About Billion Oyster Project

The mission of Billion Oyster Project is to restore oyster reefs to New York Harbor through public education initiatives. We envision a future in which New York Harbor is the center of a rich, diverse, and abundant estuary. The communities that surround this complex ecosystem have helped construct it, 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.

To date, Billion Oyster Project has collected 1.6 million pounds of shells from restaurants. These shells provide habitat for oysters in the waters of New York City. Over 45 million spat on shell oysters, and nearly 250 thousand adult oysters have been planted by Billion Oyster Project in the waters of New York City.

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New York State Department of Environmental Conservation

New York City Department of Parks and Recreation

Princess Bay Boatmen's Association

Richmond County Yacht Club

Sebago Canoe Club

SUNY Maritime College

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Introduction

You are reading the third edition of the *New York City Oyster Monitoring Report,* which summarizes data from the 2019 field season. These data were collected based on protocols developed by Dr. Michael McCann. For more information about past oyster restoration projects, refer to *Restoring Oysters to Urban Waters* (McCann 2019), available on our website.

For a quick overview, refer to the **Main Findings** (p. 5), **Site-Specific Findings** (p. 5) and **Assessing Performance at Each Site** (p. 14). The remainder of the document summarizes the results of scientific monitoring in greater detail and is intended for a technical audience. It is organized around specific topics, including **Oyster Growth** (p. 17), **Survival** (p. 21), **Disease** (p. 23), and **Reproductive Status** (p. 26), as well as **Water Quality** (p. 29), and **Biodiversity** (p. 35). These sections include introductory information from the New York City Oyster Monitoring Report: 2018, co-authored by Dr. Michael McCann and Dr. Elizabeth Burmester, followed by brief descriptions of 2019 results.

Main Findings

Oysters that continue to grow individually and through cementation with one another could form reefs at select NYC sites. In 2019, oysters at all reef sites were able to grow and cement to one another. Consistent with what we know about oyster biology, our findings from this and previous years showed that oysters grew rapidly in their first year, and older oysters grew more slowly.

Oysters at all sites experience hypoxia (i.e., low oxygen). Like all other marine animals, oysters require oxygen to support their growth and maintain good health conditions. Presently, all of the sites where Billion Oyster Project installed oysters (with the exception of SUNY Maritime, which was not monitored in 2019) experienced periodic hypoxia. The most severe and prevalent hypoxia occurred at the Governors Island EcoDock and Brooklyn Navy Yard sites, as we have documented previously. At these sites, oxygen levels are persistently low.

Disease, especially Dermo (Perkinsus marinus), was problematic for older oysters, which intensified in the fall. In 2019, we found that Dermo most impacted the oldest (3-year-old) oysters from Great Kills Harbor on Staten Island, with infection intensities reaching lethal levels in 14% of the tested individuals. Although this fraction appears relatively low, oysters at this site had the highest mortalities.

Oysters demonstrated readiness for reproduction at the Bush Terminal Park site. In the second half of June, oysters were sampled from Bush Terminal Park, Brooklyn Navy Yard, and Great Kills Harbor. Histopathological analyses revealed that oysters from Bush Terminal Park were at an even ratio of males to females, and their gonads were ripe. Some oysters were actively spawning. Many oysters from the other two sites had underdeveloped gonads.

Site-Specific Findings

This section highlights the main findings for specific restoration sites based on the data collected in 2019. Sites are divided into two groups, i.e., nurseries and reefs, as oysters at these sites are held by different structures with different configurations. Moreover, oysters living at the nursery sites fulfill other functions than the oysters living at reef sites. Oysters at nursery sites serve primarily as broodstock and can spawn directly in the environment or are spawned in the MAST Center hatchery.

NURSERIES

Brooklyn Navy Yard

At this site, adult oysters live in stacked plastic Super Trays, suspended in the water beneath buoys. Although 2019 water quality at this site was poor, with low oxygen levels, some oysters at this site achieved sexual maturity, and gametes in their gonads were developing towards spawning in late June.

Lemon Creek Nursery

Lemon Creek Nursery is the smallest of the Billion Oyster Project nurseries, with only four Oyster Gro® structures located at this site. Dissolved oxygen levels at this site were adequate.

