RESTORING OYSTERS TO URBAN WATERS

Lessons Learned and Future Opportunities in NY/NJ Harbor

The Nature Conservancy

BILLION OYSTER PROJECT

ABOUT THE NATURE CONSERVANCY

The mission of The Nature Conservancy (TNC) is to conserve the lands and waters on which all life depends. TNC's New York City Program protects and promotes nature and environmental solutions to restore natural systems and enhance the quality of life of all New Yorkers. We are committed to improving the City's air, land, and water, and we advance strategies that create a healthy, resilient, and sustainable urban environment.

ABOUT BILLION OYSTER PROJECT

Billion Oyster Project is a nonprofit organization on a mission to restore oyster reefs to New York Harbor through public education initiatives. Founded on the belief that restoration without education is temporary, and observing that learning outcomes improve when students have the opportunity to work on real restoration projects, collaborating with public schools is fundamental to Billion Oyster Project's work. Billion Oyster Project engages The Urban Assembly New York Harbor School and thousands of students across the five boroughs in restoration projects using discarded oyster shells from New York City restaurants. To date, Billion Oyster Project and partners have restored 28 million oysters to New York Harbor.

ABOUT THE PARTNERSHIP

Billion Oyster Project and The Nature Conservancy have partnered to restore the health of New York Harbor. Billion Oyster Project is working to restore oyster reefs through public education initiatives, partnering with The Nature Conservancy, as a scientific adviser, to measure oyster health, water quality, and biodiversity.

ACKNOWLEDGMENTS

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HOW TO CITE THIS DOCUMENT

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Dear Reader,

The richness and complexity of New York Harbor never fail to amaze us. When we think of the myriad creatures that live there, the millions of people who reside in its vicinity, the multiplicity of uses it supports, and the vast potential it offers, it's clear to us: New York Harbor is a crucial, life-supporting, socio-ecological system that we must understand and manage better to serve both people and nature.

When The Nature Conservancy launched Healthy Harbor NYC in 2015, to enter the complex system that is New York Harbor, it partnered with Billion Oyster Project, a local nonprofit whose staff has been restoring oysters to NY Harbor since 2010 with the support and involvement of students and regional partners. The Nature Conservancy had previously released guidance on oyster restoration, but the urban environment poses unique challenges, including impaired water quality, hardened edges, limited public access, sea-level rise, population density at the water's edge, and members of the public with diverse views on our waterfronts and water. In order to contribute to oyster restoration science, this document shares our learning so that other urban oyster scientists and restoration practitioners locally, nationally, and internationally might benefit from and build on the efforts that are described in this report.

Our findings indicate that not only is this a complex and challenging system in which to do restoration, but it is also a system with huge potential. Effective restoration efforts will improve water quality and biodiversity, and due to the proximity to people, they offer an important opportunity to connect people to their local waters and the wonders of nature. In fact, to achieve a truly healthy harbor, it is vital to involve people. To fully restore our Harbor and urban harbors around the world, multi-stakeholder planning, diverse leadership, and collective effort will be crucial.

This work is a significant step in codifying the important practice of urban oyster and harbor restoration that has been developed by Billion Oyster Project, The Nature Conservancy, and numerous regional partners. We are proud to present Restoring Oysters to Urban Waters: Lessons Learned and Future Opportunities in NY/NJ Harbor.

Sincerely,

Emily Nobel Maxwell
New York City Program
The Nature Conservancy

Pete Malinowski
Executive Director
Billion Oyster Project

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EXECUTIVE SUMMARY

Before New York City was *The Big Apple*, it was *The Big Oyster*. This report tells the story of the oyster, *Crassostrea virginica*, in one of the most heavily urbanized estuaries in the world: New York/New Jersey Harbor. These waters have been the subject of over 20 years of research and restoration, and a significant scaling-up of efforts is planned for the near future. Now is the time to assess past efforts and synthesize the lessons learned and challenges ahead.

This report:

- Summarizes the history of oysters in NY/NJ Harbor.
- Argues that restoring oysters can have large ecological benefits.
- Reviews past and present efforts to bring oysters back to these waters and involve communities in the process.

This report identifies several **lessons learned** over the past 20 years of restoration activities:

- Restoring oysters to NY/NJ Harbor is especially difficult because of a combination of factors, including insufficient breeding oysters, suboptimal environmental conditions, and challenging economic realities.
- Despite these challenges, oyster restoration is moving forward here, and restored oysters grow and survive.
- Oyster growth and survival alone cannot ensure that the population will be self-sustaining.
- Even small amounts of successful restoration can lead to big ecological impacts.
- The social benefits of engaging community members, educating them about the Harbor, and providing opportunities to interact with the water may be one of the greatest successes of local oyster restoration.

This report also identifies key **challenges and recommendations** for moving oyster restoration forward in these waters:

- Restoration efforts must focus on under-

standing and achieving successful reproduction and recruitment.

- Restoration activities must scale up, and innovative financing is needed.
- Investment in education and engagement should be continued. The outcomes should be quantified, and the activities should be designed strategically to meet those goals.
- Restoration practitioners and permitting agencies must work together to develop mutually agreeable conditions allowing restoration activities to proceed and to minimize potential public health risks.
- Practitioners should continue to monitor, learn, adaptively manage, and refine best practices.
- The restoration community should develop a shared plan that specifies the locations, timing, and methodologies, and that is based on stakeholder engagement and the desired level of services provided by a given investment in restoration.

This report celebrates the hard work and dedication of nonprofits, community members, researchers, and government agencies to bring this powerful bivalve back to NY/NJ Harbor. We are excited to share this report with advocates, policymakers, funders, fundraisers, educators, researchers, innovators, problem solvers, and students in the NY/NJ region and in other urbanized estuaries worldwide.

I. SETTING THE STAGE

New York/New Jersey Harbor[1] is the cleanest that it has been in nearly a century, but it still faces tremendous environmental challenges. The story of the Harbor has many characters and plot twists, and oysters play a central role in its history, decline, and recent revival. They are also key to a bright future for the Harbor.

WHY THIS REPORT? WHY NOW?

This report tells the tale of oysters in NY/NJ Harbor and comes at an essential time. Community-based efforts to return oysters to these waters began over two decades ago, and interest in these efforts is at an all-time high. In addition to grassroots efforts, federal and state governments and nonprofit organizations have set ambitious goals for oyster restoration. As the practice of oyster restoration matures, projects in the estuary are rapidly increasing in size to meet these goals. Now is the time to assess past efforts and synthesize the lessons learned and challenges ahead.

The goals of this document are to:

- Provide an overview of the role and history of oysters in NY/NJ Harbor. (Setting the Stage)
- Make the case that restoring oysters—even small amounts—can have large ecological benefits. ("II. Why Restore Oysters" on page 13)
- Summarize past and present restoration efforts to bring oysters back to these waters. ("III. Restoration Efforts: Past and Present" on page 20)
- Review efforts to involve communities in the work of oyster restoration. ("IV. The Human Dimensions of Oyster Restoration" on page 27)
- Identify the lessons learned over the past 20 years of restoration activities in these waters. ("V. Lessons Learned" on page 31)
- Identify next steps to advance oyster restoration in these waters. ("VI. Moving Forward" on page 33)

1 New York/New Jersey Harbor is also referred as "NY/NJ Harbor," "the Harbor," "the Hudson-Raritan Estuary," "the Estuary," or "these waters" throughout this document.

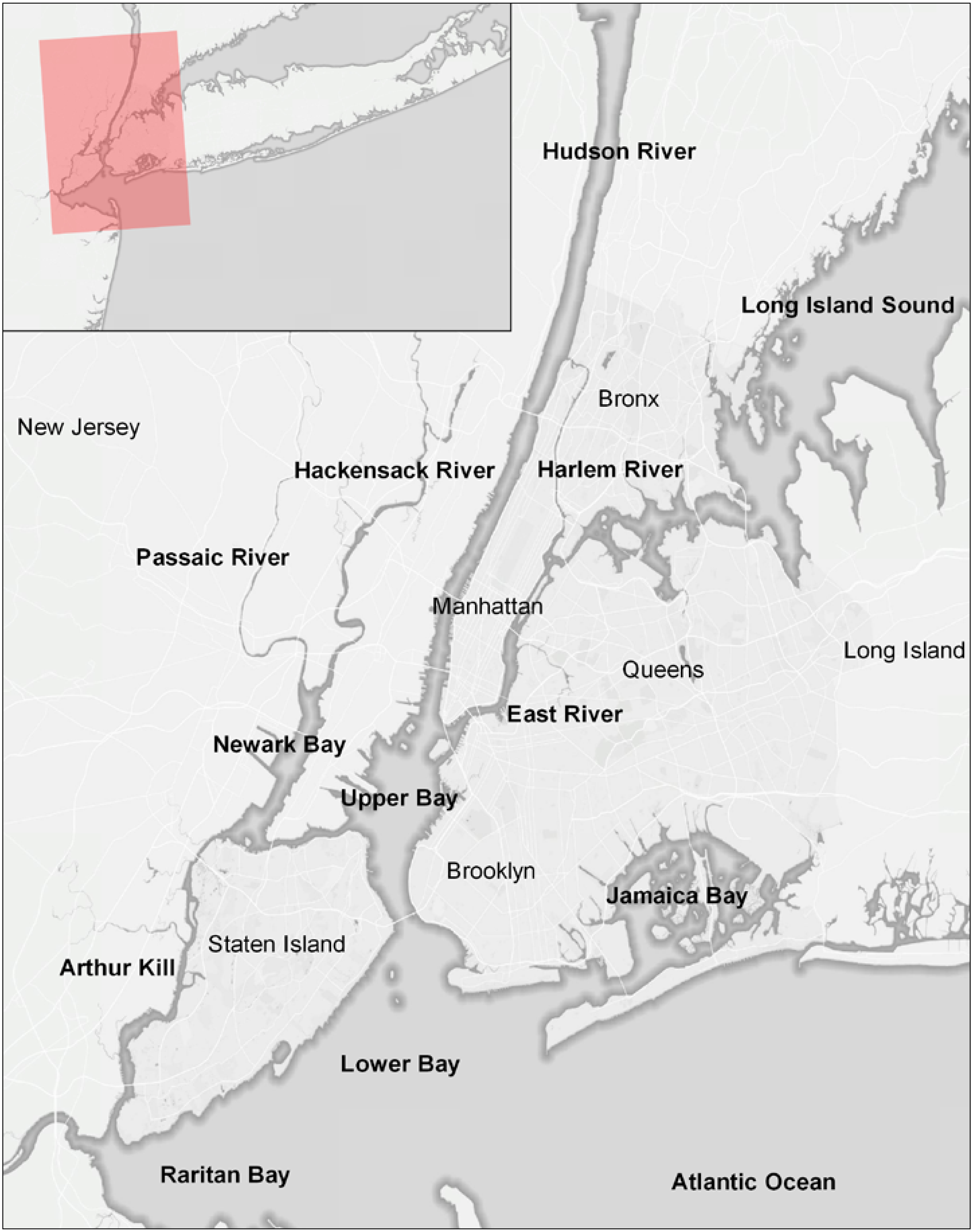

Figure 1. New York/New Jersey Harbor. Names of water bodies are in bold.

Figure 2. Map of New York Bay and Harbor produced by United States Coast Survey in 1844.

The intended audience of this document is:

- Restoration practitioners, both in the New York City metropolitan area and elsewhere, particularly other urbanized estuaries that face similar challenges.
- Advocates, policymakers, funders, fundraisers, educators, researchers, innovators, problem solvers, and students who want a quick primer on oyster restoration and who can help solve restoration challenges.

OYSTERS AND NY/NJ HARBOR

NY/NJ Harbor is the confluence of saltwater and freshwater, land and water, people and the environment, the past and the future. With a watershed of well over 14,000 square miles, the Harbor is the meeting place of the Hudson River, Long Island Sound, Raritan River, Jamaica Bay, and the Atlantic Ocean (Fig. 1). More than 24 million people call the metropolitan area surrounding NY/NJ Harbor home. These waters are the third largest shipping port in the United States.

We don't need to travel very far into the past to encounter a Harbor that was drastically different. Prior to European colonization, the Harbor was home to the Lenape and Canarsie peoples who lived off the abundant natural resources provided by the estuary. Today's city, largely characterized by concrete, steel, and glass, was a landscape of salt marshes, eelgrass beds, meadows, and maritime forests just a couple hundred years ago (Sanderson) (Fig. 2).

Before New York City was known as *The Big Apple*, it was *The Big Oyster* (Kurlansky 2006) (Fig. 3). Historically, oyster beds were the predominant bottom found below the waters of the Harbor, making them a literal and figurative foundation for the ecology and economy of this place. Society's overreliance on oysters as a food source and the many ways that we have mistreated our waters (i.e., dredging, filling wetlands, discharging raw sewage) caused the once-plentiful oyster to decline by the late 1800s. By the 1920s, the last of New York City's oyster beds was officially closed to harvest. Today, oysters are designated "functionally extinct" in most areas of the Harbor because of their extreme rarity, although small remnant populations remain (with a notable exception in the lower Hudson River).

Throughout most of the twentieth century, the waters surrounding New York City were much

Figure 3. Floating oyster houses in the East River under the Manhattan Bridge, circa 1937.

too polluted to even consider the return of oysters, but in the late 1990s, as water quality was improving, grassroots efforts to restore their population were launched. These community-based efforts were given further credence when the U.S. Army Corps of Engineers, the Port Authority of New York and New Jersey, and several partners identified oysters as a target ecosystem characteristic of a restored estuary. Their restoration plan set a target of 20 acres of oyster beds by 2020 and 2000 acres by 2050 (USACE 2016). By 2020, restoration will have been attempted on approximately 16 or more acres in these waters.

OTHER CHALLENGES IN NY/NJ HARBOR

Today, a diminished oyster population is not the only problem that the Harbor faces. Most of the natural, coastal environments, including marshes, dunes, and maritime forests, have been dredged, filled, or built on. Most of the coastline is hardened and inaccessible to the public. Despite improved water quality over the last century, outdated and under-capacity water infrastructure remain and cause problems, including the discharge of untreated sewage, low levels of dissolved oxygen, bacteria that are pathogenic to humans, legacy contaminants, floatable debris, and excess nitrogen. These issues impair the full use of our waterways by people and nature. On top of this, sea levels have been rising and will continue to rise due to global climate change, with a projected increase between one and six feet by the end of the century (NYS DEC 2017).

Will oysters be the solution to all these problems? No. Oysters cannot fix all the problems caused by aging sewer infrastructure. Oysters alone will not protect the region from rising seas or fiercer storms. Nevertheless, oysters are a part of a multi-faceted solution. Although oysters are not the only character in the story of NY/NJ Harbor, they play an important role in what a healthy and thriving Harbor will look like.

