Eastern Oysters (*Crassostrea virginica*) in the Hudson-Raritan Estuary: Restoration Research and Shellfishery Policy

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Once-extensive Eastern Oyster (*Crassostrea virginica*) reefs in the Hudson-Raritan Estuary (HRE) were destroyed almost a century ago as a result of human activities. However, because of improvements in water quality, the potential exists to reintroduce this *ecologically extinct* species to the ecosystem. For over a decade, New York/New Jersey Baykeeper has conducted oyster restoration activities in support of target ecological goals proposed in the HRE Comprehensive Restoration Plan (CRP). The critical research question is whether existing conditions at a proposed restoration site can actually support long-term Eastern Oyster survival. To determine the feasibility of restoring this native species in Keyport Harbor, New Jersey, juvenile oysters were placed in research field plots, and survivorship and growth were monitored. Data from the first reported oyster restoration research in the New Jersey (NJ) portion of the HRE indicate that oysters could indeed be reintroduced into the ecosystem. After 11 months in situ, research oyster survival rates as high as 60% were observed. Qualitative tissue observations indicated female oysters produced eggs that appeared normal and were ready for spawning. Biodiversity of species collected from the field plots was two- to threefold greater with adult research oysters present, suggesting that oysters increased the density and abundance of other marine species. Sediment deposition patterns indicated that the presence of oysters in support structures may reduce the degree of topographic relief caused by winter storm energies. The research ended abruptly on August 9, 2010, when New Jersey's Department of Environmental Protection rescinded the project permit because of concerns that research oysters were beginning to reach New Jersey's market size of 2.5 inches. Although initial data suggest that oysters can survive and reproduce in Raritan Bay and the potential exists to achieve oyster restoration goals included in the CRP, the project also highlights the current lack of agreement between shellfishery regulators and restoration practitioners with respect to oyster reintroduction in waters where shellfish harvesting is currently prohibited. Different shellfish management approaches are used in New England states (Massachusetts, Rhode Island, and Connecticut), where local control is an important management tool, and in Chesapeake Bay states (Maryland and Virginia), where federal involvement is relatively high. Situated between these two distinct shellfish-producing regions, New Jersey and New York have not supported aggressive reestablishment of historic Eastern Oyster populations in the HRE, and unlike adjacent states, have not developed long-term oyster aquaculture plans. The reluctance to support oyster restoration is due to concerns related to human health and ecological

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questions. Examples of best management practices currently employed in neighboring states offer potential solutions to address regulatory concerns and could form the basis for developing a productive long-term strategy to reestablish Eastern Oysters in the HRE.

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Anthropogenic activities in the 19th and 20th centuries negatively impacted the health of many ecosystems in the New York/New Jersey (NY/NJ) region, including a once vast Eastern Oyster (*Crassostrea virginica*) fishery (Jackson, 2001; Kennish, 1992; McCay, 1998). However, since passage of environmental regulations beginning in the 1970s, surface waters have become progressively cleaner. As a result of improvements in water quality, it is now possible that aquatic species, absent for decades or present in greatly reduced numbers, could potentially be restored in the coastal ecosystems where they were historically present.

Scientific documentation of the benefits provided by re-establishment of oysters is extensive (Beck et al., 2009, Coen and Grizzle, 2007; Coen et al., 2007, and references therein). Oyster reefs create hard substrate and vertical relief on flat soft-sediment bottom, providing habitat for numerous species of fish, invertebrates, and algae (Harding and Mann, 1999, 2001; Lenihan and Peterson, 1998). It is estimated that the presence of molluscan reef habitat can increase biomass and productivity of invertebrate fish prey species by up to 20-fold (Steimle et al., 2002), and the increased prey biomass can support an increase in fish and large crustacean biomass of up to 50 kg/m^2 of oyster reef habitat (Peterson, Grabowski, and Powers, 2003). Adult oysters are also capable of filtering prodigious amounts of water, and this natural filtration helps to reduce water-column turbidity and contributes to improvements in overall water quality. The presence of oyster reefs has been linked to the ecological health of an estuary, and a majority of states now support oyster restoration projects.

However, the ecological benefits provided by oysters have until recently been viewed in secondary terms when compared with the financial value of the shellfishery; indeed, the primary reason for restoring oysters was primarily linked to their commercial attributes. Because of the financial value of the fishery, regulatory policies have evolved to protect the health of human consumers, which in turn protects the economic health of the fishery. Two compelling trends related to shellfishery policy and estuary management in the United States (US) are now occurring simultaneously. The first trend is the growing recognition of ecological benefits derived from restoration of degraded shellfishery resources, particularly Eastern Oyster populations; the second trend is a realization that aquaculture can be an important economic driver and a factor in meeting nutritional needs of an expanding human population. These coinciding trends are causing states to clean up harvest-limited waters and to classify new oyster-growing areas outside traditionally fished bays and estuaries [National Oceanic and Atmospheric Administration (NOAA), 1998].

Restoration practitioners recognize that oysters contribute ecosystem-level functions that go far beyond the mere value of the remaining fisheries, and extensive restoration projects are now supported at both state and federal levels (Beck et al., 2009). The Boston–Washington corridor (Table 1 and Figure 1) from Massachusetts Bay to Chesapeake Bay accounts for 44% of the US waters classified for shellfishing (NOAA, 1998). However, these estuaries have been impacted by anthropogenic activities for three centuries, and many areas are now closed to shellfish harvesting because of concerns related to human health. The National Estuary Program (NEP, 2007), using four indices of estuarine condition, rates Delaware and Narragansett Bays, Long Island Sound, and the NY/NJ Harbor in "poor" condition, Mas-

Table 1. Major estuaries in the Boston–Washington corridor

State	Water body	Size (miles^2/km^2)	Reference
Massachusetts	Massachusetts Bay (total watershed)	7,350/19,038	USEPA, 2010
Rhode Island/Massachusetts	Narragansett Bay	147/342	Riposa, 2009
Connecticut/New York	Long Island Sound	1,300/3,367	Alter, 2008
New York/New Jersey (Northern)	Hudson-Raritan Estuary	1,600/4,144	USACE, New York District (CRP), 2009
Delaware/New Jersey (Southern)	Delaware Bay	782/2,030	USACE, Philadelphia District, 2007
Maryland/Virginia	Chesapeake Bay	4,479/11,601	Oxnam and Williams, 2001

CRP, the Hudson-Raritan Estuary Comprehensive Restoration Plan.