Great Kills Harbor

At this site, oysters grew very little, and gonads were underdeveloped. In the fall, some oysters were heavily infected with Dermo. The older oysters were the most infected. Oysters at this site experienced high levels of mortality.

Governors Island EcoDock

At this site, oxygen levels were frequently low, indicative of hypoxia.

SUNY Maritime

Oysters, as spat on shell, were installed at this site in 2019. Oysters grew very little and in some trays and stacks, experienced high mortality. Dense populations of oyster drills were observed, which is not uncommon at newly established sites.

ON-BOTTOM REEF PROJECTS

Paerdegat Basin

Oysters at this site experienced high mortality between the spring and fall. Oxygen levels in the water were relatively low, with occasional increases. Salinity increased over summer at this site.

Coney Island Creek

In 2019, new young oysters were installed at this site. Dissolved oxygen levels were characteristic of hypoxia.

Lemon Creek Lagoon

Oysters' growth at this site was best among all the monitored sites. There were some differences in oyster growth between the specific structures. Specifically, oysters on the bagged shell reef grew less than those on gabions and ECOncrete discs. Oxygen levels in this lagoon were adequate for oysters.

Bush Terminal Park

In 2019, reefs at the Bush Terminal Park were accessible only until July; therefore we were not able to complete the fall monitoring at this site. Oysters at this site showed good growth between fall of 2018 and spring 2019. Oysters were at an even sex ratio, they were mature and many of them were spawning. Oxygen levels were generally low at this site with periodic reoxygenation.

Overview of Sites

This report shares the results of monitoring at nine oyster restoration sites in New York Harbor (Table 1, Fig. 1). All sites were permitted and installed by Billion Oyster Project. The SUNY Maritime nursery was established in 2019. Several sites include cohorts of oysters installed over multiple years or in multiple types of gear (see *Restoration Structures* below). For example, the Sunset Park site at Bush Terminal Park has Community Reef cabinets that were installed in 2016 and 2018 and a bagged-shell reef installed in 2018. The results of each cohort or structure are typically reported separately for oyster growth, disease, and reproduction, while results for water quality are reported for the entire site. Both the Brooklyn Navy Yard and Governors Island EcoDock host floating nurseries that hold many oysters. These sites were permitted and installed prior to 2016, and this document reports on a subset of oysters that were installed at each site in 2017 or 2018 specifically for monitoring. Numbers of oysters deployed at each site are summarized in Table 1. Figure 4 shows the density of spat per shel among the seeded shells that were placed at the SUNY Maritime nursery.

Monitoring results for large-scale restoration Large-scale restoration projects at Hudson Reefs and Head of Bay are not discussed in this report. There are several new small-scale projects that will be discussed in the 2020 monitoring report, including Bayswater Point State Park and the new Brooklyn Bridge Park nursery. In 2016, Billion Oyster Project installed a Community Reef at another Brooklyn Bridge Park site. Due to ongoing Manhattan Bridge maintenance and the danger of falling debris, access to this site was revoked, and cabinets were removed. School groups, various other community groups, and individuals have been participating in Billion Oyster Project's Oyster Research Station (ORS) program since 2015. Data from this program is not included in this report.

Restoration Structures

A variety of different restoration approaches and structures were used, depending on unique site conditions, project objectives, and our continually developing understanding of best practices for oyster restoration in urban waters. Community Reefs are welded, steel structures that hold cages of oysters off the bottom (Fig. 3). These structures allow the cages to be removed for monitoring above the water surface. The term "nursery" describes restoration sites where oysters are held off the bottom in floating or suspended structures, regardless of the size or age of the oysters. Nursery gear types include OysterGros® (Fig. 6C) and Super Trays (Fig. 6F), both of which are used in commercial aquaculture. 2018 was the first year in which several restoration approaches were tested, including bagged-shell reefs (Fig. 6A) and ECOncrete® discs (Fig. 6E). Smaller versions of gabions (Fig. 6B) that have been piloted at the Hudson Reefs near the Mario Cuomo Bridge (formerly the Tappan Zee Bridge) were used at Lemon Creek Lagoon.