II. WHY RESTORE OYSTERS

Shellfish reefs, including oysters, are one of the most imperiled marine environments and have declined 85% across the globe (Beck et al. 2009). Most efforts to restore oysters are motivated by the ecological and economic benefits they can provide. This section will focus on the ecosystem services that oysters provide—specifically the benefits that humans gain from the natural environment. In addition to a discussion and analysis of improved water quality, enhanced biodiversity and reduced shoreline erosion, other sections of this report will discuss community benefits (see "IV. The Human Dimensions of Oyster Restoration"), and the economic valuation of oyster restoration (see "Appendix I. Economic Value of Oyster Restoration").

IMPROVING WATER QUALITY

Historically, oysters played a major role in maintaining water quality and clarity in NY/NJ Harbor and other estuaries (zu Ermgassen et al. 2013). As filter-feeding (or suspension-feeding) bivalve, oysters remove plankton and nonliving particles suspended in the water (Riisgaard 1988) (Fig. 4). They either ingest these particles or bind them in pseudofeces (a combination of mucus and rejected food items) that are deposited on the bottom. Filtration by oysters can increase water clarity, light penetration, and oxygen levels in water, which benefit other marine organisms (Newell & Koch 2004).

The decline of oysters in most estuaries causes a loss of this important ecosystem service. In the Chesapeake Bay, historical (pre-1870) oyster stocks could filter the volume of the entire bay every three to six days, but today's reduced populations would require nearly a year (i.e., 325 days) to filter the same volume (Newell 1988). Similar declines in filtering capacity by oysters have occurred in estuaries throughout the United States (zu Ermgassen et al. 2013), and NY/NJ Harbor is no exception.

Figure 4. Tanks with oysters (left) and without oysters (right), demonstrating the ability of oysters to filter water and increase water clarity.

Oyster filtration rates are well-studied in both the laboratory and in the field (Newell & Langdon 1996), and although the rate depends on a variety of factors, temperature and the size of the oyster typically have the largest influence (zu Ermgassen et al. 2013). Although many popular sources state that an oyster can filter up to 50 gallons of water a day, this should be considered a maximum rate. Filtration rates in natural settings are likely more variable than in the laboratory, ranging from 1.21 L h^{-1} or roughly 7.5 gallons per day (Grizzle et al. 2008) to 6 L h^{-1} or 38 gallons per day (zu Ermgassen et al. 2013).

If water volume and residence time (i.e., the average length of time a parcel of water remains in an estuary) of a tributary or bay are known, and oyster size and density are known or assumed, then it is possible to estimate the proportion of the water body that can be filtered by oysters. This methodology has been applied to hypothetical restoration scenarios in NY/NJ Harbor with encouraging results (see "Appendix II. Using the Oyster Calculator to Estimate Ecosystem Services"). Although large-scale restoration may be necessary to detect water quality improvements (Grabowski & Peterson 2007), *in situ* fluorometry was used to quantify changes in the concentration of chlorophyll *a* (the main photosynthetic pigment and a surrogate for phytoplankton abundance) at experimental reefs in the Hudson River (Hastings) and at the mouth of the Bronx River (Soundview). Detecting decreases in phytoplankton abundance (i.e., chlorophyll uptake) proved to be variable due to the low density of oysters and the strong wind and waves in this dynamic environment (Grizzle et al. 2013).

Excess nitrogen is a major driver of poor water quality in urban estuaries around the globe (Boesch 2002). It is largely a result of human population size and wastewater treatment technology. Nitrogen fuels algal blooms that can cause low oxygen levels and fish die-offs, as well as being toxic to fish, pets, humans, and other animals (Cloern 2001). In NY/NJ Harbor, New York City's 13 wastewater treatment plants alone discharge more than 150,000 pounds of nitrogen each day (NYC DEP 2012). Although tidal flushing, rapid currents, and naturally turbid waters may decrease the likelihood of nitrogen-fueled algal blooms in many portions of the Harbor, some areas with restricted flow, such as the tributaries of Jamaica Bay, may be more susceptible to blooms. It is also likely that the prodigious amounts of nitrogen produced in New York City are exported to the Long Island Sound and the New York Bight, causing water quality impairments there.

Oysters can play a role in mitigation of excess nitrogen. They can remove nitrogen from the water by assimilating it into their shells and tissues when they feed, by burying nitrogen contained in their waste in the sediment, or by enhancing processes that remove nitrogen from the water (i.e., bacterial removal via denitrification) (Kellogg et al. 2003). Studies of restored oyster reefs in the Choptank River of Maryland have shown an order of magnitude increase in nutrient flux compared with unrestored habitat. Oyster populations in the Upper Choptank can remove as much as 29,000 pounds of nitrogen per year via burial and denitrification, an ecosystem service valued at $318,836 per year (Newell et al. 2005).

Most research on the role of oysters in nutrient removal has occurred in estuaries outside New

York, but there are a few notable examples of research specific to the Hudson-Raritan Estuary. Hoellein and Zarnoch (2014) attempted to measure increased denitrification potential due to the addition of caged oysters at four sites in Jamaica Bay. Across multiple densities of oysters, they found no evidence of increased nitrogen flux (denitrification, ammonification, or nitrification), although the oysters did increase the organic content of sediments. This underwhelming outcome was likely a result of the fact that in eutrophic waters such as Jamaica Bay, sediment conditions prevent denitrification (Hoellein & Zarnoch 2014). Based on the nitrogen content of oysters grown in Jamaica Bay, Sebastino et al. (2015) estimated that 1.4 billion oysters grown over 500 acres could sequester 5% of the Bay's nitrogen load (2.7×10^5 kg N), but the oysters would need to be harvested from the water to permanently remove the nitrogen (Sebastino et al. 2015).

Currently, there is no "plug-and-play" tool for calculating nitrogen removal by oysters, because these processes are sensitive to plankton concentration, light, temperature, salinity, and a variety of other factors (zu Ermgassen et al. 2016). Therefore, we cannot make any quantitative estimates of nutrient removal via oysters in NY/NJ Harbor.

INCREASING POPULATIONS OF FISH, CRABS, AND SHRIMP

Oyster beds and reefs increase the three-dimensional complexity of the bottom environment and typically support greater biodiversity than adjacent, nonstructured habitat such as muddy or sandy bottoms. Oyster beds increase the abundance and diversity of fish, crabs, shrimp, and other organisms through several mechanisms. First, oysters create habitat for reef residents such as oyster toadfish, skilletfish, blennies, and gobies that recruit to and spend most of their lives on the reef. Many of these "recruitment-enhanced" species lay their eggs preferentially on oyster shell (Breitburg 1999, Peterson et al. 2003). The structural complexity created by oysters also acts as a refugia from predators for some species, particularly in their early life stages, increasing their survival. Higher populations of these reef residents and juveniles provide a greater prey abundance for mobile predators who come to the oyster beds to feed (Breitburg 1999). For example, black sea bass (*Centropristis striata*) and striped bass (*Morone saxatilis*) are found in greater numbers on restored reefs than on adjacent nonrestored bottom on the Atlantic coast (Breitburg 1999, zu Ermgassen et al. 2016). Finally, as oysters improve water quality, particularly water clarity, these improvements may further increase the abundance and diversity of organisms that require greater light, such as eelgrasses.

Most of the research on biodiversity enhancement by oyster beds comes from other estuaries, such as the Chesapeake, the southeastern United States, or the Gulf of Mexico (Peterson et al. 2003, zu Ermgassen et al. 2016). The research shows that restored reefs in these regions can enhance biodiversity significantly. A restored oyster reef can enhance the production of fish, crabs, and shrimp by 0.28 kg yr^{-1} m^{-2} in the South Atlantic and Mid-Atlantic (zu Ermgassen et al. 2016), 0.26 kg yr^{-1} m^{-2} in the southeastern United States (Peterson et al. 2003), and 0.40 kg yr^{-1} m^{-2} in the Gulf of Mexico (zu Ermgassen et al. 2016). In regions with active commercial fisheries, this biodiversity enhancement translates to economic benefits in increased fisheries landings (Kroeger & Guannel 2014).

The degree to which restored oysters enhance populations of fish, crabs, and shrimp will depend on geographic context, as different estuaries are home to different species. For example, while red drum (*Sciaenops ocellatus*) and spotted seatrout (*Cynoscion nebulosus*) are enhanced by oyster restoration in the Gulf of Mexico (Scyphers et al. 2011), these species do not presently occur in NY/NJ Harbor and are not expected to be enhanced by oyster restoration here. More than 20 species of fish that are known to be enhanced by oyster restoration in other estuaries do occur in NY/NJ Harbor, including striped killifish (*Fundulus majalis*)**,** skilletfish (*Gobiesox strumosus*)**,** oyster toadfish (*Opsanus tau*), and blue crab (*Callinectes sapidus*) (Table 1, Fig. 5).

The degree to which restored oyster habitat enhances biodiversity also depends on the degree to which this habitat type or other sources of three-dimensional structure are limited (Grabowski & Peterson 2007, zu Ermgassen et al. 2016). Some studies that failed to find a positive relationship between restored oyster habitat and increased populations of fish, crabs, and shrimp attributed this failure to the context of the restored reefs in the landscape and their redundancy with other suitable habitats for the organisms (e.g., Grabowski et al. 2005, Geraldi et al. 2009, Gregalis et al. 2009). In an environment like NY/NJ Harbor, where natural oyster habitat is absent and other three-dimensional structures are rare, biodiversity enhancement may be more significant than in these previous studies.

Although few studies on this topic have been conducted in NY/NJ Harbor, these few should be noted here. Peterson and Kulp (2012) studied the biodiversity associated with five 50-m^2 pilot subtidal reefs as part of the Oyster Restoration Research Project in NY Harbor. The species composition and abundance of organisms living on the reefs were largely determined by salinity, with low salinity at the Hastings site in the lower Hudson and high salinity at a site off Staten Island representing the extremes of a salinity gradient. Peterson and Kulp did not detect any difference in large mobile crabs, shrimp, and fish on or off the reefs, which they attributed to the small size of the pilot reefs. In Keyport Harbor, NJ, no significant changes in species diversity were detectable at sites with a variety of oyster restoration structures (e.g., reef balls, reef blocks) and the same sites after the structures were removed, but species richness and abundance were typically greater on the restoration structures (Ravit et al. 2012).

There are ongoing efforts to attempt to document species that use restored oyster structures in NY/NJ Harbor. NY/NJ Baykeeper is conducting a trapping study at their restoration sites at Naval Weapons Station Earle and Soundview at the mouth of the Bronx River. The Nature Conservancy (TNC) and Billion Oyster Project (BOP) are conducting a study at restored reefs at Bush Terminal Park (Brooklyn) and Lemon Creek Lagoon (Staten Island) (Fig. 6).

Figure 5. Oyster reefs can enhance the recruitment of tautog or blackfish (*Tautoga onitis*) (top) and oyster toadfish (*Opsanus tau*) (bottom).

REEFS AS A COMPONENT OF MULTI-LAYERED COASTAL DEFENSES

Oyster reefs and beds are natural structures that can act as breakwaters and reduce both wave energy and wave height (Meyer et al. 1997, Piazza et al. 2005, Stone et al. 2005, Scyphers et al. 2011). Reductions in wave energy and height can promote the accumulation of sediments and reduce or eliminate marsh erosion (Kroeger & Guannel 2014). For example, subtidal breakwater reefs (1 m high x 25 m long) slowed shoreline retreat by more than 40% in Mobile Bay, Alabama, although the vegetated edge behind the breakwaters still eroded nearly 3 m in just two years (Scyphers et al. 2011). Brandon et al. (2016) used sedimentary reconstructions and hydrodynamic modelling to suggest that oyster beds may have reduced wave energy by 30% to 200% prior to their decline in NY/NJ Harbor.

Can oysters protect New York City against sea-level rise? No. Can oysters be used in *select* areas of NY/NJ Harbor to reduce the erosion of soft shorelines? Perhaps. Oysters will have limited capacity to protect the coastlines of NY/NJ Harbor because of their subtidal position in the water and because most of the waterfront is composed of hardened edges such as vertical bulkheads (Figs. 7, 8). In NY/NJ Harbor, harsh winters with freezing waters prevent oysters from establishing in the intertidal zone. In other estuaries where more of the shoreline is soft-edged (e.g., marsh) and where milder winters allow oysters to grow intertidally, they can provide greater coastal resilience benefits. Nevertheless, restored oyster beds or reefs may provide coastal protection in select areas of NY/NJ Harbor, especially areas with soft edges like salt marshes and mudflats that are eroded by wave action. Some areas in NY/NJ Harbor where this strategy may apply include Jamaica Bay and the Staten Island and New Jersey sides of Raritan Bay. A comprehensive mapping of the areas in NY/NJ Harbor suitable for oyster restoration, along with the coastline type, erosion rates, and other hydrodynamic characteristics, can help identify the sites where this strategy may be applicable.

A similar effort completed in Breton Sound, Louisiana, identifies areas where oysters are most likely to reduce erosion (La Peyre et al. 2015). Oysters do not need to do the work of reducing erosion and protecting shorelines by themselves. They can be integrated into human-made breakwater structures to enhance wave attenuation and add co-benefits such as water filtration and biodiversity enhancement. Two such examples of an integrated built and living breakwater (i.e., a hybrid of green and grey infrastructure) in NY/NJ Harbor include NY/NJ Baykeeper's living shoreline at Naval Weapons Station Earle (Raritan Bay) and BOP's planned oyster habitat enhancement of the Staten Island Living Breakwaters. TNC's *Urban Coastal Resilience Report*[2] has demonstrated that hybrid coastal infrastructure strategies like these can provide sufficient, cost-effective flood management and superior ecosystem services compared with gray-only alternatives (TNC 2015).

2 Available at https://global.nature.org/content/urban-coastal-resilience-valuing-natures-role

Table 1. Species enhanced by oyster habitat in other estuaries that also occur in NY/NJ Harbor.