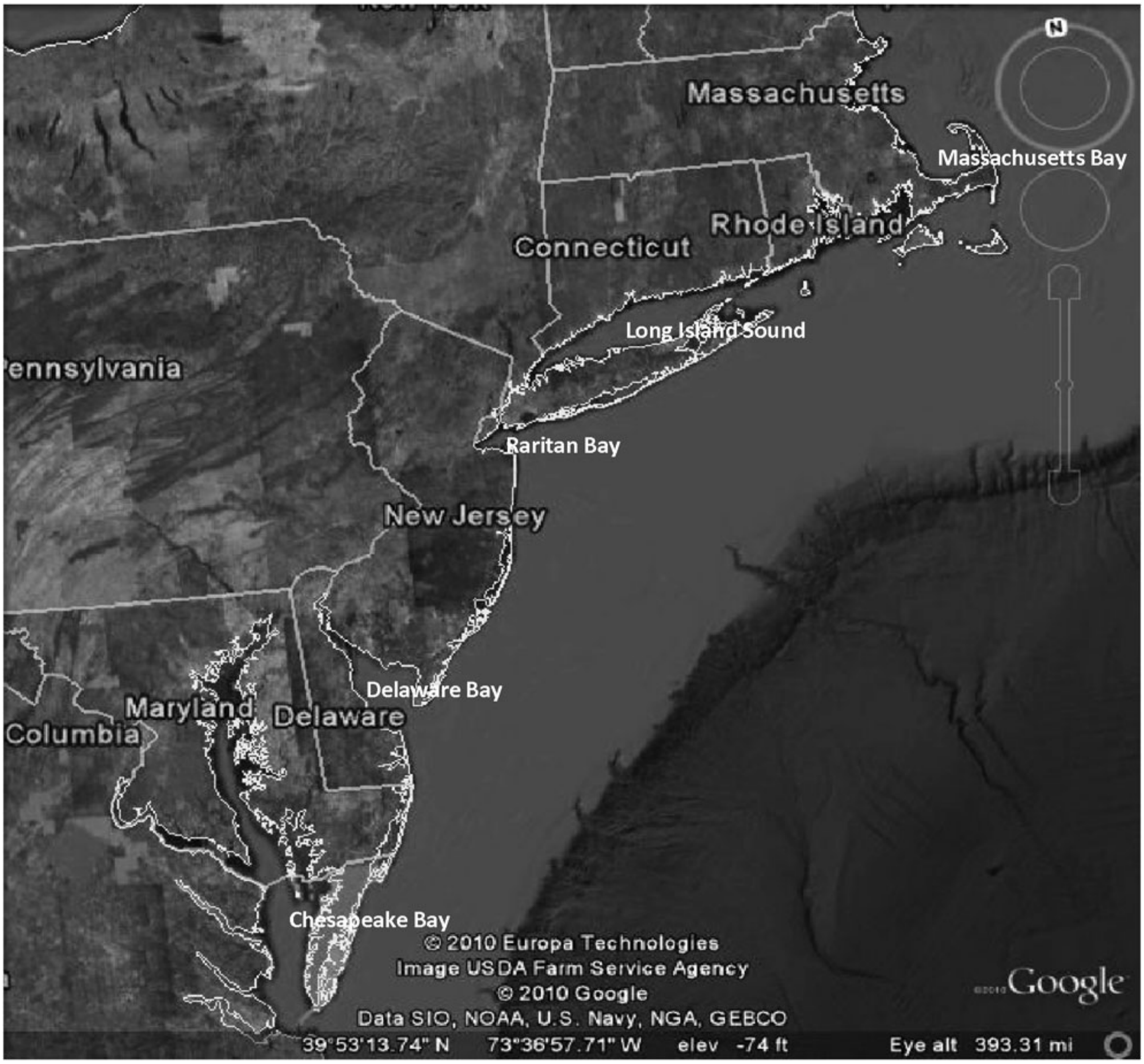

Figure 1. Shellfish producing estuaries in the Boston–Washington corridor.

sachusetts Bay in "fair" condition, and Barnegat Bay in "good to fair" condition. Returning ecological benefits associated with oyster restoration to waters that are not currently approved for commercial shellfish harvesting requires creative restoration and regulatory approaches.

A draft comprehensive restoration plan (CRP) for the Hudson-Raritan Estuary (HRE) was developed by the US Army Corps of Engineers (USACE, New York District, 2009) through the NY/NJ Harbor and Estuary Program (HEP), a consortium consisting of various federal and state (NJ and NY) partners, including the NJ Department of Environmental Protection (NJDEP) and nongovernmental organizations (NGOs). CRP restoration goals call for the reestablishment of 500 acres of oyster reef by 2015 (Bain et al., 2007). Due to fecal coliform contaminant loadings in the HRE, oyster harvesting in the majority of these waters is prohibited by the NJDEP under the state's shellfish management plan (Zimmer, 2004). However, anecdotal evidence, observations by the authors, and recently completed studies by other scientific researchers (T. Medley, personal communication) suggest that isolated wild oyster populations either remain in the HRE or are in the process of returning to the system.

Reestablishment of the Eastern Oyster is a mechanism to support continued improvements in water quality, to enhance habitat conducive to survival of biodiverse aquatic communities, and to protect shorelines from erosion (USACE, New York District, 2009). *These restoration goals are not to reestablish a commercial fishery in waters where historic contamination is still present.*

Although restoration of benthic habitat is viewed by the HEP as a particularly important goal, it is also one of the most difficult to achieve because of the amount of degradation that has occurred within the HRE, the presence of historic and current contaminants (Contamination Assessment & Reduction Project, 2007), and major alterations in natural hydrologic patterns (USACE, New York District, 2009). Due to these environmental constraints, it is important to test the effectiveness of restoration strategies and designs by using low-cost research prior to implementation of large-scale and expensive restoration activities. The critical research question is whether existing conditions at a proposed restoration site can actually support long-term oyster survival.

Although closed for commercial shellfish harvesting, the Keyport Harbor research site was continuously approved by NJDEP for NY/NJ Baykeeper oyster restoration activities since 2001. However, initial restoration attempts, using seed oysters and spat set on clamshells placed in intertidal mounds failed within two seasons because of destruction of the mounds and dispersal of the shells. It is believed that this destruction resulted from high energy in Raritan Bay associated with winter storms, and during a 2006 bottom survey no spat recruitment or living adult oysters were observed. In 2007, Rutgers University scientists were engaged by Baykeeper to conduct an Eastern Oyster restoration feasibility study. A primary goal of the field research was to test restoration options capable of withstanding winter storm energies in Raritan Bay. In the summer of 2009, juvenile oysters were placed on the $\frac{1}{4}$-acre NJDEP-approved Keyport Harbor research site. However, in August 2010, the NJDEP stopped the research because oysters were beginning to reach NJ market size of 2.5 inches. The destruction of an estimated 30,000 research oysters was ordered based on concern over potential illegal poaching (Martin, 2010).

Today, New Jersey (NJ) finds itself facing a challenging dilemma. The state's environmental agency, charged with protecting and restoring the environment, has banned the use of commercial shellfish for research, restoration, and educational purposes in waters deemed too contaminated (Martin, 2010). Because the majority of HRE waters are closed to shellfish harvesting, the ban essentially precludes any oyster research, restoration, or educational activities in all northern NJ waters. The ban was initiated after the state's ongoing lack of compliance with its own regulatory plan [developed under National Shellfish Sanitation Program (NSSP) guidelines] caused the US Food and Drug Administration (USFDA, 2009a) to threaten to shut down interstate shellfish commerce from NJ. The NJDEP stated that if it bans the placement of commercial shellfish species in contaminated bodies of water (most specifically the HRE), the need for marine patrols and monitoring will be reduced. This approach does not take into account the extensive naturally occurring hard clam population in Raritan/Sandy Hook Bays (Figure 2) estimated by the NJDEP to number close to one billion animals (Celestino, 2003) that require monitoring.

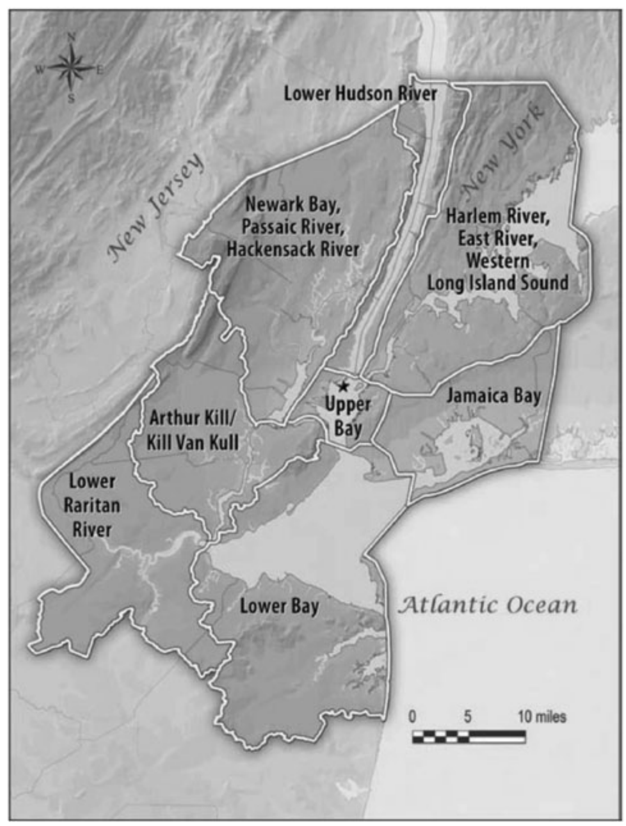

Figure 2. Map of the Hudson-Raritan Estuary (HRE) indicating the location of the Keyport Harbor restoration research site. Map courtesy of CRP (USACE, New York District, 2009).

The challenging policy issue is how ecological benefits of HRE oyster restoration can be reconciled with shellfishery regulations written for an industry based in the southern waters of the state. The NJ prohibition also raises other policy questions: Should a public agency be allowed to prohibit specific scientific research and environmental restoration? Should a public agency charged with protecting the environment prohibit viable restoration of damaged ecosystems in an effort to support financial interests in other regions? What is the cost to society of not allowing research in degraded water bodies?