Oyster Sources

In New York Harbor, oyster populations are not only limited by the lack of suitable hard substrate to colonize but also lack sufficient breeding individuals to seed those substrates. Therefore, restoration in most parts of NY Harbor requires the introduction of live oysters. For these Billion Oyster Project restoration sites, spat on shell oysters were used: high densities of juvenile oysters were "set" on oyster shell that was collected from local restaurants or other sources and cured. In some cases, the juvenile oysters were attached to other substrates, such as ECOncrete® discs. Two oyster strains were used: 1) larvae acquired from Muscongus Bay Aquaculture (Maine) and raised and settled onto shell or other structures in the MAST Center hatchery on Governors Island by Billion Oyster Project staff, or 2) larvae set onto shell or other structures that came from adult oysters which had been living in Oyster Research Stations (i.e., hanging cages with oysters monitored by students and community groups) or oyster nurseries, and which were conditioned and spawned in the MAST Center hatchery. For the latter method, the adult oysters were retrieved from either the Oyster Research Stations at Richmond County Yacht Club (Great Kills Harbor, Staten Island) or from the Billion Oyster Project EcoDock on Governors Island. In both cases, the adult broodstock was originally from aquaculture sources (either Muscongus Bay, Maine, or Fishers Island, New York) but had acclimated to local conditions.

