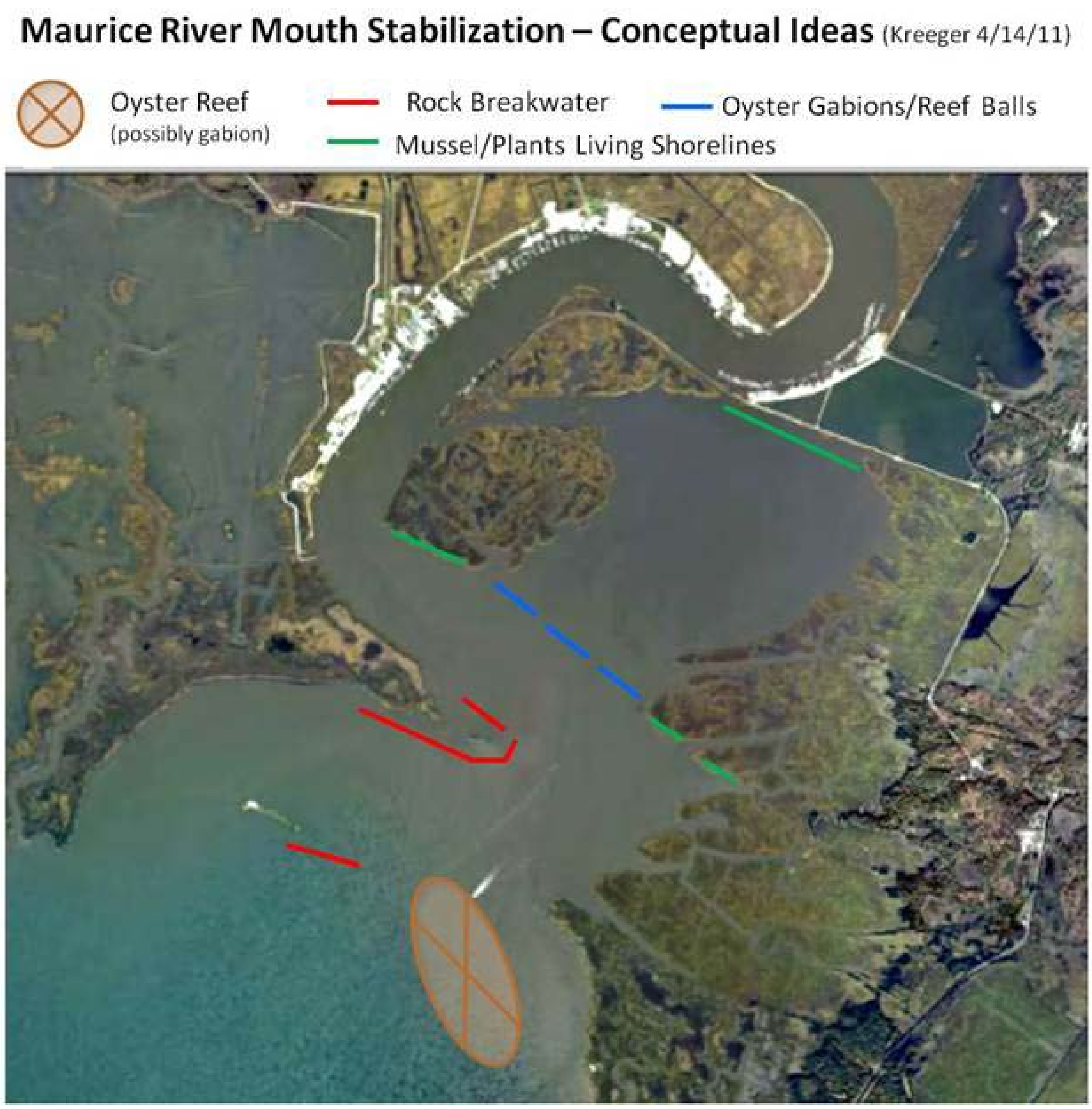

Figure 14: Conceptual example of a hybrid strategy for stabilizing an eroding tributary shoreline.

Area 4: Climate Change Area Targets for Future Planning

Increasing sea levels and channel deepening are likely to increase the volume of the tidal estuary, thereby allowing more seawater to move farther up Delaware Bay. Combined with increasing demands for freshwater from aquifers and the Delaware River, the Delaware Bay is expected to become saltier (Kraeuter & Kreeger, 2010). Since oyster diseases are more prevalent in saltier conditions, future oyster populations will likely expand up-Bay, whereas down bay populations will be reduced due to increased disease mortality. The mortality areas will shift north and may already be changing (Kraeuter and Kreeger 2010). The current low mortality beds in the upper Bay may become the new high productivity beds of the future.

We therefore recommend focusing more scientific research and long –term sustainability planning on the low and very low mortality beds, which include Hope Creek, Fishing Creek, and Liston Range. New bed creation should carefully consider climate change combined with expected watershed change as areas further up bay from the current seed beds become higher priorities for area management of oyster stocks. Potential oyster bed locations have been identified using acoustic data from DNREC bathymetric mapping. From these scans, two areas have been identified which might have suitable bottom, located north of current upper beds on either side of the C&D canal (Fig. 15). Prioritizing the upper beds for protection, careful management, and possibly establishing new beds (Table 5) could help oyster populations to adapt to changing climate (Kraeuter & Kreeger 2010).