A review of shellfish management policies within the Boston–Washington corridor suggests that local customs play a large part in the evolution of a state's regulatory approach. Individual states are responsible for classifying their shellfish waters, inspecting harvest and processing facilities, patrolling to deter illegal harvesting, and conducting laboratory testing of shellfish and water samples (USFDA, 2009b). This devolution of power to the states, coupled with historic precedents, has resulted in policies, management, and enforcement plans that vary greatly by state (Table 2). The New England states (Massachusetts, Rhode Island, and Connecticut) incorporate a high degree of local control; the Chesapeake Bay states (Maryland and Virginia) in close proximity to Washington, DC, have a high level of involvement with federal agencies working in cooperation with state and NGO entities (Tables 3 and 4). Federal involvement could also be a function of the size and importance of Chesapeake Bay, the largest estuary in North America.

A survey of northeastern coastal states operating within the NSSP guidelines shows oyster restoration and aquaculture activities are expanding in the Boston–Washington corridor (Tables 2–4), and such a review is instructive in addressing NJ policy questions. Key elements of the various restoration and aquaculture activities illustrate multiple approaches to reestablishing the Eastern Oyster, while simultaneously addressing restoration management in waters closed to harvesting (Tables 2–4).

Research Materials and Methods

Study Location

The Raritan Bay system is approximately 25 miles long, oriented in an east–west direction, and triangular in shape; freshwater from the Raritan River flows out along the NJ shore due to a counterclockwise gyre (Jeffries, 1962). The physiochemical properties of the Bay are typical of an estuary and quite variable: the salinity range is 11–30 ppt, and dissolved oxygen concentrations range from 4 to 12 mg/L. The system is subject to potentially high nutrient loadings (total nitrogen, 164–3,452 μg/L; total phosphorus, 14–218 μg/L), and the chlorophyll a ranges from 2.5 to 34.5 μg/L. Raritan Bay receives discharges from combined sewer overflows and US Environmental Protection Agency (USEPA) fecal coliform counts (five-tube test) range from 2 to 1,600 colony-forming units (NJDEP monitoring data, 2001-7; J. Watson, personal communication). Runoff from the highly developed watershed during intense rain events increases turbidity, and total suspended solids can range from 3 to 56 mg/L (NJDEP monitoring data, 2001–7; J. Watson, personal communication).

The Keyport, NJ, research site is located in the southwestern portion of Raritan Bay (40° 26′ 05″ N; 74° 11′ 05″ W) adjacent to Chingorora Creek (Figure 2). The bottom substrate consists of patchy shell, gravel, and hard sand. The site was once a part of the historic Eastern Oyster fishery known as the *Great Beds of Raritan Bay*, which was com-

Table 2. States in the Boston–Washington corridor allowing oyster restoration in waters closed to shellfish harvest.

State	Restoration allowed in closed waters	Reference
Massachusetts	Yes: research (2008–present)	http://massoyster.org/
Rhode Island	Yes: gardening in closed waters	Cox, 2008
Connecticut	Yes: fisheries enhancements	B. Hancock, personal communication
New York	Yes: research	Hudson River Foundation, 2010
New Jersey	**No**	**Martin 2010**
Delaware	Yes: gardening in contaminated inland bays	Rossi-Snook, Ozbay, and Marenghi, 2010
Virginia	Yes	B. Hancock, personal communication
Maryland	Yes	B. Hancock, personal communication

Table 3. Public agencies and major nongovernmental organizations (NGOs) engaged in oyster restoration in the Boston–Washington corridor

States	Public agencies	Major NGO partners
New England		
Massachusetts	Cape Cod Economic Development Commission	Cape Cod Extension Program
	Department of Fish & Game	Mass Audubon
	Mass Div Marine Fisheries	Mass Oyster Restoration Project
	NOAA	Shellfish Advisory Committee
		The Nature Conservancy
Rhode Island	Department Environmental Management (DEM)	The Nature Conservancy
Connecticut	Conn Dept of Agriculture–Aquaculture Div	The Nature Conservancy
	Conn Dept of Environmental Protection	
	Local Municipal Shellfish Commissions	
Chesapeake States		
Virginia	Chesapeake Bay Commission	Chesapeake Bay Foundation
	Chesapeake Bay Protection & Restoration[a]	Virginia Institute Marine Science
	NOAA	Virginia Oyster Heritage Program
	Potomac River Fisheries Commission	
	US Army Corps of Engineers	
	VA Department of Environmental Quality	
Maryland	Chesapeake Bay Commission	Aquaculture Coordinating Council
	Chesapeake Bay Protection & Restoration[a]	Chesapeake Bay Foundation
	Maryland Dept of Natural Resources (DNR)	Living Classrooms Foundation
	Maryland Dept of the Environment	Oyster Recovery Partnership
	Maryland Environment Service	University of Maryland
	NOAA	
	Oyster Advisory Commission	
	Potomac River Fisheries Commission	
	USACE	
New York, New Jersey		
New York	Harbor & Estuary Program[b]	Hudson River Foundation
	NY Dept Environmental Conservation	Jamaica Bay EcoWatchers
	NYC Dept Environmental Protection	New York Board of Education
	USACE	NY/NJ Baykeeper
New Jersey–Northern Hudson-Raritan Estuary	Harbor & Estuary Program[b]	Hudson River Foundation
		NY/NJ Baykeeper
		Rutgers University Center for Urban Environmental Sustainability (CUES)
New Jersey–Southern	NJ Dept Environmental Protection	Barnegat Bay Partnership
	NJDEP Div Fish & Wildlife	Barnegat Bay Shellfish Restoration Program
	NOAA	Delaware Bay Partnership
	Ocean County Board of Freeholders	Mullica River Oyster Restoration Project
	USACE	PORTS
	USEPA	ReClam the Bay
		The Nature Conservancy
		Rutgers Haskin Shellfish Labs
Delaware Bay	Delaware Dept of Natural Res & Environ Control	Delaware Bay Partnership
	NOAA	
	USACE	
	USEPA	

[a] Chesapeake Bay Protection & Restoration Federal consortia is chaired by the US Environmental Protection Agency (USEPA) and includes the Departments of Agriculture, Commerce, Defense, Homeland Security, Interior, and Transportation.
[b] NY/NJ Harbor & Estuary Program partners include the New Jersey Department of Environmental Protection (NJDEP), State of New Jersey, New York State Department of Environmental Conservation (NYDEC), New York City Department of Environmental Protection (NYCDEP), State of New York, US Army Corps of Engineers (USACE), Port Authority of New York & New Jersey, National Oceanic and Atmospheric Administration (NOAA), National Park Service (NPS), Department of the Interior, USEPA, Interstate Environmental Commission, New Jersey Meadowlands Commission (NJMC), New York Department of State, Hudson River Foundation (HRF), Citizens Advisory Committee, National Parks Conservation Association, New Jersey Harbor Dischargers Group, Science and Technology Advisory Committee, New York/New Jersey Baykeeper, and Metropolitan Waterfront Alliance.
PORTS, Promoting Oyster Restoration Through Schools.

Table 4. Examples of oyster restoration funding sources in the Boston–Washington corridor

State	Funding	Funding sources	Reference
Massachusetts		Massachusetts Audubon, TNC, NOAA	http://www.massaudubon.org/news/index.php?id=1108&type=press%20%28downloaded%2010/26/10%29 (accessed November 24, 2010)
		MOP: donations only	Andrew Jay, personal communication, November 24, 2010
Rhode Island	$792,000	USDA NRCS	http://www.ri.nrcs.usda.gov/news/PDF/OysterRestorationProject6_09.pdf (accessed November 29, 2010)
New York	$1.3 Million	PA NY/NJ, USACE, HEP	Hudson River Foundation, 2010
	$2.4 Million		
	Shelter Island Bay bottom lease $1/year	Land donations (private industry)	Beck et al., 2004
New Jersey Northern	$1.0 Million	NY/NJ Baykeeper	http://www.nynjbaykeeper.org
New Jersey Barnegat	$15 Million ($1 million/year last 15 years)	USEPA	http://www.app.com/article/20100806/BARNEGATBAY01/100729084/Barnegat-Bay-once-a-pristine-waterway-faces-an-uncertain-future
New Jersey Southern	$1.5 Million	NOAA, Fish America	http://www.state.nj.us/dep/fgw/artmullica07.htm
Delaware	$5 Million (DE & NJ)	Congress through USACE	http://www.delawareestuary.org/pdf/press_release_100509.pdf (accessed December 12, 2010)
Virginia	Millions: federal	NOAA	Executive Order 13508 (NOAA, 2009)
	$1.2 million (2007)		Blue Ribbon Oyster Panel, 2007
	(state general fund)	Charitable Trusts	
	$800,000 NOAA (2007)	Private Industry	
Chesapeake Bay	$30+ million (1999–2009)	NOAA	http://www.noaa.gov/oysters/oyster-restoration (accessed November 22, 2010)
	$1.3 million (2010)	Chesapeake Bay Trust	http://www.cbtrust.org/site/apps/nlnet/content2.aspx?c=miJPKXPCJnH&b=5594627&ct=8919591&notoc=1
Maryland	$5 million	NOAA, USACE (Congress appropriations)	Congress approves funding . . . December 22, 2009 (accessed November 22, 2010)
	$1 million	USDA NRCS	WBOC News, October 26, 2010 (accessed November 22, 2010)
	$10.6 million (2011)	State and federal funds	Chesapeake-bay.org. (accessed November 22, 2010)

