New York City Oyster Monitoring Report

2022

ABOUT BILLION OYSTER PROJECT

The mission of Billion Oyster Project is to restore oyster reefs in New York Harbor through public education initiatives. Oyster reefs contribute to several ecosystem services, including providing habitat complexity that enhances species biodiversity and abundance, improving water quality through filtration and sediment stabilization, and enhancing shoreline resilience and adaptation.

We envision a future in which New York Harbor is the center of a rich, diverse, and abundant estuary. The communities surrounding this complex ecosystem have contributed to its construction and, in return, benefit from it with endless opportunities for work, education, and recreation. The Harbor is a world-class public space, well-used and well-cared for—our Commons.

By 2035, Billion Oyster Project aims to create self-sustaining oyster populations by introducing 1 billion oysters, creating 100 acres of oyster reef habitat, and engaging 1 million people in their work.

To date, Billion Oyster Project has collected 2.5 million pounds of shells from restaurants. These shells provide habitat for oysters in the waters of New York City. Over 122 million live oysters have been reintroduced by the Billion Oyster Project in the waters of New York City, and over 11,000 NYC students have been engaged in the process.

RECOMMENDED CITATION

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ACKNOWLEDGEMENTS

Restoring New York Harbor takes a city! We are grateful to the thousands of students, educators, volunteers, partners, funders, and supporters who are making oyster restoration a reality. We thank all who contributed to a successful season of monitoring, maintenance, and data collection in 2022. We'd also like to specifically acknowledge the property managers for working with us to install these oyster reefs, and the many BOP Ambassadors and Volunteers for their support and efforts - thank you!

ORGANIZATIONS

New York City Department of Parks and Recreation
One°15 Brooklyn Marina
Brooklyn Bridge Park Conservancy
Brooklyn Bridge Park Corporation
Brooklyn Navy Yard
The Trust for Governors Island
Hudson River Park Trust
Princess Bay Boatmen's Association
Richmond County Yacht Club
Sebago Canoe Club
SUNY Maritime College

SUPPORTERS

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TABLE OF CONTENTS

INTRODUCTION

This is the fifth edition of the New York City Oyster Monitoring Report. The report was produced by Billion Oyster Project and summarizes the 2022 monitoring results of 12 oyster study sites (**Figure 1**, **Table 1**) in New York Harbor. Data were collected by academic partners, community scientists, students, teachers, etc., using protocols developed by Dr. Michael McCann from The Nature Conservancy. For more information about past oyster restoration projects, please refer to our annual reports, which are available on our website.

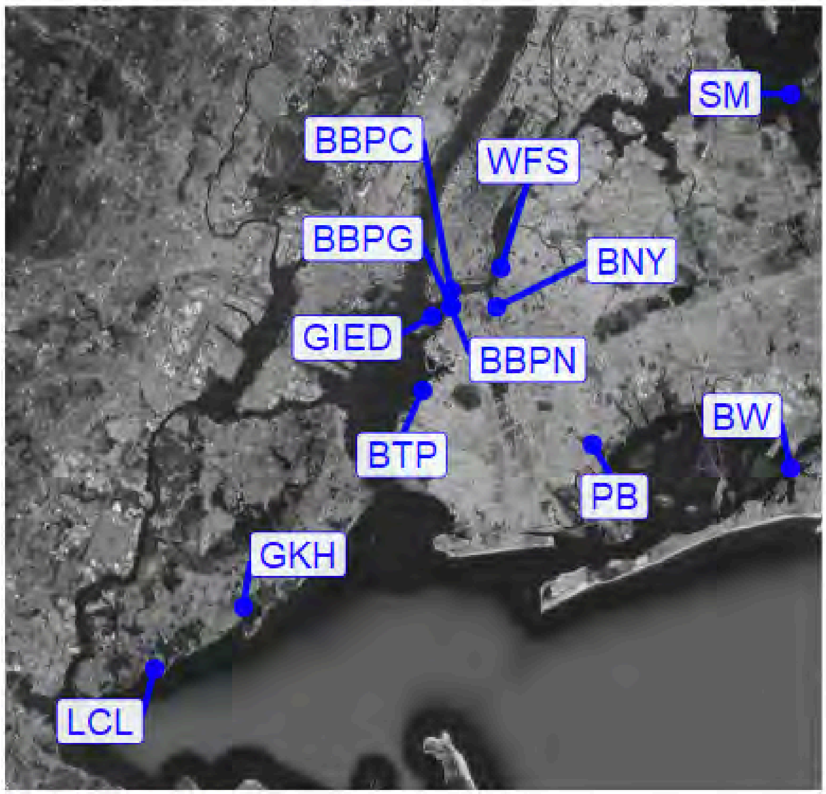

Figure 1. 2022 oyster restoration sites in New York Harbor described in this report. Refer to Table 1 for acronym definitions.

Billion Oyster Project deploys oysters in various restoration structures; refer to **Oyster Structures** and **Oyster Sources** (p. 6-8) for more information. For a quick overview of findings from 2022, refer to the **Main Findings** (p. 11) and **Site-Specific Findings** (p. 12). The remainder of the document summarizes the results of scientific monitoring in greater detail for each site and is intended for a technical audience. These sections are organized around specific topics, including **Performance Metrics** (p. 15), **Oyster Growth** (p. 16), **Oyster Survival** (p. 23), **Recruitment** (p. 26), **Water Quality** (p. 28), and **Biodiversity** (p. 36).

While this report focuses on active restoration sites maintained and monitored, it's important to note that Billion Oyster Project is also involved in other activities throughout the city. For example:

- Since 2015, school groups, various community groups, and individuals have been participating in Billion Oyster Project's Oyster Research Station program. Data from this program are not included in this report.
- In May 2021, Billion Oyster Project and New York Harbor School introduced 5,000 donated adult oysters to the Governors Island reef site in the Buttermilk Channel between Brooklyn and Manhattan as part of the Supporting Oyster Aquaculture and Restoration (SOAR) effort led by The Nature Conservancy and The Pew Charitable Trusts.
- In 2016, the New York City Department of Environmental Protection in partnership with Billion Oyster Project created oyster reef habitat at Head of Bay as part of their *Developing a Self-Sustaining Oyster Population* project in Jamaica Bay. The installation includes four reefs composed of a mix of bivalve shells and crushed porcelain within a one-acre site and for the first two years of the project, a system of floating cages holding ~40,000 adult oysters. The overall goal of the project was to establish a self-sustaining oyster population that could create a larvae source for Jamaica Bay. In 2018, the final year of the project, Billion Oyster Project deployed the adult oysters on two of the reefs. No oysters were deployed to the other two reef sites.

Large-scale oyster restoration projects in which Billion Oyster Project served as a sub-consultant in an oyster production capacity, such as those at Hudson River Park in Tribeca (north of Pier 26) and Gansevoort (south of Pier 54), are also not discussed in this report. Reports can be found on the Hudson River Foundation's website[1]. Other restoration projects in progress that Billion Oyster Project participates in include the Living Breakwaters and the long-running Soundview Reef oyster habitat restoration project. To learn more about the Living Breakwaters project, please visit the project website[2] for the most current update. Billion Oyster Project wrapped up the latest phase of oyster restoration at Soundview in September 2022[3]. Alongside partner organizations, Billion Oyster Project plans to conduct post-construction monitoring of the restored oyster reef at Governor Mario M. Cuomo/New NY Bridge Project at Tappan Zee.

[1] https://www.hudsonriver.org/article/hudson-river-foundation-publications
[2] https://stormrecovery.ny.gov/living-breakwaters-project-background-and-design
[3] Final report available upon request: contact jzhu@billionoysterproject.org

Oyster Structures

Billion Oyster Project applies oyster restoration techniques at each site based on site-specific conditions, project objectives, and our evolving understanding of best management practices for oyster restoration in a heavily urbanized city. These techniques include:

- **Bagged shell** (**Figure 2A**): individual plastic mesh bags that hold approximately 600 spat-on-shell and 0.3 cubic yards of material. Individual bags are placed within a 10’ x 6.6’ plot and secured with PVC pipes that are inserted on the outer edge of the plot.
- **Gabions** (**Figure 2B**): welded steel structures filled with spat-on-shell. Once installed, they act as surrogate reef structures in the absence of natural oyster reefs while the juvenile oysters grow, and create a multidimensional habitat for endobenthic, epibenthic, and hyperbenthic species. BOP has used three sizes of gabions (cube: 1’ x 1’, rectangle: 2’ x 1’, large: 4’ x 2’ x 2’).
- **SEAPA Cages** (**Figure 2C**): 20L baskets typically used in aquaculture to grow oysters, these structures are filled with spat-on-shell and suspended off-bottom in stacks of 2-3 to form nurseries.
- **Community Reef Cabinets** (**Figure 2D**): welded rebar frames that contain mesh files filled with oysters. Cabinet reefs facilitate hands-on programming by students and community members. These cabinets have a complex opening mechanism designed to deter poaching. BOP uses two sizes of cabinets, a 4’ x 2’ x 2’ welded rebar frame with 14 mesh files, and a 10’ x 2’ x 2’ with 28 mesh files.
- **ECOncrete® disks** (**Figure 2E**): 26 cm x 11 cm cast concrete units made of innovative concrete admixture and aggregate to encourage biofouling. Each disk weighs approximately 10-12 pounds.
- **SuperTrays** (**Figure 2F**): UV-resistant aquaculture plastic trays measuring 2’ x 2’. Super Trays are stackable and may be bridled together using ⅜ inch polypropylene line to facilitate setting in the remote setting facility or suspension from floating docks or piers.

Figure 2 A-F. Examples of structures previously used to install oysters: (A) bags, (B) mini-gabions, (C) OysterGros®, (D) community reef files, (E) ECOncrete® discs, and (F) Super Trays. (Photos courtesy of Finola Fung-Khee, Dr. Elizabeth Burmester, Robina Taliaferrow, and Dr. Michael McCann).

Oyster Sources

In 2022, Billion Oyster Project sourced larvae from Muscongus Bay Aquaculture (Maine, USA), and the MAST Center Hatchery in the Harbor School on Governors Island (New York, USA). Larvae are directly set to cured shells (recycled from partner restaurants, **Figure 3)** or other reef substrate in the Remote Setting Facility at Red Hook Terminals or the MAST Center Hatchery. The seeded structures are then deployed to permitted restoration sites. Wild oyster larvae may also recruit to restoration sites and set to the developing reef. For more information on the oyster life cycle and our shell collection process, please check out Billion Oyster Project's website.

Figure 3. This spat-on-shell was set at the hatchery on Governors Island. (Photo courtesy of Rebecca Resner)

OVERVIEW OF 2022 ACTIVITIES

All sites described in this report were permitted and installed by Billion Oyster Project. The number of oysters deployed to each site is summarized in **Table 1**. The list below summarizes updates or changes to activities and quantities since the issuance of the 2020-2021 New York City Oyster Monitoring Report:

1. Billion Oyster Project installed fourteen bagged shell seeded with live spat and six unseeded ECOncrete discs at the Williamsburg Field Station - Seawall Ledge site.
2. No data was collected from the cabinet reefs at the Williamsburg Field Station due to restriction of access by the landowner and site safety concerns.
3. Two community cabinets at Coney Island Creek were removed in December 2022 in compliance with permit conditions.
4. No monitoring occurred at the SUNY Maritime site in 2022 due to pier construction.

Table 1. Restoration structures and installation details.

Site	Structure	Install date	Larvae source *	Size at installation (shell height, mm)	Number of oysters installed
Brooklyn Navy Yard (**BNY**)	Super Tray Nursery	4/10/2017	Muscongus Bay, ME	34.9	2,750
Paerdegat Basin (**PB**)	Cabinet Reef	7/27/2018	Muscongus Bay, ME	~5	480,000
Great Kills Harbor (**GKH**)	Super Tray Nursery	8/23/2016	Muscongus Bay, ME	27.7	15,836
		6/12/2017	Oysters reared in Great Kills Harbor oyster cages	4.1	141,327
		7/10/2019	Muscongus Bay, ME	2-5	200,000
Lemon Creek Lagoon (**LCL**)	ECOncrete® Discs	8/15/2018	Governors Island Nursery Broodstock	~5	242,000
	Gabions	8/15/2018	Muscongus Bay, ME	~5	
	Bagged Shell Reef	8/15/2018	Muscongus Bay, ME; Governors Island Nursery Broodstock	~5	
Bush Terminal Park (**BTP**)	Cabinet Reef	6/28/2016	Muscongus Bay, ME	~2	969,452
	Cabinet Reef	8/22/2018	Muscongus Bay, ME; Governors Island Nursery Broodstock	~5	180,000
	Bagged Shell Reef	8/23/2018	Muscongus Bay, ME; Governors Island Nursery Broodstock	~5	135,000
SUNY Maritime (**SM**)	Super Tray Nursery	8/28/2019	Muscongus Bay, ME	<10	1,739,714
	Super Tray Nursery	8/10/2021	Muscongus Bay, ME	<10	2,570,689
Coney Island Creek (**CIC**) +	Community Reef	6/24/2021	Muscongus Bay, ME	2-5	117,772
Governors Island EcoDock (**GI**)	Super Tray Nursery	6/11/2022	Muscongus Bay, ME	<10	937,000
Bayswater Point State Park (**BW**)	Bagged Shell Reef	7/20/2020	Muscongus Bay, ME	~5	30,514
	Bagged Shell Reef	9/14/2020	Muscongus Bay, ME	2-5	384,235
Brooklyn Bridge Park Nursery (**BBPN**)	SEAPA Cage Nursery	8/28/2020	Muscongus Bay, ME	2-5	215,280
Brooklyn Bridge Park - One15 Marina	Cabinet Reef (**BBPC**)	9/8/2021	Muscongus Bay, ME	2-5	185,071
	Gabions (**BBPG**)	8/30/2021	Muscongus Bay, ME	2-5	588,861
Williamsburg Field Station (**WFS**)	Bagged Shell Reef	9/17/2021	Muscongus Bay, ME	2-5	270,000
		10/25/2022	Muscongus Bay, ME	2-5	36,735
	Cabinet Reef	9/15/2021	Muscongus Bay, ME	2-5	151,422

* See text for a complete explanation of oyster sources.
+ Due to regulatory requirements, all oysters installed at this site were removed at the end of the year.