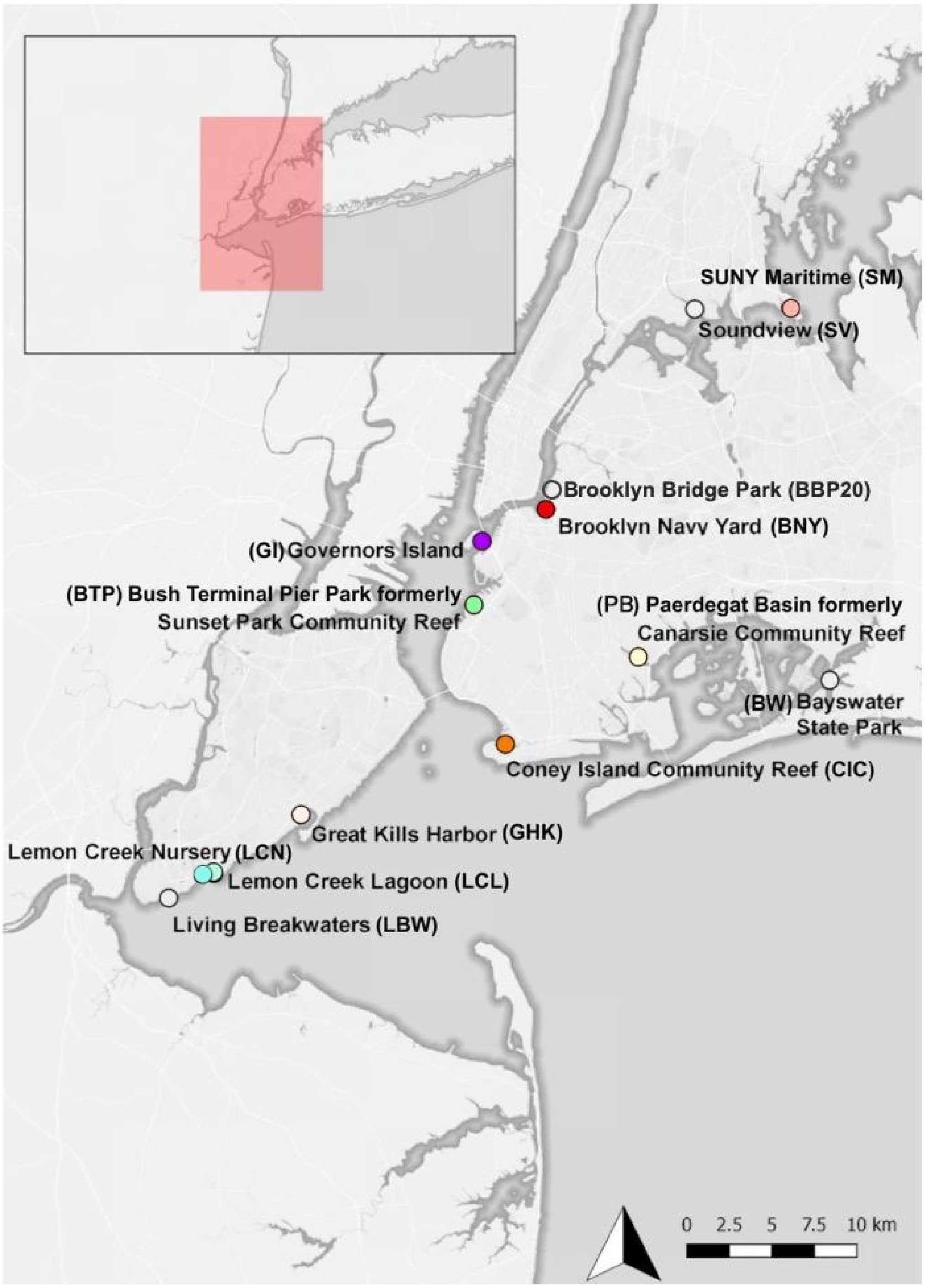

Figure 1. The nine current oyster restoration sites in New York Harbor described in this report are represented by colored circles. The future restoration sites are indicated with white circles.

Figure 2. Billion Oyster Project Community Reefs Regional Manager Tanasia Swift trains community scientists to conduct oyster monitoring protocols at the Coney Island Community Reef. (Photo courtesy of Robina Taliaferrow)

Figure 3. Cabinets were installed at the Bush Terminal Park site in Brooklyn. (photo courtesy of Elizabeth Burmester)

Table 1. Restoration structures and installation details

Site	Structure	Install date	Larvae source ±	Size at install (shell height, mm)	Number oysters installed
Brooklyn Navy Yard * **(BNY)**	Super Tray Nursery	4/10/2017	Muscongus Bay, ME	34.9	2,750
Paerdegat Basin **(PB)**	Community Reef	7/27/2018	Muscongus Bay, ME	~5	480,000
Coney Island Creek **(CIC)** +	Community Reef	9/18/19	Muscongus Bay, ME	~5	14,223
Governors Island EcoDock * **(GI)**	Super Tray Nursery	8/21/2018	Muscongus Bay, ME	~5	~20,000
	Super Tray Nursery	4/10/2017	Muscongus Bay, ME	29.5	7500
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
Lemon Creek Nursery **(LCN)**	OysterGro® Nursery	6/12/2017	Oysters reared in Great Kills Harbor oyster cages	4.1	228,780
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)**	Community Reef	6/28/2016	Muscongus Bay, ME	~2	969,452
	Community 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

* Details for the Governors Island EcoDock represent only a small fraction of the oysters at the site.

± See text for a complete explanation of oyster sources.

+ Due to regulatory requirements, all oysters installed at this site in 2018 were removed at the end of the season.

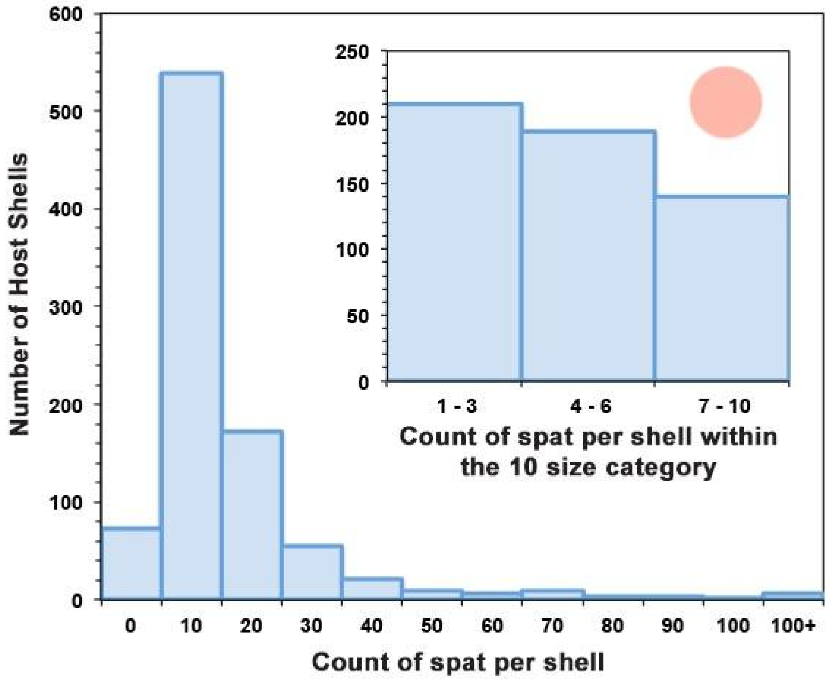

Figure 4. Distribution of spat counts. Oysters were deployed in Super Trays at the newly established SUNY Maritime (SM) site.