TNC, The Nature Conservancy; NOAA, National Oceanic and Atmospheric Administration; MOP, Massachusetts Oyster Project; USDA, US Department of Agriculture; NRCS, Natural Resources Conservation Service; PA NY/NJ, Port Authority of New York and New Jersey; USACE, US Army Corps of Engineers; HEP, Harbor Estuary Program; USEPA, US Environmental Protection Agency.

pletely decimated by the end of World War I (Mackenzie, 1992). Oysters are currently *ecologically extinct* from the research site. Preliminary tests to determine overwinter survival patterns were conducted in 2007 and 2008; in both years, over 70% of the juvenile seed oysters placed in Keyport Harbor survived. Testing of oysters for the common pathogens *Haplosporidium nelsoni* (*MSX*) and *Perkinsus marinus* (*Dermo*) by Rutgers Haskins Shellfish Research Laboratories in 2005 found low infection rates (no *MSX* and average *Dermo* infection intensity of 1.1).

Based on these preliminary results, field test plots were established in 2009 in Keyport Harbor at a location approved continuously since 2001 by NJDEP for oyster restoration. A total of 18 individual plots covered the $\frac{1}{4}$ acre research site. To withstand winter storm energies, three support structures were tested by using a random block experimental design (Figure 3). Reefblk (Coastal Environments, Inc.) and a proprietary arch structure (designed at the Rutgers University Department of Environmental Science to increase water flows around the oysters) consisted of rebar supports to which polypropylene mesh cages were securely attached. Reefballs (Roman Stone Construction Company) are concrete structures that juvenile oysters attach to directly. Reefblk and Reefball are commercially available products that have been successfully utilized in oyster restoration projects in coastal US waters.

Experimental Design

Approximately 50,000 juvenile oysters were placed in research field plots on September 16, 2009. Based on literature values for naturally occurring oyster populations (Mann et al., 2009), initial oyster density was approximately 500 oysters/m^2.

Oyster Growth and Survival

Reefballs and cured surf clamshells were placed in the Baykeeper larvae setting tanks, and oyster eyed larvae (purchased from Horn Point Laboratories, Cambridge, MD) were allowed to attach naturally. Prior to placement on the research site, a 15 × 18-cm area was marked on the face of one Reefball from each Reefball plot. The live oyster spat within this area were counted and their lengths from umbo hinge to edge of shell measured; any dead spat were removed. This same area on each Reefball was again measured during August 2010, and the numbers and lengths of both living and dead oysters were recorded.

Juvenile seed oysters approximately 30 mm long (purchased from Aeros Cultured Oyster, Southold, NY) were randomly selected and placed in 1.25-cm net mesh aquaculture cages, which were then attached to the Reefblk and arch rebar support structures. Larvae set naturally on surf clamshells resulted in approximately 20–25 spat per shell

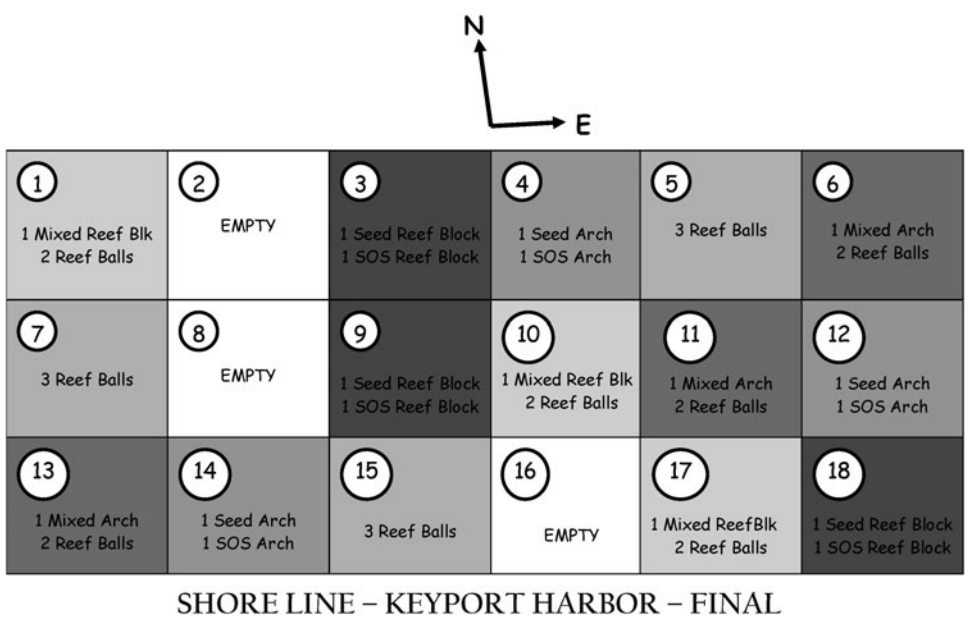

Figure 3. Schematic detail of the $\frac{1}{4}$-acre research reef field plots. SOS, spat-on-shell oysters.

(SOS). After the SOS reached a minimum length of at least 10 mm, the clamshells were placed in 2.5-cm mesh aquaculture cages at approximately the same density as the seed oysters, and these cages were attached to the Reefblk and arch rebar structures.

Subsets of 250 seed and 250 SOS oysters were randomly selected for their respective plots and placed in separate mesh aquaculture bags. The lengths of the randomly selected oysters were measured, and the subsets were then attached to the top of the rebar structures next to the larger oyster cages. The subset oysters were retrieved and remeasured during July 2010; survival and growth rates for the oyster seed and SOS associated with each structure were calculated. To compare survival rates in the subset samples versus the large cages, oysters were recovered from an arch and Reefblk cage, and the size and proportion of living and dead oysters were calculated and compared to the size and proportion of live and dead oysters in the subset cage.

To qualitatively assess the health of the year old adults, 10 research oysters were retrieved in June 2010 prior to spawning. The oysters were weighed, shucked, and individual shell and wet body weights were determined. The oysters were preserved in 10% formalin and subsequently transferred to ethanol solutions. The oysters were then placed in a casing and immersed in a 57°C (135°F) paraffin bath. After removal from the bath, the paraffin solidified, and the sample was sliced into 5-μm-thin cross sections (Reichert Histostat Rotary Microtome), placed on a microscope slide, and baked at 60°C (140°F) for 30 minutes to remove residual paraffin. The slide was then exposed to lithium carbonate, which stained the oyster tissues dark blue, allowing us to determine whether abnormalities were present in various soft tissues, including the mantle, gill, digestive, and reproductive systems.

Biodiversity

To test whether the presence of the oysters and/or the structures had an effect on the Keyport Harbor marine community, unbaited fish traps (small mesh shrimp and minnow trap and larger mesh semi-oval fish trap; Memphis Net & Twine, Memphis, TB) were placed in pairs: (a) adjacent to the three types of support structures, (b) in empty research plots, and (c) 50 meters outside the eastern and western edges of the research footprint (Figure 3). After 24 hours, the traps were retrieved and the captured animals identified at the genus and/or species level by F. Steimle and M. Comi. A Shannon Diversity Index score for each structure was calculated after four sampling events between July 21 and 29, 2010. Two additional sampling events to characterize the marine community composition adjacent to structures with no oysters present were conducted after removal of the research oysters (September 8–9, 2010).

Sedimentation

To determine whether the presence of oysters and their support structures influenced sediment deposition patterns, bottom elevations were obtained by using laser surveying equipment (CST/Berger Dual Beam Rotary Laser, Watseka, IL) and standard surveying methods (Lindeburg, 1992). Sediment elevations at the four corners of the individual plots were recorded during low tide (fall 2008). The surveys were tied into North American Datum 1983 (NAD83) survey datum by using the US Geological Survey benchmark located at the end of Walnut Street in Keyport, NJ. The elevation of the benchmark was carried approximately 3,000 feet along the shoreline, and the level was installed inshore of the reef. By using the same procedure, the reef was again surveyed (summer 2009) prior to installation of the research plots. These two data sets provided a baseline for changes in Keyport Harbor sediment elevation after winter storm events prior to the oyster research installation. The measurements were repeated in June 2010 after the oysters were in place for 10 months to determine: (a) if sediment elevation patterns changed with oysters present, and (b) if the presence of the oysters increased scouring. Sediment topography outside the research plot on the western and eastern sides served as No Oyster controls. Maps were generated by entering the survey data into ArcMap (Esri, Redlands, CA); a raster image of the surface was created within ArcMap by using its Natural Neighbor toolbox function.