2022 Main Findings

Oyster Growth & Mortality

Oyster growth trends are positive at sites monitored in both spring and fall. Generally, there is a decline in survival between spring and fall. Although oyster density typically decreases post-installation due to competition for space and expected mortality, the shell height of surviving oysters tends to increase beyond Year 1.

Wild Recruitment

Wild recruitment was observed in more than half of the sites that were monitored on a biannual frequency. The monitoring of wild recruitment at active restoration sites and as part of pre-construction monitoring of potential restoration sites is necessary to understand oyster population dynamics across a broader spatial and temporal scale.

Water Quality

While average dissolved oxygen levels were within the preferred range for oysters at most sites, some sites showed episodes of hypoxia, particularly BW, GI, and GKH. Salinity fluctuates throughout the year across all sites: the salinity fell below the optimal range for oysters at BBPN, BW, and GI, possibly due to episodic decreases of freshwater input. pH levels also fluctuated across all sites throughout the year, occasionally measuring in the lower end of the preferred range for oysters.

Biodiversity

A variety of infaunal, epibenthic, and mobile species rely on oyster reefs as a habitat in which to feed, reproduce, and shelter. Common species like oyster toadfish, blackfish, naked goby, barnacle, sea squirt, and mud crab were consistently observed at most sites.

Adaptive management is key to successful oyster restoration.

Although oyster restoration and research activities have been underway in NY/NJ Harbor for nearly two decades, it's still a newly developing restoration field. Therefore, an adaptive management approach, specifically, the ability to apply lessons learned from the data and monitoring results to pivot and make adjustments to protocols and restoration techniques, is essential. An example of adaptive management employed in 2022 is the annual replacement of mesh files at Brooklyn Bridge Park; the frequent handling of these structures by BOP staff, volunteers, and community groups during programmatic activities decreases the lifetime of each file. This necessitates maintenance or replacement of these files on an annual basis. A second example of adaptive management is the use of an alternative mesh material for a bagged shell reef. At the Williamsburg Seawall Ledge site, at which we piloted various restoration techniques in a high wave energy environment in 2020 and 2021, BOP used a biodegradable mesh for the bagged spat-on-shell units installed in 2022. This biodegradable material became newly available after the initial installation in 2021 and presented an opportunity for BOP to trial a new, non-plastic restoration technique.

Site-Specific Findings

Oyster nurseries are off-bottom installations that support small populations of juvenile and reproducing adult oysters. These oysters spawn and produce larvae, which may supplement existing populations of wild and restored adult oysters by providing larvae to adjacent restoration sites. Some nurseries also serve as short-term holding areas for juvenile oysters before their deployment to reef sites.

On-bottom reefs (below mean low water) feature hard substrate, seeded with juvenile oysters; these types of restoration projects seek to create complex, three-dimensional habitat, improve species biodiversity, and restore self-sustaining oyster populations. At these on-bottom reef sites, Billion Oyster Project monitors oyster growth, mortality, disease, and recruitment to better understand the development of the nursery and reef. Primary findings for our on and off-bottom installations are summarized below.

Nurseries

Brooklyn Bridge Park

In 2020, Billion Oyster Project established an oyster nursery consisting of thirty SEAPA cages, suspended off-bottom from the floating docks at One15 Marina. Continuous monitoring reveals a consistent trend of positive growth, high survival rates, and indications of natural recruitment within this nursery environment (**Figure 5**). These parameters suggest that conditions may be supportive of oyster restoration at this site. Measured dissolved oxygen and salinity concentrations are also within optimal ranges, with occasional fluctuations in salinity, which further indicates that conditions are conducive to oyster growth and survival.

Brooklyn Navy Yard

In 2017, Billion Oyster Project installed 200 Super Trays of adult oysters at this site. Due to construction in the adjacent basin, monitoring activities were not conducted at this site in 2022. Routine maintenance occurred.

Governors Island EcoDock

The EcoDock functions as a temporary nursery for oysters cultivated in the MAST Hatchery. Oysters are raised in stacks of Super Trays suspended from the dock until they are ready for deployment to other restoration sites. However, the constant movement of oysters and their eventual relocation pose challenges for regular monitoring at this site. Moreover, the high-energy environment exposes oysters to episodic hypoxia, fluctuations in salinity, and pH levels.

Great Kills Harbor

In 2016, Billion Oyster Project installed eight stacks of Super Trays beneath the pier at Richmond County Yacht Club, each containing three trays filled with adult oysters. Subsequent installations in 2017 and 2019 added six stacks each, filled with spat-on-shell. While oysters are growing, the site has grappled with significant mortality, attributed to an infestation of boring sponges. These parasitic organisms weaken oyster shells, resulting in heightened mortality rates. Despite optimal salinity ranges, oysters at this location may face stress due to periodic hypoxia.

SUNY Maritime College
Monitoring activities were suspended in 2022 due to construction on Olivet Pier, which necessitated the removal of 60 Super Trays of adult oysters from this site.

On-Bottom Reef Projects

Bayswater Point State Park
In 2020, Billion Oyster Project established a bagged shell reef consisting of 66 plastic mesh and coconut coir bags filled with spat-on-shell and 30 bags filled with blank shells. Oysters showed positive growth and recruitment during both spring and fall monitoring periods, although oyster survival declined slightly between the two seasons. Oysters experienced episodic hypoxia and fluctuations in salinity and pH levels at intertidal intervals.

Brooklyn Bridge Park - One15 Marina
In 2021, Billion Oyster Project set up a field station comprising three 4’ x 2’ x 2’ community reef cabinets with 14 files of spat-on-shell each cabinet near Pier 4 Beach, alongside a deepwater reef consisting of five 4’ x 2’ x 2’ gabions filled with spat-on-shell, situated offshore of Pier 4 in Brooklyn Bridge Park. Both installations are at or below mean low water. Oysters in the community reef cabinets displayed positive growth and signs of recruitment one-year post-installation. However, oyster survival notably declined between spring and fall monitoring, possibly due to oyster drill predation and frequent handling for community engagement. Oysters in the deepwater gabions also showed positive growth and signs of recruitment one-year post-installation, with high survival observed, although only one post-installation monitoring was conducted.

Bush Terminal Park
In 2016, Billion Oyster Project installed five 10’ x 2’ x 2’ community reef cabinets with files of spat-on-shell; in 2018, Billion Oyster Project expanded the footprint to include an additional five community reef cabinets with a new cohort of spat-on-shell. Also in 2018, Billion Oyster Project installed one bagged shell reef comprising 96 plastic mesh bags (66 bags filled with spat-on-shell and 30 bags filled with blank shells). Oysters exhibited positive growth across all structures. Survival varied across structures; the survival of cabinet oysters decreased between spring and fall monitoring but increased in the bags of oysters. Increased survival in the bagged shell reef may be due to larger sample sizes in the fall.

Coney Island Creek

In 2019, Billion Oyster Project installed a 10’ x 2’ x 2’ community reef cabinet in Coney Island Creek, near Kaiser Park. In 2021, staff replaced the cabinet with two smaller 4’ x 2’ cabinets, reducing the footprint. Oysters at this site displayed positive growth, a decrease in survival between seasons, and significant signs of recruitment.

Lemon Creek Lagoon

In 2018, Billion Oyster Project deployed three types of substrate at the site, including 36 ECOncrete® disks, twelve 1’ x 1’ x 1’ gabions, and a bagged shell reef with 96 bags. Despite positive oyster growth, no recruitment was observed across the structures. With high sedimentation occurring at this site, only a limited amount of structures were retrieved by staff and volunteers for monitoring. Hence, reported oyster density may not accurately reflect oyster survival at this site given the small sample size.

Paerdegat Basin

In 2018, Billion Oyster Project established five community reef cabinets measuring 10’ x 2’ x 2’, filled with both spat-on-shell and blank shells. Oysters at this site exhibited positive growth, with consistent survival rates observed across seasons.

Williamsburg Field Station

In 2021, Billion Oyster Project installed several structures at different depths and locations: one 2' x 2' x 2' field station cabinet suspended via davit, four on-bottom cabinets at North 1st Street Pier, thirty-six Intermas™ biodegradable mesh bags of spat-on-shell at the seawall ledge beneath Domino Park, and a 4’ x 2’ piling wrap at an esplanade piling. In 2022, six blank ECOncrete discs and fourteen plastic mesh bags of spat-on-shell were added to the site. While only one monitoring session occurred post-installation for the 2021 cohort, the bagged shell reef exhibited positive trends in oyster growth with high survival and recruitment. However, no monitoring was conducted for the piling wrap and field station cabinets. The piling wrap shifted from its original position and is now fully subtidal at the base of the piling, likely due to high-energy waves from the East River, and access to the field station cabinets was restricted.

PERFORMANCE METRICS

To assess the performance of oyster restoration and evaluate oyster survival, growth, and recruitment, Billion Oyster Project uses six metrics as Baggett et al. (2014) recommended. These metrics may translate to a qualitative analysis of performance: "good," "moderate," and "poor" performance. These metrics do not indicate whether the restoration activities are providing ecosystem benefits (e.g., ecological uplift or biodiversity enhancement, water quality improvements, etc.). Not all metrics can be applied to every site due to the type of site conditions, date of restoration installation activity, or age of restored oysters. Some metrics are not relevant in Years 1-2 post-construction. For example, the presence of more than one oyster-size class would not be expected in Year 0 or Year 1 at a site at which juvenile oysters were recently installed. The six performance metrics are described in **Table 2**. Disease and reproduction status were reported as performance metrics for oyster health in previous reports. Due to funding and staffing capacity, disease and reproduction status are not included in this year's report.

Table 2. Performance metrics for oysters at restoration sites.

Metric Category	Parameter and unit of measurement	Explanation	What indicates good oyster performance?
Growth	Shell height of oysters that are less than 6 months old (unit: mm/day)	Growth of spat is measured based on multiple spat shell height measurements during the first 6 months post-settling. Growth during this time is most rapid.	Spat growth equal to or faster than 0.25 mm/day is classified as rapid.
	Continued shell height of oysters that are greater than 6 months old (unit: mm)	The growth of older oysters is assessed based on less frequent measurements, typically performed once in spring and once in fall.	Average shell height increases within the growing season and between years.
	Oyster "reefing" or cementation (unit: count of oysters per clump)	As oysters increase in size, they should "reef" or cement to each other or other hard structures.	Oysters attached to each other and to restoration structures. This outcome is desirable at reef sites but not within nursery gear.
Survival	Density of live oysters: a) Live oysters per clump OR b) Live oysters per unit area (e.g., m^2) OR c) Live oyster per unit structure	As spat, oysters naturally have a high mortality rate. After an initial period of high mortality, survival increases, and the density of oysters (i.e., number of oysters per clump or number of oysters per m^2) should stabilize.	Oyster density stabilizes after initial mortality.
Recruitment	Multiple peaks on size distribution histograms	Size frequencies are calculated based on the total number of assessed oysters that are then classified into specific size groups.	On the histogram, more than one peak indicates the recruitment of new oysters. A much larger size of the smaller oysters' peak in comparison to the older oysters' can indicate the development of a sustainable reef.
	New spat = natural recruitment	Mature oysters produce larvae that are pelagic and swim in the water for 2-3 weeks. After, the larvae transition to the bottom, settling onto hard structures such as other oyster shells or rocks.	The presence of naturally recruited wild oyster spat.

Assessing Performance At Each Site

The oyster performance metrics were applied to the 12 restoration sites. Of those sites, four (Governors Island EcoDock, Great Kills Harbor, Lemon Creek Lagoon, and Bush Terminal Park) include multiple cohorts or restoration techniques. In those cases, the performance metrics are reported for each cohort or restoration technique. **Table 3** summarizes growth and survival at nursery sites, while **Table 4** summarizes growth and survival at on-bottom reef sites. Subsequent sections of this report describe in greater detail the oyster data used to complete this assessment and provide other environmental data that either describe oyster habitat suitability (e.g., water quality and biodiversity) or characterize other organisms at select sites.