Figure 5. This spat-on-shell was set at the hatchery on Governors Island. (Photo courtesy of Rebecca Resner)

Figure 6. Examples of structures employed 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)

Performance Metrics

To assess the performance of oyster restoration at each site, several metrics were used, focusing on oyster survival, growth, disease, and reproduction. These metrics specify qualitative categories that essentially translate to “good,” “moderate,” and “poor” performance. These metrics do not indicate whether the restoration activities are providing ecosystem benefits (e.g., biodiversity enhancement, water quality improvements). Not all metrics can be applied to every site due to the type of installation site conditions, age of restoration activity, or other constraints. Some metrics are not relevant in the first 1 to 2 years of restoration. For example, the presence of more than one oyster size class would not be expected immediately at a site where juvenile oysters were installed. The nine performance metrics are described in Table 2.

Assessing Performance at Each Site

The oyster performance metrics were applied to the eight restoration sites. Of those sites, four (Governors Island EcoDock, Great Kills Harbor, Lemon Creek Lagoon, and Bush Terminal Park) had multiple cohorts or restoration approaches. In those cases, the performance metrics are reported for each cohort or restoration approach. Tables 3 and 4 provide a high-level overview of oyster performance at each site. The remainder of the document reports in greater detail on oyster data used to complete this assessment and provides other environmental data that either describe oyster habitat suitability (e.g., water quality) or characterize other organisms at select sites.

Table 2. Performance metrics for oysters at restoration sites. * See *Reproductive Status* (p. 39) for more information about quantitative assessments.

Metric Category	Parameter and unit of measurement	Explanation	What indicates good oyster performance?
Growth	Shell height in oysters are <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.
	Shell height (oysters are > 6 months old); unit: mm	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)	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 m2) should stabilize.	Oyster density stabilizes after initial mortality
Disease	Disease prevalence (unit: %) and intensity (unit for MSX is qualitative i.e. low, medium, high and for Dermo described by Mackin scale from 0 to 5)	Dermo and MSX are types of oyster diseases that can lead to lower fitness and mortality. Prevalence describes the proportion of individuals that are infected, while intensity describes the infection degree.	Only older (>2-3 years old) oysters are susceptible to disease, and those are sampled at a subset of Billion Oyster Project sites. Oysters growing at sites of highest salinity are most vulnerable.
Reproduction*	Stages of gonadal development (unit: % of individuals per stage)	Stages are determined based on expert assessment of gonad condition that describes the development of gonads and gametes within them and readiness to spawn.	Oysters mature following their 2nd year of life. Therefore only these larger/older oysters are sampled. An equal ratio of males and females with developing or fully ripe gonads indicates a well-performing oyster population.
	Sex ratio	Oysters switch sexes during their adult life. They all begin as males. As oysters mature, their ratio in population approaches 50:50 (i.e., one female for one male).	
	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.

Table 3. Oyster growth and survival performance metrics at Billion Oyster Project sites. First-year growth rates are calculated based on data from years when oysters were initially deployed.