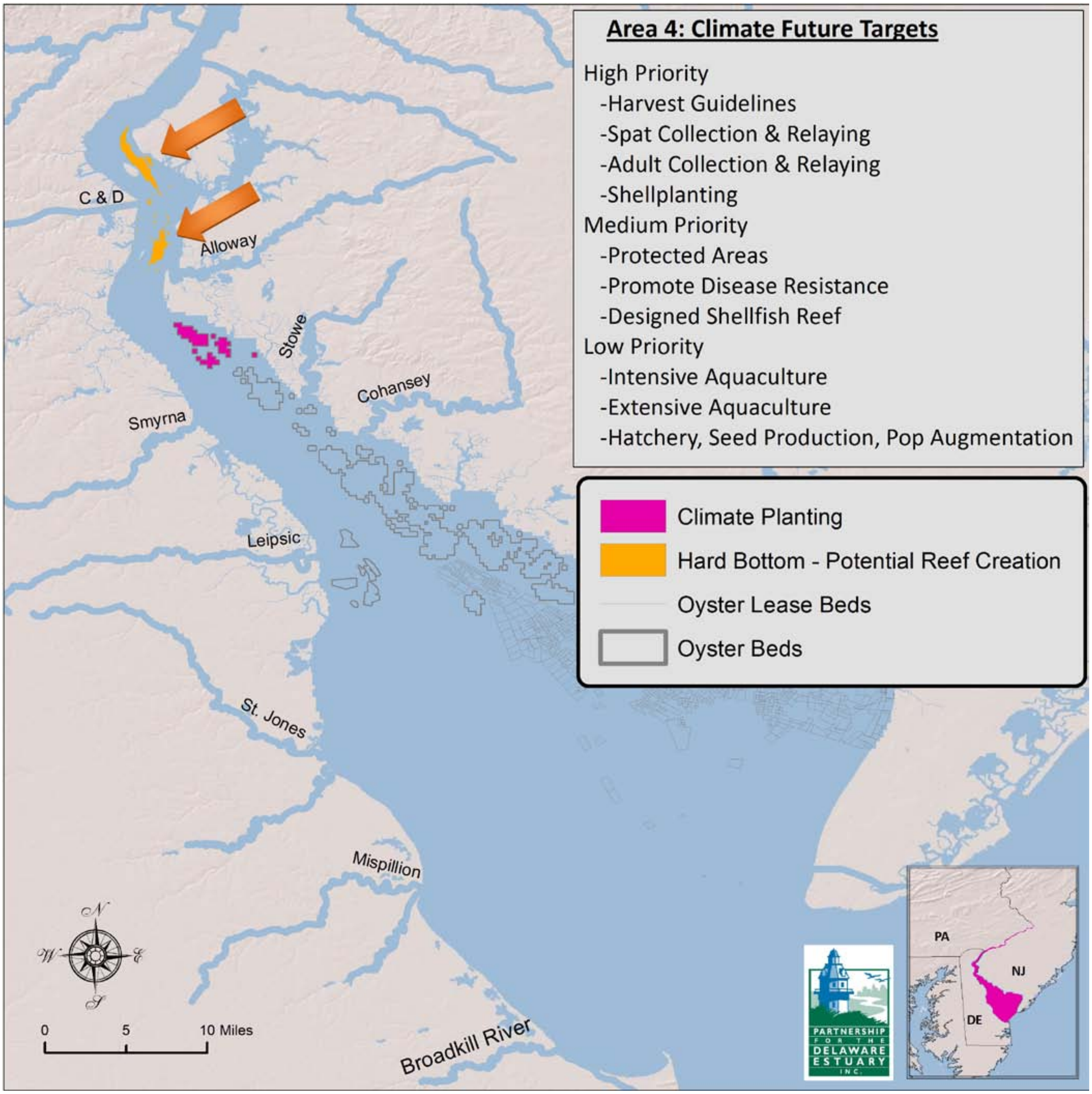

Figure 15: Area 4 - climate change targets for future oyster enhancement on extant upper beds, and potential areas for oyster bed creation.

Table 5: Recommended Tactics for Area 4 – Climate Change Target Areas

High Priority		**Medium Priority**		**Low Priority**	

Harvest Guidelines

The very low mortality beds are within special restricted zones, so no direct harvest for market is allowed. However, oysters are moved from these beds to the more southern beds so that they can be harvested later. It is imperative that these upper beds be studied and monitored to deduce basic population dynamics and biology so that area management and climate planning are strategic.

Spat Collection & Relaying (Future)

In the future, spatted shell might be placed on the very low mortality beds to augment naturally low recruitment and replace removed shell.

Adult Collection & Relaying (Future)

Currently, a limited number of adult oysters are removed each year from the very low mortality beds to augment the high productivity beds in the mid-Bay region. If monitoring and studies indicate that oyster or shell abundance becomes depleted due to this practice, then the reverse could be considered whereby adults could be collected and relayed to the upper beds from high mortality areas or spat on shell from Cape Shore. Relaying is expensive and this tactic would need to be justified and funded.

Shell planting (Future)

Since oysters grow slowly in the low and very low mortality areas, shell accumulation will curtail enhancement without shell plant augmentation. However, it would only be desirable if the shell had spat (e.g. from Cape Shore). Currently, natural recruitment up-bay is too sporadic to waste valuable shell resources without a better chance of success, but this could be an option for the future if recruitment dynamics change.

Special Management Areas

If new beds are created in the areas surrounding the C&D canal, these areas could be set aside for special investigations. Special area management of the newly developing or created beds may be desirable if they become more productive. Basic monitoring of environmental conditions and food availability should be undertaken before SMAs are adopted. Possibly, experimental lots of oysters could be placed in prospective areas for new bed creation and set aside on a 2-5 year rotation to confirm sustainability therein.

Promote disease resistance

If adults are relocated into Area 4 to augment beds or seed new beds, preference should be given to disease resistant stocks, such as from the high mortality beds, thereby promoting broader integration of disease resistance across the Bay.

Designed Shellfish Reef

The areas surrounding the C&D canal (Figure 15) are recommended for eventual new reef creation where the bottom substrate is already firm. This should be a recommendation only when surveys show that conditions are conducive to establishment of oysters, and is more of a future strategy priority.

Intensive Aquaculture

See Table 3 for a description.

Extensive Aquaculture

See Table 3 for a description.

Hatchery, Seed Production, Population Augmentation

See Table 4 for a description

Target Species: Ribbed Mussels

Ribbed mussels (*Geukensia demissa)* are an intertidal species that primarily lives in association with tidal salt marsh plants. Ribbed mussels thrive in salinity ranges between 12-30 ppt. The marsh plant smooth cordgrass (*Spartina alterniflora)* provides a surface for mussels to attach, and the mussels fertilize the plants. Ribbed mussels form dense beds on the edges of salt marshes increasing resistance of the marsh shoreline to erosion, which helps to stem marsh loss.

Figure 16: Ribbed mussel with *Spartina* grasses.

A top concern for ribbed mussels is habitat loss, since tidal marshes are declining in health and acreage. This has been a 7% loss on the New Jersey Bay Shore between 1996-2006 (Whalen et al., 2011). Salt marshes are projected to lose 25-50% of their area under a one meter sea level rise scenario. Therefore, a top enhancement tactic for ribbed mussels is salt marsh preservation and enhancement. Living shoreline enhancement is a suitable tactic in low energy areas, since it uses ribbed mussels to stabilize marsh edges. In other, more landward areas of salt marshes, an array of tactics exist to enhance marsh condition or acreage such as by directed placement of sediments and facilitation of landward migration.

Recommended Ribbed Mussels Enhancement Areas with Tactics

All salt marshes in the Delaware Bay, the habitat of marsh mussels, have been identified as conservation priorities. By winter 2012, the Partnership for the Delaware Estuary will be releasing an inventory of living shoreline priority areas, which target salt marsh and marsh mussel habitat. This inventory should be a useful tool for further refining ribbed mussel priority areas for direct enhancement. In addition, more ribbed mussel survey data and ecosystem services studies are needed to better prioritize specific areas for ribbed mussel enhancement in the future.