Table 3. Oyster growth and survival performance metrics at nursery sites. NA = not applicable

Nurseries	Growth			Survival	Recruitment	
	Growth rate of oysters that are less than 6 months old	***Continued shell height of oysters that are greater than 6 months old***	***Oyster "reefing" or cementation***	***Density stabilizes after initial mortality, year to year***	***Multiple size classes***	***Spat on unseeded or off-reef structures***
Brooklyn Bridge Park - *SEAPA Cages* (2020)	**Slow** 8.2 mm (9/2020) 9.0 mm (10/2020) *0.03 mm/day*	**Yes** 19.2 mm (5/2021) 27.1 mm (10/2021) 31.3 mm (5/2022) 43.4 mm (10/2022)	**Yes**	**Declining** 50 oysters/clump (5/2021) 47 oysters/clump (10/2021) 4.9 oyster/clump (5/2022) 2.4 oysters/clump (10/2022)	NA	**Yes**
Brooklyn Navy Yard - *Super Trays* (2017)	NA (installed at 1+ year)	NA (insufficient data)	NA	NA (insufficient data)	NA	NA
Governors Island EcoDock - *Super Trays* (2022)	NA (insufficient data)	NA (oysters are <1 year old)	NA	NA (oysters are <1 year old)	NA	NA
Great Kills Harbor - *Super Trays* (2016)	NA (installed as 1+ yr)	**Yes** 84.2 mm (11/2017) 81.7 mm (6/2018) 105.3 mm (11/2018) 84.1 mm (7/2019) 97.9 mm (11/2019) 99.3 mm (11/2021) 127.4 mm (5/2022) 125.7 mm (10/2022)	**Yes** However, oysters were maintained to prevent them from cementing to gear.	**Declining** 200 live/tray (6/2018) 162 live/tray (11/2018) 41.3 live/tray (7/2019) 21.7 live/tray (11/2019) 6.8 live/tray (11/2021) 14.5 live/tray (5/2022) 10.4 live/tray (10/2022)	**Yes**	**No**
Great Kills Harbor - *Super Trays* (2017)	**Rapid** 4.1 mm (6/2017) 33.5 mm (9/2017) *0.35 mm/day*	**Yes** 44.3 mm (6/2018) 78.0 mm (11/2018) 87.1 mm (7/2019) 88.1 mm (10/2019) 119.6 mm (11/2021) 121.2 mm (5/2022) 120.3 mm (10/2022)		**Declining** 299 live/tray (6/2018) 287 live/tray (11/2018) 23.5 live/tray (7/2019) 19.0 live/tray (10/2019) 8.0 live/tray (11/2021) 6.2 live/tray (5/2022) 7.5 live/tray (10/2022)	**Yes**	**No**
Great Kills Harbor - *Super Trays* (2019)	NA (insufficient data)	**Yes** 110.7 mm (11/2021) 121.0 mm (10/2022)		**Declining** 21.3 live/tray (11/2021) 15.2 live/tray (10/2022)	**Yes**	**No**

Table 4. Oyster growth and survival performance metrics at on-bottom reef sites. NA = not applicable

Reefs	Growth			Survival	Recruitment	
	Growth rate of oysters that are less than 6 months old	***Continued shell height of oysters that are greater than 6 months old***	***Oyster "reefing" or cementation***	***Density stabilizes after initial mortality, year to year***	***Multiple size classes***	***Spat on unseeded or off-reef structures***
Bayswater Point State Park - *Bagged Shell Reef* (2020)	**Slow** 8.4 mm (9/2020) 14.1 mm (11/2020) *0.10 mm/day*	**Yes** 39.5 mm (5/2021) 52.2 mm (10/2021) 38.7 mm (5/2022) 42.8 mm (10/2022)	**No**	**Stable** 1.0 oysters/clump (5/2021) 1.2 oysters/clump (10/2021) 0.4 oysters/ clump (5/2022) 0.4 oysters/ clump (10/2022)	**Yes**	**Yes**
Brooklyn Bridge Park - *Cabinet Reef* (2021)	**Rapid** 5 mm (9/2021) 16.3 mm (10/2021) *0.25 mm/day*	**Yes** 14.6 mm (5/2022) 24.3 mm (10/2022)	**Light**	**Declining** 6.5 oysters/clump (10/2021) 4.1 oysters/ clump (5/2022) 1.3 oysters/ clump (10/2022)	**Yes**	**Yes**
Brooklyn Bridge Park - *Gabion Reef* (2021)	NA (insufficient data)	**Yes** 19.6 mm (8/2022)	NA	NA (insufficient data)	NA	NA
Bush Terminal Park - *Bagged Shell Reef* (2018)	**Moderate** 5 mm (7/2018) 20 mm (11/2018) *0.20 mm/day*	**Yes** 33.7 mm (6/2019) 50.2 mm (7/2019) 109.4 mm (5/2021) 92.6 mm (10/2021) 56.6 mm (5/2022) 83.9 mm (7/2022) 89.4 mm (10/2022)	**Yes**	**Slight Decline** 1.3 oysters/clump (5/2021) 0.1 oysters/ clump (5/2022) 0.6 oysters/ clump (7/2022) 0.5 oysters/ clump (10/2022)	**Yes**	**No**
Bush Terminal Park - *Cabinet Reef* (2016)	**Rapid** 2 mm (6/2016) 8.34 mm (7/2016) *0.30 mm/day*	**No** 119.3 mm (6/2019) 74.6 mm (7/2019) 107.6 mm (5/2021) 92.6 mm (10/2021) 128.4 mm (5/2022) 127.0 mm (7/2022) 110.5 mm (10/2022)	**Yes**	**Slight Decline** 0.6 oysters/clump (5/2021) 0.4 oysters/clump (10/2021) 0.9 oysters/clump (5/2022) 0.5 oysters/clump (7/2022) 0.4 oysters/clump (10/2022)	**Yes**	**No**
Bush Terminal Park - *Cabinet Reef* (2018)	**Rapid** 5 mm (8/2018) 23.7 mm (10/2018) *0.30 mm/day*	**No** 33.3 mm (6/2019) 40.6 mm (7/2019) 107.6 mm (5/2021) 92.6 mm (10/2021) 76.0 mm (5/2022) 73.9 mm (10/2022)	**Yes**	**Stabilizing** 0.3 oysters/clump (10/2021) 0.5 oysters/clump (5/2022) 0.5 oysters/clump (10/2022)	**Yes**	**No**
Coney Island Creek - *Cabinet Reef* (2021)	**Rapid** 5 mm (6/2021) 41.9 mm (10/2021) *0.31 mm/day*	**Yes** 47.7 mm (10/2021) 45.3 mm (5/2022) 49.1 mm (10/2022)	**Yes**	**Stabilizing** 3.4 oysters/clump (4/2021) 0.8 oysters/clump (5/2022) 1.1 oysters/clump (10/2022)	**Yes**	**Yes**
Lemon Creek Lagoon - *ECOncrete®* (2018)	**Rapid** 5 mm (8/2018) 45.9 mm (11/2018) *0.47 mm/day*	**Yes** 54.00 mm (5/2019) 103.4 mm (11/2019) 101.5 mm (7/2020) 108.9 mm (10/2020) 106.7 mm (4/2021) 111.7 mm (5/2022) 107.9 mm (10/2022)	**Moderate**	**Declining** 7.3 live/disc (7/2020) 14.3 live/disc (10/2020) 10.5 live/disc (4/2021) 1.0 live/disc (5/2022) 4.3 live/disc (10/2022)	**Yes**	**Yes**
Lemon Creek Lagoon - *Gabions* (2018)	**Rapid** 5 mm (8/2018) 36.4 mm (11/2018) *0.34 mm/day*	**No** 48.6 mm (5/2019) 88.9 mm (11/2019) 101.4 mm (10/2019) 93.1 mm (7/2020) 109.3 mm (5/2022) 97.8 mm (10/2022)	**Yes**	**Declining** 23.7 live/m^2 (10/2020) 7.5 oysters/clump (5/2022) 1.0 oysters/ clump (10/2022)	**Yes**	**Yes**

Lemon Creek Lagoon - *Bagged Shell Reef* (2018)	**Moderate** 5 mm (8/2018) 22.8 mm (11/2018) *0.20 mm/day*	**Yes** 49.3 mm (7/2019) 65.0 mm (11/2019) 77.7 mm (7/2020) 94.0 mm (10/2020) 114.4 mm (4/2021) 45.9 mm (5/2022) 69.6 mm (10/2022)	**No**	**Declining** 0.7 oysters/clump (4/2021) 0.3 oysters/clump (5/2022) 0.1 oysters/clump (10/2022)	**Yes**	**Yes**
Paerdegat Basin - *Cabinet Reef* (2018)	**Rapid** 5 mm (8/2018) 39.1 mm (12/2018) *0.25 mm/day*	**Yes** 41.1 mm (5/2019) 52.3 mm (8/2019) 57.4 mm (7/2020) 59.7 mm (10/2020) 67.4 mm (5/2021) 92.0 mm (10/2021) 78.0 mm (5/2022) 78.6 mm (10/2022)	**Yes**	**Stabilizing** 0.9 oysters/clump (5/2021) 0.8 oysters/clump (10/2021) 0.7 oysters/clump (5/2022) 0.8 oysters/clump (10/2022)	**Yes**	**No**
Williamsburg Field Station - *Cabinet Reef* (2021)	**Slow** 4.4 mm (11/2020) 5.1 mm (12/2020) *0.034 mm/day*	NA (insufficient data)	NA	NA (insufficient data)	NA	**Yes**
Williamsburg Field Station - *Bagged Shell Reef* (2021)	NA (insufficient data)	**Yes** 21.8 mm (10/2022)	**Light**	NA (insufficient data)	NA	**Yes**
Williamsburg Field Station - *Bagged Shell Reef* (2022)	NA (insufficient data)	NA (oysters are <1 year old)	NA	NA (oysters are <1 year old)	NA	**Yes**

Size Frequency Distribution

Oysters are expected to survive and grow over time (**Figure 4**), although smaller oysters may experience higher mortality rates. As variability exists within a site (e.g., oyster density and specific location on the reef) and among individual oysters (e.g., genetic variations), these differences are likely to become more noticeable as the oysters grow. To visually analyze these changes, Billion Oyster Project uses smoothed density plots or histograms, which are adjusted for differences in sample sizes. These plots allow for easy assessment of oyster growth or the impacts of other factors by comparing graphs from different sampling periods, structures, or cohorts.

In the case of a single cohort of oysters of similar age, their shell heights are expected to follow a normal distribution, forming a bell-shaped curve with a single peak and two nearly symmetrical tails. However, if there are multiple cohorts (different age groups) of oysters present in a single sample, two peaks, not necessarily of equal size, may be visible. When comparing data from different sampling dates, it is not uncommon to observe smaller oysters in later samples than those noted in earlier samples. This could be due to slow growth during specific periods or because only a portion of the oyster population is sampled. Additionally, the appearance of smaller oysters in later samples may also be a result of the emergence of a new cohort on an established reef due to natural recruitment and settlement.

To assess these patterns, size frequency distributions of three nursery sites and eight on-bottom reef sites are presented as smooth density plots in **Figures 5 - 7** and **8 - 15**, respectively. These plots allow for a visual understanding of the growth patterns and size distribution of oysters at the monitored locations, providing valuable insights into the dynamics of the oyster populations in different environments.

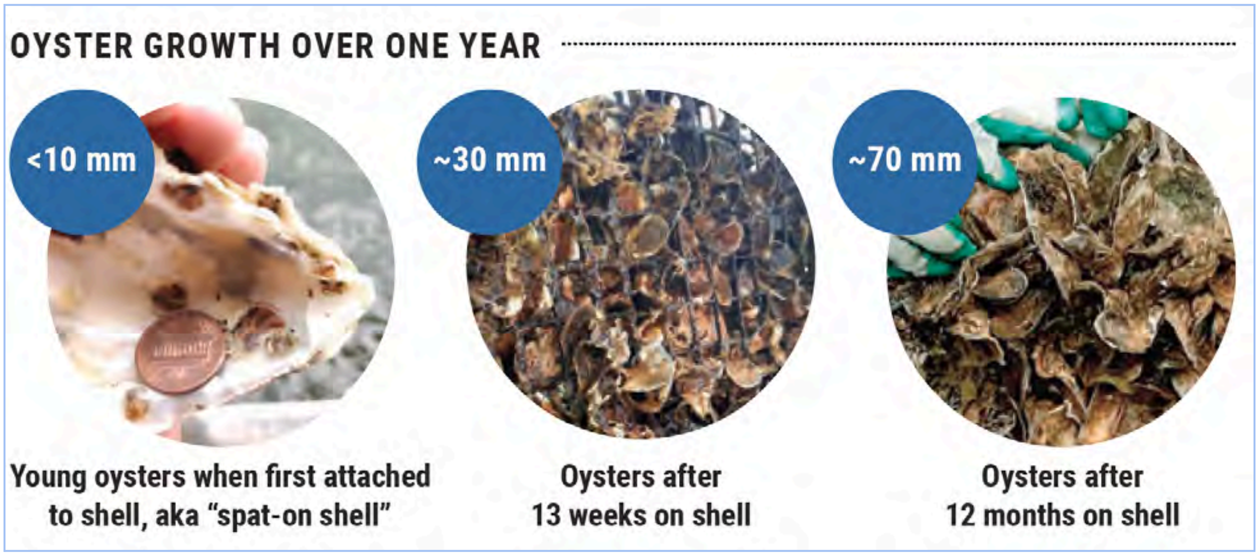

Figure 4. These photos show oyster growth in the first year of restoration at sites with fast growth. (Photos courtesy of Billion Oyster Project Staff)

Nurseries

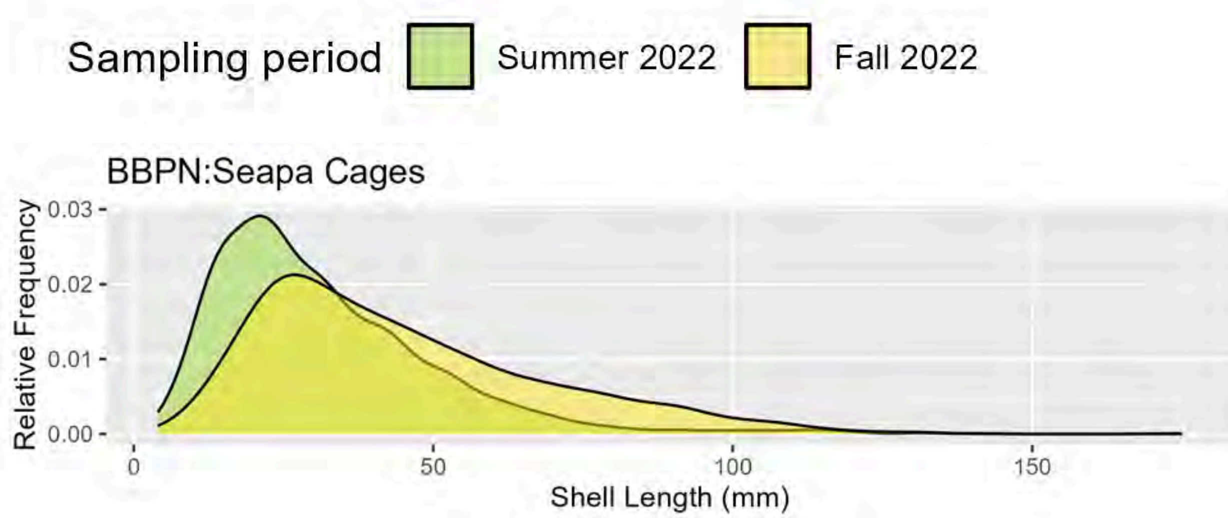

Figure 5. Size frequency distribution graph shows increasing shell length for a single cohort at Brooklyn Bridge Park, One15 Marina Nursery (BBPN).