Statistical Analysis

Oyster survival and size associated with each structure were analyzed by using two-factor analyses of variance (ANOVAs) (*structure* factor: Reefball vs. Reefblk vs. arch, and *type* factor: seed vs. SOS vs. set; $N = 7{,}330$ observations). All summary statistics and ANOVAS were conducted using SAS general linear models (GLM; SAS Software, version 9.2; SAS, Cary, NC). Relative growth rates were calculated by using the following formula (Hunt, 1990): $G = (\log_e N_2 - \log_e N_1)/t$, where G = the mean rate of increase over the time interval; N = the average length of oysters in millimeters; t = time (320 days). Captured species diversity ($N = 20$ sampling events) was compared by means of the Shannon index of diversity by using the following formula (Magurran, 1988): $H = -Ep_i\ln(p_i)$ where H = the sample diversity; p_i = the proportion of the number of a single species to the total number of individuals in the sample; and $\ln = \log_e$. One-way ANOVA was conducted to test community diversity differences between samples. Post hoc means were tested using Tukey's honestly significant difference (HSD) method.

Research Results and Conclusions

To the best of our knowledge, this is the first peer-reviewed report of a potentially viable oyster reestablishment occurring in the HRE.

Oyster growth and survival. The support structure and the type of juvenile oyster produced significant differences in oyster survival and size patterns (Table 5). Qualitative histological observations of mantle, gill, and digestive tissues detected no abnormalities. Female oyster egg development also appeared normal, and based on the egg size and individualization, female oysters appeared ready to spawn. The observed female to male sex ratio was 50:50.

Biodiversity. Because of the small number of sampling events, no significant statistical differences in the Shannon index of diversity were observed among the various structures. However, the decrease in Shannon diversity scores when oysters were not present was particularly noticeable for the arch and Reefblk structures; the number of individuals captured when the oysters were present was two- to threefold greater than the numbers after removal of the oysters (Table 6). Conversely, the empty plot diversity scores actually increased after oyster removal.

Sedimentation. Although more seasonal data need to be collected to determine whether these initial results are repeatable, the presence of the oysters and their housing structures did not appear to increase sediment scouring. A comparison of changes in the research plot topography suggests that during the winter storm season the presence of the oysters and their cages might contribute to increased sediment stability (Figure 4).

Initial success of the largest oyster reintroduction attempted to date within the HRE is evidenced by the decision of the NJDEP to rescind the project permit after an estimated 3% of the living oysters (202 of 7,330 measured year-old adults) began to reach NJ's market size of 2.5 inches. In addition to the 60% survival evidenced by recovered SOS in Reefblk supports, healthy gametes signifying the ability to spawn were also a positive indicator for the potential of longer-term reintroduction success. Depending on oyster larval transport patterns in Raritan Bay, the ability to spawn could result in attachment of juvenile

Table 5. Mean dimension (± standard error) attained by eastern oysters after 11 months in Keyport Harbor, New Jersey

	No. of Individuals		Length (mm)		Height (mm)	
Structure	**Live**	**Dead**	**Live**	**Dead**	**Live**	**Dead**
Arch	256	1,282	45.1 ± 0.69^{a}	39.5 ± 0.31^{A}	14.7 ± 0.25^{c}	12.4 ± 0.10^{C}
Reef Block	472	358	37.2 ± 0.49^{b}	31.6 ± 0.52^{B}	12.6 ± 0.25^{d}	12.6 ± 0.03^{C}
Reef Ball	18	99	$40.8 \pm 1.84^{a,b}$	28.4 ± 0.88^{B}	NA	NA
Type juvenile						
Seed	330	925	46.9 ± 0.55^{e}	43.77 ± 0.31^{D}	13.7 ± 0.19	12.4 ± 0.10
Spat-on-shell	398	715	34.2 ± 0.46^{f}	30.0 ± 0.31^{E}	NA	NA
Set on Reef Ball	18	99	40.8 ± 1.84^{g}	28.4 ± 0.88^{E}	NA	NA
Live two-factorial ANOVA			$F_4 = 88.20$ $p < 0.0001$			
LENGTH			HEIGHT			
Structure	$F_2 = 16.27$ $p < 0.0001$		Structure	$F_2 = 16.27$ $p < 0.0001$		
Type	$F = 217.08$ $p < 0.0001$		Type	$F = 217.08$ $p > 0.0001$		
Dead two-factorial ANOVA			$F_4 = 266.04$ $p < 0.0001$			
Structure	$F_2 = 7.70$ $p = 0.0056$					
Type	$F = 436.83$ $p < 0.0001$					

Oysters were housed in/on Reefblk, Reef Ball, or arch structural supports. Letters indicate statistically significant differences in length or height. ANOVA, analysis of variance; NA, not applicable.

Table 6. Species and number of individuals observed in Keyport Harbor, New Jersey, during four sampling events (July 21–29, 2010) with oysters present, and two sampling events after oysters were removed (September 8–9, 2010)

Species (common name)	Latin name	Reefblk with	Arch with	Reef Ball with	Empty with	Reefblk without	Arch without	Empty without
American eel	*Anguilla rostrata*	1	2	1	—	—	1	—
Blue claw crab	*Callinectes sapidus*	17	7	8	7	4	2	4
Conger eel	*Conger oceanus*	—	1	—	1	—	—	—
Ctenophore	*Phylum ctenophora*	50	55	34	20	10	10	15
Grass shrimp	*Palaemonetes*	156	208	232	66	18	38	41
Hermit crab	*Pagurus longicarpus*	12	13	22	20	23	15	19
Mud crab	*Neopanopeus*	11	9	13	2	15	—	4
Mud snail	*Ilyanassa obsoleta*	159	205	113	48	—	27	103
Oyster drill	*Urosalpinx cinerea*	1	1	1	—	—	—	—
Pipefish	*Syngnathus fuscus*	1	2	2	—	—	1	—
Spider crab	*Libinia emarginata*	3	—	—	1	3	12	7
Spotfin butterfly fish	*Chaetodon ocellatus*	—	—	—	—	1	—	—
Tautog	*Tautoga onitis*	—	—	—	—	1	—	—
Toad fish	*Opsanus tau*	—	1	1	1	—	—	—
Total	All Species	411	504	427	166	75	106	193
Shannon Diversity score		2.92	2.52	2.82	1.99	2.41	1.85	2.33

oysters to adult shells, initiating the reef creation process, although further research is required to test this possibility.

The research data raise questions regarding choice of support structure, as well as the type of juvenile that could yield the best long-term oyster survival in Keyport Harbor. Based on the limited results of this study, the most successful restoration approach to reestablish the Eastern Oyster in Keyport Harbor could be SOS housed in Reefblk structures. However, with only one year of data, it is premature to draw this conclusion, and additional time is needed to characterize longer-term survival and spawning patterns and to observe whether any oyster larvae would ultimately set on the adult oyster shells in this location.

The increased biodiversity (Table 6) associated with the presence of adult research oysters is very encouraging and warrants further study. We hypothesize that the catch data suggest that the presence of oysters contributed to enhanced habitat structural complexity, which positively affected prey density and abundances relative to higher tropic levels in the marine food web. The crustaceans observed are important fish prey and, during all fish trap sampling events with oysters present, finfish were captured.

While our research indicates that oysters could indeed survive at the Keyport Harbor location within Raritan Bay, this prospect raises critical *policy* questions related to the proposed CRP goals of restoring oysters in contaminated waters currently closed to shellfish harvesting.

Oyster Restoration Policy Discussion

Status of the Northeastern and Mid-Atlantic Eastern Oyster Fishery

Oysters were a primary fishery in estuaries of the eastern US from Native American times until present. Collapse of the fishery along the continental margin followed a north to south trajectory through the late 19th and early 20th centuries (Kirby, 2004; Lind, 2009; Mackenzie, 2007); the degradation pattern of historic oyster reef loss was first observed in the oldest urban harbors, including Boston and New York City. Overharvesting and pollution led to the near eradication of the Eastern Oyster, and populations in the northeast/mid-Atlantic region today are estimated to range from ecologically extinct to 10% of historic levels (Beck et al., 2009). Therefore, large-scale human intervention is needed if oyster populations are to be reestablished.