Common Name	Scientific Name	What Oysters Enhance	Reference
Bay anchovy	*Anchoa mitchilli*	Growth	2, 3
Sheepshead	*Archosargus probatocephalus*	Recruitment	2, 3, 5
Silver perch	*Bairdiella chrysoura*	Growth	2
Blue crab	*Callinectes sapidus*	Recruitment	2, 4, 5
Black sea bass	*Centropristis striata*	Growth	2, 3, 5
Sheepshead minnow	*Cyprinodon variegatus*	Growth	3
Striped killifish	*Fundulus majalis*	Recruitment	5
Skilletfish	*Gobiesox strumosus*	Recruitment	3, 5
Naked goby	*Gobiosoma bosc*	Recruitment	3, 5
Feather blenny	*Hypsoblennius hentz*	Recruitment	3
Pinfish	*Lagodon rhomboides*	Recruitment	2, 5
Grey snapper	*Lutjanus griseus*	Recruitment	3, 5
Rough silversides	*Membras martinica*	Growth	3
Inland silversides	*Menidia beryllina*	Growth	3
Atlantic silversides	*Menidia menidia*	Growth	2, 3
Atlantic croaker	*Micropogonias undulatus*	Growth	2
White perch	*Morone americana*	Growth	3
Striped bass	*Morone saxatilis*	Growth	1, 5
Gag grouper	*Mycteroperca microlepis*	Recruitment	2, 3, 5
Oyster toadfish	*Opsanus tau*	Recruitment	2, 3, 5
Black drum	*Pogonias cromis*	Growth	2
Tautog	*Tautoga onitis*	Recruitment	3

References: 1: Breitburg 1999, 2: Kroeger & Guannel 2014, 3: Peterson et al. 2003, 4: zu Ermgassen et al. 2016, 5: Scyphers et al. 2011.

Note: Enhancement of recruitment refers to species that are limited in recruitment by habitat area; enhancement of growth refers to species that are limited by predation and food availability (Peterson et al. 2003). Presence in NY/NJ Harbor is based on NYC DCP 2009, Lake 2012, USACE 2015 and the author's best judgment.

Figure 6. (top) Since 2017, The Nature Conservancy and Billion Oyster Project have used seining (shown here), trapping, underwater video and other methods to document the biodiversity on restored reefs at Bush Terminal Park (Brooklyn) and Lemon Creek Lagoon (Staten Island).

Figure 7. (center) Oyster reefs in warmer climates can grow intertidally (i.e., above the mean low tide line) and provide wave attenuation for soft edges (e.g., marshes) behind them.

Figure 8. In NY/NJ Harbor, hardened shorelines (bottom left), such as bulkheads or seawalls or rip-rap, are more common than soft shorelines (bottom right), such as marshes and mudflats.

III. RESTORATION EFFORTS: PAST AND PRESENT

Oyster restoration in NY/NJ Harbor began as a grassroots effort in the late 1990s and has evolved significantly since then. The following section is an attempt to capture the changes, challenges, and lessons learned from nearly two decades of oyster restoration in the Harbor. This review is based on a review of over 70 documents, including published scientific literature, white papers, grant reports, newsletters, and websites, as well as a survey of 18 members of the NY/NJ Harbor & Estuary Program's Oyster Restoration Working Group (Appendix III on page 44) and interviews with several restoration practitioners and researchers.

REVIEW OF PAST AND PRESENT EFFORTS

This section will primarily focus on benthic (i.e., bottom) restoration projects and will highlight the topics of costs, structures and substrates, and permits and policy. The information comes from 33 benthic oyster restoration projects, including four that will be installed soon (Fig. 9, Appendix IV on page 46). Other aspects of the restoration process are included as appendices to this report, including *Site Selection* (Appendix V on page 52), *Producing Oysters for Restoration* (Appendix VI on page 54), and *Restoration Monitoring and Performance Metrics* (Appendix VII on page 58). This review has primarily focused on the larger restoration projects and does not count numerous efforts by academic researchers, community-based organizations, and student researchers to understand the performance of oysters in these waters.

COSTS AND FUNDING

Of the 33 benthic reef projects in NY/NJ Harbor, including four projects that will be installed soon (Fig. 9, Appendix IV on page 46), 18 projects had cost data available. Project costs ranged from $8,000 to $1,375,000 and averaged $256,302. The

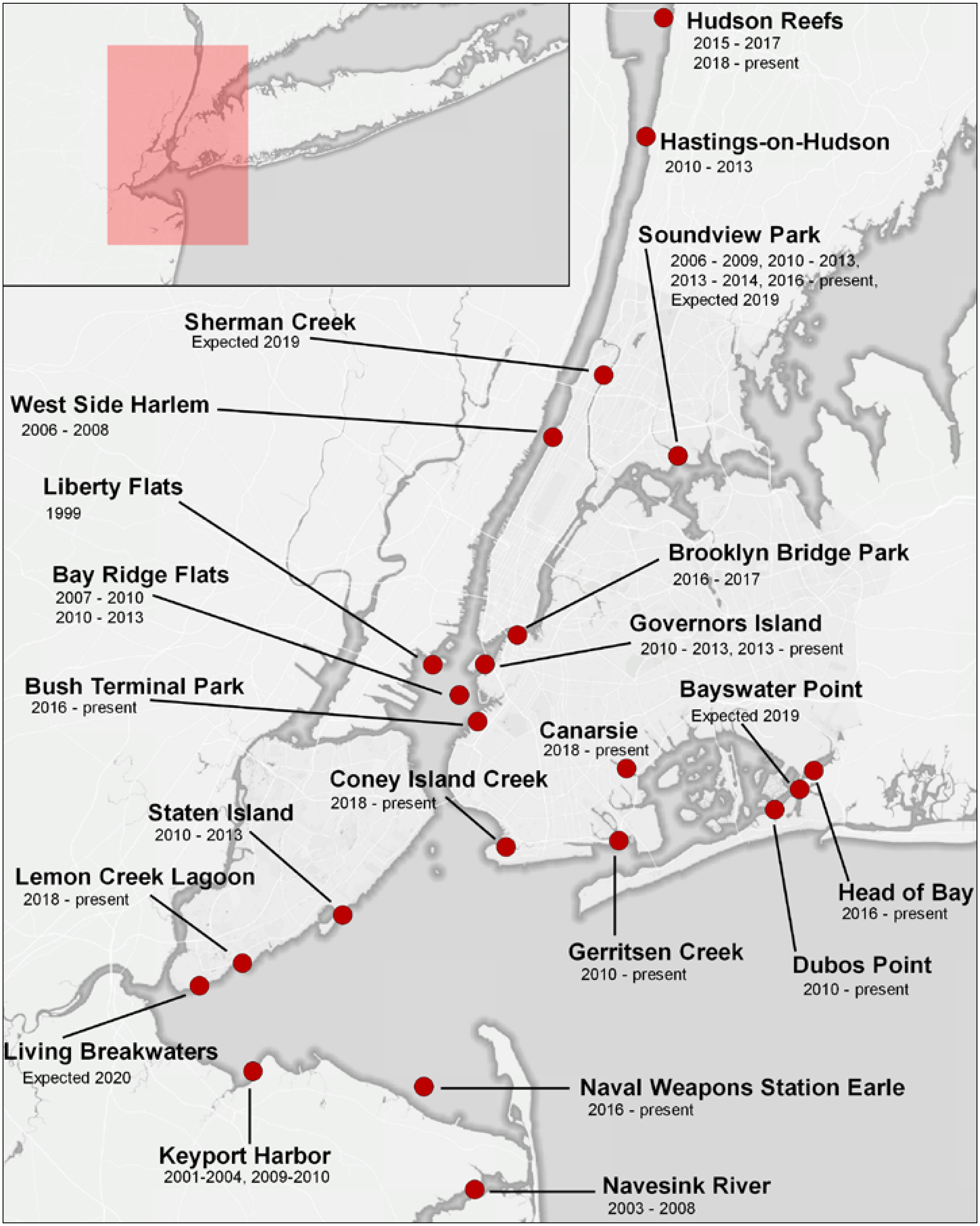

Figure 9. Benthic oyster research and restoration projects in NY/NJ Harbor. Dates indicate the time when oysters or substrates were actively planted or monitored.

total cost of the 18 projects for which data are available is nearly $2.5 million dollars. Assuming a similar cost structure for the other projects (i.e., same cost per acre), roughly $6.7 million has been spent on oyster restoration in NY/NJ Harbor. This amount does not include the Staten Island Living Breakwaters project and other projects that are in design phases and will have substantial costs. Total project cost can be difficult to estimate, and organizations may include different components in their calculations of costs (e.g., permitting, materials, installation, monitoring, maintenance, community engagement and education, overhead). Given this variable composition of cost estimates and the unique goals of each project, it is difficult to determine an average cost per acre. Using the average project size (0.5 acre) and the average project cost ($256,302), the average cost per acre is $509,402. These preliminary data suggest that oyster restoration may be more expensive in NY/NJ Harbor than in other estuaries. For example, restoration in Chesapeake Bay costs about $51,000 to $110,000 per acre (USACE 2016). These estimates of cost from the Chesapeake region likely do not include the extensive community engagement and post-restoration monitoring efforts that are typically included in NY/NJ Harbor costs. In addition, the material costs per acre in NY/NJ Harbor should be expected to decrease over time as restoration practice scales up. Due to the small sample size in the present review, this cost per acre figure should be used cautiously at this point.

STRUCTURES AND SUBSTRATES

Oysters can be deployed via a variety of substrates and structures, according to the goals or desired functions of the restoration project, characteristics of the site, and logistical or budget capacity of the restoration practitioners (Table 2, Fig. 10). In NY/NJ Harbor, most restoration approaches either target benthic (i.e., bottom) habitat or are floating or suspended in the water column (i.e., "nurseries"). Restoration practitioners have learned that due to the high-energy environments found in many portions of NY/NJ Harbor, the living oysters need to be contained in structures or attached to heavy substrates, or they and their substrates will be transported and lost. In 1999, NY/NJ Baykeeper deployed loose clam shell on Liberty Flats just off lower Manhattan and adjacent to Ellis Island. The belief was that providing substrate for oyster larvae, incorrectly believed to be present in the water, could kickstart restoration. This technique is successful in other estuaries. Unfortunately, when divers returned to survey the reef within the next year, the rapidly moving waters had transported or buried nearly all the shell. Additional attempts to use loose spat on shell at five sites throughout the Harbor as a part of the Oyster Restoration Research Project in 2010 found that loss (i.e., transport or burial) of shell occurred at all sites with fast-moving water. Restoration practitioners learned from these early attempts. In 19 of 27 benthic restoration projects that used live oysters since 1999, some form of containment, such as cages, bags, or spat set onto hard objects (e.g., reef balls), was used. Table 2 and Figure 10 describe some of the restoration structures that have been used in NY/NJ Harbor.

PERMITS AND POLICY

According to members of the NY/NJ Harbor & Estuary Program Oyster Restoration Working Group, the biggest challenge to oyster restoration in NY/NJ Harbor is regulations and permitting (66.67% of respondents) (Appendix III on page 44). The list of permits, reviews, and approvals that must be acquired to restore oysters is long and is unique for each project (Table 3). The preparation of permit applications and other activities to ensure compliance represent a significant investment of resources for organizations that are often operating on tight budgets.

One of the main concerns for regulators who issue permits for shellfish restoration in NY/NJ Harbor is the issue of "attractive nuisance." Due to contamination, the oysters should not be consumed, but members of the public may try to harvest the oysters anyway without authorization. The oysters' attractiveness to the public makes their presence in the Harbor a nuisance. This perception of risk is further heightened by the fact that the same regulatory agencies responsible for permitting ecological restoration (e.g., New York State Department of Environmental Conservation) also have responsibility for ensuring that the state's commercial shellfish industry follows the National Shellfish Sanitation Program. Therefore, if individuals become sick from eating oysters they poached, this could have consequences for the entire state's shellfish industry.

The conditions for permitting oyster restoration are much more difficult in the New Jersey waters of NY/NJ Harbor. In 2010, the New Jersey Department of Environmental Protection banned oyster restoration activities in waters that are closed to harvest due to concerns about human consumption of contaminated oysters. The ban required NY/NJ Baykeeper to remove oysters from the water in Keyport Harbor and end their oyster gardening program, resulting in the destruction of over 50,000 oysters. In January 2016, the NJ State Legislature passed a bill requiring the governor to review and revise the ban (A3944/S2617), although then-Governor Chris Christie never took these actions. A review of state regulations commissioned by NY/NJ Baykeeper and TNC of New Jersey found that New Jersey's regulations were the strictest in the United States (Gibson 2017).

Because of this strict regulatory environment, restoration organizations in both states have attempted to site restoration projects in locations that have greater security or that are closed to the public. NY/NJ Baykeeper now conducts most of its restoration activities at Naval Weapons Station Earle, a United States Navy base in Sandy Hook Bay that is closed to the public. BOP has restored oysters at Head of Bay in Jamaica Bay, close to the John F. Kennedy International Airport security zone.

In 2017, BOP struggled to receive permits for a community reef in Coney Island Creek in Brooklyn. These waters are notoriously polluted, receiving at least 57 million gallons of combined sewer water and stormwater from combined sewer overflow events during rainstorms in 2015 (Waterfront Alliance 2017), as well as additional pollution from other illicit sources. The New York state regulators deemed these waters too contaminated to allow oyster restoration activities. In 2018, BOP reached a compromise with New York state, in which oysters will be removed from the site before they reach "market size."

Table 2. Oyster restoration structures used in NY/NJ Harbor.

Location	Structure	Materials	Sites
Benthic	Loose spat on shell on base of shell and rock	Clam and/or oyster shell, rock	Bay Ridge Flats, Dubos Point, Governors Island, Hastings-on-Hudson, Soundview, Staten Island Reef
Benthic	Reef ball	Cement/concrete	Hudson Reefs, West Side Harlem, Keyport Harbor, Naval Weapons Station Earle
Benthic	ECOncrete discs	Cement/concrete	Lemon Creek Lagoon, Staten Island Living Breakwaters±
Benthic	Oyster castle	Cement/concrete	Naval Weapons Station Earle, Sherman Creek±
Benthic	Reef block	Cement/concrete	Keyport Harbor, Naval Weapons Station Earle
Benthic	Gabion	Rebar, wire mesh	Hudson Reefs, Soundview, Lemon Creek Lagoon, Staten Island Living Breakwaters±
Benthic	Rutgers arch	Rebar, plastic mesh	Keyport Harbor
Benthic	Oyster cabinets	Rebar, wire mesh	Bush Terminal Park, Brooklyn Bridge Park, Paerdegat Basin, Coney Island Creek
Benthic	Oyster condo	Rebar, wire mesh	Governors Island
Benthic	Bagged shell	Plastic	Bush Terminal Park, Lemon Creek Lagoon, Bayswater State Park±, Soundview
Floating/suspended	Oyster gardens	Wire mesh, plastic mesh, plastic-coated wire	City-wide
Floating/suspended	Floating bags	Plastic	Lemon Creek, other suitability studies
Floating/suspended	Super Tray	Plastic	Governors Island EcoDock, Great Kills Harbor, Brooklyn Navy Yard
Floating/suspended	OysterGro	Plastic-coated wire, plastic mesh	Head of Bay, Lemon Creek
Floating/suspended	Pile wrap	Plastic-coated wire mesh, steel cable	Hudson River Park Pier 32

Notes: ± anticipated installation

Figure 10. Many structures have been used in oyster restoration in NY/NJ Harbor to contain oysters or provide substrates to which oysters can attach, including loose spat on shell, bagged shell, ECOncrete disc, and wire mesh cages in welded rebar structures (Billion Oyster Project's "Community Reefs").