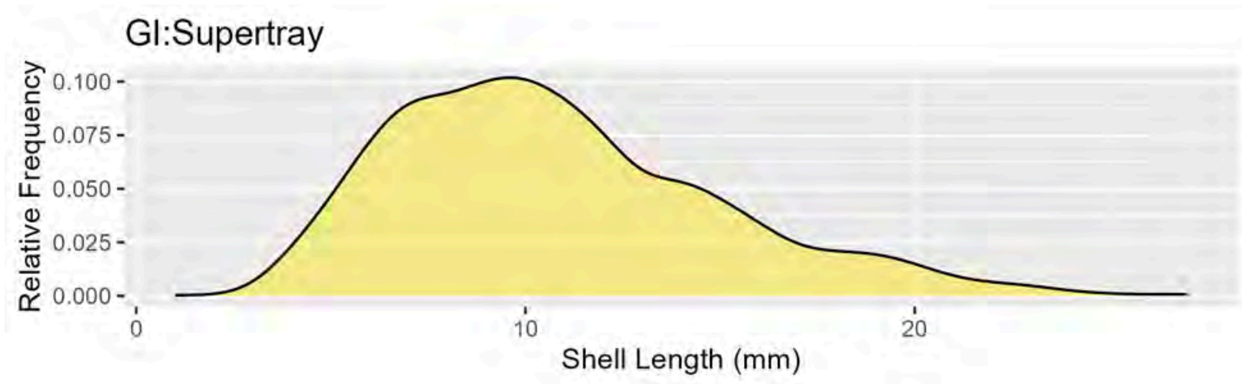

Figure 6. Size frequency distribution graphs of oysters grown over the summer at Governors Island Ecodock (GI) before being deployed to ORS cage or restoration sites.

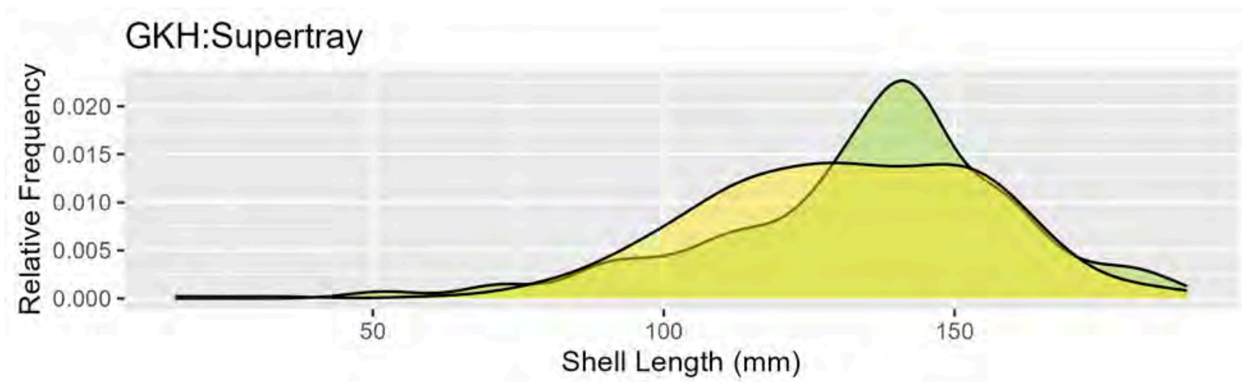

Figure 7. Size frequency distribution graph shows a stable shell length over two monitoring seasons for a single cohort at Great Kills Harbor Nursery (GKH).

On-Bottom Reef Projects

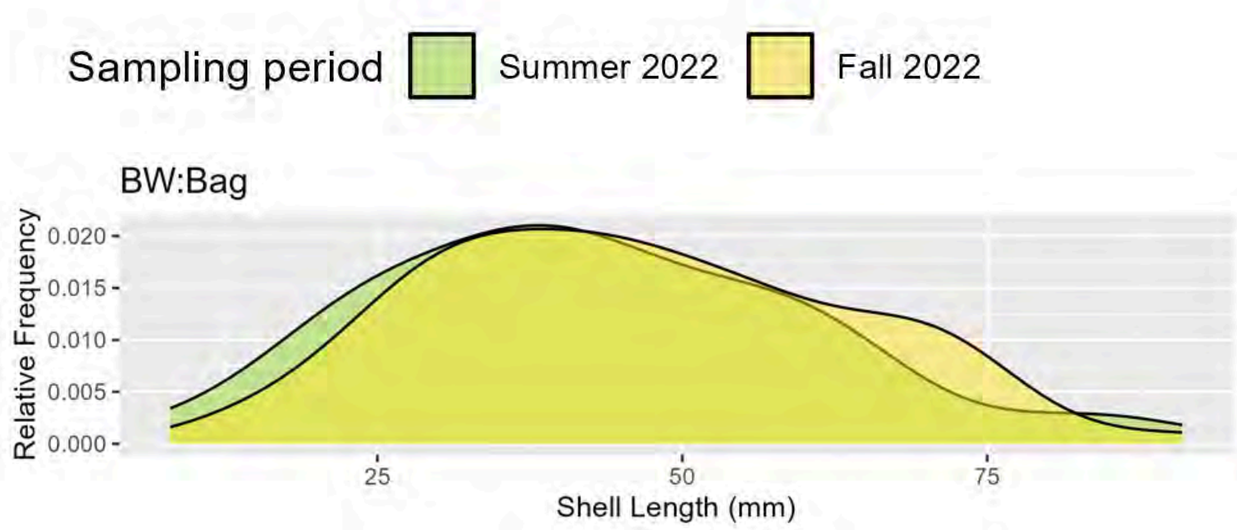

Figure 8. Size frequency distribution graph shows increasing shell length over two monitoring seasons for a single cohort at Bayswater Point State Park (BW).

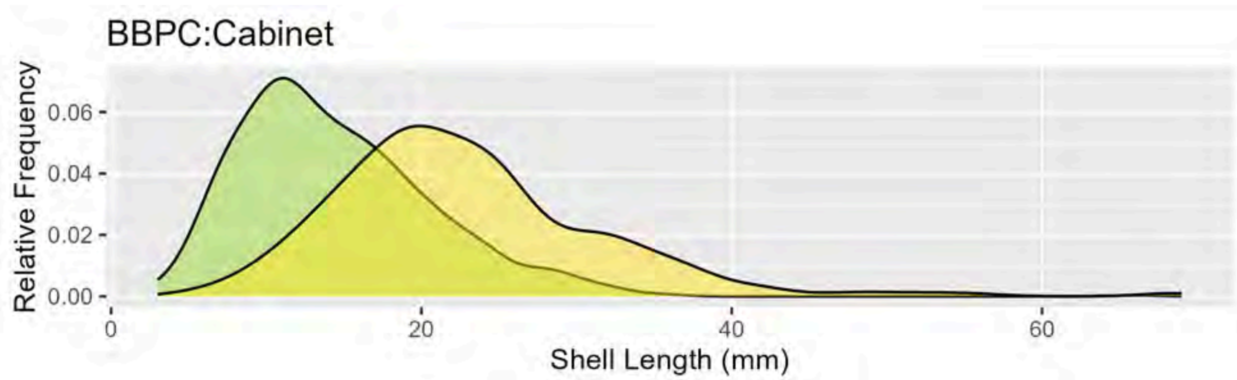

Figure 9. Size frequency distribution graph shows increasing shell length over two monitoring seasons for the cabinet cohort at Brooklyn Bridge Park (BBPC).

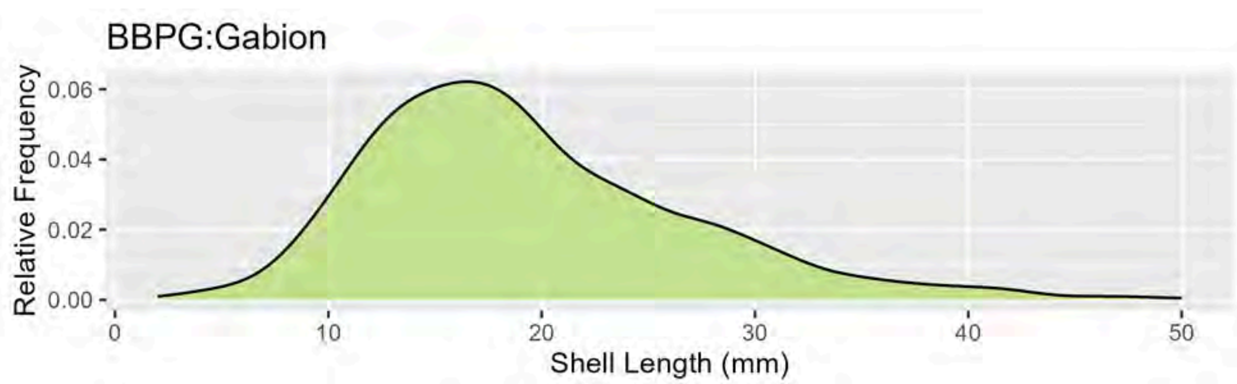

Figure 10. Size frequency distribution graph of oysters from 5 subtidal gabions at Brooklyn Bridge Park (BBPG).

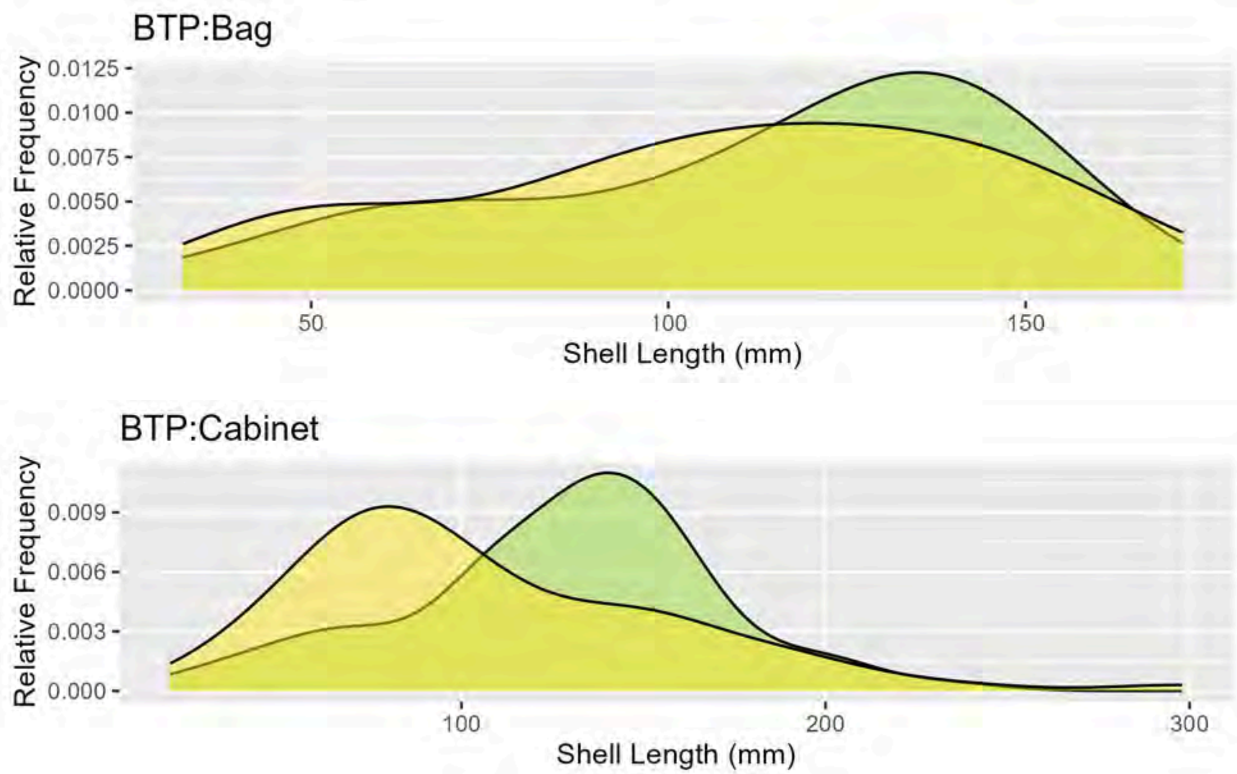

Figure 11. Size frequency distribution graph shows signs of wild recruitment in the bagged shell reef and cabinets over two monitoring seasons for oysters at Bush Terminal Park (BTP).