Since colonial times, northeastern shellfisheries had been managed at the local level; today, responsibility for shellfish regulation and policy resides primarily at the state level. A program to protect human health is jointly administered by coastal states and NSSP, and the US Department of

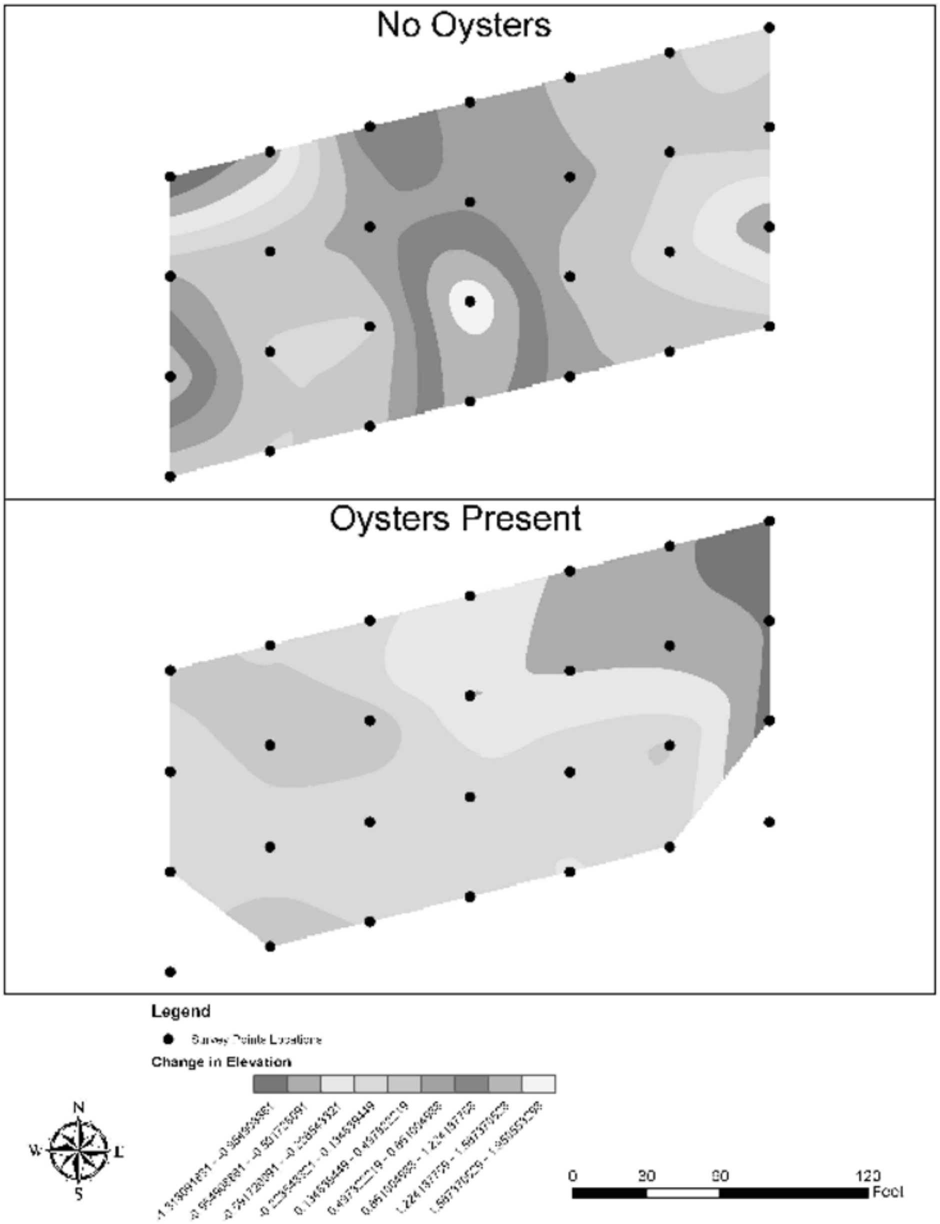

Figure 4. Map of sediment topographic elevation changes after the winter storm season (**A**) without oyster research structures (2008–9) and (**B**) with oysters and research structures in place (2009–10).

Agriculture is involved in aquaculture initiatives. The NSSP is a cooperative, voluntary alliance among states, the FDA, and the shellfish industry (NOAA, 1998). Each state is empowered to develop its own shellfish management plan (USFDA, 2009b) under NSSP guidelines; all states involved in interstate shellfish transportation must adhere to the guidelines administered by the Interstate Shellfish Sanitation Conference.

Unlike neighboring New England or Chesapeake Bay states, NJ and NY have not readily embraced restoration of their historic oyster fisheries. This can be observed in waters shared among multiple states. For example, Connecticut has an active restoration program in Long Island Sound that involves local communities, NGOs, and the aquaculture industry. The Long Island Sound Study (LISS, 2002) identifies more than double the number of restorations in progress or completed in Connecticut versus New York (NY) waters.

Another example is seen in Delaware Bay, where shellfish restoration involves NJ and Delaware. In 1996, the NJ Legislature established the Oyster Industry Revitalization Task Force to develop recommendations to revitalize the industry and bring economic benefits to Delaware Bay. However, the Delaware Bay oyster resource continued to deteriorate between 2001 and 2005 because of consistent failure of juvenile oyster recruitment. In 2005, a five-year oyster restoration project commenced in NJ and Delaware waters. Shell placement areas were approximately 25 acres; 169,437 bushels of shell were placed in NJ and 118,819 bushels of shell in Delaware. The 2005 shell planting raised baywide juvenile oyster recruitment by an estimated 54% in the planted areas (USACE, Philadelphia District, 2006). The project received a 2008 White House award for creating new habitat on 241 acres of natural oyster beds in Delaware Bay (Delaware Department of Natural Resources and Environmental Control, 2009). However, two years later (2010), the Delaware Bay program was out of money, and project partners were publically trying to raise funds to continue restoration efforts. In 2010 NJ planted 93,500 bushels of shell, and in 2011 the Partnership for the Delaware Estuary and the Delaware Bay Oyster Restoration Taskforce raised $200,000 to plant 159,000 bushels of shell.

Although the CRP (USACE, New York District, 2009) identifies oyster restoration as a primary goal, only NY is willing to allow limited oyster research activities in the HRE. NJ policy bans oyster research activities from all northern NJ waters that comprise the HRE. Reasons given publically by NJDEP (Martin, 2010) for the research ban are to protect human health (a research oyster could be illegally harvested and illegally make its way into the human food chain) and to bring NJ into compliance with FDA shellfish industry requirements (meet conditions of the oyster fishery management plan prepared by NJ and submitted to the FDA).

Shellfish Management: Chesapeake Bay Approach (Virginia, Maryland)

Maryland and Virginia have set aside large sanctuaries and reserves, and are increasing acreage devoted to the aquaculture of Eastern Oysters. This effort is being lead by NOAA and USACE at the federal level through agency coordination of a baywide strategy that includes Maryland, Virginia, and the Potomac River Fisheries Commission (Tables 3 and 4). Significant federal support for Chesapeake restoration culminated in President Barack Obama's Executive Order 13508 (NOAA, 2009), which established a Federal Leadership Committee for Chesapeake Bay. Federal action was taken after acknowledgment that regulatory approaches of the last several decades have not been sufficient to restore and protect Chesapeake Bay's oyster resources (Blue Ribbon Oyster Panel, 2007).

Maryland's new Oyster Restoration and Aquaculture Development Plan went into effect in 2010 to change unsuccessful management practices of the last 25 years—practices that reduced the oyster population to 1% of historic levels and contributed to an 80% decline in oyster habitat and a 90% decline in oyster harvests (Maryland Department of Natural Resources, 2010). The Maryland restoration plan was developed after more than 150 public meetings with multiple stakeholder groups. The plan focuses on escalating the number and size of no-harvest sanctuaries while encouraging oyster aquaculture activities by opening approximately 600,000 new acres for aquaculture leases. Maryland will use the restoration sites purely for their ecological role (Campbell, 2010), leaving the 19 new sanctuaries unharvested for a five-year period (Maryland Department of Natural Resources, 2010) and expanding the network of oyster sanctuaries from 9% to 25% of Chesapeake Bay's remaining oyster bars.