Priority areas for ribbed mussels include wetland edges (where ribbed mussels can achieve greatest population biomass) and tributary watersheds in need of water quality improvements as a result of nutrient loadings, pathogens, and suspended solids. In addition, shoreline stabilization tactics using ribbed mussels or other tactics such as oyster breakwaters should be prioritized to address increasing erosion energies and fetch and thereby preserve larger tracts of marsh, or protect crucial infrastructure and coastal communities (see Table 6). PDE is also collaborating with Rutgers to prepare a Practitioner's Guide to mussel based living shorelines in the Delaware Estuary, expected fall 2011.

Area 5: Ribbed Mussel Target Areas

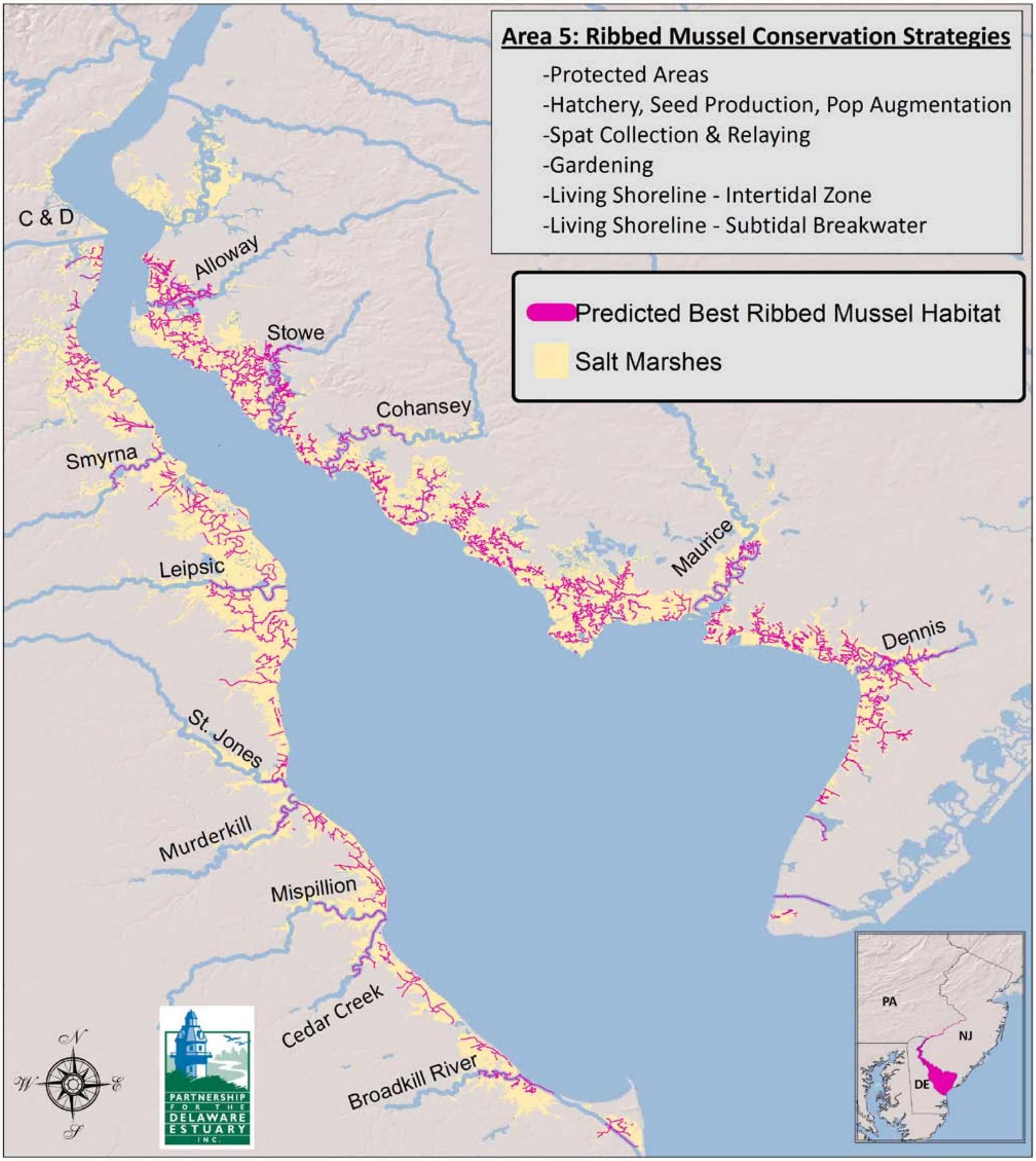

Figure 17: Area 5 - Ribbed mussels live throughout salt marshes but are most dense along intertidal creeks and edges, which are shown here as their best habitat.

Table 6: Recommended tactics for Area 5 to improve ribbed mussels in the Bay.

Special Management Areas

Ribbed mussels live in salt marshes, which merit their own protection for many reasons. More must be done to stem the loss of these wetlands.

Hatchery, Seed Production, Population Augmentation

Spawning ribbed mussels in a laboratory has been accomplished, however, funding to develop large-scale methods that can be used for restoration and enhancement of ribbed mussel populations is needed. Such methods could grow seed mussels and plant them along salt marshes to stabilize edge erosion. Mussel seed can also be furnished to shellfish gardeners.

Spat Collection & Relaying

In salt marshes, structures might be positioned to catch ribbed mussel spat for use in restoration projects. Little is known about factors that govern ribbed mussel recruitment, which appears spatially variable. More research is needed to identify areas where mussel spat can be reliably collected and to develop spat collection methods. Natural spat collection could eventually be less expensive than hatchery propagation. Relay techniques also need R&D.

Gardening

The same principles of oyster gardening could easily be applied to ribbed mussels and without shellfish sanitation concerns because ribbed mussels are not a commercial species. Mussel gardening would provide an educational activity and could help to raise mussels for restoration purposes and water quality improvement, potentially also benefitting oysters in impaired waters. Research is needed to determine if there is an optimal size for planting mussels, and mussel gardening could provide cost-effective research opportunities.

Living Shoreline – Intertidal Zone

Living Shorelines incorporating ribbed mussels is a new restoration tactic that appears effective at helping to stem erosion in low to moderate energy areas along salt marshes. The approach takes advantage of the stabilizing benefits of mussel byssal threads and their mutualism with *Spartina* plants. This restoration boosts populations of ribbed mussels, while also providing other ecological benefits.