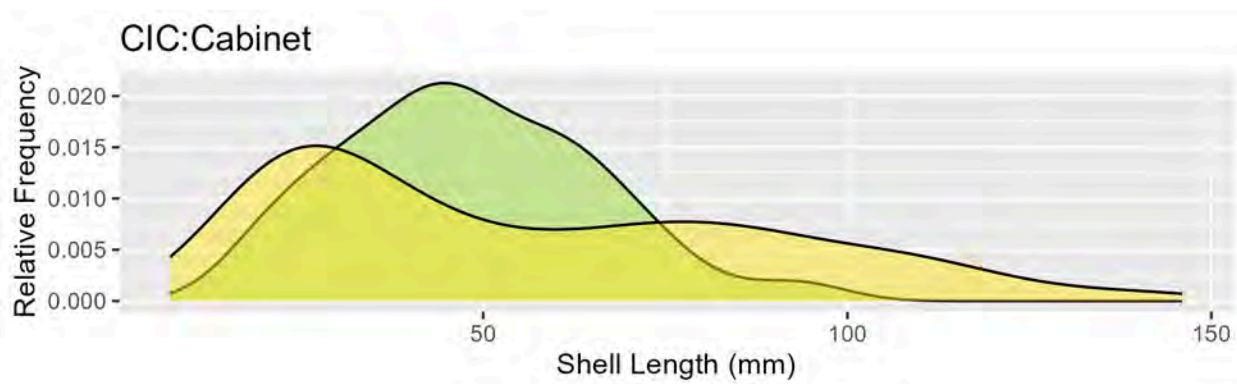

Figure 12. Size frequency distribution graph shows an increasing shell length and wild recruitment over two monitoring seasons for a single cohort at Coney Island Creek (CIC).

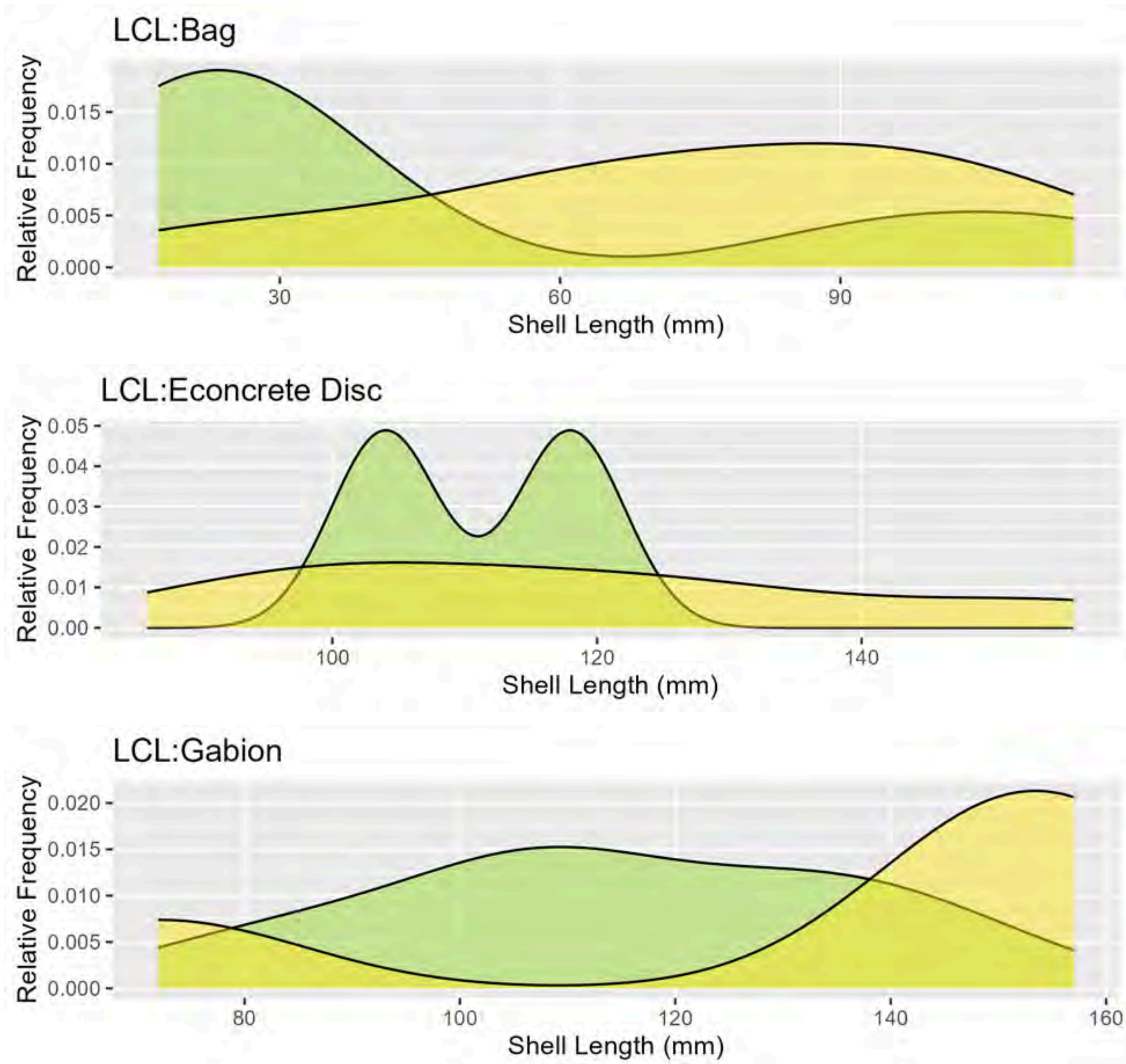

Figure 13. Size frequency distribution graphs show an increasing shell length over two monitoring seasons for oysters in all structures at Lemon Creek Lagoon (LCL).

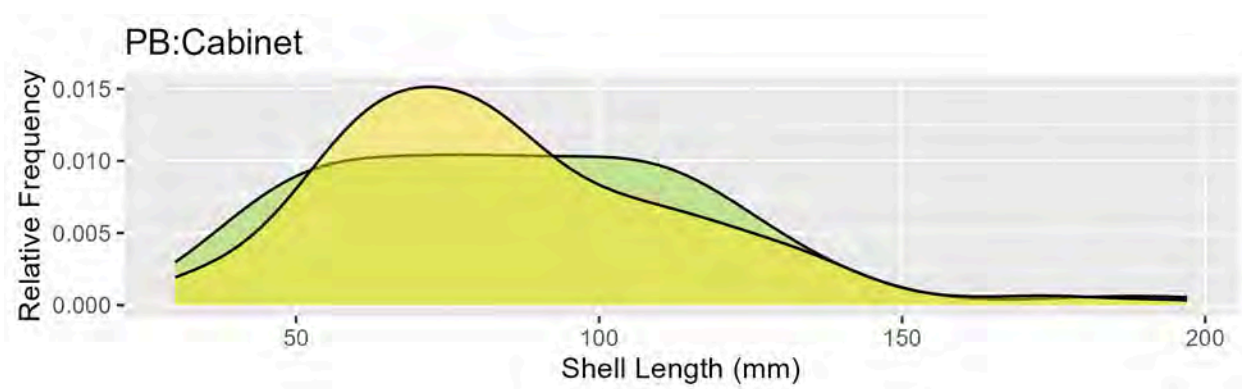

Figure 14. Size frequency distribution graph shows a stabilizing shell length over two monitoring seasons for a single cohort at Paerdegat Basin (PB).

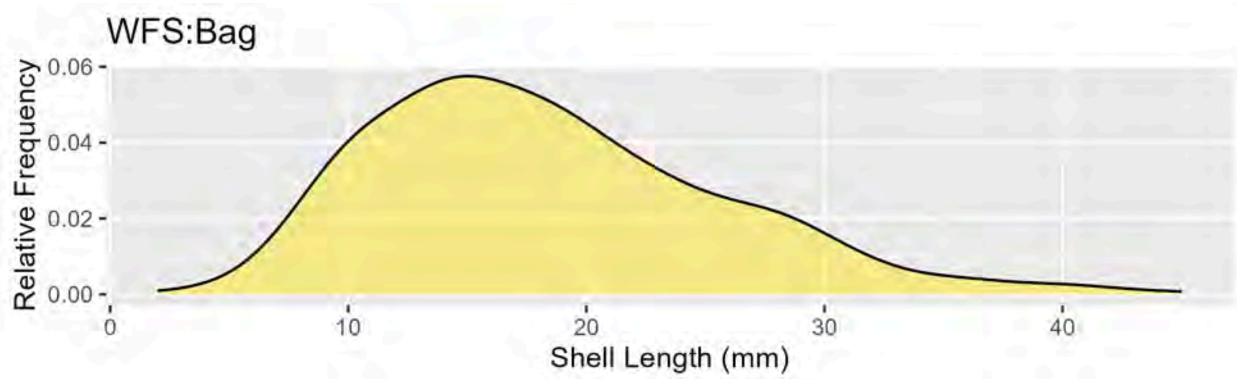

Figure 15. Size frequency distribution graph of oyster shell length at Williamsburg Field Station (WFS).

Oyster Survival

Like growth, oyster survival is an important metric in understanding the success of oyster restoration, but it can be difficult to track over time as oyster reefs become more spatially complex and as new recruits settle to the reef.

Juvenile oysters, called spat, attach to hard substrate in high densities. These spat grow quickly over the first 1–2 years of life, but as they grow they must also compete for space. As a result, only a few oysters are expected to survive. On an individual basis, mortality is thus expected to be greatest in the first several years after installation. As oysters grow, the mortality rate of mature individuals should decline and stabilize over time. Target density for oysters may vary depending on the type of reef structure and the structure's maintenance requirements. Mortality can be measured in several ways, depending on the reef structure, pace of oyster growth, and accretion:

(1) *Live oysters per "clump"*: this technique focuses on post-installation spat survival in the new environment. A clump is defined as a group of oysters growing on a single shell. It is typically used during spat counts before and shortly after installation and before oysters grow through mesh openings and attach to reef structures. Ideally, the density of live oysters per clump stabilizes over time. Billion Oyster Project utilized this technique at the following sites:
   - Brooklyn Bridge Park (nursery and cabinet reef)
   - Bush Terminal Park
   - Bayswater Point State Park
   - Governors Island Ecodock
   - Lemon Creek Lagoon (bagged shell reef)
   - Paerdegat Basin Community Reef
   - Williamsburg Field Station

(2) *Live oysters per unit structure*: this technique determines the density of live oysters within a structure of known volume that is not suitable for overgrowth. Because neither live oysters per "clump" nor density (i.e., per square meter) is an accurate indicator, density is determined using a volumetric approach. Ideally, stabilization of the density of live oysters per unit structure stabilizes over time, with wild recruitment observed. Billion Oyster Project utilized this technique at the following sites:
   - Great Kills Harbor
   - Lemon Creek Lagoon (ECOncrete® discs and mini gabions)

Live Oyster Per "Clump"

It is typical for oyster survival and density to decline over time due to competition for space and food. This pattern is evident across most sites, except for the Bush Terminal Park and

Bayswater Point State Park bagged shell reefs, Coney Island Creek and Paerdegat Basin community cabinets (**Table 5**). At Bush Terminal Park, the bagged shell reef appears to be fostering oyster recruitment, resulting in increased oyster density and survival across seasons. The rise in oyster density at Bayswater Point State Park, Coney Island Creek, and Paerdegat Basin sites may be attributed to larger sample sizes in the fall monitoring while oyster survival shows a consistent decline over seasons.

Previous reports suggest that oyster density usually stabilizes at around 1–2 live oysters per clump. However, at Bush Terminal Park, Bayswater Point State Park, Lemon Creek Lagoon, and Paerdegat Basin, the number of live oysters per clump is notably low, averaging less than one oyster per clump in all super trays (**Table 5**). This could be due to the frequent handling of oysters at BTP and oysters being inundated with soft mud or sediment at the latter three sites, resulting in high oyster mortality.

Table 5. Oyster density (i.e., live oyster per clump) at Brooklyn Bridge Park Nursery (BBPN), Brooklyn Bridge Park Gabions (BBPG), Brooklyn Bridge Park Cabinets (BBPC), Bush Terminal Park (BTP), Bayswater Point State Park (BW), Coney Island Creek (CIC), Governors Island EcoDock (GI), Lemon Creek Lagoon (LCL) bagged shell reef, Paerdegat Basin (PB), and Williamsburg Field Station (WFS). ND = no data and n = total sample size.