Virginia's Blue Ribbon Oyster Panel (2007), composed of representatives from public agencies, the seafood industry, environmental NGOs, and research universities, focused on the ecological functions provided by oysters and the needs of industry. Panel recommendations include development of a long-term management plan for each of Virginia's major river systems and bays, based on input from public agencies, university researchers, and local stakeholders. The panel also acknowledged that poor water quality has the potential to undermine all oyster restoration efforts, and noted that a long-term commitment must be made to sewage treatment plant upgrades, storm-water management, and runoff improvements if the long-term health of the oyster populations is to be sustained.

New England Approach (Massachusetts, Connecticut, Rhode Island)

Dating from the earliest European colonists, New England has had a tradition of strong local control of the shellfish industry (Lind, 2009), and this legacy has led to a shellfish management approach that differs from the Chesapeake Bay approach. Massachusetts Environmental Police are responsible for protecting the state's bays and shorelines, while local Shellfish Constables watch for violations and participate in enforcement actions. Municipal shellfish management plans are drafted by the coastal towns, whose constables work together with the State Division of Marine Fisheries personnel to monitor surface waters. Regulations are enforced by the constables (Lind, 2009), who are trained for their jobs through a standardized two-week program at the Massachusetts Maritime Academy.

Like Massachusetts, each Connecticut municipality sets its own shellfisheries regulations (Getchis, 2009). Since 1845, coastal Connecticut towns have conveyed the right to cultivate and harvest shellfish by designating shellfish grounds within town waters and then transferring private property rights to the submerged land (Opton-Himmel and Whelchel, 2010). Connecticut has jurisdiction over shellfisheries south of the State Jurisdiction Line, whereas all other fisheries are under the jurisdiction and control of the towns where they are located (Opton-Himmel and Whelchel, 2010), and municipal Shellfish Commissions participate in management of local shellfishery resources and commercial shellfishing (Getchis and Pomeroy, 2009). In the Connecticut portion of Long Island Sound, 14% (55,600 acres) of the submerged land is under municipal control, and privately held shellfish grounds are subject to municipal real-estate taxes (Opton-Himmel and Whelchel, 2010). Municipal evidence related to water-body health safety is carefully considered by the state, which under the NSSP has the ultimate authority for shellfish water classifications (Connecticut Department of Agriculture, 2010; Opton-Himmel and Whelchel, 2010).

When Rhode Island's oyster fishery experienced a sharp decline, the state began an individual oyster gardening program (2006) to provide oysters for restoration sites. Initially, gardeners were restricted to shellfish waters open for harvest, but, based on success of the program, gardening sites were expanded (2007) to included conditionally closed waters (Allard Cox, 2008). Rhode Island is working in cooperation with the federal government and local NGOs to conduct oyster restoration in salt ponds and in Narragansett Bay (Rhode Island Department of Environmental Management, 2011), and the Rhode Island Department of Environmental Management is overseeing placement of oysters into shellfish spawner sanctuaries.

Aquaculture Revitalizes the Oyster Industry

Although Virginia's public oyster harvest from state resources is diminishing, an oyster aquaculture sector is emerging rapidly. Between 2005 and 2008, aquaculture plantings increased fourfold, approaching 30 million oysters. Virginia oyster hatcheries produced 26.7 million seed oysters in 2007 and are expanding larvae SOS cultivation, estimated at 1.66 billion eyed larvae in 2009 (Murray and Oesterling, 2009). The Blue Ribbon Oyster Panel (2007) recommended that Virginia establish *aquaculture zones* for open, but controlled, access to accommodate expansion of aquaculture.

As in Chesapeake Bay, oyster aquaculture is now a growing factor in New England oyster production. In 2007, Massachusetts was the seventh largest producer of cultured shellfish in the US, cultivating almost 1,000 acres whose sales topped $5.2 million. Over 25 farmers produced 30,000 bushels of oysters, an increase of 165% between 1998 and 2005. Massachusetts has established and funded three aquaculture centers (Buttner et al., 2007), which with state partners have formed the Massachusetts Shellfish Aquaculture Innovation Consortium. Aquaculture research is being conducted at Woods Hole Oceanographic Institution and the University of Massachusetts at Dartmouth, and undergraduate training in aquaculture is now offered through Salem State College.

Connecticut's oyster industry declined to near zero production in the late 1960s, but has subsequently recovered to become one of the leading suppliers of oysters in the US (USACE, Philadelphia District, 2006). Shellfish production represents the largest segment of Connecticut's aquatic farm industry, and the state's largest farms are now underwater, covering more than 77,000 acres of leased and franchised shellfish grounds (Getchis and Pomeroy, 2009). Rhode Island farm raises Eastern Oysters, which in 2006 represented 97% of the $1,348,525 farm gate value produced by 28 companies (Rice, Leavitt, and Alves, 2009) In 2008, the US Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) awarded Rhode Island $792,000 to support oyster farmers. This effort yielded approximately 2.5 million oysters that were planted on restoration sites, and in 2009 additional funding allowed farmers to produce approximately 9 million oysters for restoration. Aquaculture farms in Rhode Island numbered 33 in 2009, a 10% increase from the previous year. The area under cultivation increased to 135 acres, and oysters are the number one aquaculture product produced (2,821,166 oysters sold for consumption), valued at $2.7 million for consumption and restoration (Coastal Resources Management Council, 2009). In September 2010, Rhode Island expanded what is believed to be the first large-scale oyster restoration program that principally involves aquaculture farmers, who will apply their aquaculture expertise to public resource restoration projects. Oysters will be stocked in over 25 acres of spawner sanctuaries where harvesting will be prohibited for 3–5 years (Rhode Island Department of Environmental Management, 2011).

New Jersey and New York Oyster Restoration Management Approaches

"*From 1990–1995 the oyster industry provided little in jobs or revenue in NJ*" (USACE, Philadelphia District, 2006, my emphasis), and oysters are still a very small component of the NJ shellfish industry; in 2008, the state's oyster landings were valued at $2.5 million (less than those for Rhode Island). One of the last viable oyster beds in NJ is situated in the Mullica-Great Bay estuary. To maintain these vestiges of the oyster industry, NJ placed 2,000 bushels of juvenile oysters on the beds in 2001 and an additional 2,000 bushels of oysters in 2006 (J. Normant, NJDEP, quoted in Miller, 2010). New Jersey today appears to have three separate oyster-related policies operating concurrently in southern waters (Delaware Bay, Barnegat Bay) versus the HRE.

Delaware Bay

Project PORTS (Promoting Oyster Restoration Through Schools) is a community-based NJ restoration program in Delaware Bay. This project is unique because it owns waterfront land for restoration activities. Bags of shell are placed in the Bay to recruit wild oysters, which are then transferred to a 10-acre conservation reef site. The program was originally started as a USDA extension program to support the oyster industry in southern NJ (Shadel et al., 2010). The NJDEP has been in the process of establishing Aquaculture Development Zones for over seven years, mainly in Delaware Bay; however, as of 2009, no definitive areas were yet being accessed (Flimlin and Myers, 2009).

Barnegat Bay

The shellfish water quality in Barnegat Bay has seen a marked improvement since passage of the Clean Water Act; 45 sewage discharge inputs have been eliminated, and the waters are now clean enough for shellfish to be harvested from Barnegat Bay. According to the NJDEP, this success has come by focusing financial resources on the most significant pollution problems (Connell, 2010). Barnegat Bay has 237 water quality–monitoring locations (Connell, 2010) versus 51 water quality–monitoring locations in the combined Raritan/Sandy Hook Bays (Zimmer, 2004). However, 293 acres of Barnegat waters open to shellfishing were downgraded in 2009 to Prohibited from Special Restricted (NJDEP, 2009). In spite of the intense focus by NJ and an investment by the USEPA of $1 million annually for the last 15 years, the overall water quality in Barnegat Bay continues to deteriorate (Kennish et al., 2007). The Barnegat Bay Shellfish Restoration Program is an agriculture extension program with support from NJ and nonprofit partners (Shadel et al., 2010). Since there is no naturally occurring oyster population in Barnegat Bay, oysters are raised in enclosed upwellers and then placed on an 18-acre reef site in the bay.

Hudson-Raritan Estuary

While state and federal agencies have invested in southern NJ waters by limited placement of juvenile oysters and shell to attract natural oyster larvae, the northern waters, including Raritan Bay, remain closed to oyster research and restoration, and receive no state money or resources for oyster restoration activities. Waters north of Raritan Bay do not even appear on NJ shellfish water classification maps and are not included in any quantitative or qualitative analyses of NJ shellfish water quality. Although NY is allowing limited scientific research in Raritan Bay opposite the NJ coastline, NJ's ban has precluded NJ from being part of the research or from receiving any of the federal funds (Table 4) supporting this research initiative.