Living Shoreline – Subtidal Breakwater

Subtidal (oyster) breakwaters indirectly protect ribbed mussel habitat by reducing wave energy forces, and protecting against marsh erosion. When used together with intertidal living shorelines, this tactic may be effective at collectively boosting shellfish habitat for several species.

Target Species: Other Bivalves

There are a number of other marine bivalve species inhabiting the Delaware Estuary, but we know too little about their abundance, distribution, and ecological importance to consider them as enhancement priorities for this report. Below we provide some comments on a few candidate species that are believed to be locally abundant and might have high population biomass. Future iterations of shellfish restoration prioritization would benefit from studies that obtain more information about the distributions and population sizes of these and other bivalves (including native freshwater mussels in the upper estuary).

The intertidal polyhaline zone contains numerous incidental species on the flats which can become emersed on low tides, but little information is available to document these species or their abundances. Populations of hard clams (*Mercenaria mercenaria* (Linnaeus 1758), razor clams (*Tagelus plebeius* Lightfoot 1786, and *Ensis directus* Conrad 1843) and hooked mussels (*Ischadium recurvum* Rafinesque 1820*)* are reported from many of the intertidal flats of the lower bay. Blue mussels (*Mytilus edulis* Linnaeus 1758) are common on intertidal structures such as rock jetties and piers, but there is little natural hard substrate like this in the system (Kreeger & Kraeuter, 2010).

The hooked mussel*, Ischadium recurvum* (Rafinesque, 1820), can be locally abundant and mixed with oysters, but there are no comprehensive data on distribution or abundance in the Delaware system. There are limited reports of live *Mya arenaria*, and occasional individuals are found. The deep burrowing nature of this species prevents it from being sampled by any of the standard grabs, dredges or other gear. It is possible that significant populations exist in the Delaware Estuary, but there is no information. Hard clams, *Mercenaria mercenaria* (Linnaeus, 1758), is only a minor species in the mesohaline portion of Delaware Bay because of high turbidity, and above this area is at the lower end of its salinity tolerance (Kreeger & Kraeuter, 2010).

The clam Rangia cuneata (Gray), clam was found in the Delaware system around the C&D Canal in a 1969 survey. It has been reported in a number of marsh creeks on the New Jersey side of the bay. It is not known if this species is native to the Delaware Bay, or if it was introduced through the C&D Canal from the Chesapeake Bay (Gallagher & Wells, 1969). Most data on this species are anecdotal, and not comprehensive surveys have been conducted. However, the clam was found in abundance at certain stations in the upper Estuary as part of the Delaware Estuary Benthic Inventory in 2009. There is one non-native species of estuarine bivalve that is extremely abundant in the oligohaline and freshwater upper Estuary is the Asian clam, *Corbicula fluminea*. This species is intolerant of salinities >2ppt, but is mentioned because it could be the most numerically abundant bivalve in the entire basin. No action is advised for these species.

Funding Options

In the past, funding for bivalve shellfish conservation has been obtained through a mix of industry contributions, governmental grants and project appropriations, and support from non-profits and agencies for scientific studies that benefit bivalve populations. Most of the investment has focused on oysters, which have been an important commercial species since settlement. Examples follow.

- Oyster Industry. Commercial oystermen have traditionally recognized the importance of sustaining shell budgets and managing stocks to both boost harvests and ensure long-term sustainability. This culture of self-policing and reinvestment continues today as evidenced by their active support for scientific monitoring, area management, and self-taxing for cultch fund contributions.
- Other Industries. Numerous companies that operate within the Delaware Estuary and its watershed have often provided support for conservation of various natural resources, including bivalves. For example, the DuPont Clear into the Future program has supported scientific research on oyster diseases and recently contributed to the shellplanting effort. PSEG has supported the construction of the new Rutgers aquaculture facility, as well as research on the role of ribbed mussels in sustaining salt marsh health.
- Federal Agencies. Through an appropriation to the Army Corps of Engineers, $5 million was directed to oyster shellplanting between 2005 and 2010, resulting in up to 50-fold increases in spat recruitment on planted areas and a net positive, bay-wide shell budget by 2010. Grants from the National Science Foundation, NOAA Sea Grant, Army Corps of Engineers, US Environmental Protection Agency, and the US Fish & Wildlife Service also have supported various scientific studies on bivalve shellfish that benefit managers and conservation planners.
- State Agencies. The States of Delaware and New Jersey, and the interstate Delaware River Basin Commission, have provided both financial and staff support for shellplanting by the Delaware Bay Oyster Restoration Task Force. State environmental agencies also undertake or support important shellfish sanitation and water quality monitoring.
- Non-Governmental Organizations. Entities such as the National Fish and Wildlife Foundation, Partnership for the Delaware Estuary (PDE), American Littoral Society, and the Nature Conservancy have provided grants, in kind resources, or staff to facilitate the restoration, monitoring, and scientific study of bivalve populations. In addition to funding oyster projects, these groups have recently been active in developing living shoreline tactics that promote other species such as ribbed mussels. Most recently, PDE committed $50,000 as a challenge to raise funds to sustain shellplanting in 2011, and more than $200,000 has been raised enabling the project to proceed for at least this year.
- Academic Institutions. Numerous regional universities, most notably led by the Rutgers Haskin Shellfish Research Laboratory, have provided in-kind support, staff and students to perform critical monitoring and scientific study of the area's bivalve resources.

In-kind support from non-federal partners (industry, academia, non-profits) is often critical to leveraging federal funding due to match requirements.

Despite these past successes, more significant and sustained funding is needed to promote the conservation priorities recommended in this report. Climate change, combined with continued increases in development and human populations, threaten to increasingly tax the Delaware Estuary. These threats are far ranging and are expected to affect all bivalve species (Kreeger et al 2010). For example, rising salinity from sea level rise and freshwater withdrawals threaten to increase Dermo disease mortality of oysters, whereas escalating losses of salt marsh acreage threaten ribbed mussels. Staving the potential loss of ecosystem services (ribbed mussels, oysters, and other species) and economic goods (oysters) should justify greater investment in sustaining these key living resources.

Appendix I: Spatial Considerations for Oysters

For oysters, the survivorship, growth and productivity are governed by many factors that will define the best areas for enhancement. Chief among these are disease pressure, recruitment, and food resources, all of which vary widely across the system. While we have a good understanding of mortality from disease and its relationship to salinity, we have a less clear understanding of the causes of spatial variation in food resources and recruitment. Nevertheless, it is clear that the middle beds have maximum oyster production because of the balanced benefits of higher food quality in the lower estuary, lower disease mortality in the upper estuary, and sufficient recruitment to replenish the loss of adults (Fig. 18). These patterns and other considerations listed below were used to deduce the best areas for different types of restoration tactics.