Table 3. Required permits for some of the oyster research and restoration activities in the New York waters of NY/NJ Harbor.

Type	Agency	Permit/Approval Process	Notes
Federal and State	USACE / NYS DEC / NYS OGS / NYS DOS	Joint application	For permits and concurrence for activities affecting streams, waterways, waterbodies, wetlands, coastal areas, sources of water, and endangered and threatened species.
Federal	USACE	USACE Section 10 (Rivers & Harbors Act)	Prohibits obstruction or alteration of navigable waters of the United States without a permit
Federal	USACE	USACE Section 404 of Clean Water Act	Prohibits discharge of dredged or fill material in waters of the United States without a permit
Federal	USACE	Nationwide permit	5: Scientific Measurement Device; 27: Aquatic Habitat Restoration, Enhancement, and Establishment Activities; or 48: Existing Commercial Shellfish Aquaculture Activities
Federal	NOAA	Essential Fish Habitat	
Federal	NPS	Federally managed property	Only applies to sites within Gateway National Park
Federal	USCG	Local Notice to Mariners and mandated Private Aids to Navigation	
State	NYS DEC	Shellfish Importation permit and License to Collect and Possess Non-Endangered and Non-Threatened Species	
State	NYS DEC	Section 401 of the Clean Water Act (Article 15)	Water Quality Certification for the activities in state waters for any activity that may result in a discharge of a pollutant into waters of the United States, including any dredged or fill materials
State	NYS DEC	Article 15, Protection of Waters Program	Environmental Conservation Law implementing regulations 6 New York Codes Rules and Regulations Part 608
State	NYS DEC	Article 25, Tidal Wetlands Permit	For activities in tidal wetlands and adjacent areas
State	NYS DEC	Temporary Revocable Permit	To use and occupy a portion of state lands
State	NYS OPRHP	Revocable Permit	Short-term permit for individuals or group events on NYS DEC-managed public lands and conservation easements
State	NYS DOS	State-owned land under water	
State	NYS DOS	Federal Consistency Assessment Form for NYS Coastal Management Program	
City	NYC MOEC	City Environmental Quality Review	
City	NYC DCP	Coastal Management Plan with Waterfront Revitalization Plan Consistency Review	
City	NYC DPR	Research Permit	

Acronyms: NOAA: National Oceanic and Atmospheric Administration; NPS: National Park Service; NYC DCP: New York City Department of City Planning; NYC DPR: New York City Department of Parks and Recreation; NYC MOEC: New York City Mayor's Office of Environmental Coordination; NYS DEC: New York State Department of Environmental Conservation; NYS DOS: New York State Department of State; NYS OGS: New York State Office of General Services; NYS OPRHP: New York State Office of Parks, Recreation, and Historic Preservation; USACE: United States Army Corps of Engineers; USCG: United States Coast Guard DEC: New York State Department of Environmental Conservation; NYS DOS: New York State Department of State; NYS OGS: New York State Office of General Services; NYS OPRHP: New York State Office of Parks, Recreation, and Historic Preservation; USACE: United States Army Corps of Engineers; USCG: United States Coast Guard

IV. THE HUMAN DIMENSIONS OF OYSTER RESTORATION

Of the almost 1,600 miles of waterfront in NY/NJ Harbor, only 37% is accessible to the public (Boicourt et al. 2016). The biggest success of oyster restoration in NY/NJ Harbor in the last 20 years is the increase in public support or awareness of oysters and the Harbor in general (56.3% of respondents) according to a survey of members of the NY/NJ Harbor Estuary Program Oyster Restoration Working Group (Appendix III on page 44). Some of the members of this group view public attention and engagement as an even bigger success than the results of restoration or research findings (43.8% of respondents). Restoration organizations generate this public support through programming opportunities throughout NY/NJ Harbor (Table 4).

CONNECTING NEW YORKERS TO THE HARBOR

Engaging community members in the restoration process has multiple benefits. Volunteer restoration activities provide a sense of satisfaction, participation, exploration, and personal growth for participants (Miles et al. 1998, Grese et al. 2000). In addition, a common theory of change among many restoration practitioners is that active, educated, and engaged members of the public will be vocal advocates for environmental issues in the civic realm.

Every year, volunteers help restoration professionals scale up productivity on labor-intensive tasks, such as building restoration structures, sorting and cleaning oyster shell, doing oyster gardening (Appendix VIII on page 61), installing reefs (Figs. 11, 12), or monitoring restored oysters. Engaging in these hands-on restoration activities can gradually transform volunteers into advocates for related environmental causes (Svendsen & Campbell 2008). The same logic extends to environmental education initiatives that engage local school children in oyster restoration (Tidball & Krasny 2011). Year by year, volunteer by volunteer, oyster growers are cultivating a constituency of New Yorkers who have experience tangibly caring for their harbor.

Expertise, inquiry, authenticity, accountability, and adaptability are all important—and interconnected—components of community engagement and education initiatives that make an impact. Oyster restoration organizations in NY/NJ Harbor have hired or temporarily contracted professional educators and community outreach specialists to design, launch, and manage many of their public-facing programs. Experts in adult learning, community organizing, volunteer engagement, and environmental education bring valuable conceptual knowledge and real-world experience to these programs (Knowles et al. 2015).

Designing useful engagement and education initiatives often begins with a series of questions about likely participants (Vella 1994): Who are they? What skills and knowledge do they bring with them? What do they need to learn to either get the job done right (volunteers) or satisfy a curricular requirement (students)? This line of inquiry can ensure that a project is authentically (and sustainably) engaging for volunteers and students alike and that it responds to their various needs, hopes, and interests (Freire 2013, Silva & Laird 2017). Effective projects are also accountable, laying out clear and measurable objectives that let participants, project managers, and other stakeholders know precisely what volunteers and students are achieving through their participation in oyster restoration efforts (Guba & Lincoln 1989, Vella et al. 2000). Initiatives must ultimately adapt to shifting restoration needs, to changing participant priorities, and to emergent insights into what is (and isn't) working (Schon 1984).

TNC and the Center for Whole Communities published a *Field Guide to Conservation in Cities in North America* in 2017. Freely available online[3], the guide provides insightful stories of engaging, equitable, and economically just urban conservation efforts that pair environmental experts with grassroots participants. The guide includes "Whole Measures for Urban Conservation," a set of 16 rubrics for crafting and implementing community engagement initiatives that expand on the insights offered here.

3 Available at https://www.nature.org/ourinitiatives/urgentissues/nature-in-cities/cities-network/field-guide-for-conservation-in-cities.xml

Figure 11. (top) Billion Oyster Project staff, New York Harbor School students, The Nature Conservancy staff and community partners ready to install a reef at Lemon Creek Lagoon in Staten Island in summer 2018.

Figure 12. (bottom) Billion Oyster Project staff and community partners installing a reef at Coney Island Creek (Brooklyn) in summer 2018.

Table 4. Community engagement programs focused on oysters in NY/NJ Harbor.

Organization	Program	Description	Metrics
NY/NJ Baykeeper, The River Project, New York Harbor School	Oyster Gardening 2004–2014	Volunteer stewardship of oysters in suspended cages by non-professionals (e.g., community members, school groups) off piers and docks (Appendix VIII).	>140 oyster gardens
NY/NJ Baykeeper	EcoVolunteers	Adult volunteers get an immersive experience monitoring scientific and community reefs at Soundview, Bronx.	>100 volunteers on 12 dates in 2016
BOP*	Community Reefs	In-water educational experiences that foster community stewardship and long-term management of local natural resources.	4 sites (2 additional pending); 30 community partners; 10 schools; 4,000 individuals as of 2018
BOP	Oyster Research Stations	Volunteer stewardship of oysters in suspended cages by non-professionals (e.g., community members, school groups) off piers and docks. Includes curriculum for middle school classes (Appendix VIII).	215 stations, 534 monitoring expeditions, 585 team leads (i.e., adults), 761 team members (i.e., students)
BOP	Public & Corporate Volunteers	Regularly scheduled volunteer days on Governors Island throughout spring and summer. Volunteers build oyster cages, prepare recycled shell for seeding, sort and count baby oysters, and more.	>1,000 public volunteers, 130 corporate volunteers in 2017
BOP	BOP Ambassadors	Long-term adult volunteers provide outreach at events, support field team at reef sites, engage students in educational programming, and help facilitate community science trainings and volunteer days.	20 Ambassadors worked 408 hours in 2017
BOP	BOP Exhibit	Public exhibit on Governors Island with displays on history and ecology of oysters and NY Harbor.	4,883 visitors in 2017
New York Harbor School	Career & Technical Education (CTE)	Students design and weld oyster reef structures, operate and maintain vessels, grow oysters, and conduct research projects at these sites. They gain experience in maritime trades and access to locally available marine careers.	500+ Harbor School students contributed to BOP through their CTE experience
The River Project	Living Oyster Reef Ecosystem Exhibit	Wet Lab facility on Pier 40 (Hudson River) that features live NY Harbor organisms, including a Living Oyster Reef Ecosystem exhibit for student and adult education.	2,824 students on 113 field trips and 763 drop-in visitors in 2017
Hudson River Park Trust	Shell-ebrate Oysters	Hands-on public program with opportunities to interact with oysters, help tag or monitor oysters, and learn about the history of oysters in the Hudson.	2,000 participants in 2017
Hudson River Park Trust	Oyster Volunteer Groups	School and corporate volunteers help to build oyster wraps, tag oysters, and measure and count adult oysters and spat on shell clusters.	200 participants in 2017
Hudson River Park Trust	Community EcoPaddle	Interactive discussion of local oyster history and science and on-water oyster monitoring via kayaks.	

* BOP = Billion Oyster Project

V. LESSONS LEARNED

Restoring oysters to NY/NJ Harbor is complicated because of a combination of challenges.

Functionally extinct: Oysters are functionally extinct in NY/NJ Harbor. Less than 0.01% of the historical population exists today, and the bottom of the Harbor is an inhospitable surface for restoring oysters. Oyster restoration practitioners must add hard substrate (e.g., shell, rock) to the muddy Harbor floor and then seed the surface with living oysters. In some other estuaries, there are still sufficient breeding populations of oysters, so new installations of hard substrate are all that is needed to grow existing populations.

Restoration in closed waters: NY/NJ Harbor is closed to shellfish harvest because of poor water quality. The lack of a commercial or recreational oyster harvest means that governments invest less in restoration because there is no economic benefit of enhanced fisheries. Agencies that permit shellfish restoration projects view them as potential public health risks, worrying that restored oysters could be illegally harvested and consumed from polluted waters. Two-thirds of restoration practitioners in NY/NJ Harbor have identified regulation and permitting as one of the biggest challenges to oyster restoration in these waters (Appendix III on page 44).

High-energy environment: NY/NJ Harbor is a high-energy environment with strong currents and wakes, both naturally and from boat traffic. Historically, oyster reefs likely buffered these disturbances and made local waters more hospitable to ongoing oyster growth. Today, restored oysters need to be secured in place with cages, bags, or other structures, which is a logistical challenge and likely raises the costs of restoration.

Subtidal only: In estuaries with a warmer climate, oysters can live in the intertidal zone, but in NY/NJ Harbor, oysters are primarily limited to subtidal environments (i.e., submerged below the average low-tide height). This means that there are fewer suitable places for restoration and that restored oysters are more susceptible to subtidal predators and biological fouling.

Economic realities: The economic aspect of restoring oysters in NY/NJ Harbor is not as promising as in other estuaries. Production and installation of oysters and restoration structures are more expensive than elsewhere because of the small scale of projects and the higher costs associated with the NY/NJ metropolitan region. A cost-benefit analysis has not been conducted here, but the results may not be favorable for oyster production because there is no benefit of harvestable oysters in these waters. It is difficult to assign monetary values to the ecological and social benefits of oyster restoration that do exist in NY/NJ Harbor (e.g., education and engagement), although they are important.

Unknown impacts of water quality: Although remarkable improvements have been made in the last several decades, water quality in the Harbor is still impaired on several scales. It is unknown whether poor water quality, evident in low oxygen events or legacy and contemporary toxins and contaminants, prevents successful restoration.

Despite these challenges, oyster restoration is moving forward here, and restored oysters are growing and surviving. Restoration has been attempted on over 10 acres since 1999. Rapid growth and good survival has been observed in many restoration projects throughout the Harbor.

But oyster growth and survival alone are not enough to achieve a self-sustaining population. 2018 was a remarkable year for oyster recruitment in the Harbor, with naturally occurring oyster spat observed at many sites in the Lower Hudson River (Piers 25 and 40, 125th Street Piers), near the mouth of Jamaica Bay (Coney Island Creek), and Soundview at the mouth of the Bronx River. But human intervention in oyster populations remains necessary, meaning that continued investments are required in staff, equipment, and other operations. The question remains: how much reproduction and recruitment is necessary to create a self-sustaining population, and at what sites? Which sites serve as population sources or population sinks? How do remnant, wild populations interact with restored oysters? Further research is necessary to understand the connectivity among restoration sites in the Harbor.

If restoration is successful, small amounts of restoration could lead to big ecological impacts. By filtering water, oysters improve water clarity and remove excess nutrients such as nitrogen, a function that may reduce harmful algal blooms. Oysters bring life to the water, by providing habitat for fish, crabs, shrimps, and other organisms. The addition of complex, three-dimensional habitats created by oysters is especially important in environments such as New York Harbor, where soft, muddy substrates are the norm. Even a restoration project as small as 10 or 20 acres may provide substantial ecosystem benefits.

The social benefits of engaging community members, educating them about the Harbor, and providing them with opportunities to interact with the water may be one of the greatest successes of local oyster restoration. In New York City, several thousand students, volunteers, and community members participate in oyster-related educational and stewardship activities each year. The benefits of these activities are especially important in an urbanized setting such as NY/NJ Harbor, where much of the population lacks access to green and blue spaces. Waterfront access and traditional connections to the water have been severely diminished over the past two centuries. Engaging communities around oyster restoration can open the door to deeper learning about ecology and the value of a healthy environment, helping to create future stewards and advocates for the Harbor.

VI. MOVING FORWARD

Restoration efforts must focus on understanding and achieving successful reproduction and recruitment. We need a better understanding of how reproduction and recruitment of restored oysters vary throughout the Harbor and from year to year.