	Site, Structure & Installation Year	First year growth rate mm/day	Post 1st year growth: a). Latest shell height mm (measurement date), b). mm grown since fall 2018, c). mm/month grown in 2019	Cementation
Nurseries	BNY (Super Tray 2017)	ND	b). 12 (2017- 2018)	Yes/Light
	GI (Suepr Tray 2017)	ND	a). 68.7 (10/18)	Yes/Light
	GI (Super Tray 2018)	0.09	ND	Yes/Light
	GKH[a] (Super Tray 2017)	0.35	a). 110.3[a] (11/7/19); b). 5; c). 0.4-0.5	Yes*
	GKH (Super Tray 2019)	ND	a). 52.2 (10/23/19)	Yes*
	LCN (Oyster Gro® 2017)	0.4	a). 101.4 (10/29/19); b). 26	Yes/Light & inconsistent
	SM (Super Tray 2019)	0.18	ND	ND
Reefs	PB (Cabinet 2018)	0.25	a). 50.0 (8/2019); b). 11; c). 2.8	Yes
	CIC (Cabinet 2018)	0.36	ND	Yes
	LCL (ECOncrete® 2018)	0.47	a). 103.4 (11/4/19); b). 57; c). 16	Yes
	LCL (Mini Gabions 2018)	0.34	a). 93.5 (11/4/19); b). 57; c). 15	Yes
	LCL (Bagged Shell 2018)	0.2	a). 65.0 (11/4/19); b). 42; c). 4.8	No
	BTP (Bagged Shell 2018)[b]	0.17	a). 31.6 or 35.0 (6/17/19); b). 12 or 15	Yes/Light
	BTP (Cabinet 2016)	0.3	a). 118.3 (6/17/19); b). 32	Yes
	BTP (Cabinet 2018)	0.3	a). 33.6 (6/17/19); b). 10	Yes

Table 4. Oyster disease and reproduction performance metrics at Billion Oyster Project restoration sites. * See Table 8 for explanation of gonad condition scores.

		Disease		Reproduction	
		MSX Prevalence %; Intensity %	Dermo Prevalence % Lethal Intensity %	Individuals with gonad condition scores G1–S4%*	Sex Ratio
Nurseries	BNY (Super Tray 2017)	ND	ND	27.6	34 : 66
	GI (Super Tray 2017)	ND	ND	ND	ND
	GI (Super Tray 2018)	ND	ND	ND	ND
	GKH (Super Tray 2016)	0	86.4; 13.6	10	43 : 57
	GKH (Super Tray 2017)	0	63.3; 3.3	16.7	47 : 53
	GKH (Super Tray 2019)	ND	ND	ND	ND
	LCN (Oyster Gro® 2017)	3.3, 6.7	33.3/0	ND	ND
	SM (Super Tray 2019)	ND	ND	ND	ND
Reefs	PB (Cabinet 2018)	ND	ND	ND	ND
	CIC (Super Tray 2019)	ND	ND	ND	ND
	LCL (ECOncrete® 2018)	ND	ND	ND	ND
	LCL (Mini Gabions 2018)	ND	ND	ND	ND
	LCL (Bagged Shell 2018)	ND	ND	ND	ND
	BTP (Bagged Shell 2018)	ND	ND	ND	ND
	BTP (Cabinet 2016)	ND	ND	89.3	43 : 57
	BTP (Cabinet 2018)	ND	ND	ND	ND

Oyster Growth

Oyster growth alone is not sufficient to achieve a self-sustaining population, but it is a necessary component for success that can be assessed rapidly following restoration. Rapid growth rates suggest that the oysters at that location are able to reach reproductive maturity quickly. We expect oysters to rapidly increase shell heights within the first few months following installation and then continue to increase shell heights throughout subsequent years, although at a slower rate (Fig. 7). For this report, we classified juvenile growth into three categories: rapid (≥25 mm/day), moderate (0.25-0.15 mm/day), and slow (≤0.15 mm/day).