<u>Oyster Bed Locations</u>

Locations of the New Jersey were digitized from the New Jersey Stock Assessment reports (Powell, Ashton-Alcox, & Bushek, 2011), and based on a 0.2 minute grid system used by the NJDEP to manage the fishery. This seedbed digitization was satisfactory for the conceptual planning exercises of this report, but should be ground-truthed before being applied to project implementation. The New Jersey lease bed shapefiles came directly from NJDEP (NJDEP, 2005), and Delaware oyster bed shapefiles were obtained from DNREC (Greco & Bruce, 2011). Disease zone classifications were taken out of the SAW 2010 report and a dataset obtained from DNREC on 5 year mortality averages for Delaware oyster beds (Powell, Ashton-Alcox, & Bushek, 2011; DNREC, 2011). The methodology applied to the Delaware mortality dataset was based on the methodology used to classify morality zones on New Jersey oyster beds (Powell, Ashton-Alcox, & Bushek, 2011). Roxanne benthic scans were obtained from DNREC and considered for oyster bed locations, but were ultimately not used because of conflicts with other data from Delaware (oysterbed shapefiles) and New Jersey (SAW and NJ bed corners shapefiles). Also considered but not used were shapefiles of the NJDEP oyster bed corners (NJDEP, 2005).

<u>Substrate</u>

Substrate conditions in the Delaware Bay were examined in 2009 through the Delaware Bay and River Benthic Mapping Project, conducted by the Delaware Coastal Program. Substate data was used to identify areas with hard bottom up-river from the northern-most extant oyster beds for potential bed creation tactics.

Food Quality for Nutrition

Bivalves have different nutrition needs seasonally, depending on cycles of growth, reproduction, and winter survival. Oysters generally sequester carbohydrate reserves in the late summer and fall), which are then used for over winter survival and to fuel gametogenesis (Kennedy, Newell, & Eble, 1996). In the sping, they have high demands for protein and some lipids during gametogenesis. The best food composition for larvae depends on age, but generally also requires ample protein and specific fatty acids. To deduce best growing areas for oysters from a nutritional perspective, oyster food (seston) has been surveyed at up to 18 stations across the Delaware Estuary and up to ten times per year during 2009-2011(Kreeger, Thomas, & Powell, 2011). The results of this study indicate that fall condition of oysters correlates strongly with summer levels of dietary protein and carbohydrate and is inversely correlated with total suspended solids (food quantity), and best areas tend to be lower in the system. Specific areas for maximizing shellfish productivity will be further pinpointed as this new information is fully analyzed and interpreted (Fig. 18).

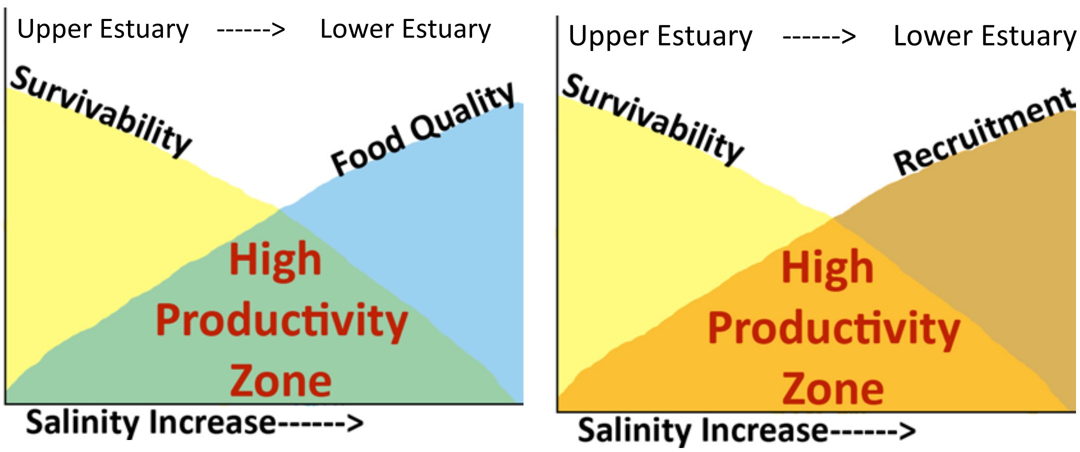

Figure 18: This figure demonstrates how oyster survivability, food quality, and recruitment interact in the transition areas between the upper and lower estuary and across salinity gradients.

Salinity and Disease

The first wave of MSX hit the oyster population between 1953 and 1969, which caused oyster abundance on the leased beds (down bay) and beds in the high mortality area of the seed beds to decline (Ford & Bushek, in prep). Oyster populations throughout the bay declined as a result of the second MSX epizootic in 1985, and then again following a second disease in the 1990s called Dermo (Ford, 1997). The important spatial consideration is the relationship between oyster disease and salinity (Fig. 18). At low salinities (below 10 ppt), MSX (*Haplosporidium nelsoni*) does not persist; and, while Dermo (*Perkinsus marinus*) can survive at these salinities, it does not cause mortality (Ragone-Calvo & Burreson, 1994). Oyster beds in New Jersey and Delaware are classified into 4 major areas to reflect salinity and disease zones (Fig. 10) and restoration activities must account for the presence of diseases and climate cycles that affect salinity and disease such as wet and dry or warm and cold years.

Ship Traffic/Bay Uses

Shellfish restoration should not conflict with ship traffic and other commercial/recreational uses. Conservation/restoration areas should also not overlap with dredge areas or surrounding high impact areas surrounding dredge zones. Any of the current oyster beds do not conflict with ship and dredging areas, but areas of the proposed new bed creation (i.e. C&D Canal areas) should be careful not to develop in a dredging area.

Climate Change

With climate change, channel dredging, and the consumptive removal of freshwater from the aquifers and the Delaware River, the Delaware Bay salt wedge will extend further up-bay making the Bay saltier. Higher disease levels come with higher salt, so oyster populations may need to shift distributions up the estuary to follow the migrating salinity contours. There is some concern however that availability of suitable substrate for oyster reefs further northward in the system will be diminished because the river constricts and much of the bottom is softer and deeper. Therefore, we have identified hard bottom areas that might be potential new colonization sites and reef creation options up-bay from existing oyster reefs.

Chemistry & Contamination

The Delaware Estuary Benthic Inventory effort recorded benthic contamination levels at over 250 sites around the Delaware Estuary. Although data are available, analysis has not been completed to compare contamination levels to benthic production and species distributions. However, spatial planning for shellfish enhancement should consider relationships between bivalve health relative to contaminant levels, since oysters and other bivalves can be impaired by water and substrate contamination (Kraeuter & Kreeger, 2010). At this point we know that most of this contamination does not come from the ocean so continued efforts to reduce contaminant input from riverine, upland and atmospheric sources is desirable.