First, we need comprehensive data on the presence of larvae and oyster recruits across the Harbor and through time. Then we need to understand the mechanisms driving these patterns. Using an adaptive management approach, we can continually learn from and improve our restoration techniques to overcome these environmental challenges. For example, we can work to mitigate poor conditions, choose sites where conditions are more suitable, restore oysters at densities that result in successful fertilization and reproduction, and use hydrodynamic modeling to understand the connectivity among restoration sites. This emphasis on reproduction and recruitment should be reflected in monitoring efforts, including qualitative and quantitative assessments of gonad condition and more comprehensive monitoring of larvae and spat across the Harbor, both at restoration sites and among potential wild, source populations.

Restoration activities must scale up. BOP has a goal to restore 200 acres and one billion oysters to NY Harbor by 2035. The U.S. Army Corps of Engineers has a goal to restore 2,000 acres of oysters in the entire Hudson-Raritan Estuary by 2050. These are ambitious goals, given current restoration trends. By 2020, roughly 15 acres of oyster restoration will have been attempted in these waters. In most cases, these efforts have not yet resulted in self-sustaining populations. The current production capacity of BOP is approximately 25 million juvenile oysters per year. The organization would need to produce roughly 60 million juvenile oysters per year to reach its goal by 2035—more than doubling its current capacity. The Horn Point Oyster Hatchery at the University of Maryland Center for Environmental Science produces roughly 1 billion juvenile oysters for restoration in the Chesapeake Bay each year. To reach that level, BOP and other restoration organizations will rely on public investments and private philanthropy.

Other innovative finance solutions worth exploring may include:

- Impact investing strategies to create capital for oyster restoration while producing returns for investors.
- A shellfish hatchery based in New York City to generate funds for restoration activities by selling sanitary seed to commercial shellfish farmers in harvestable waters of Long Island, New Jersey, and elsewhere.
- Mitigation funds generated by public and private sector development projects in advance of adverse ecological impacts.

These are not simple propositions, but innovation will be necessary to pay for ambitious restoration initiatives.

Continue to invest in education and engagement, quantify the outcomes and design strategically. Because the social outcomes of involving community members in this work, especially young people, may be one of the biggest successes of oyster restoration, these efforts should continue to be supported. As the scale of restoration projects become larger, organizations with social and educational missions will need to proactively ensure that engagement objectives are not left behind. Organizations involved in education and engagement should articulate the desired outcomes of their work (e.g., increased stewardship or advocacy, enhanced quality of life, improved understanding of Harbor ecology). Then activities can be designed to produce these outcomes, and the outcomes can be quantified to determine whether they are achieving their goals. If education and engagement can be proven to produce intended and desirable outcomes, this can lead to greater investment from a variety of sources.

Solve permitting challenges together. Restoration practitioners and permitting agencies will need to work together to develop mutually agreeable conditions that allow restoration activities to proceed and to minimize potential public health risks. Permitting oyster restoration is frequently identified as the biggest challenge to this work, even for relatively small-scale projects. As restoration projects become larger, permitting challenges and the perceived risk that people will consume restored oysters from closed waters will only increase. Restoration organizations should continue to work to reduce the risk of having oysters poached from their restoration sites by choosing secure sites, using secure gear to hold oysters, working with local partners to watch for illegal poaching, and increasing public awareness of the health risks of consumption through signage and education outreach to community members. Regulatory agencies can also contribute to public messaging and outreach initiatives, as well as increasing patrolling efforts to ensure continued compliance with National Shellfish Sanitation Program standards. Ultimately, some level of public health risk is unavoidable, just as a public kayak launch poses safety concerns. Strategies should be pursued to minimize risk to a reasonable extent, without the expectation of eliminating it completely.

Continue to monitor, learn, adaptatively manage, and refine best practices. Most ecological restoration is not monitored (Kennedy et al. 2011), but post-restoration data are necessary to determine project performance and adaptively manage the habitat. In these waters, oyster restoration projects are monitored an average of roughly three years post-restoration (Appendix IV on page 46). Monitoring oyster restoration requires a longer-term perspective. Success cannot be evaluated in one or two years. Oysters typically require at least two years to reach reproductive viability. Rather than monitoring frequently in the first years following restoration, less-frequent but longer-term restoration (e.g., twice a year for 6 years) may be a better use of limited resources, although this is counter to many one- to three-year grant cycles. Practitioners should continue to experiment with restoration, including the best locations and approaches in the Harbor. We still have a lot to learn and the best methods for restoration in these waters are still unknown. While best practices and recommendations (e.g., habitat suitability models for site selection, monitoring guidelines for performance evaluation) do exist, they will need to be applied and refined for the unique conditions here. Greater data-sharing and communities of learning should be supported to allow practitioners to learn from each other.

Develop a shared plan for oyster restoration. Establishing a goal of oyster restoration on the basis of acreage or number of oysters is insufficient. Actionable plans specifying the location, timing, and methodology of restoration throughout the Harbor are needed to guide restoration efforts and achieve higher-level goals. Also, goals for restoration should be based on the desired level of services that the restoration will provide. For example, our goals for the amount of restoration to perform should not be based on acres alone, but rather on the amount of nitrogen we want to see removed by oysters, or the amount of additional fish produced as a result of water filtration by the oysters. These goals should be developed by the community, with all relevant stakeholders involved. The creation of a comprehensive restoration plan will require the collaboration of several parties and will be informed by our learning over the past 20 years. It is no small endeavor, so it is necessary to devote resources to leadership and participation in the process. Questions remain as to who will lead the process, who should be at the table for these discussions, and how to resolve conflict in the process of developing shared goals and vision for this work.

NY/NJ Harbor can look to the Chesapeake Bay as a model, specifically the Chesapeake Watershed Agreement, which specifies the tributaries where oyster restoration will occur and which was signed by all states in the Chesapeake watershed and several federal agencies (Chesapeake Bay Program 2014, 2015). These parties also co-created quantitative success metrics with targets and thresholds for oyster restoration at both the tributary and reef scales. Although the process is daunting, investing in the development of a shared vision and goals is necessary for multiple parties to work together to meet ambitious goals.

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APPENDIX I. ECONOMIC VALUE OF OYSTER RESTORATION

Not all constituencies may be convinced of the value of oyster restoration. To some, a greater abundance of fish and crabs, improved water quality, or more educational opportunities for New Yorkers may be insufficient justification for supporting oyster restoration. For these audiences, the dollars-and-cents value of an investment in oyster restoration may be more compelling. While it is inherently difficult to "put a price tag on nature," there are methodologies that estimate the costs and benefits of conservation activities, including restoration (Pearce et al. 2006, Wegner & Pascual 2011).

To date, there are no economic valuations of the benefits provided by oyster restoration for NY/NJ Harbor. To understand the economics of oyster restoration in these waters, we can look to other estuaries where similar analyses have been attempted. In general, these analyses attempt to quantify the economic value of the ecosystem services provided by oysters, including the harvest of oysters and other enhanced species ("provisioning" services); improvements to water quality and shoreline stabilization ("regulating" services); education and recreation, including fishing and increased swimming or boating due to water quality improvements ("cultural" services); and nutrient cycling ("supporting" services) (Henderson & O'Neil 2003, Grabowski et al. 2012, Kroeger 2012, Kroeger & Guannel 2014). One study estimated that a $150 million investment in oyster restoration in Alabama would build 100 miles of reefs, create 240 jobs per year for 10 years, boost regional annual household income by $7.6 million for 10 years, save nearly $150 million on bulkhead construction, increase recreational fishing spending by almost $5 million, and increase the fish, crab, and oyster harvest by nearly $7 annually (Kroeger & Haner 2012).

The economics of oyster restoration will be different in NY/NJ Harbor for several reasons. There are no commercial oyster fisheries; recreational fisheries that may be enhanced by restoration are relatively small; nitrogen is not regulated through a total maximum daily load as in the Chesapeake Bay, so nitrogen trading credits cannot be quantified; and the costs of restoration in these waters are still very high relative to other regions (e.g., Chesapeake Bay) because production has not scaled (see "Costs and Funding," p. 20). In NY/NJ Harbor, education and engagement may be some of the most important benefits of oyster restoration, but these are precisely the most difficult benefits to value. [However, Hoagland and Jin (2017) did attempt to estimate the educational value of oyster restoration activities in terms of the money spent by schools that participated in oyster-related educational programs at Hudson River Park Trust.] Therefore, the cost-benefit or return on investment of oyster restoration calculated in other estuaries is not directly applicable to these waters.

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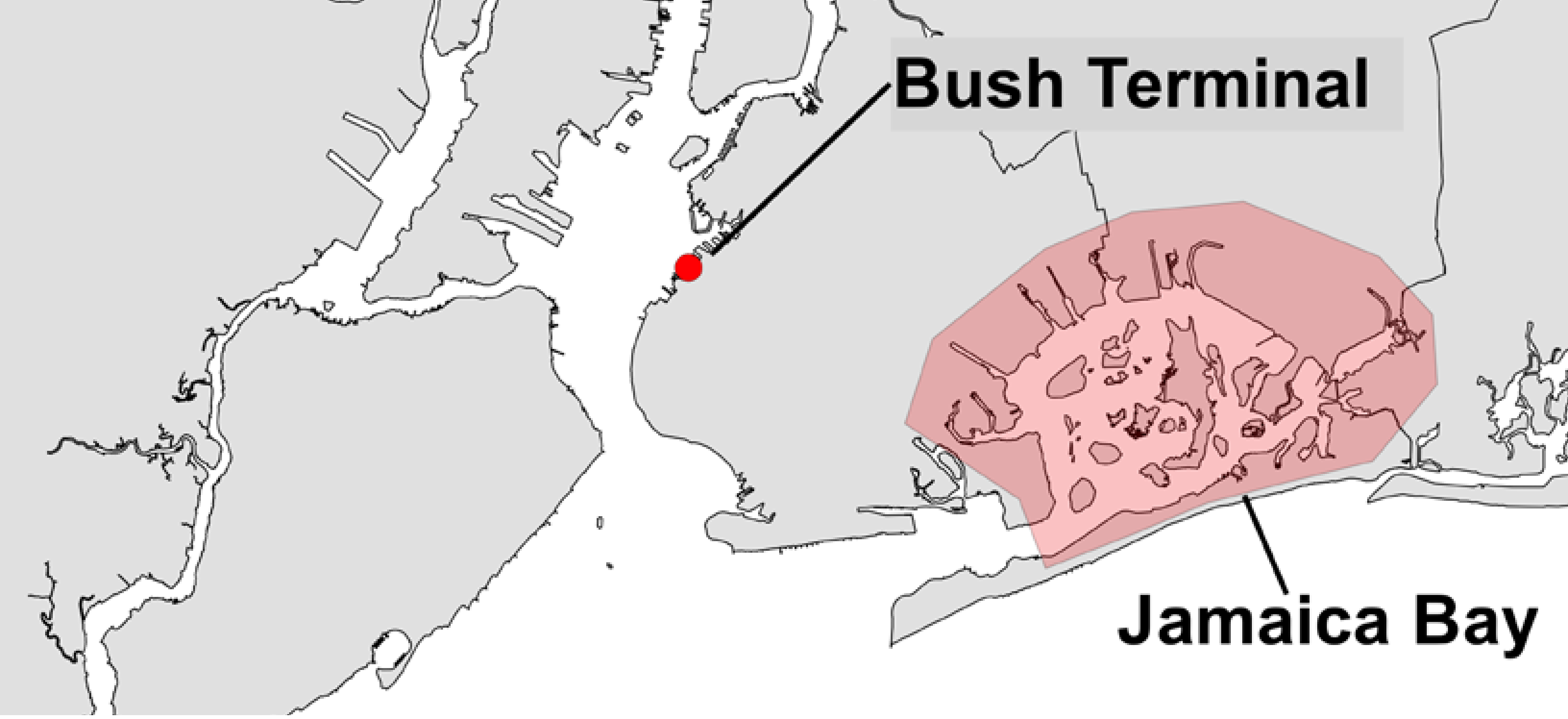

Figure S1. Map of Bush Terminal (Brooklyn) and Jamaica Bay, where ecosystem services that would result from hypothetical restoration scenarios were calculated.

APPENDIX II. USING THE OYSTER CALCULATOR TO ESTIMATE ECOSYSTEM SERVICES

Our best understanding of oyster ecosystem services is summarized in "Setting Objectives for Oyster Habitat Restoration Using Ecosystem Services: *A Manager's Guide*" (zu Ermgassen et al. 2016) and the accompanying Oyster Calculator, which is online at http://oceanwealth.org/tools/oyster-calculator. It allows users to specify attributes of the water body and characteristics of the restored oyster population and then estimate impacts of restoration on water filtration and fish, crab, and shrimp enhancement.

Restoring less than 1% of Jamaica Bay's 13,000-acre area to oyster beds would produce major ecosystem benefits (Fig. S1). Restoration of nine acres could filter 3% of Jamaica Bay's volume. Restoration of 144 acres could filter 50% of the bay volume and increase the striped killifish, skilletfish, oyster toadfish, and blue crab populations by nearly 5.5 million individuals[4].

The U.S. Army Corps of Engineers' proposed oyster restoration at Bush Terminal Park could have enormous impacts (Fig. S1). The proposed project, which includes 31.65 acres of spat on shell, 8.48 acres of gabion blocks, 3.49 acres of oyster condos, and 0.1 acres of oyster trays (USACE 2017), could filter 5.3 million to 346 million gallons per day[5]. These restored oysters could filter a volume equivalent to approximately one-quarter of the daily NYC wastewater treatment discharge, or 1,235 million gallons (NYC DEP 2012). Esti-

4 Residence time: 35 d, bay volume: 208 million m^3, temperature: 22°C, 25 oysters m^{-2} at 38 mm shell height and 25 oysters m^{-2} at 76 mm shell height

5 Temperature: 22°C, 50 oysters m^{-2}

mates also show that the project could help increase populations of blue crab by 233,000, oyster toadfish by 209,000, skilletfish by 1.2 million, and striped killifish by nearly 3,000. Other species will likely be enhanced by restored oysters, but more research specific to the NY/NJ region is needed to determine quantitative estimates.

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APPENDIX III. SURVEY OF NY/NJ OYSTER RESTORATION PRACTITIONERS

In the fall of 2017, The Nature Conservancy conducted a survey to assess the current and future status of oyster restoration in NY/NJ Harbor. Members of the NY-NJ Harbor Estuary Program Oyster Working Group were surveyed. This group consists of oyster restoration practitioners from governmental and non-governmental organizations, government regulators, academic researchers, and other civic and environmental organizations involved with oyster restoration in the Hudson-Raritan Estuary.