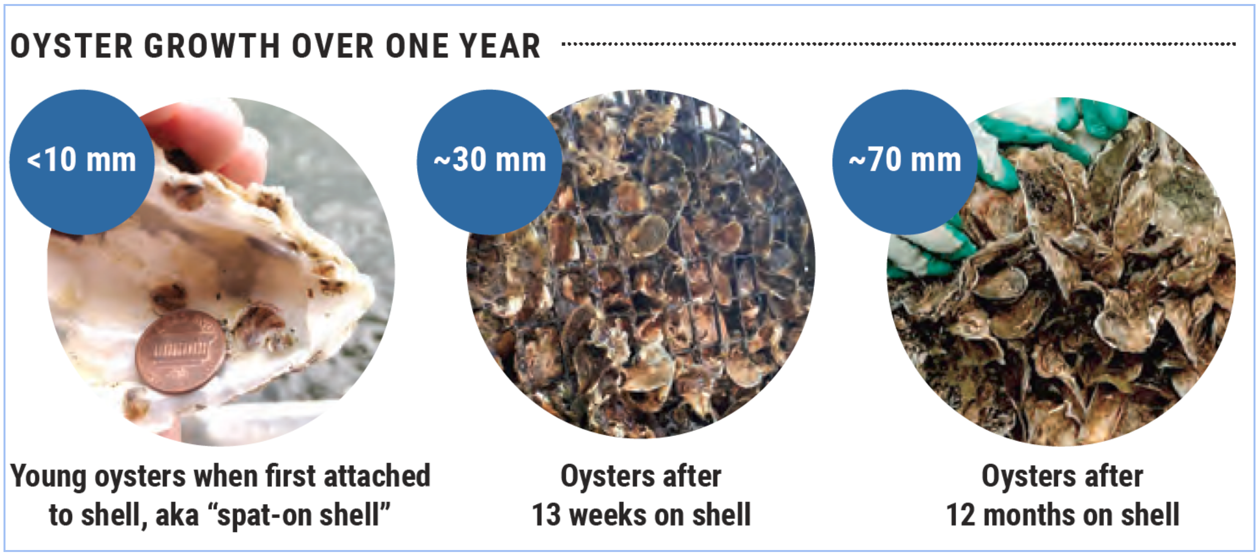

Figure 7. These photos show oyster growth in the first year of restoration at sites with fast growth. (Photos courtesy of Billion Oyster Project Staff)

Oyster growth was quantified by measuring change in shell height to the nearest millimeter over time. Methods for measuring oyster shell height depended on the specifics of the oyster restoration structure and the nature of oyster growth. At some sites, oysters remained in loose clumps and could be separated from each other (Burmester and McCann, 2018). In other cases, the oysters were cemented to each other or to a substrate, and only oysters growing at or near the surface were measured. All growth results are summarized in Table 3.

Figure 8. Field technicians measure oyster growth at Great Kills Harbor. (Photo courtesy of Elizabeth Burmester)

In the case of ECOncrete® discs, the entire disc surface was surveyed. For gabions, oysters growing out of a single face (i.e., side) were measured. For the community reef files, a 0.1-m^2 quadrant was placed in the center of the broadest side of the file and oysters in that quadrat were measured. For both approaches (i.e., loose clumps of oysters or quadrats), if oyster densities were high, only a subset of 30 randomly selected oysters was measured for each unit (i.e., gabion, shell bag, community reef file), and at least three replicate units were sampled.

Oyster growth was assessed through three performance metrics:

1) Increase in shell height in first year as spat on shell,

2) Continued increase in shell height after year 1, and

3) Oysters "reefing" or cementing to each other or gear.

Growth rates are presented in Table 3 to give a general sense of the magnitude of growth in the first year. Calculating and comparing numerical growth rates (e.g., mm per day or mm per month) should be done with caution, particularly when the amount of time between sampling dates or the season of sampling dates differed or when the initial size of oysters was unequal.

Size Frequency Distributions

Size frequency distributions (i.e, the number of individuals in a population or sample that fit into different-size bins) allow the viewer to examine the range of sizes of individuals within a population and provide greater detail than a single average size value.