In 2010, NY approved six small oyster research projects (total acreage, $\frac{1}{8}$ acre) designed to determine the feasibility of long-term oyster restoration in NY's HRE waters. Although permitting very limited scientific studies in closed waters (Hudson River Foundation, 2010), NY has not yet committed to restoring historic oyster populations in the HRE. The research, overseen by the Hudson River Foundation, is occurring in partnership with NGOs, as well as federal, state, and municipal agencies (Table 3). New York is also considering leasing underwater land owned by Suffolk County in Long Island Sound, and a leasing program was scheduled to be in place by the end of 2010 when the revamped lease law sunsetted. A major constraint expressed by NY with respect to expansion of their aquaculture industry is the need for research that quantifies ecological effects of benthic harvesting (Rivera and Timmons, 2009).

Recommendations for New Jersey Hudson-Raritan Estuary Shellfish Management Policy

New Jersey's oyster research ban is extremely shortsighted and serves to distract from developing solutions that could support HRE oyster restoration. By failing to fund the shellfish inspection and monitoring program, the state has jeopardized its entire shellfish industry. The most recent USFDA (2009a) Annual Program Evaluation Report found

NJ was out of compliance with patrol requirements in 70% of the classified waters statewide (does not include waters north of Raritan Bay that are unclassified) and that the state did not comply with inspection frequencies for shellfish dealers. This lack of compliance led to a warning from the FDA and the possibility of a determination that shellfish from NJ should no longer be accepted in interstate commerce. Rather than ban research because monitoring patrols are inadequate, techniques from other states should be considered to better serve the interests of regulators, restoration practitioners, the public, and the coastal environment.

Waters Secure from Illegal Activities

Maryland has set aside millions of dollars for high-tech law-enforcement surveillance devices to protect their sanctuaries and oyster beds from illegal activities. Maryland's Natural Resources Police may be the first to use a chiefly national security monitoring system (the Maryland Law Enforcement Information Network) for natural resource protection. The extensive system of radar and cameras will monitor poaching in Chesapeake Bay, and video taping of illegal activities could potentially increase conviction rates for individuals engaged in prohibited activities (Recalde, 2010). Virginia's Blue Ribbon Oyster Panel (2007) recommends increasing penalties for illegal activities, and these recommendations include revocation of fishing licenses for harvesting of oysters from closed areas or sanctuaries, tampering with experimental equipment, or violating consumer health protection regulations.

As the Maryland approach illustrates, security camera installations and high-tech surveillance equipment can be incorporated not only to deter poaching, but as an aide in convicting those who would participate in this illegal activity. The HRE is home to military installations and secure Homeland Security sites, whose locations are patrolled by the military 24–7. These locations should be evaluated for their potential as oyster restoration and research sites. In fact, the Naval Weapons Station Earle sent a letter of support to the NJDEP offering their Homeland Security–patrolled waters for Baykeeper's oyster research activities (Capt. D. Harrison, personal communication), and the naval waters are now being tested for their ability to support Eastern oyster overwinter survival.

The Chesapeake approach of increasing penalties so there is significant financial and commercial loss for anyone caught illegally harvesting should also be employed by NJ as a deterrent to illegal activities. The placement of oysters in closed water no-harvest *sanctuaries*—where commercial harvesting is not allowed—makes enforcement even easier. Anyone seen harvesting would be committing an illegal act.

The New England practice of training and empowering local constables to enforce regulations should be tested in the HRE. A training program for local shellfish officers that is based on existing New England models should be modified for testing in closed HRE waters and delivered to enforcement teams through collaboration with NJ universities. Information describing illegal activities (individuals involved, location, description of activities) should be made publicly available to encourage municipal oversight and reporting.

Expansion of the Oyster Industry and Consumer Protection

As the East Coast oyster aquaculture industry is growing, NJ is falling behind producers in competing states because NJ lacks a strategic comprehensive long-term oyster restoration–aquaculture plan. Sanctuary areas need to be developed in collaboration with the shellfish industry, local communities, federal agencies, and the NGO restoration community. The sites can be policed by a consortium of public, private, and NGO participants. Since *no* harvesting would be allowed in the sanctuaries, the patrols would not need to have the same level of training as State Conservation Officers, and the sites could potentially be overseen at the local municipal level as is done in New England.

The low volume of approved oysters harvested in NJ needs to be marketed as safe, healthy, locally produced, nutritious food. Consumable oysters from the state's southern waters can be identified at the time of harvest. (Permanent tags are commercially available for this purpose.) This program could be modeled on the Jersey Fresh agriculture marketing campaign. By identifying oysters that are caught in approved waters, oysters taken illegally from unapproved waters would be more difficult to introduce illegally into the food chain, and the safely harvested or aquacultured oysters could be marketed to command a premium price.

Water Quality Improvements

HRE waters are closed to oyster restoration and research because they still do not meet the "fishable and swimmable" standards set by the Clean Water Act. The specific reason for classifying shellfish waters as Prohibited is the presence of high levels of *Escherichia coli*, a bio-indicator for the presence of untreated sewage. While southern NJ water quality has improved since passage of the Clean Water Act, the northern waters remain impaired. The states of NJ and NY are the regulatory agencies responsible for issuing permits and penalties to dischargers responsible for the continued sewage pollution. It is therefore in NJ's power to address water quality impairments as agencies in the Chesapeake watershed are doing and as NJ itself has done in Barnegat Bay.

Public, Private and NGO cooperation

The extensive restoration and aquaculture activities that are taking place in neighboring states are based on multiple partnerships, outreach to stakeholder groups, high levels of community input and cooperation, and education and research supported by state universities (Tables 3 and 4). The HRE restoration plan was endorsed by the NY/NJ Harbor & Estuary Program, of which NJ and NY are members, as are the federal agencies and the NGO community involved in oyster restoration activities in HRE waters. NJ needs to engage in a cooperative effort with these partners to support the CRP oyster restoration goal in the state's northern waters.

The NJDEP Commissioner has set up a Science Advisory Board. This group should advise the commissioner with respect to implementation of best shellfish restoration/aquaculture management practices in neighboring and competing states. The board should also be charged with devising strategies that clean up impaired water bodies and with developing a long-term shellfish restoration plan that supports the HRE CRP goals.

Conclusions

The Clean Water Act set a goal of fishable and swimmable US waters by 1983. Obviously, we have not reached this target in the HRE, due in large measure to the failure to eliminate pollution inputs, including sources of sewage that cause waters to be closed to shellfish harvesting. Bioimprovements to ecosystem habitat and water quality, just where they are needed most, are now prohibited, without a clear strategy for NJ to address these critical issues and meet Clean Water Act requirements in the HRE. Keyport Harbor data indicate that Eastern Oysters can survive under present conditions in specific sections of Raritan Bay. The NJ policy banning oyster research and restoration in contaminated waters highlights that the approaches needed to achieve restoration goals in impaired waters are significantly different from policies required to manage commercial shellfisheries. Although such approaches are not mutually exclusive, policies and rules for areas where restoration activities could be beneficial need to be crafted to support the success of restoration professionals and facilitate the reestablishment of ecologically impaired species in non-harvestable waters.

Practices in neighboring states show that restoration and support for commercial interests are not mutually exclusive. Examples of meeting NSSP consumer safety requirements while continuing to expand oyster restoration and aquaculture activities can be seen in states adjacent to NJ and NY. Solutions to the obstacles perceived in restoring HRE oysters can be found by considering alternative approaches now in use in these states. These strategies can be applied to support the work of restoration practitioners and in growing an aquaculture industry if NJ and NY are willing to consider creative best management practices and to establish meaningful and inclusive collaborations. This must happen because the future of the HRE and the states' remnant oyster industries depend on it. Adopting a policy of no research or restoration activity, or many more years of continued small studies, is unproductive and places NJ and NY at a great disadvantage as regional competitors expand their Eastern Oyster resources.

Authors' note. At the time of this writing, NY/NJ Baykeeper is trying to secure permission from the NJDEP to place Eastern Oyster research cages in the Homeland Security patrolled waters of the Naval Weapons Station Earle pier complex, located on Raritan Bay in Middletown, NJ. The NJDEP did approve a US Navy plan to verify that the naval patrols would be sufficient to deter poaching and protect human health during a 2011–12 oyster overwinter survival test. However, at the time of this writing, the NJDEP has not given permission to expand the scope of this oyster restoration research.

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