The survey was conducted via Google Forms and was circulated to the Oyster Working Group listserv on September 19, 2017, and in person at the Oyster Working Group meeting on September 25, 2017. There were 18 responses to the survey by November 12, 2017. The Oyster Working Group listserv includes 74 e-mail addresses, making the response rate nearly 25%.

This document summarizes the responses to the first three questions, which asked participants to identify the biggest successes, challenges, and unknowns of oyster restoration in NY/NJ Harbor. All questions allowed for free-response by participants and were then categorized on the basis of common themes.

Question 1: What are the biggest successes of oyster restoration in NY/NJ Harbor in the last 20 years? Name two or three.

The most commonly identified success of oyster restoration in NY/NJ Harbor was greater support and awareness for oyster restoration and Harbor health (9/16 respondents). Over one-third of respondents (7/16) reported that particular research findings (e.g., "Knowledge that water quality in the Harbor is favorable for oysters") or restoration results (e.g., "Improvement of habitat") were one of the biggest successes. Several respondents (5/16) also reported that work and results at particular sites (e.g., Soundview Bronx; Raritan Bay; Jamaica Bay; Governors Island) were one of the biggest successes. Other successes of oyster restoration included the work of specific organizations (e.g., NY/NJ Baykeeper, Billion Oyster Project), water quality improvements enabling oyster restoration, and work with regulators to acquire permits for oyster restoration.

Response	**Count**	**%**
Support or awareness of oysters and Harbor	9	56.3
Research findings or restoration results	7	43.8
Specific sites	5	31.3
Specific organizations	5	31.3
Attention / changes to water quality issues	3	18.8
Regulation / permitting	2	12.5

Question 2: What are the biggest challenges currently facing oyster restoration in NY/NJ Harbor? Name two or three roadblocks to successful restoration.

Two-thirds of respondents (12/18) stated that working with regulatory agencies and acquiring permits were a major challenge to oyster restoration in NY/NJ Harbor. In addition, 22.2% (4/18) of respondents mentioned challenges such as a lack of understanding of the mechanisms of oyster success, insufficient funding for restoration, poor water quality, lack of substrate, and lack of larval recruitment. Two or three respondents identified six other challenges, and another six challenges were identified by just one respondent. Many of these challenges focused on specific threats or stressors to oysters (e.g., disease, predation, poor water quality), although some were cross-cutting themes regarding the restoration process (e.g., lack of collaboration, lack of long-term restoration planning, insufficient oyster hatcheries).

Response	**Count**	**%**
Regulation / permitting	12	66.7
Lack of understanding of mechanisms of success	4	22.2
Insufficient funding	4	22.2
Poor water quality	4	22.2
Lack of substrate	4	22.2
Lack of larvae or recruitment / reefs not self-sustaining	4	22.2
Lack of wild, local oysters / insufficient adaptation or diversity	3	16.7
Urbanization (vessel traffic, hardened shoreline, dredging, etc.)	3	16.7
Disease	3	16.7
Predation	3	16.7
Scale is too small	2	11.1
Lack of collaboration / community involvement	2	11.1
Overly oyster-centric focus of restoration activities	1	5.6
Poor food quality / quantity	1	5.6
Ocean acidification	1	5.6
Insufficient oyster production / hatcheries	1	5.6
Lack of long-term planning	1	5.6
Lack of data on long term survival	1	5.6

Question 3: What are the biggest unknowns regarding oyster restoration in NY/NJ Harbor? Name two or three things we need to know to have successful restoration.

Two of the top three unknowns for oyster restoration in NY/NJ Harbor were associated with the theme of oyster reproduction. Roughly one-third of the respondents identified larval dispersal and recruitment dynamics (7/18), how to achieve self-sustaining reefs (6/18), and how to scale up oyster reef restoration (6/18) as the biggest unknowns regarding oyster restoration. Other respondents mentioned a lack of understanding of the mechanisms or causes contributing to differences in growth (3/18 respondents) or mortality (3/18 respondents), the effects of disease (3/18 respondents), and the management of predators and competitors (3/18 respondents). Eleven other unknowns were identified by two or fewer respondents.

Response	**Count**	**%**
Larval dispersal / recruitment dynamics	7	38.9
How to get a self-sustaining reef?	6	33.3
How to scale up? What scale is needed?	6	33.3
Effects of disease	3	16.7
Causes of growth	3	16.7
Causes of mortality / long-term mortality dynamics	3	16.7
Management / effect of predators or competitors	3	16.7
Effects of food quality / quantity	2	11.1
Effects of pesticides / herbicides / chemicals	2	11.1
Effects of sedimentation / high-energy environments	2	11.1
Best restoration methods	1	5.6
Effects of climate change	1	5.6
Unknown factors	1	5.6
Best locations for restoration	1	5.6
Lack of reference site / success metrics	1	5.6
How to produce locally adapted oysters	1	5.6
Will public support continue?	1	5.6
Cost/benefit analysis of restoration	1	5.6

APPENDIX IV. REVIEW OF PAST RESTORATION EFFORTS

Project	Year(s)	Organization(s)	Size (ac)	Cost[1]	Cost per acre	Funding source	Restoration structures	Oysters contained?	Oyster stage	Oyster source	Non-NY/NJ brood stock	Local brood stock	Years monitored
Bay Ridge Flats Reef	2007–2010	Bart Chezar, NY Harbor School	0.007	8,000	1,142,857	Gowanus Dredgers, self-funded	Caged oysters, oysters on mats, shell piles	yes and no	spat	NMFS Milford, CT raised at Cornell Extension; Flowers Oyster Company (Oyster Bay, NY)	yes	no	4
Bay Ridge Flats Reef	2010–2013	Oyster Restoration Research Partnership[2]	0.01	50,000[4]	5,000,000	NY/NJ Harbor & Estuary Program	Loose spat on shell on base of shell and rock	no	spat	Bremen, ME; Fishers Island, NY; Soundview Bronx, NY	yes	yes	3
Bayswater Point State Park Community Reef	Expected 2019	Billion Oyster Project, Jamaica Bay-Rockaway Park Conservancy, NYS Dept. of Parks Recreation and Historic Preservation	0.001	100,000	100,000,000	Simons Foundation, Jamaica Bay-Rockaway Park Conservancy	Mesh bags w/ spat on shell	yes	spat	unknown	unknown	unknown	2
Brooklyn Bridge Park Community Reef	2016–2017	Billion Oyster Project	0.001	unknown	unknown	Simons Foundation	Spat on shell in cages ("oyster filing cabinets")	yes	spat	Larvae from Muscongus Bay, ME	yes	no	2
Bush Terminal Pier Park Community Reef - Phase I	2016–ongoing	Billion Oyster Project	0.001	unknown	unknown	Simons Foundation	Spat on shell in cages ("oyster filing cabinets")	yes	spat	Larvae from Muscongus Bay, ME	yes	no	3[3]
Bush Terminal Pier Park Community Reef - Phase II	2018–ongoing	Billion Oyster Project	0.001	unknown	unknown	Simons Foundation	Spat on shell in cages ("oyster filing cabinets")	yes	spat	Larvae from Muscongus Bay, ME	yes	no	1[3]

Project	Year(s)	Organization(s)	Size (ac)	Cost[1]	Cost per acre	Funding source	Restoration structures	Oysters contained?	Oyster stage	Oyster source	Non-NY/NJ brood stock	Local brood stock	Years monitored
Bush Terminal Pier Park Bagged Shell Reef	2018–ongoing	Billion Oyster Project	0.001	unknown	unknown	unknown	Mesh bags w/ spat on shell (96) and blank shell (30)	yes	spat	Larvae from Muscongus Bay, ME; larvae from Muscongus Bay adults acclimated at Governors Island, NY for several years	yes	no	1[3]
Canarsie Community Reef (Paerdegat Basin)	2018–ongoing	Billion Oyster Project	0.001	200,000	NA. Includes significant community outreach.	Governor's Office of Storm Recovery Env. Youth Education Program	Spat on shell in cages ("oyster filing cabinets")	yes	spat	Larvae from Muscongus Bay, ME	yes	no	1[3]
Coney Island Creek Community Reef	2018–ongoing	Billion Oyster Project	0.0002	200,000	NA. Includes significant community outreach.	Governor's Office of Storm Recovery Env. Youth Education Program	Spat on shell in cages ("oyster filing cabinets")	yes	spat	Larvae from Muscongus Bay, ME	yes	no	1[3]
Dubos Point Reef	2010–ongoing	NYC Dept. of Environmental Protection	0.01	351,500[4]	35,150,000	NYC Dept. of Env. Protection	Loose spat on shell on base of shell and rock	no	spat	Spawned from Flowers Oyster Company broodstock (Oyster Bay, NY)	no	no	9[3]
Gerritsen Creek Reef	2010–ongoing	NYC Dept. of Environmental Protection	0.0005	351,500[4]	70,300,000	NYC Dept. of Environmental Protection	Oyster balls (with spat)	yes	spat	Spawned from Flowers Oyster Company broodstock (Oyster Bay, NY)	no	no	9[3]
Governors Island Reef	2010–2013	Oyster Restoration Research Partnership[2]	0.01	50,000[4]	5,000,000	NY/NJ Harbor & Estuary Program	Loose spat on shell on base of shell and rock	no	spat	Bremen, ME; Fishers Island, NY; Soundview Bronx, NY	yes	no	3

Project	Year(s)	Organization(s)	Size (ac)	Cost[1]	Cost per acre	Funding source	Restoration structures	Oysters contained?	Oyster stage	Oyster source	Non-NY/NJ brood stock	Local brood stock	Years monitored
Governors Island Reef	2013–2017	Billion Oyster Project	0.02	85,530	4,276,500	unknown	Loose spat on shell, oyster condos	yes and no	spat	Fisher Island, NY broodstock; Muscongus Bay, ME larvae	yes	no	5
Hastings-on-Hudson Reef	2010–2013	Oyster Restoration Research Partnership[2]	0.01	50,000[4]	5,000,000	NY/NJ Harbor & Estuary Program	Loose spat on shell on base of shell and rock	no	spat	Bremen, ME; Fishers Island, NY; Soundview Bronx, NY	yes	yes	3
Head of Bay Nursery & Reef	2016–ongoing	NYC Dept. of Env. Protection, Billion Oyster Project, Hudson River Foundation, HDR, U of New Hampshire, Cornell Cooperative Extension	1	1,330,000	1,330,000	NYC Dept. Env. Protection, National Fish and Wildlife Foundation	Reef: loose clam, oyster, porcelain; Nursery: OysterGros on a floating long-line	yes	adult	Duxbury, MA	yes	no	3[3]
Keyport Harbor Reef	2001–2004	NY/NJ Baykeeper	0.25	unknown	unknown	unknown	Lose clam shell, spat on shell	no	spat, gardened oysters	unknown	unknown	unknown	3
Keyport Harbor Reef	2009–2010	NY/NJ Baykeeper	0.25	unknown	unknown	Conservation Resources Inc. (Chevron Settlement) and NACO (NOAA)	Reef balls, reef block, Rutgers arch design	yes	spat, juveniles	Horn Point, MD	yes	no	0.75
Lemon Creek Lagoon Reef	2018–ongoing	Billion Oyster Project, SCAPE	0.001	unknown	unknown	Governors Office of Storm Recovery	Mesh bags w/ spat on shell (96) and blank shell (30), gabions w/ spat on shell, ECOncrete discs w/ spat	yes	spat	Larvae from Muscongus Bay, ME, and larvae from Muscongus Bay adults acclimated at Governors Island, NY for several years	yes	no	1[3]

Project	Year(s)	Organization(s)	Size (ac)	Cost[1]	Cost per acre	Funding source	Restoration structures	Oysters contained?	Oyster stage	Oyster source	Non-NY/NJ brood stock	Local brood stock	Years monitored
Liberty Flats Reef	1999	NY/NJ Baykeeper	0.8	35,000	43,750	Pew Charitable Trusts, NJ Sea Grant, Victoria Foundation	Loose clam shell (no spat)	NA	none	NA	NA	NA	1
Naval Weapons Station Earle	2016–ongoing	NY/NJ Baykeeper	0.25	unknown	unknown	National Fish and Wildlife Foundation, Mushett Family Foundation, Wallerstein	0.25-acre cages filled with spat on shell, reef block filled with spat on shell, reef balls with oysters	yes	spat	Horn Point, MD; Haskin Shellfish Research Lab	yes	no	3[3]
Naval Weapons Station Earle	2016–ongoing	NY/NJ Baykeeper	0.91[5]	unknown	unknown	Neptune Settlement	Living Shoreline-oyster castles set with oyster spat	yes	spat	Horn Point, MD; Haskin Shellfish Research Lab	yes	no	2[3]
Navesink River Reef	2003–2008	NY/NJ Baykeeper	0.5	unknown	unknown	Restore America's Estuaries	Loose clam shell, spat on shell; transplanted oysters from gardens	no	spat, gardened oysters	Horn Point, MD and Haskin Shellfish Research Lab for larvae; Flowers Oyster Company (Oyster Bay, NY) for seed	yes	no	5
Sherman Creek Reef	Expected 2019	New York Restoration Project	370′ linear feet (0.025 ac)	100,000	4,000,000	NYS Department of Environmental Conservation	Oyster castles	NA	none	NA	NA	NA	unknown
Soundview Park Reef	2006–2009	NYC Parks Natural Resources Group	0.01186	unknown	unknown	Congressman José E. Serrano Wildlife Conservation Society-NOAA Lower Bronx River Partnership	Bagged clam shell, loose shell in trays	NA	none	NA	NA	NA	4

Project	Year(s)	Organiza-tion(s)	Size (ac)	Cost[1]	Cost per acre	Funding source	Restoration structures	Oysters con-tained?	Oyster stage	Oyster source	Non-NY/NJ brood stock	Local brood stock	Years moni-tored
Soundview Park Reef	2010–2013	Oyster Resto-ration Research Partnership[2]	0.01	50,000[4]	5,000,000	NY/NJ Harbor & Estuary Program	Loose spat on shell on base of shell and rock	no	spat	Bremen, ME; Fishers Island, NY; Soundview Bronx, NY	yes	yes	3
Soundview Park Reef	2013–2014	Hudson River Foundation, NY/NJ Baykeeper, Billion Oyster Project, Florida Atlantic Univer-sity, U of New Hampshire, NYC Parks	1	unknown	unknown	Wildlife Conserva-tion Society, NOAA	Loose spat on shell on shell and rock, gabions w/ shell	yes and no	spat	unknown	unknown	unknown	2
Soundview Park Reef	2015–ongoing	NY/NJ Baykeep-er	1	unknown	unknown	unknown	Loose spat on shell on shell and rock base, gabions w/ shell	yes and no	spat	unknown	unknown	unknown	4[3]
Soundview Park Reef	Expect-ed 2019	Billion Oyster Project, NYC Parks, NYS Dept. of Env. Cons., Rocking the Boat, Bronx River Alliance, NY Harbor School, Hudson River Founda-tion	5	1,375,000	275,000	NYS Dept. Env. Cons.	Gabions (250) w/ 25 M spat on shell, loose spat on shell, spat on shell in cages ("oyster filing cabi-nets")	yes and no	spat	unknown	unknown	unknown	4
Staten Island Living Break-waters	Expect-ed 2020	Billion Oyster Project, SCAPE	1	unknown	unknown	Governor's Office of Storm Re-covery	Gabions, ECOncrete discs, loose spat on shell	yes and no	spat	unknown	unknown	unknown	un-known
Staten Island Reef (near Great Kills Harbor)	2010–2013	Oyster Resto-ration Research Partnership[2]	0.01	50,000[4]	5,000,000	NY/NJ Harbor & Estuary Program	Loose spat on shell on base of shell and rock	no	spat	Bremen, ME; Fishers Island, NY; Soundview Bronx, NY	yes	yes	3