Figure 10 Data Sources

(Powell, Ashton-Alcox, & Bushek, 2011) – Location of NJ oyster beds and mortality zone
locations(Bushek, 2010) – Mortality information
(DNREC, 2010)– DE oyster beds mortality
(USGS, 2011) – National Hydrography Dataset Tidal Creeks
(ESRI, 2009) – World Shaded Relief Maps

Figure 11 Data Sources

(Powell, Ashton-Alcox, & Bushek, 2011) – Identification of highly productive NJ oyster beds
(DNREC, 2005)– Locations of official Delaware oyster beds
(NJDEP, 2005)– NJ Lease Beds
(USGS, 2011) – National Hydrography Dataset Tidal Creeks
Bill Shadel, American Littoral Society, Personal Communication, Dec. 29, 2010 – PORTS location
(ESRI, 2009) – World Shaded Relief Maps

Figure 12 Data Sources

(PORTS, 2011) (Shadel, 2011)– Location of PORTS project area

Personal communication with John Kraeuter, Dave Bushek, Angela Padeletti – Oyster intertidal sitings
(Powell, Ashton-Alcox, & Bushek, 2011) – SAW report
(NJDEP, 2011) – Shellfish classification zones for harvest restrictions
(USGS, 2011) – National Hydrography Dataset Tidal Creeks
Bill Shadel, American Littoral Society, Personal Communication, Dec. 29, 2010 – PORTS location
(ESRI, 2009) – World Shaded Relief Maps

Figure 13 Data Sources
(Bushek, 2010) – 2010 Oyster Seedbed Monitoring Report
Personal Communication with Haskin shellfish experts Dr. David Bushek and Dr. John Kraeuter
(USGS, 2011) – National Hydrography Dataset Tidal Creeks
(ESRI, 2009) – World Shaded Relief Maps

Figure 15 Data Sources
(DNREC, 2011) - DNREC bathymetry scans with Roxanne sensors, used to show hard bottom areas
(Powell, Ashton-Alcox, & Bushek, 2011) – Locations of oyster seed beds
Personal Communication with Haskin shellfish experts Dr. David Bushek and Dr. John Kraeuter for potential climate enhancement site locations.
(USGS, 2011) – National Hydrography Dataset Tidal Creeks
(ESRI, 2009) – World Shaded Relief Maps

Appendix II: Spatial Considerations for Ribbed Mussels

Marsh Mussel Current Locations

The ribbed mussel, *Geukensia demissa* grows within and along intertidal habitats. Their byssal threads attach to the stems of *Spartina* plants and to other ribbed mussels to form symbiotic complexes (Coen & Walters, 2011) whereby mussels help plants by filtering nutrients from the water and depositing them in the sediments, and plants provide attachment surfaces (Bertness, 1984; Kreeger & Newell, 2000).

In order to map predicted habitat for this species, we used the National Hydrography Dataset (NHD) which contains more detail on marsh creeks and ditches compared to the NWI data. (In NHD, relevant FType attributes were found to represent: 336=ditches, 558=large tidal creeks, 460=small tidal creeks.) For the map in Figure 17, the small tidal creeks and ditches overwhelmed the map at the Bay scale, so we only used FType 558. Ribbed mussels are most abundant and biggest within 1 - 3 meters in from a marsh edge, with a majority of the population living within the first 1.5 - 2 meters (Kreeger & Gatenby, 2007). Although mussels can be found throughout marshes, for area prioritization we applied a 2 meter buffer to all the FYype 558. For a true site design exercise, we recommend also using 2 meter buffers around codes 336 and 460 in the FType to predict best marsh mussel habitat. Figure 19 shows the workflow in GIS to accomplish the predicted best mussel habitat modeling.

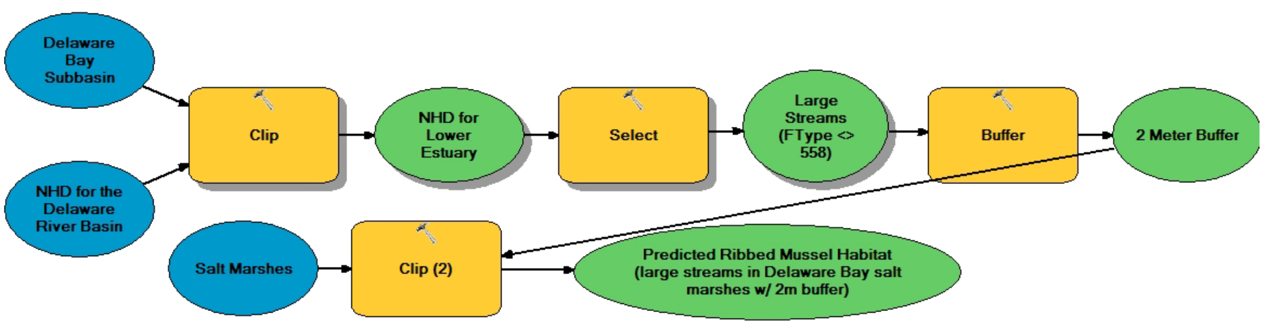

Figure 19: GIS model of the process for obtaining predicted ribbed mussel habitat. The output was further refined by removing known non-habitat, based on local knowledge by field experts.

Habitat loss due to erosion is the single largest threat to ribbed mussels and net acreage loss from their intertidal salt marsh habitat may be a consequence of sea level rise (Kraeuter & Kreeger, 2010). Since mussels are an ecologically significant species for the system, salt marsh preservation and enhancement is perhaps the single most effective tactic available to enhance or stave losses to this bivalve species. Any enhancement tactic aimed at enhancing ribbed mussels should consider the sustainability of their broader habitat context at the site.

Salinity
Marsh mussels are known to prefer salinities between 12-30 ppt (Dillwyn, 1817).

Build out

The Delaware Bay supports a wide variety of industry and commercial uses which require infrastructure built out into the bay. Planning for restoration and conservation must consider these factors when choosing site locations. This infrastructure may include: cables or lines for electricity, water, gas or communication, port structures, and wind farms. These layers were utilized for this analysis, but would be important for project design. Similarly, the shoreline condition must be assessed for specific areas to deduce the presence of other structural alterations such as bulkheads and rip rap.