Site	Structure Type and Year of Installation	Live Oysters Per Clump			% Survival		
		Spring	Summer	Fall	Spring	Summer	Fall
BBPN	*SEAPA Cages 2020*	**4.89** (n = 2670)	ND	**2.39** (n= 1827)	**93.40%**	ND	**88.23%**
BBPG	*Gabion 2021*	ND	**5.08** (n = 761)	ND	ND	**88.17%**	ND
BBPC	*Cabinet 2021*	**4.11** (n = 966)	ND	**1.34** (n = 912)	**85.60%**	ND	**41.56%**
BTP	*Bagged Shell 2018*	**0.09** (n = 32)	**0.60** (n = 48)	**0.51** (n = 54)	**6.25%**	**38.78%**	**48.21%**
	Cabinet 2016/2018	**0.67** (n = 76)	**0.46** (n = 78)	**0.46** (n = 169)	**56.76%**	**43.90%**	**40.00%**
BW	*Bagged Shell 2020*	**0.40** (n = 112)	ND	**0.41** (n = 215)	**33.93%**	ND	**29.77%**
CIC	*Cabinet 2021*	**0.77** (n = 180)	ND	**1.08** (n = 516)	**76.67%**	ND	**62.98%**
GI	*Super Trays 2022*	ND	ND	**5.41** (n = 2423)	ND	ND	**80.31%**
PB	*Steel Cabinet 2018*	**0.70** (n = 120)	ND	**0.76** (n = 199)	**70.00%**	ND	**69.85%**
LCL	*Bagged Shell 2018*	**0.26** (n = 32)	ND	**0.10** (n = 73)	**24.24%**	ND	**9.46%**
WFS	*Bagged Shell 2021*	ND	ND	**2.87** (n = 274)	ND	ND	**94.16%**
	Bagged Shell 2022	ND	ND	**3.39** (n = 443)	ND	ND	**63.04%**

Live Oysters Per Unit Structure

To determine live oysters per unit structure at Lemon Creek Lagoon sites, Billion Oyster Project assessed all oysters on each ECOncrete® disk and the faces of a subset of mini gabions. The increase in live oysters per unit structure for Great Kills Harbor and ECOncrete disks at Lemon Creek Lagoon was not due to new recruitment but rather an increase in sample size between spring and fall (**Table 7**). The spike in oyster survival on the ECOncrete disks at Lemon Creek Lagoon was likely influenced by the larger sample size. Oysters in the mini gabions of Lemon Creek Lagoon experienced significant mortality due to high sedimentation at the site.

Table 7. Oyster density (i.e., live oysters per unit structure) at Great Kills Harbor (GKH), Lemon Creek Lagoon (LCL) ECOncrete disks and mini gabion.

Site	Structure Type and Year of Installation	Live Oysters Per Unit Structure		% Survival	
		Spring	Fall	Spring	Fall
GKH	*Super Trays 2016/2017/2019*	**9.89** (n = 151)	**11.50** (n = 749)	**58.94%**	**36.85%**
LCL	*ECOconcrete 2018*	**1.00** (n = 3)	**4.25** (n = 29)	**50.00%**	**58.62%**
	Mini-Gabion 2018	**7.50** (n = 30)	**1.00** (n = 69)	**50.00%**	**5.80%**

Wild Recruitment

The presence of juvenile oysters, or "recruits," is a positive indicator of progress toward a self-sustaining oyster population (**Figure 16**). While it is difficult to determine without genetic testing if the young recruits at a site are the offspring of the restored oysters or wild oysters, their presence indicates that site conditions are suitable for larval transport and survival. For example, the juvenile oysters observed on intertidal rocks at Coney Island Creek are not the offspring of the restored oyster population at that site, as they were less than one year old and therefore not yet reproductively mature. The recruits' presence, however, indicates that a naturally occurring source population is nearby and that site conditions are supportive of larvae development and spat settlement.

Figure 17 displays wild recruitment (oyster shell height less than 15 mm) observed at selected BOP restoration sites across the harbor. Data sources vary and include informal surveys of the substrate adjacent to restored reefs or nurseries, such as intertidal rip-rap or bulkheads, as well as "unseeded" restoration structures like ECOncrete® discs or bagged shell not set with larvae in the hatchery. Among the sites listed in **Figure 17**, no recruitment was observed at Bush Terminal Park, Paerdegat Basin, or Great Kills Harbor.

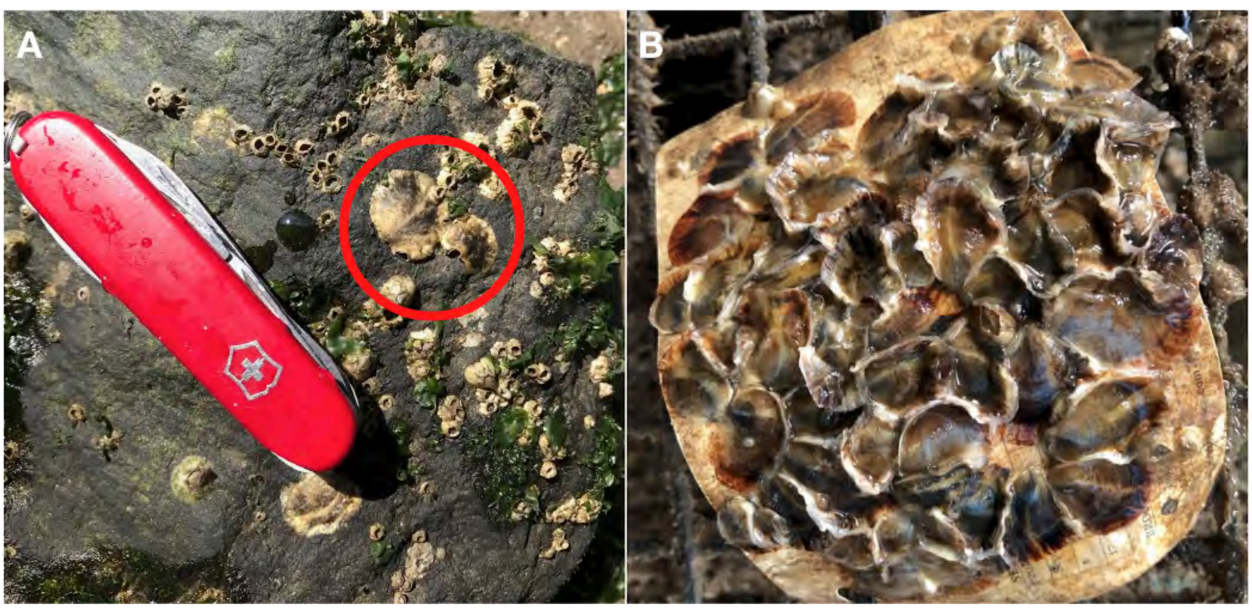

Figure 16. (A) Wild oyster recruits circled in red, along with barnacles and anemones, on intertidal rocks adjacent to the Coney Island Community Reef in summer 2018 (Swiss Army multitool for size comparison), and (B) wild oyster recruits seen at West Harlem Piers Park at 125th Street in Manhattan.

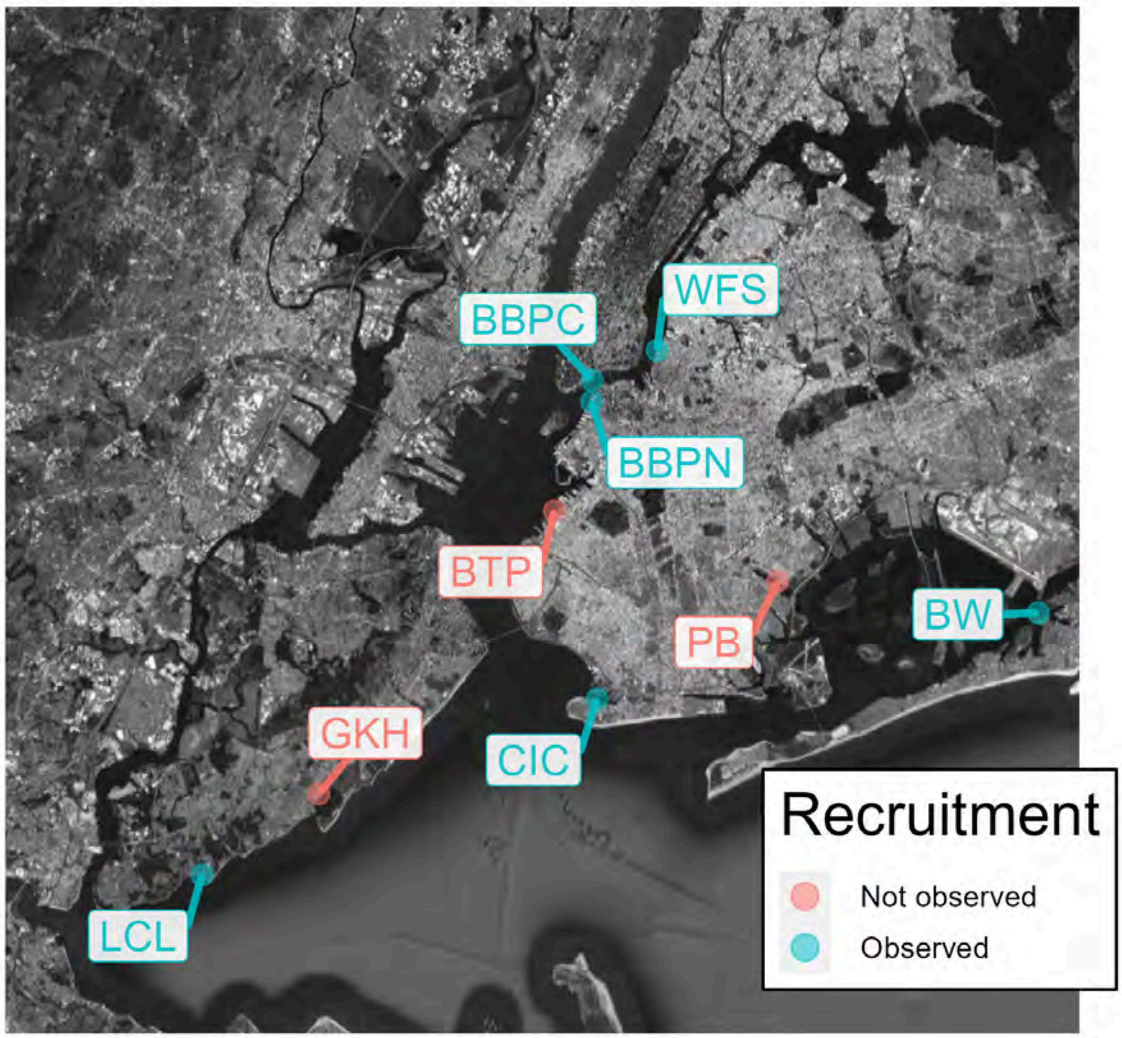

Figure 17. Map of restoration sites where wild recruitment (shell length <15 mm) was observed. Sites in red did not show recruitment, while sites noted in blue observed wild oyster recruitment.

WATER QUALITY

Oysters influence and are influenced by water quality, and monitoring water quality is essential to identify environmental conditions that favor oyster survival, growth, and reproduction.

Extreme events, such as hypoxia or low dissolved oxygen, can significantly impact the success of oyster restoration more than average water quality conditions. These extreme events are often challenging to detect using traditional monitoring methods, which rely on regular site visits that may miss critical events that occur at specific times, such as low oxygen levels at night or early in the morning. To overcome this limitation, Billion Oyster Project deploys Onset HOBO water quality loggers (models U-24, U-26, and MX 2501) that continuously record temperature, salinity, dissolved oxygen, and pH data at 15-minute intervals at field sites.

In 2022, loggers deployed at four sites collected continuous water quality measurements, including water temperature (**Figure 18**), dissolved oxygen (**Figure 19**), and salinity (**Figure 20**), values. Only two sites collected continuous pH (**Figure 21**) values due to the limited equipment availability. Billion Oyster Project staff actively maintained the deployed loggers throughout the field season to prevent fouling and sediment build-up, retrieve data, and recalibrate the sensors using an independent water quality measurement with a Horiba U-52 multiparameter instrument. These independent measurements served as point water quality references for comparison.

It is important to note that due to differences in the deployment and maintenance schedule, adherence to quality assurance protocols, and exclusions of specific time periods, the data collected from the sites may not span the same time periods. The Onset HOBOware Pro software was used to compute salinity values from conductivity data, while the Horiba instrument collected water temperature values and field check values. The software also adjusted the dissolved oxygen values based on the salinity time series, considering adjustments for fouling.

By collecting continuous water quality data, Billion Oyster Project gains valuable insights into the dynamic changes in environmental conditions that may affect oyster populations and helps in making informed decisions regarding oyster restoration efforts.

Continuous Water Quality Measurements

Water temperature data presented in this report were collected using conductivity loggers. The average water temperature values at BBPN, BW, and GI exhibited a steadily increasing trend in the summer, followed by a decreasing trend in the fall (**Figure 18**). Due to growing concerns about fish die-offs in late summer 2022, water quality loggers were placed at GKH to collect baseline water quality data. GKH also displayed a decreasing water temperature trend compared to the other sites.

Concerning dissolved oxygen levels, the average values at most sites appear to be suitable for oysters, being greater than 5 mg/L (**Figure 19**). However, some sites experienced episodes of low dissolved oxygen levels (hypoxia), which can be harmful to oysters, with levels dropping below 3 mg/L in BW, GI, and GKH (**Figure 19**).

In terms of salinity, all sites encountered significant salinity fluctuations, with BBPN, BW, and GI falling below the suitable range (approximately 20 – 25 ppt) for oysters (**Figure 20**). The changes in salinity from site to site were likely influenced by episodic decreases, possibly attributed to freshwater input from rain events. GKH was the only site that did not experience the episodic decrease, possibly due to its southern location compared to the other sites and its exposure to higher salinity from interactions with the Atlantic Ocean.

After long-term storage, the pH loggers needed some technical maintenance and calibration before they were deployed in late summer at BW and fall at GKH. Both sites had pH values that approached the lower threshold for suitability of 7.5 in the summer and early fall (**Figure 21**). If these low pH values persist during other times of the year, they may pose a threat to oysters at these sites (Brown & Hartwick 1988).

Continuous monitoring of water temperature, dissolved oxygen, and salinity is crucial to understanding the environmental conditions that oysters face in their habitats. These data help in evaluating the suitability of restoration sites and provide insights into potential stressors that oyster populations may encounter, such as hypoxia events and fluctuations in salinity.