Project	Year(s)	Organiza-tion(s)	Size (ac)	Cost[1]	Cost per acre	Funding source	Restoration structures	Oysters con-tained?	Oyster stage	Oyster source	Non-NY/NJ brood stock	Local brood stock	Years moni-tored
Tappan Zee Bridge Reef - Phase I	2015–2017	Billion Oyster Project, Hudson River Foundation, NY Dept. of Trans., NYS Dept. of Env. Cons., U of New Hampshire, AKRF	0.003	84,670	28,223,333	New York State Thruway Authority	Gabions w/ shell, reef balls (2 sizes) (no spat)	NA	none	NA	NA	NA	3[3]
Tappan Zee Bridge Reef - Phase II	2018–ongoing	Billion Oyster Project, AKRF	5	106,811 (construction & delivery of gabions), 35,420 (2 yr monitor)	28446	NYS Thruway Authority	Gabion cages (422) - 2′ square frame w/ 1′ diameter center tube w/ oyster shell (no spat)	NA	none	NA	NA	NA	2
West Side Harlem Reef	2006–2008	NYC Economic Development Corporation	0.006	unknown	unknown	NYC Economic Development Corporation	Reef ball (no spat)	NA	none	NA	NA	NA	2

Notes: This table only includes benthic (i.e., bottom) oyster restoration research projects in NY/NJ Harbor. Floating or suspended projects, including cage studies, temporary feasibility studies, and oyster gardening, are not included.

1 Values may include materials, monitoring, maintenance, community outreach, salaries, overhead, etc. but exact components are often not specified.
2 The Oyster Restoration Research Partnership includes the Hudson River Foundation, the U.S. Army Corps of Engineers, NY/NJ Baykeeper, NY/NJ Harbor Estuary Program, the NY Harbor School and others.
3 Monitoring is ongoing.
4 Cost is estimated by splitting total cost evenly across multiple sites.
5 Site will be populated over several years to reach the 0.91-acre target.

APPENDIX V. SITE SELECTION

One of the guiding principles in the field of restoration ecology is to begin restoration attempts in locations where damage is relatively low and remnant populations exist (McDonald et al. 2016). Unfortunately for oyster restoration in NY/NJ Harbor, few oyster populations naturally occur in this area (except for portions of the Hudson River near the Governor Mario M. Cuomo Bridge, which replaced the Tappan Zee Bridge), and many of the stressors that were likely involved in the historical decline of the oyster are still present (although oyster overharvest is no longer a concern). In the absence of remnant populations, Brumbaugh et al. (2006) recommend focusing on locations where oyster populations existed historically, assuming these sites still have attributes conducive to shellfish growth.

Several habitat suitability models exist for oysters (Battista 1999, Barnes et al. 2007, Pollack et al. 2012, Soniat et al. 2013, Swannack et al. 2014, Theuerkauf & Lipcius 2016) and some have been developed specifically for the waters of NY/NJ Harbor (Starke et al. 2011, USACE 2016). In general, habitat suitability models use spatially explicit environmental datasets to create an index of habitat suitability for a given species and project those suitability values onto a map of potential species distribution or restoration opportunities. Variables commonly used for oyster habitat suitability indices include salinity, substrate type, water depth, and water temperature. The model by Starke et al. (2011) used sedimentary environment, sediment type, depth, and salinity to predict oyster habitat suitability for the lower Hudson River (from approximately Haverstraw Bay) to the Upper Bay portions of NY/NJ Harbor. This model found that the majority of "suitable" (i.e., > 75%) habitats were in the shallow regions of the Hudson River near the Governor Mario M. Cuomo Bridge and Haverstraw Bay, but the most suitable sites (although they were relatively rare) were in the Upper Bay, where salinity is higher. Using information in the *Hudson Raritan Estuary Comprehensive Restoration Plan* (USACE 2016), oyster habitat suitability was estimated on the basis of depth, salinity, dissolved oxygen, and total suspended solids. Large portions of Jamaica Bay, Raritan Bay, and Upper New York Bay are deemed suitable for oyster restoration.

In general, habitat suitability models focus on environmental (i.e., abiotic) variables and do not consider interactions with other organisms (e.g., predators, disease), even though they may have serious consequences on species occurrence. Habitat suitability models also typically do not consider connectivity among populations and source-sink dynamics (but see North et al. 2010), which can have major implications for the persistence of the metapopulation. Furthermore, these models primarily focus on ecological suitability. Restoration is motivated by a suite of factors beyond the enhancement of the focal species. In the case of oysters, restoration is motivated by the ecosystem services that it can deliver, particularly water filtration, nutrient cycling, and biodiversity, so a consideration of where these services are needed should inform the process of site selection. In addition to these traditional ecosystem services, for restoration organizations like the Billion Oyster Project, oysters are a vehicle for youth and community engagement and education. Therefore, the target communities and demographics must also be considered.

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APPENDIX VI. PRODUCING OYSTERS FOR RESTORATION

Unlike other estuaries where remnant populations of breeding oyster exist, oysters are functionally extinct in in NY/NJ Harbor. If there was an adequate breeding population, then the addition of substrate alone might be enough to foster oyster recovery. Unfortunately, this is not the case for most of NY/NJ Harbor (with a notable exception for the lower Hudson River, south of the Governor Mario M. Cuomo Bridge). Therefore, most projects (27 of 33) in these waters used live oysters in their restoration attempts (Appendix IV on page 46). Nearly all of them (26 of 27) used spat or juveniles, rather than adult oysters.

The production of oysters for restoration purposes mimics aquaculture in many ways. There are several guides to remote setting, algal production, and other hatchery techniques (Helm & Bourne 2004, Kemp et al. 2006, Wallace et al. 2008, Cosgrove et al. 2009). The description of the oyster production process that follows is based on these guides and informed by restoration practices that are common in NY/NJ Harbor.

The oyster production process can begin either with adult oysters that serve as broodstock for spawning or with larval oysters acquired from a hatchery. If adult oysters are used as broodstock, they are first conditioned by feeding them a diet of cultured phytoplankton (Fig. S2). Once the oyster gonads have "ripened," spawning is induced by cycling warmer water through the environment (Fig. S3). After the eggs hatch, the developing larvae spend 7–14 days in a conical larval tank and are fed cultured phytoplankton (Fig. S4). Once larvae have developed an eye spot and have a shell height of roughly 290 μm (at which time they are called "eyed larvae"), they are introduced to a setting tank containing bagged shell or other structures (Fig. S5) (see Structures and Substrates, p. X). When larval oysters are acquired from a hatchery, they are introduced directly to the setting tank. Once they are in the setting tank, larvae settle and undergo metamorphosis, attaching to the hard substrate. Setting tanks are typically on a flow-through system and use seawater pulled from nearby sources, although the oysters may need supplemental feeding with algal pastes. Ideally, the juvenile oysters (i.e., spat) will be deployed to restoration sites after spending one to two weeks in the setting tank. Other times, they may be transferred to grow-out facilities, such as off-bottom floating or suspended nurseries, until they are ready for final deployment. In some cases, oysters have been held in grow-out facilities for more than a year before being transplanted to restoration sites. There is some evidence that these older and large oysters have higher survival rates, although the costs associated with holding and maintaining oysters in grow-out facilities are higher.

Prior to the formation of Billion Oyster Project (BOP), the staff of the New York Harbor School produced oysters for the 2010 Oyster Restoration Research Project in an outdoor remote setting facility located on Lima Pier on Governors Island. Starting in 2013, BOP moved most of its oyster production to the new Marine and Science Technology Center on Governors Island, which is also home to New York Harbor School classrooms and labs. In addition to indoor setting tanks, BOP also operates larger outdoor setting tanks in the warmer months. BOP is developing plans to pilot in situ setting methods, in which oyster larvae develop and are set on site.

NY/NJ Baykeeper has also operated several oyster production facilities in the region. Starting in 2005, the organization produced oysters at a facility located at Moby's Lobster Deck in Highlands, NJ, until it was destroyed by Superstorm Sandy in 2012. Today, NY/NJ Baykeeper has its aquaculture facilities at Naval Weapons Station Earle and produced roughly a quarter million juvenile oysters in 2013.

Although best practices typically advise the use of local genetic strains in restoration efforts, only three of the 20 projects that specified oyster source used local sources (i.e., adults collected within the estuary) (Appendix IV on page 46). A large majority of efforts, 19 of the 20 projects that specified oyster source, used larvae or broodstock from out-of-state sources. This dependence on non-local oyster sources is understandable due to the dearth of local sources, although it may have negative consequences for restoration success if non-local oysters are not adapted to local conditions.

Another concern regarding current restoration practice is the frequent use of aquaculture lineages and the fitness of these oysters for restoration purposes. Oysters selected for success in aquaculture (e.g., fast growth to market size in favorable conditions) may not have the suite of traits necessary for restoration success (e.g., successful reproduction and recruitment under stressful conditions). This research question is being actively pursued by Matt Hare of Cornell's Department of Natural Resources via reciprocal transplant experiments of oysters from several lineages throughout the NY/NJ estuary.

Most efforts to produce live oysters use recycled adult oyster shells for setting spat on shell (Fig. S6). In other estuaries, oyster processing facilities (i.e., shucking houses) may provide shell to restoration efforts. In NY/NJ Harbor, restaurants that serve oysters are the primary sources of shell. Since 2015, BOP has run a shell recycling program, initially in partnership with Earth Matter (an organic waste reduction and composting nonprofit) and now with Lobster Place (a New York City wholesale and retail seafood company). Nearly 70 restaurants in New York City set aside a total of 20 to 30 thousand pounds of shell each month to be recycled. After shells are collected, they are cured by exposure to natural air and light for several months at facilities in Staten Island and on Governors Island. Since 2015, more than 1,000,000 pounds of shell have been diverted from landfills and are instead destined for restoration purposes6. Participation in the shell recycling program is free for restaurants because the program's costs are covered by grant funding.

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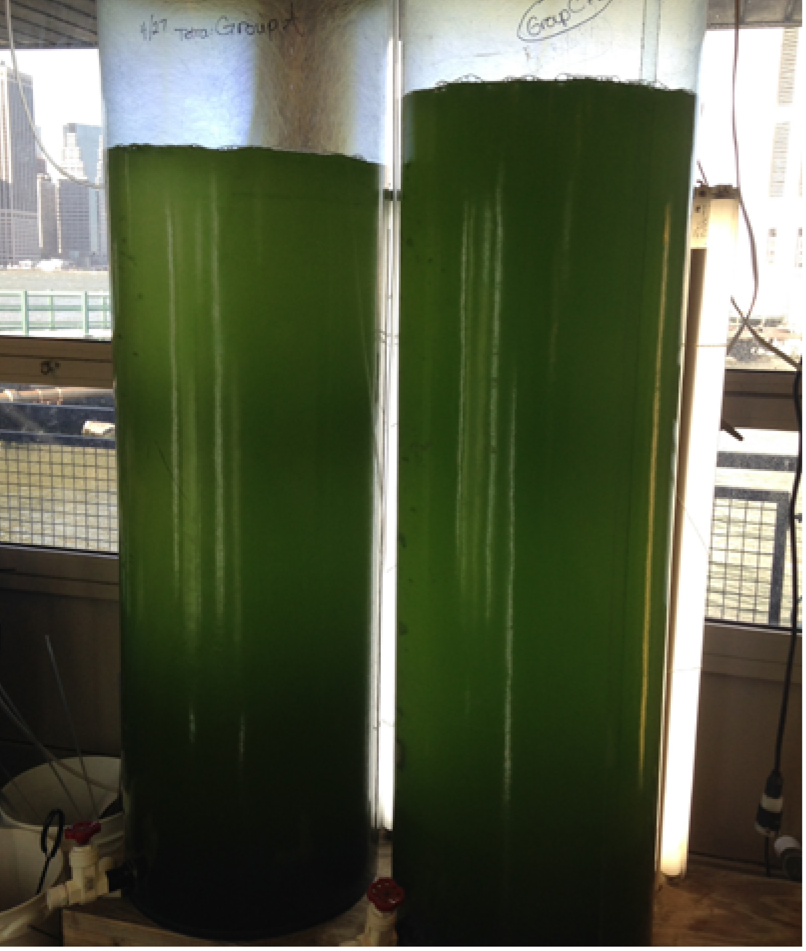

Figure S2. (top left) Phytoplankton are cultured in algae kalwal fiberglass tubes for use as a high-nutrient feed for conditioning adult oysters, larvae, and juveniles.

Figure S3. (top right) Shallow spawning tables with temperature-controlled inputs can be used to induce spawning in conditioned adult oysters.

Figure S4. (bottom right) Conical tanks with tapered bases hold free-swimming larval oysters and are equipped with bottom-valves to facilitate water changes.

Figure S5. (bottom left) A setting tank holds cured oyster shells or other structures to support larvae that are ready to settle (i.e., metamorphose). Juvenile oysters can be held for several days or a few weeks prior to deployment at the restoration site. A standpipe facilitates water changes.

Figure S6. A pile of oyster shells collected from restaurants in New York City by Billion Oyster Project is cured for several months on Governors Island, prior to use in restoration efforts.

APPENDIX VII. RESTORATION MONITORING AND PERFORMANCE METRICS

Monitoring is a necessary component of the restoration process. Monitoring provides data that can be used to assess whether restoration goals are being met and whether adaptive management needs to be implemented (McDonald et al. 2016). Monitoring uncovers drivers of restoration performance and allow comparisons of restoration activities in different geographic areas. Unfortunately, post-restoration monitoring does not often receive the attention or resources it deserves. In the Chesapeake Bay, only 43% of oyster beds were monitored after restoration (Kennedy et al. 2011). As a result, it is not possible to assess changes in oyster populations at many restored reefs.