Slope, Tidal Range, Fetch, Energy

The requirements for slope, tidal range, fetch, and energy are known for the establishment of *Spartina* marshes via restoration. Since ribbed mussels live in *Spartina* marshes, these are likely the same conditions needed to establish ribbed mussels. However, these ideal restoration conditions do not represent the total range of natural habitat conditions where ribbed mussels could be found. For *Spartina* restoration with bio-based living shorelines a slope of 10:1 is preferred with low energy, a fetch of 0.5 miles, and tidal range between tidal low and mean high water (Whalen et al., 2011). Again, ribbed mussels can live outside this range of parameters, but more research is needed to determine their natural thresholds for slope, tidal range, fetch, and energy.

Climate Change

To predict future status and trends in bivalve populations, we must continue to learn lessons from past status and trends regarding the current distribution of species in the system. Ribbed mussels are threatened with loss of the marsh habitat that they reside in due to sea level rise, erosion and limited ability for tidal marshes to migrate inland.

Figure 17 Data Sources

(USGS, 2011) – NHD dataset filled in more of the tidal creeks. A 2 meter buffer was applied to identify potential marsh mussel habitat.

(USFWS, 2007) – TNC used this data to create the salt marshes shapefile, which they sent back to us.

The predicted habitat for marsh mussels could be further refined by incorporating element of fetch, slope, tidal range, and energy. Unfortunately, detailed data for these factors was not available for this project, but this information would be useful for project designs.

Appendix III: Inventory of Shellfish Conservation Projects in the Delaware Estuary and around the Nation

Species	Location	State	Date	Project Type	Project Description	Abstract Title	Source
Oyster	Delaware Bay	NJ, DE	2005 - 2008	Shell planting	Lead by the Army Corps of Engineers funding, ~1.8 million bushels of shell was planted on Delaware and New Jersey seed beds over 1044 acres of beds. In NJ, some replanting took place to take advantage of high recruitment areas.	N/A	Bushek 2011
Oysters	Delaware Bay	NJ, DE	2009-2010	Shell planting	Followup plants with non-USACE funds took place in the years following the USACE shell planting project.	N/A	Bushek, 2011
Oysters	Delaware Bay	NJ	1956-1999	Shell planting	Since the mid-1950s, New Jersey has planted shell across 16 locations to boost oyster populations. Roughly 7.7 million bushels were planted over the five decades.	N/A	Kraeuter, 2011
Oysters	Delaware Bay	NJ	2006-present	Oyster Education	Promoting Oyster Restoration Through Schools (PORTS) aims to restore oyster habitat while educating children about stewardship of the resource.	Seeding the Future - Promoting Oyster Restoration Through Schools: Project PORTS	(Shadel, 2011) (Rutgers, 2010)
Ribbed Mussels	Delaware Bay	NJ, DE	2008 - Present	Living Shoreline	Delaware Estuary Living Shoreline (DELSI) uses bags of oyster and clam shells, coconut-fiber logs, and coconut-fiber matting are being used to prevent the tide from eroding marshland.	Delaware Estuary Living Shoreline (DELSI)	
Oysters	Delaware Bay	NJ	1957-Present	Disease Research	Haskin Shellfish Research Lab was well positioned to study oyster diseases at the first epizootic outbreak of MSX in 1957. It continues to study oyster diseases and produce disease resistant animals ever since.	Haskin Shellfish Research Lab	(Rutgers, 2009)

Oyster	Inland Bays	DE	2003-Present	Gardening	Cooperative effort using citizen volunteers to produce juvenile oysters for stocking demonstration reefs.	Delaware Center for the Inland Bays Oyster Gardening Program	(UDel, 2010)
Oyster	Chesapeake Bay, Maryland	MD	1994	Reintroduction	Optimal restoration sites are identified through reconnaissance and research, and hatchery-produced seed and juveniles are introduced here to produce a self-sustaining natural system.	Large Scale Oyster Restoration in the Maryland Portion of the Chesapeake Bay: Adaptive Management from Site Selection and Planting to Monitoring	(CSR, 2008)
Oyster	Delaware Bay, New Jersey	NJ	2005	Shell Planting	Oyster shell is required for oyster recruitment and the formation of beds and reefs. Thus shell was planted along NJ's oyster beds to stem both shell loss and declines in oyster abundance, and to increase recruitment rate.	The Delaware Bay Oyster Restoration Program	(CSR, 2008)
Oyster	Chesapeake Bay, Virginia	VA	2006	Living Shorelines	Three oyster shell reefs, three rip rap reefs, and six stacked sets of two to four concrete modular reefs were constructed and were seeded with oysters to develop a living shoreline. Comparisons were made between reef construction types.	Living Oyster Reef Shorelines Using Alternative Substrate in the Lynnhaven River, Chesapeake Bay, Virginia	(CSR, 2008)
Oyster	Great South Bay, New York	NY	2004	Reintroduction	Acquisition of underwater land and restocking of shellfish populations into a network of spawner sanctuaries to boost reproductive potential of present shellfish.	Restoring Shellfish in Great South Bay, Long Island, New York, to Enhance Ecosystem, Economic, and Social Viability of a Suburban Estuary	(CSR, 2008)
Oyster	Northern South Carolina	SC	2008	Living Shorelines	Creation of oyster reefs within inlets and tidal creeks affected by water quality degradation from surrounding development to improve water quality and facilitate sustainable development.	Oyster Reef Restoration as One Aspect of Coastal Ecosystem Sustainable Development	(CSR, 2008)
Oyster	Charleston, South Carolina	SC	2008	Living Shorelines	Crab traps of different varieties are being used as a base for artificial oyster reefs to successfully recruit oysters and spawn restoration.	The Role of Abandoned Crab Traps in Oyster Reef Restoration	(CSR, 2008)

Oyster	Lower Hudson, NY and NJ	NY	2008	Reintroduction	Oysters being reintroduced to various sites throughout the Lower Hudson to examine the hyrdrological conditions most effective for oyster recruitment and survival.	Costs and Benefits of Oyster Restoration to the Lower Hudson: Perspectives on Physiology, Metapopulation Structure, and Habitat Value	(CSR, 2008)
Oyster	Caraquet Bay, New Brunswick	NJ	2008	Reintroduction	Oyster population restoration in the Caraquet, Gulf of Saint Lawrence through techniques including shell spreading, desilting, seeding, and relay.	Shellfish Restoration in the Southern Gulf of St. Lawrence: A Case Study in Caraquet Bay, New Brunswick, Canada	(CSR, 2008)
Oyster	Bronx River, New York	NY	2006	Shell Planting	Hard substrate is being provided for oyster spat to settle on, which leads to increases in subtidal diversity and water quality improvement as oyster recruitment and reestablishment begins.	Restoring the Eastern Oyster in an Urban Estuary: A Community Effort in the Bronx River, NY	(CSR, 2008)
Oyster	Galveston Bay, Texas	TX	2008	Hydrology	A study determining the feasibility of using processed industrial waste water to manage the ambient salinity in a small embayment that has been impacted by Dermo disease and the Southern Oyster Drill.	Processed Waste Water: Potential Tool for Promoting Oyster Reefs in High-Salinity Waters	(CSR, 2008)
Oyster	Great Wicomico River, Chesapeake Bay	MD	2004	Reintroduction	Restoration of oyster reefs through three experimental treatments including medium relief reefs, low relief reefs, and unrestored bottom to enhance a degraded reef network.	Unprecedented Restoration of a Native Oyster Metapopulation in Chesapeake Bay	(CSR, 2008)
Oyster	Cedar Key, Florida	FL	2007	Living Shorelines	Using destroyed and abandoned culture equipment as substrate to construct oyster reef habitat.	Turning "Derelict" Clam Culture Equipment into Oyster Reef Building Blocks through Reclamation of Shellfish Aquaculture Leases in Cedar Key, Florida, USA	(CSR, 2008)