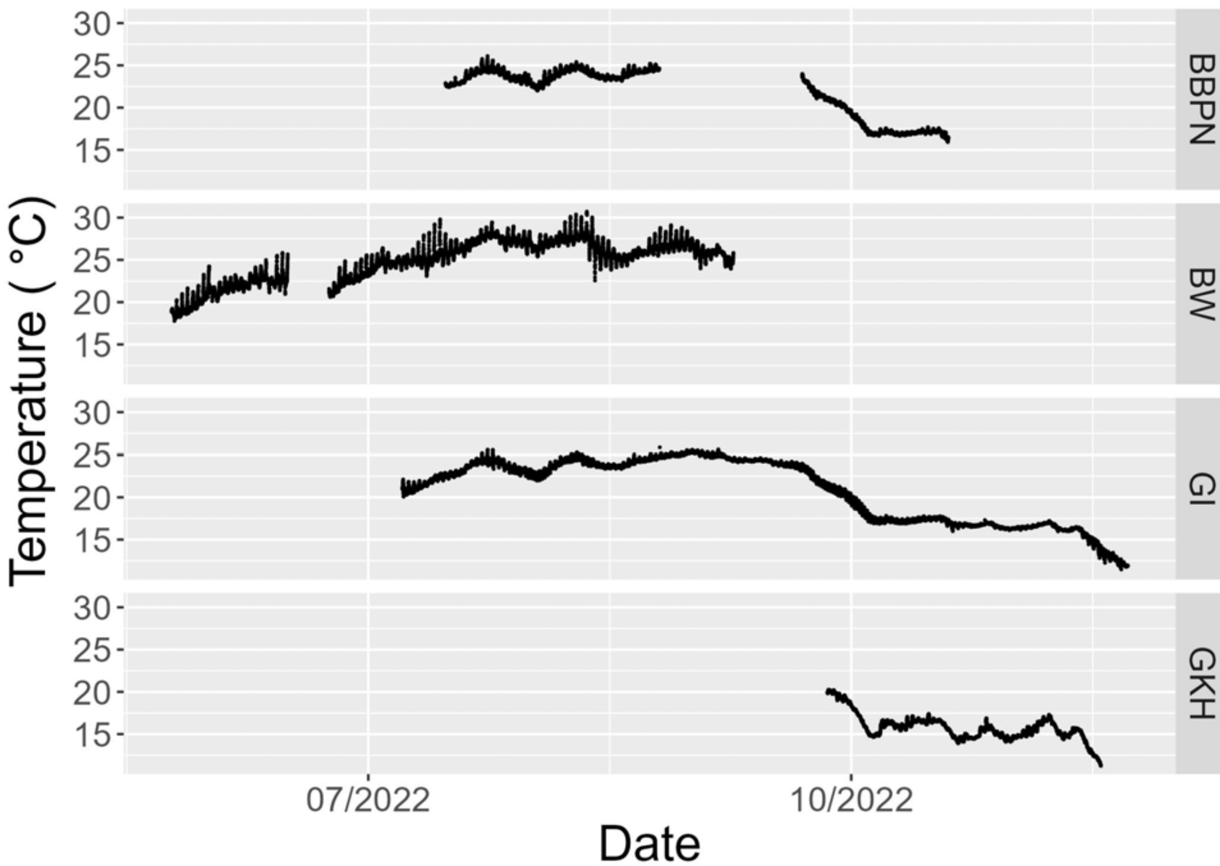

Figure 18. High-resolution (recorded every 15 minutes) water temperature data for Brooklyn Bridge Park Nursery (BBPN), Bayswater Point State Park (BW), Governors Island Ecodock (GI), and Great Kills Harbor (GKH).

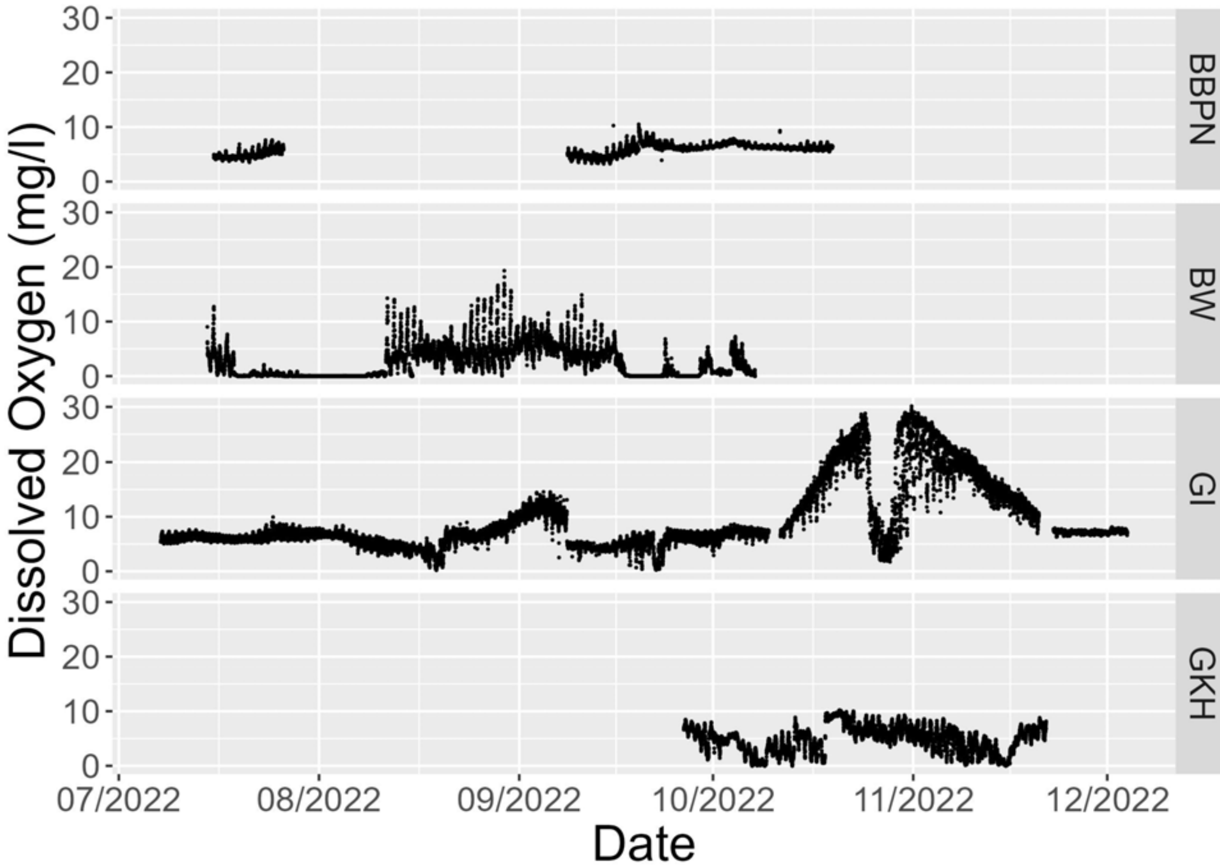

Figure 19. High-resolution (recorded every 15 minutes) dissolved oxygen for Brooklyn Bridge Park Nursery (BBPN), Bayswater Point State Park (BW), Governors Island EcoDock (GI), and Great Kills Harbor (GKH).

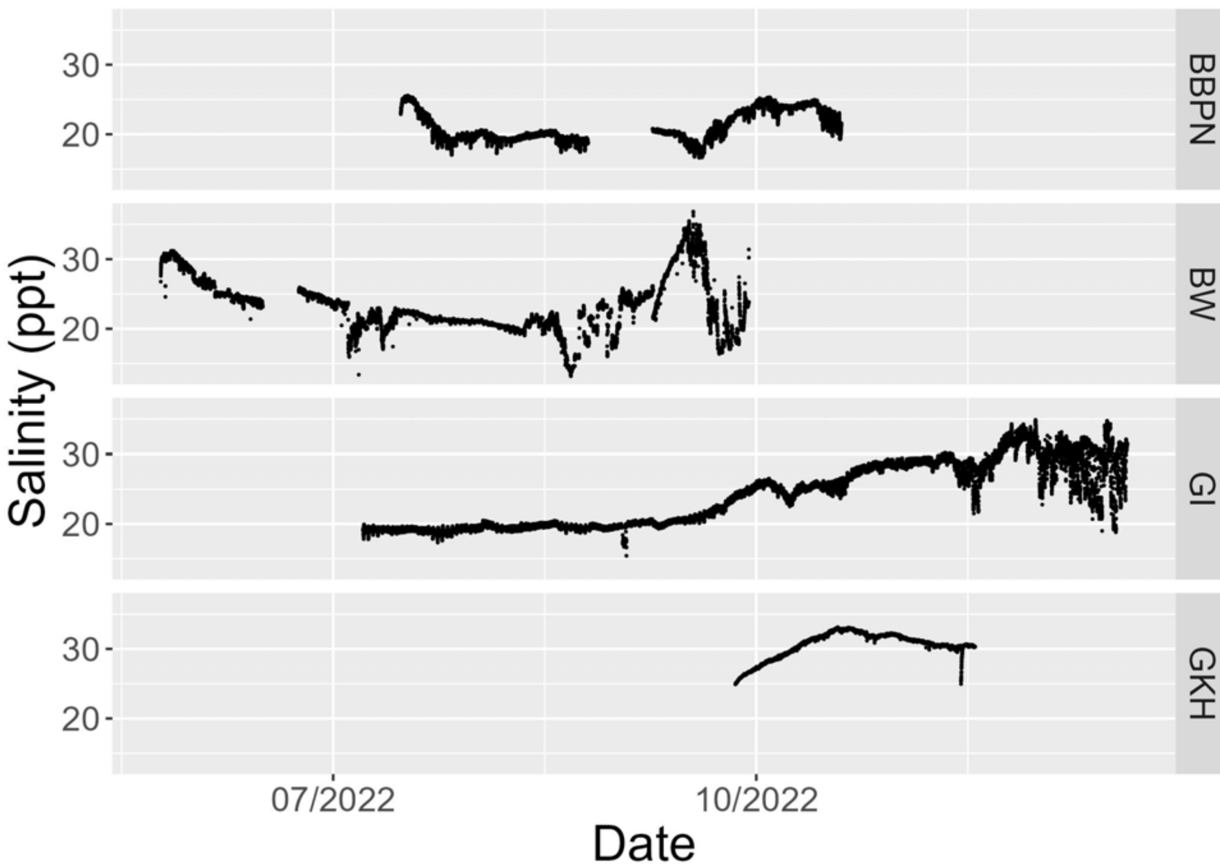

Figure 20. Salinity data for Brooklyn Bridge Park Nursery (BBPN), Bayswater Point State Park (BW), Governors Island Ecodock (GI), and Great Kills Harbor (GKH). Salinity data was calculated using high-resolution conductivity and water temperature data (recorded every 15 minutes) and default factory settings of Onset HOBOware Pro Software.

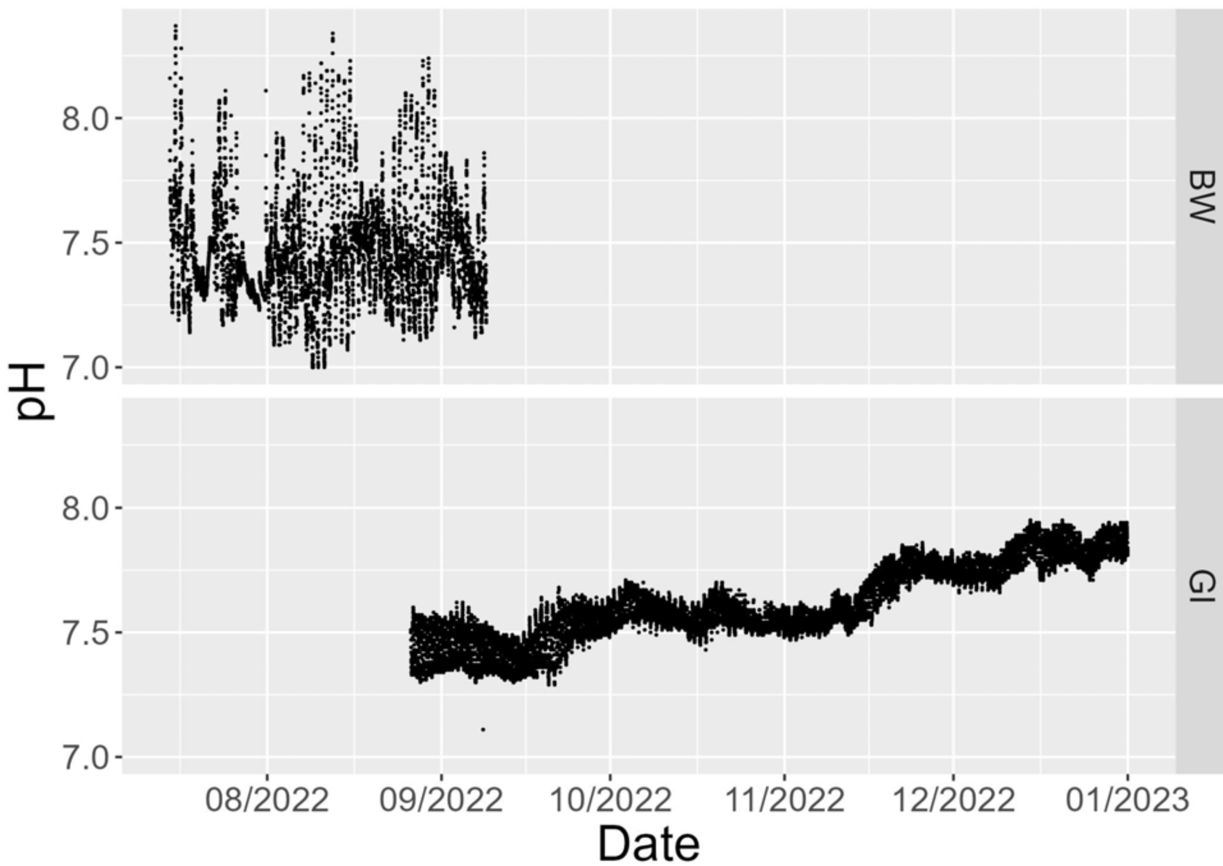

Figure 21. pH data for Bayswater Point State Park (BW), and Governors Island Ecodock (GI).