A working group of shellfish scientists and restoration practitioners from The Nature Conservancy, the National Oceanic and Atmospheric Administration (NOAA), Florida Atlantic University, and University of South Alabama established standardized metrics to be used in the monitoring of all oyster restoration sites. Their recommendations are described in *Oyster Habitat Restoration: Monitoring and Assessment Handbook* (Baggett et al. 2014). Monitoring metrics are designated as "Universal Metrics" and "Universal Environmental Variables" that should be measured at every restoration site, "Ancillary Monitoring Considerations" that may be of interest depending on the project or research needs, and "Restoration Goal-based Metrics" that attempt to quantify the ecosystem benefits of restoration (Table S1). The *Monitoring and Assessment Handbook* recommends methods, sampling and experimental designs (e.g., before/after control-impact designs, stratified random sampling, determining sample size) (Baggett et al. 2014). It recommends that most of the Universal Metrics, which focus on characteristics of the oyster reef itself, be carried out for four to six years after restoration, or for a minimum of one to two years post-construction. This is likely a longer monitoring time frame than is used in most restoration projects. Among benthic restoration projects in NY/NJ Harbor, the average monitoring duration is 3.0 years, with a range of 9 months to 9 years (Appendix IV on page 46), meaning that most projects are not monitored for long enough. Fortunately, 100% of the projects received at least some post-restoration monitoring (Appendix IV on page 46).

For the most part, the *Monitoring and Assessment Handbook* offers general or qualitative performance criteria for assessing reefs rather than specific measures. For example, reef height is measured according to a performance criterion of "positive or neutral change." Shoreline gain/loss is measured as "a trend of decreasing shoreline loss, or shoreline gain, with a goal of having statistically less shoreline loss or greater shoreline gain than pre-construction conditions and at the control or reference site." The authors wisely do not suggest specific numbers such as a reef height of 100 cm or shoreline loss of less than 1 m per year; rather, they recommend that each project develop specific, quantitative performance criteria based on the site conditions and history.

In the Chesapeake Bay, the Oyster Metrics Workgroup, which consists of federal agencies (NOAA and U.S. Army Corps of Engineers), state agencies (Maryland Department of Natural Resources, Vir-

Table S1. Monitoring Recommendations from *Oyster Habitat Restoration: Monitoring and Assessment Handbook* (Baggett et al. 2014).

Type	Metric
Universal Metrics	Reef area: Project footprint
	Reef area: Total reef area
	Reef height
	Live oyster density
Universal Environmental Variables	Water temperature
	Salinity
	Dissolved oxygen
Ancillary Monitoring Considerations	Presence of predators or competitors
	Disease prevalence and intensity
	Oyster condition index
	Gonad development status
	Sex ratio
	Shell volume for determination of shell budget
	Percent cover of reef substrate
Restoration Goal-Based Metrics	Nearby reef density and size-frequency distribution
	Nearby reef large oyster abundance
	Density of selected species or taxa
	Shoreline loss/gain
	Shoreline profile/elevation change
	Density and percent cover of marsh/mangrove plants
	Seston and chlorophyll a concentration
	Light penetration

ginia Marine Resources Commission), academic scientists, and restoration practitioners, created quantitative successes metrics with targets and thresholds for oyster restoration at both the tributary and reef scale (Oyster Metrics Workgroup 2011). The group specified both *operational goals* for reef construction and *functional goals* for desired ecological outcomes. The metrics specify quantitative targets that take historical conditions into consideration. For example, the group set a *target* oyster density of 50 oysters and 50 grams dry weight per square meter covering at least 30% of the target restoration area, with a *minimum threshold* of 15 oysters and 15 grams dry weight per square meter on that same area. Tributary-level targets include metrics such as a minimum of 50% of currently restorable area constituting at least 8% of historic oyster habitat within a given tributary. Developing shared goals and agreed upon metrics is likely a challenging effort, especially when goal setting crosses multiple states. The efforts in the Chesapeake were spurred by Executive Order 13508, *Strategy for Protecting and Restoring the Chesapeake Bay Watershed*. Similar enabling conditions may not exist in other estuaries.

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APPENDIX VIII: OYSTER GARDENING IN NY/NJ HARBOR

Not all gardens need soil or produce vegetables. Some gardens produce oysters and hang from the end of piers, bulkheads, and docks. Oyster gardening is the volunteer stewardship of oysters in suspended or floating structures by non-professionals (e.g., community members, school groups) for aquaculture, restoration, or educational purposes. In some waters, gardeners may grow their oysters for consumption, but in the Hudson-Raritan Estuary, oyster gardening is solely for educational and restoration purposes.

These efforts began in 1997, when Ben Longstreth of NY/NJ Baykeeper started an Oyster Growth Study at 15 sites throughout the Harbor (NY/NJ Baykeeper 2006). Building on the success of this study, in 2000 Baykeeper started an oyster gardening program at 25 sites in New Jersey, with successful oysters eventually being transplanted to restoration sites in Keyport Harbor and the Navesink River. From 2006 to 2014, Baykeeper partnered with The River Project and New York Harbor School to expand the program to New York waters. Despite a setback in 2010 when the NJ Department of Environmental Protection banned oyster gardening and restoration in the state, over 140 organizations participated in the oyster gardening program between 2004 and 2014 (Table S2).

OYSTER GARDENING GENERATES DATA

In most oyster gardening programs, the stewards of each garden also collect data on the growth and survival of oysters. These efforts provide pilot data to inform the suitability of sites for larger restoration efforts. Of the oyster gardens that were active between 2004 and 2014, 79 recorded oyster shell height on more one occasion, and growth rates at these sites were calculated as the change in shell height divided by the number of days. To standardize comparisons, growth rates were only calculated for periods of 150 days or fewer and for gardens that were installed in June or July of a given year (to avoid including winter growth). Growth rates ranged from <0 to almost 0.65 mm d^{-1} with an overall average of 0.19 mm d^{-1} (± 0.14 SD, n = 53) (Fig. S7). Spatial patterns in growth rate are apparent, with high growth rates in the Lower Bay, low growth rates in the Arthur Kill/Kill Van Kull and Lower Hudson River, and substantial variation in the Harlem River, East River, and Western Long Island Sound region (Fig. S8).

Table S2. Organizations stewarding oyster gardens in NY/NJ Harbor between 2004 and 2014.

Organization Type	Number
Non-profit	30
School	26
Individual	25
Park	3
Business	3
Marina	2
Total	141

OYSTER GARDENING AS A PLATFORM FOR LEARNING

In addition to the restoration benefits of oyster gardening, the practice also has educational benefits for students and adults (Table S3). Oyster gardening creates an opportunity for volunteer stewards to access the waterfront; learn and teach about Harbor ecology, water quality, and other environmental issues; and create a sense of place (Krasny et al. 2014). Since 2014, oyster gardening in New York has been led by Billion Oyster Project (BOP). Funded by the National Science Foundation and in collaboration with academic research partners, this program aims to use oyster garden-

Table S3. Statistics for Billion Oyster Project Oyster Research Stations as of February 2019.

215 oyster research stations
534 published monitoring exhibitions (i.e., monitoring events)
585 team leads (adults)
761 team members (students)

ing and associated curricula to enhance learning and life outcomes for students who are historically underrepresented in the Science, Technology, Engineering, and Mathematics (STEM) fields. The oyster gardens, now dubbed "Oyster Research Stations," contain compartments for live oysters and mobile organisms and tiles to encourage the settlement of fouling organisms (Fig. S9). BOP's *Field Science Manual* contains five monitoring protocols that can be carried out by an entire class of middle school students during field exhibitions (BOP 2016).

While early oyster gardening efforts required gardeners to mail paper copies of data sheets to a central organization, today's gardeners can upload their data to a digital platform[7] so that data and learning can be shared among stewards. In addition to on-the-water stewardship and monitoring protocols, BOP created a curriculum that integrates oysters and Harbor ecology into STEM topics and aligns with New York State Learning Standards. Teachers receive monitoring training from BOP staff on Governors Island and participate in professional development opportunities throughout the year. Finally, students participating in the BOP Oyster Research Station program share their research findings at a symposium held on Governors Island at the end of each school year.

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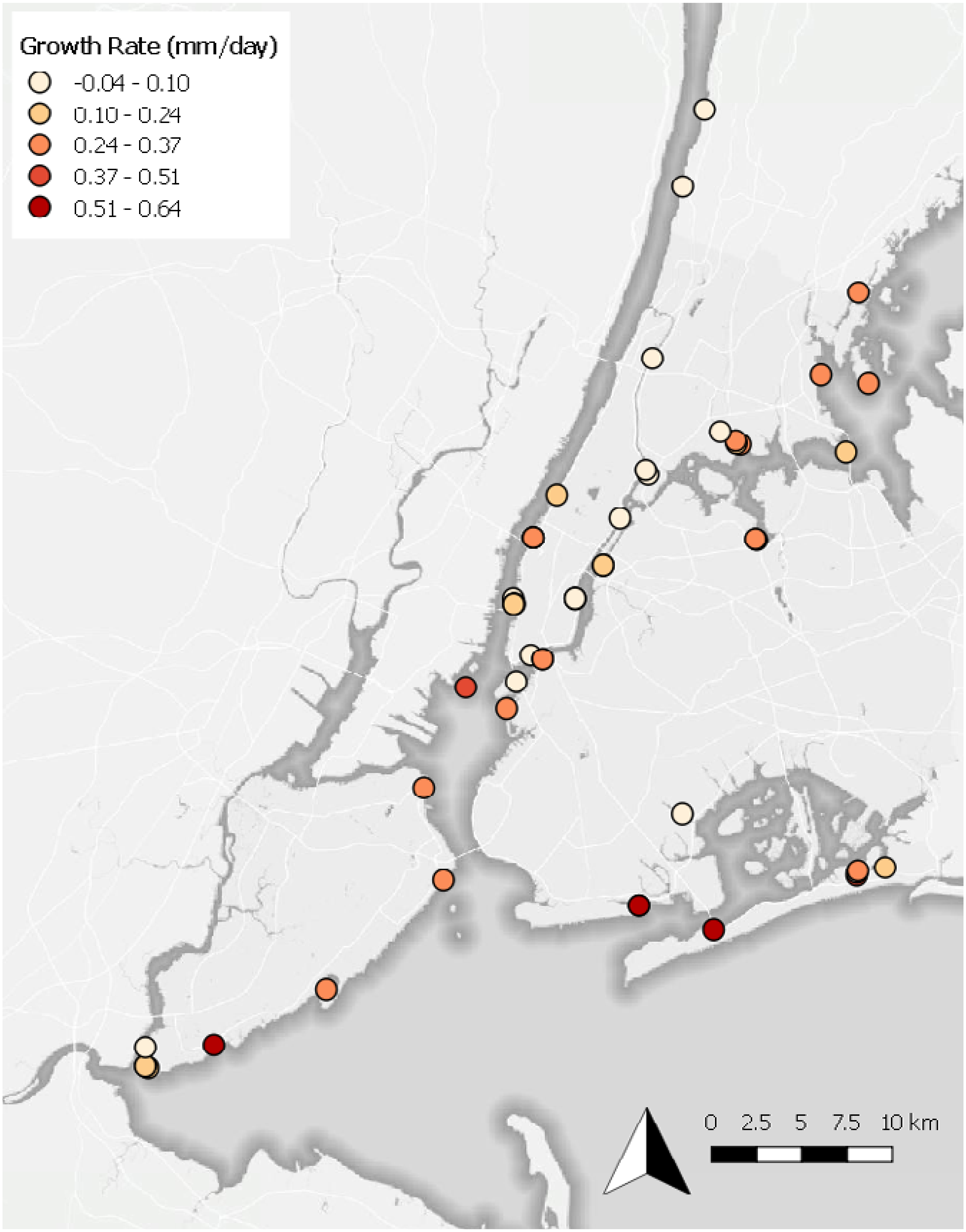

Figure S7. Shell height growth rates for gardens in the community science program run by NY/NJ Baykeeper, The River Project, and NY Harbor School 2004-2014. Growth rates are calculated for gardens started in June or July of a given year and calculated for periods up to 150 days to facilitate comparison.

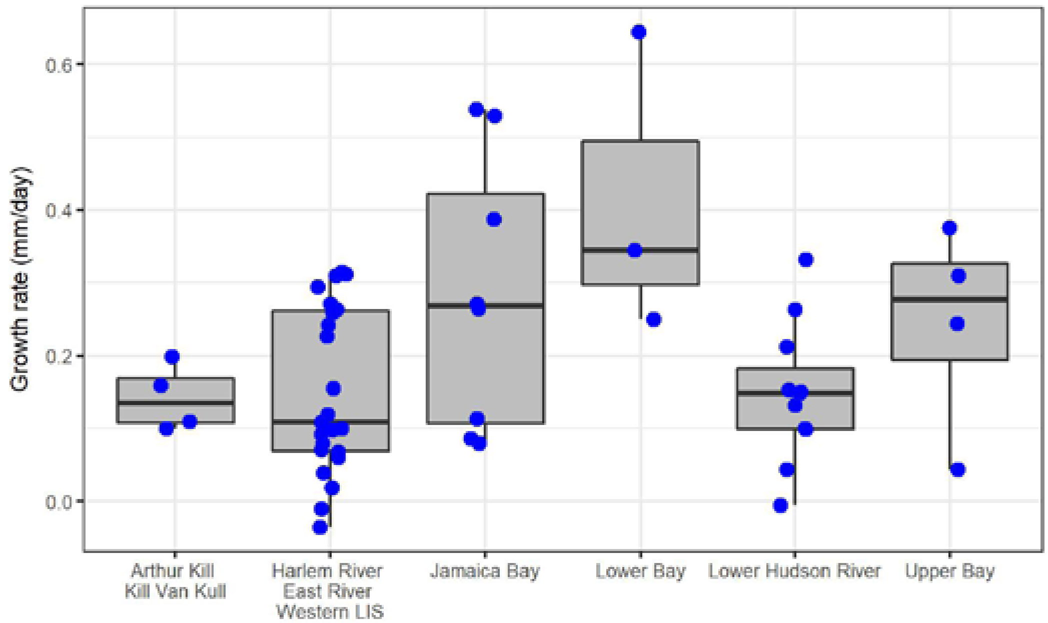

Figure S8. Shell height growth rates for gardens started in June or July of a given year and calculated for periods up to 150 days to facilitate comparison. Middle line of boxplots is the mean. Upper and lower edges are 75th and 25th quartiles. Individual data points are blue.

Figure S9. (from left to right) Tagged clump of oysters for monitoring; side and top views of an Oyster Research Station.

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