Oyster	Sanibel, Florida	FL	2006	Hydrology	Daily tidal flows and natural salinities were re-established through the addition of culverts.	Restoration of Oysters and Adjacent Vegetated Habitats: Methodologies, Reef Success Assessed and Potential Indirect Effects in this Recently Reconnected and Substrate-Limited Area on Sanibel, FL	(NSA, 2011)
Oyster	Annapolis, Maryland	MD	2011	Aquaculture	A submersible aquaculture system was designed to grow out eastern oysters for specific conditions in the Chesapeake Bay.	A Submersible Oyster Aquaculture System for the Chesapeake Bay	(NSA, 2011)
Geukensia demissa	Stony Brook, New York	NY	2008	Monitoring	Mussel recruitment in different regions of a salt marsh were examined over a period of two years.	East Meets West: The Novel Use of Rocky Intertidal Bivalve Recruitment Techniques in a Salt Marsh Ecosystem	(NSA, 2011)
Oyster	Port Norris, New Jersey	NJ	2005	Shell Planting	A shell-planting program was established in the Delaware Bay to enhance the recruitment of native oysters.	So Happy Together: Why Shell-Planting and Sustainable Fishing Work for Oyster Populations in the Delaware Bay	(NSA, 2011)
Oyster	New York Harbor	NY	2010	Reef Building	Experimental scale oyster reefs were established with the development and performance to be measured over two years.	Initiation of a Long-Term Commitment to Restore Oyster Populations in the New York Harbor Region	(NSA, 2011)
Oyster, more?	National		2011	Overview	Summary of achievements to date, mechanisms for increasing the scale, and possible for directions for shellfish restoration.	Taking Shellfish Restoration to Scale: A Decade of Development in Restoring Shellfish Habitats	(NSA, 2011)
Oyster	Annapolis, Maryland	MD	2008	Reintroduction	Citizens grow and tend to young oysters which are eventually planted on non-harvest sanctuary sites.	Marylanders Grow Oysters Program: Results of Citizen Based Efforts to Enhance Oyster Sanctuaries in Chesapeake Bay	(NSA, 2011)
Oyster	Martha's Vineyard, Massachusetts	MA	2008	Reintroduction	Dermo-resistant oyster strains were planted in a Dermo-plagued habitat in an effort to restore a native population.	Strategies to Restore Oyster Populations in Two Salt Ponds on Martha's Vineyard	(NSA, 2011)

Oyster	Annapolis, Maryland	MD	2011	Monitoring	An examination of measuring success of oyster restoration not simply in population numbers but effects on the surrounding ecosystem.	Oyster Restoration in the Maryland Portion of the Chesapeake Bay: Measures of Success and Failure	(NSA, 2011)
Oyster	Great Bay, New Hampshire	NH	2010	Reintroduction	Volunteers collect shells at local restaurants which are used to produce "mini-reefs" on which spat is laid and introduced, followed by monitoring.	Working with New Hampshire Residents to Restore Oyster Populations to the Great Bay Estuary	(NSA, 2011)
Oyster	Long Beach, California	CA	2010	Reintroduction	Oysters reefs were constructed on thick, consolidated oyster beds and the resulting numbers were compared to those grown on thin, unconsolidated beds and mudflats.	Restoration of Olympia Oysters: Oyster Settlement, Survival, Growth, and Community Biodiversity on Constructed Oyster Beds	(NSA, 2011)
Oyster	North Carolina Coastal Federation	NC	2011	Shell planting, Living Shorelines, Breakwaters, Education	Oyster shell and marsh plants were used in restoration projects to prevent erosion, create habitat, and restore oyster reefs and shorelines.	Restoring estuarine habitat, one oyster shell at a time.	(RAE, 2011)
Oyster	Indian River Lagoon	Fl	2011	Reef Creation, Education	Success stories of oyster reef restoration in Fl: 31 reefs restored using 11,912 restoration mats; 13,000 volunteers; 5 restored reefs with seagrass recruitment.	Oyster success story: Restoring oyster reefs and engaging citizens in Indian River Lagoon, Fl	(RAE, 2011)
Oyster	Tampa Bay	Fl	2001 - 2011	Education, shell restoration	Tamp Bay Watch's Community Oyster Reef Enhancement Program in a highly successful community-based program since 2001.	Case Studies of oyster shell restoration in Tampa Bay: Lessons learned	(RAE, 2011)
Oyster	Galveston Bay	TX	2008 - 2011	Reef cleaning/ enhancement	Galveston Bay's commercial oyster fishery and oyster reefs were severely impacted when Hurricane Ike struck in 2008. Using various methods, TPWD restored 1500 acres of public oyster reefs covered in hurricane-derived sediment.	Recovering from the storm: oyster reef restoration in Galveston Bay, Texas	(RAE, 2011)

Oyster	Georgia's Inshore	GA	2003 - 2011	Reef Creation, shellplanting, education	Community based restoration program	Oyster restoration efforts through G.E.O.R.G.I.A. – generating enhanced oyster reefs in Georgia's Inshore Areas	(RAE, 2011)
Oyster	Jamaica Bay	NY	2011	Reef creation, oyster balls, hatchery seed production	Remote setting of eastern oyster larvae on to whole shell and reef balls was chosen as the best way of creating small reefs in the eutrophic waters of Jamaica Bay. P	Building oyster reefs in an urban estuary – the Jamaica Bay experience	(RAE, 2011)
Multiple Species	United States	All	2005	Sanctuaries, harvest guidelines, reef creation, hatcheries, intertidal enhancement	Suggests steps to take when considering shellfish restoration and examples of strategies.	A practitioners guide to the design and monitoring of shellfish restoration projects.	(Brumnaugh, Beck, Coen, Craig, & Hicks, 2005)

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