Point Water Quality Measurements

Using a Horiba U-52 Multiparameter Meter (**Figure 22**), point water quality data was measured at several sites. Measurements by the handheld sonde are used to check the reliability of the loggers' data. The handheld sonde measures temperature, dissolved oxygen, salinity, pH, conductivity, turbidity, and total dissolved solids. All samples were collected just below the water surface, adjacent to the restored oysters. Typically, three replicate samples, taken at least two minutes apart, were recorded on each sampling date.

The point water quality samples provide only a snapshot of the water quality conditions at a site and are typically taken as complementary measurements to the regularly maintained water quality data loggers. It is important to note that such snapshot measurements cannot describe the suitability of conditions for oysters or other biota because they do not accurately demonstrate the high variability in parameter values. Water quality within an estuarine site changes rapidly and is influenced by tidal stage, time of day, or season (Wallace et al. 2014, Baumann et al. 2015), which is why high-frequency measurements are required.

Table 10 presents the average values for temperature, pH, dissolved oxygen, and salinity for four sites in 2022. Most sites had average pH values that were above or near the suitable pH of 7.5, with the exception of Brooklyn Bridge Park Nursery, Governors Island Nursery, and Great Kills Harbor where pH dipped below 7.5 temporarily (**Table 10**). Average dissolved oxygen values seemed to be suitable at most sites (> 5 mg/L), but Brooklyn Bridge Park Nursery had an average dissolved oxygen of 4.35 mg/L in mid-July (**Table 10**), which is lower than optimal. All sites had average salinity values within suitable ranges for oysters, which was near the optimal level of around 20 ppt (**Table 10**). These water quality measurements are essential for understanding the environmental conditions that may influence oyster survival, growth, and reproduction at the restoration sites.

Figure 22. Billion Oyster Project summer intern deploying the Horiba probe at Brooklyn Bridge Park One15 Marina (right) and recording point water quality measurements using the Horiba hand-held device (left). (Photos courtesy of Jennifer Zhu)

Table 10. Average point water quality measurements (water temperature, pH, dissolved oxygen, and salinity) taken by Horiba U-52 Multiparameter Meter at ten sites (BBPN = Brooklyn Bridge Park Nursery, BW = Bayswater Point State Park, GI = Governors Island Ecodock, and GKH = Great Kills Harbor). Values highlighted in red are outside the range of suitability for oysters.

Site	Date	Sample Size	Temperature (°C)	pH	DO (mg/L)	Salinity (ppt)
BBPN	07/15/2022	3	23.07	7.39	4.35	21.92
BBPN	07/26/2022	3	24.16	7.35	5.97	18.07
BBPN	08/09/2022	3	25.21	7.39	5.90	19.16
BBPN	08/25/2022	3	25.32	7.09	7.77	18.95
BBPN	09/08/2022	3	23.93	7.37	5.19	20.28
BBPN	09/21/2022	3	23.31	7.15	6.69	19.98
BBPN	10/04/2022	3	16.73	7.74	7.17	20.37
BBPN	10/19/2022	3	15.92	7.84	6.42	17.30
BW	05/24/2022	3	19.02	8.43	9.72	23.23
BW	06/15/2022	3	26.33	8.99	16.69	22.75
BW	06/23/2022	3	21.97	7.81	5.25	23.74
BW	07/14/2022	3	29.51	8.29	9.02	22.91
BW	08/11/2022	3	29.52	8.26	13.13	21.16
BW	09/08/2022	3	25.50	7.87	8.76	21.02
BW	10/07/2022	3	17.91	7.98	8.97	21.86
GI	08/05/2022	3	23.43	7.25	6.51	18.93
GI	08/25/2022	3	24.78	7.45	6.50	19.42
GI	09/08/2022	3	23.89	7.31	5.44	20.20
GI	10/11/2022	3	16.52	7.76	6.38	20.84
GI	10/25/2022	3	16.35	7.27	6.78	23.11
GI	11/22/2022	6	11.35	8.02	7.82	20.42
GI	12/20/2022	3	7.06	7.16	10.75	19.35
GKH	08/17/2022	3	24.93	7.35	5.87	21.60
GKH	09/26/2022	3	19.87	7.86	6.63	22.07
GKH	10/18/2022	3	16.03	7.81	8.33	21.44
GKH	11/21/2022	3	7.06	8.02	8.00	23.26

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Oyster reefs play a crucial role in enhancing the three-dimensional complexity of shallow estuarine environments, fostering greater biodiversity compared to adjacent non-structured habitats such as muddy or sandy bottoms. Existing research on biodiversity enhancement by oyster beds primarily comes from other estuaries, including the Chesapeake Bay, bodies of water in the southeastern United States, and the Gulf of Mexico (Peterson et al., 2003; zu Ermgassen et al., 2016), though the scientific literature also documents this trend in New York Harbor as more restoration projects that seek to add structured habitat develop. The extent to which restored oysters enhance populations of fish, crabs, and shrimp depends on the specific biogeographic context, species abundance, and species composition at each site.

In 2022, the Billion Oyster Project recorded the presence of non-oyster species inhabiting restored oyster reefs at several community reef/field station sites during spring and fall monitoring events. This methodology allows for the assessment of organisms residing in and around the community reefs, providing valuable insights into the impact of oyster restoration efforts on the surrounding ecosystem. It is crucial to note that the absence of specific fish species may be attributed to various factors, such as avoidance of human handling of the structures, seasonal migration patterns, food availability, or site conditions. Therefore, the absence of certain fish species does not necessarily reflect their true absence at the site.

To conduct the biodiversity assessment during monitoring events, project staff retrieved structures at five sites (Brooklyn Bridge Park Nursery, Bush Terminal Park, Coney Island Creek, Great Kills Harbor, and Lemon Creek Lagoon) and transferred the contents to plastic trays. This transfer included collecting all the organisms dislodged from the external surface of and within structures. Each tray was rinsed with ~10 gallons of seawater sourced directly from the site. This rinsing process allowed for the collection of any additional dislodged organisms that may have been present in the structure. This thorough approach ensured that the biodiversity assessment covered a wide range of species residing in the vicinity of the reef, providing a comprehensive understanding of the ecological interactions within the restoration site.

In **Table 11**, the recorded taxa encountered at the five sites are listed. Specifically, seven taxa were captured at Brooklyn Bridge Park Nursery, Bush Terminal Park, and Coney Island Creek, while fifteen and eight taxa were captured at Great Kills Harbor and Lemon Creek Lagoon, respectively. It's important to note that the restoration techniques and oyster density varies across all sites, making it challenging to compare taxonomic richness across the sites. While no specific species were observed at all five sites, common species that were consistently observed in most sites (3 sites or more) include naked goby, oyster toadfish, blackfish, barnacle, sea squirt, and mud crab (**Table 11**). At larger-scale on-bottom reef sites, trends in biodiversity may also be inferred through the comparison of pre-construction and post-construction benthic sampling data.

Visual examples of some of the animals found in association with the Billion Oyster Project oyster reefs are provided in **Figure 23**. These visual representations offer insights into the diverse ecosystem supported by the oyster restoration activities, highlighting the positive impact of the project on the surrounding marine environment.

Table 11. Species observed in restoration structures during monitoring events at BBPN (Brooklyn Bridge Park Nursery), BTP (Bush Terminal Park), CIC (Coney Island Creek), GKH (Great Kills Harbor), and LCL (Lemon Creek Lagoon).

Vertebrates						
Scientific Name	**Common Name**	**BBPN**	**BTP**	**CIC**	**GKH**	**LCL**
Anguilla rostrata	American eel				X	
Archosargus probatocephalus	Sheepshead				X	
Centropristis striata	Black sea bass			X	X	
Cottoidea spp.	Sculpin					X
Gobiesox strumosus	Skilletfish	X				
Gobiosoma bosc	Naked goby		X		X	X
Opsanus tau	Oyster toadfish		X	X	X	
Tautoga onitis	Black fish	X		X	X	
Tautogolabrus adspersus	Cunner				X	
Triglidae spp.	Sea robin				X	
Invertebrates						
Scientific Name	**Common Name**	**BBPN**	**BTP**	**CIC**	**GKH**	**LCL**
Order Amphipoda	Amphipod	X				
Callinectes sapidus	Blue crab				X	
Cirripedia spp.	Barnacle	X		X	X	X
Clathria prolifera	Red beard sponge		X			
Cliona celata	Boring sponge				X	X
Crepidula fornicata	Slipper shell			X		
Geukensia demissa	Atlantic ribbed mussel					X
Hemigrapsus sanguineus	Asian shore crab				X	
Ilyanassa obsoleta	Eastern mud snail		X			X
Molgula manhattensis	Sea squirt	X	X		X	
Mytilus edulis	Blue mussel	X		X		
Nemertea spp.	Ribbon worm					X
Palaemon paludosus	Grass shrimp				X	
Panopeus spp.	Mud crab		X		X	X
Class Polychaeta	Polychaete worm(s)					
Pomatoceros spp.	Tubeworm			X		
Urosalpinx cinerea	Atlantic oyster drill	X	X			

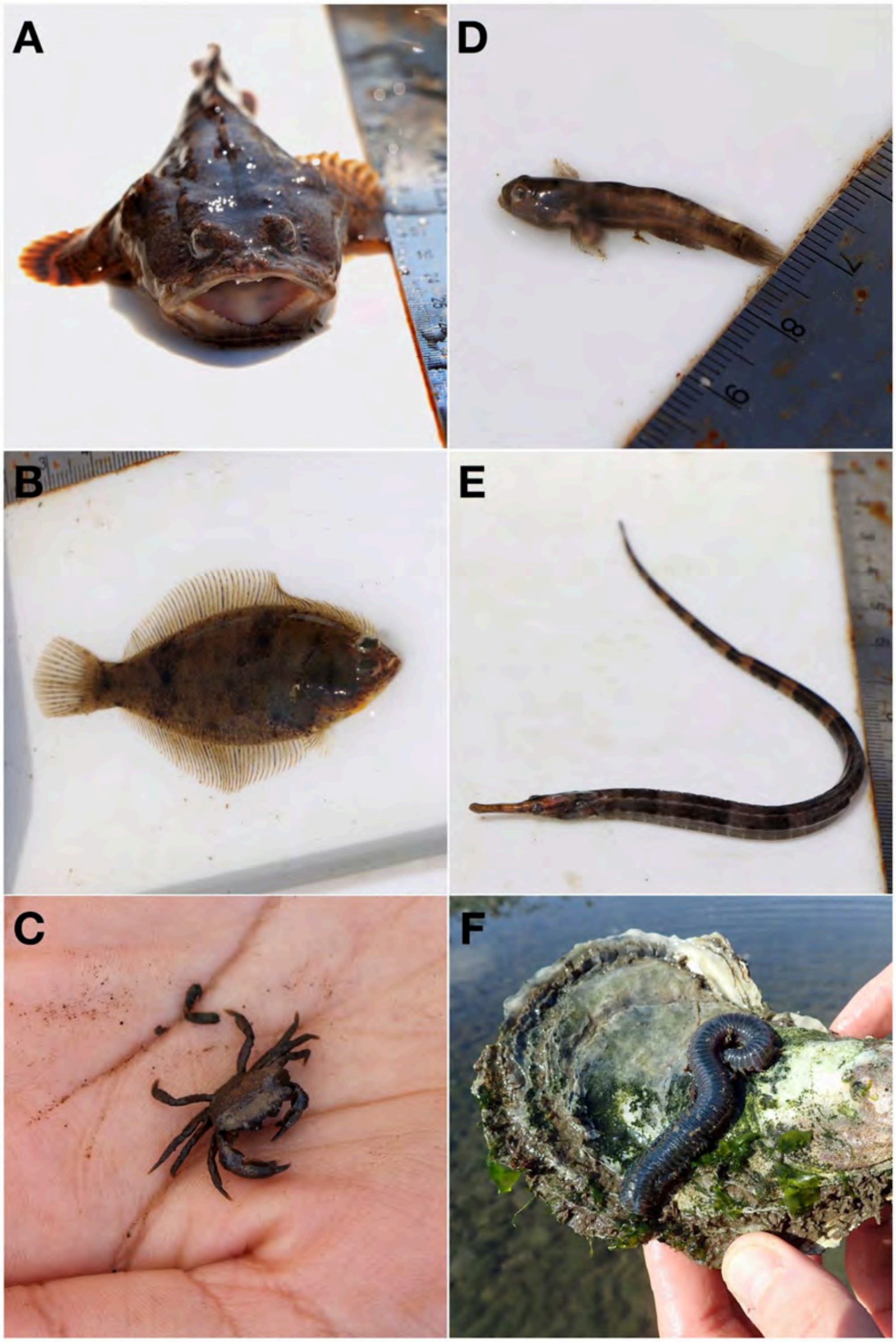

Figure 23. Examples of organisms inhabiting restored reefs: (A) Oyster toadfish (*Opsanus tau*), (B) Winter flounder (*Pseudopleuronectes americanus*), (C) Mud crab (*Panopeus sp.*), (D) Naked goby (*Gobiosoma bosc*), (E) Northern pipefish (*Syngnathus fuscus)*, and (F) Clam worm (*Nereis* sp.). (Photos courtesy of Elizabeth Burmester)

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