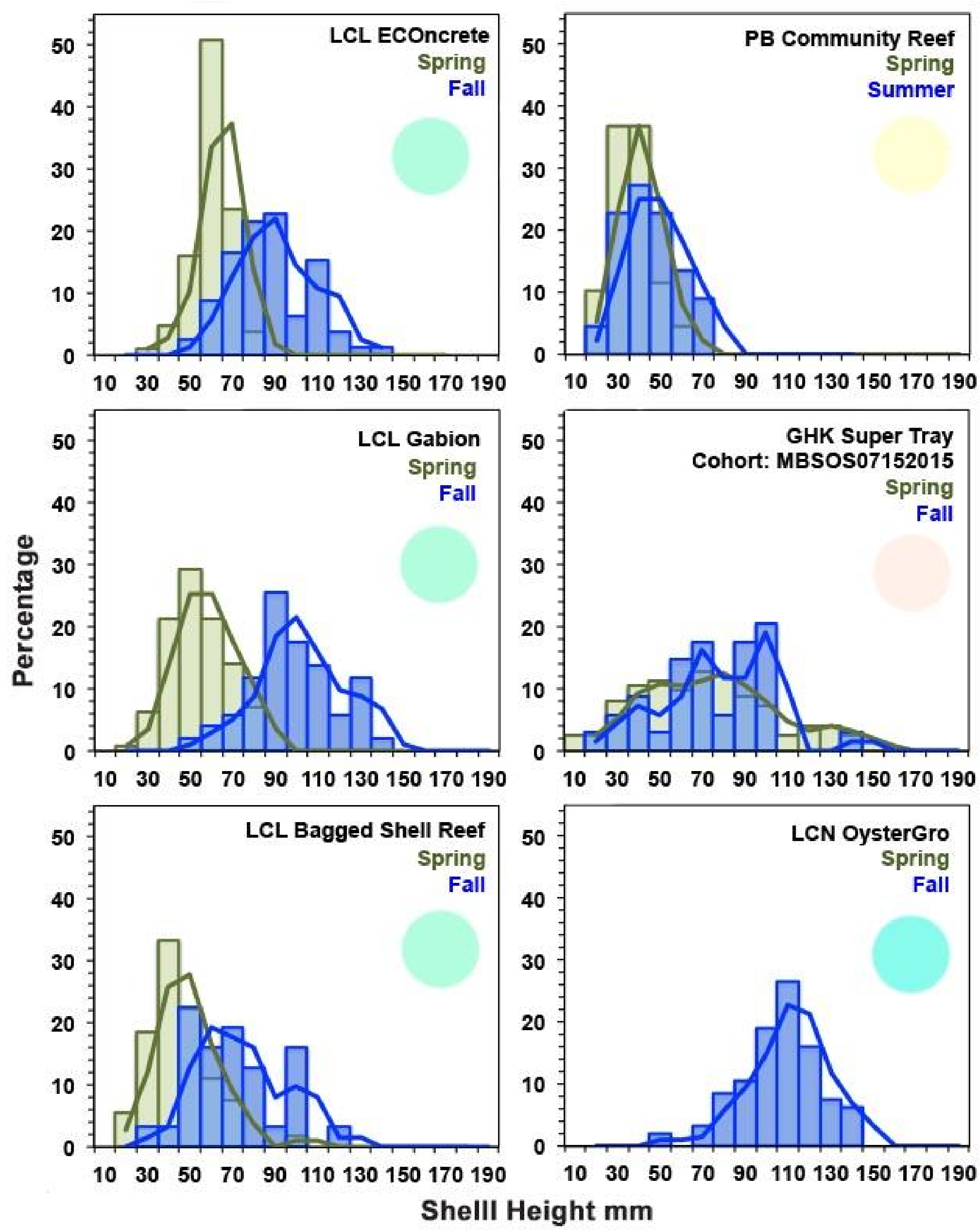

Figure 9. Size frequency is expressed as % of all live oysters that fall into a specific shell height category. Oysters were held in various structures, including bagged shell, community reef cabinets, ECOncrete®, OysterGro®, gabions, and Super Trays. Oysters were measured at different times from June through November of 2019.

Size frequency distributions can also provide information about reproduction and recruitment. We expect a single cohort of oysters of a similar age to have a normal distribution of shell heights (i.e., "a bell curve") with a single peak and two nearly symmetrical tails. If more than two cohorts of oysters present, then two (not necessarily equal-sized) peaks may be visible.

Oyster Survival

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

Oyster survival is determined by measuring changes in oyster density over time. Juvenile oysters must compete for space and resources. As a result, spat grow quickly over the first 1–2 years of life, but they also experience heightened mortality rates during this time. On restored oyster reefs, mortality is expected to be greatest for the first year after installation and to level off over time. Target density for oysters may vary based on the type of installation structure and the type of maintenance that structure may require. Depending on the installation structure as well as the pace of oyster growth and accretion, density can be measured in several ways:

(1) *Live oysters per "clump"*: typically used for first spat counts prior to and shortly after installation before oysters grow through mesh openings and attach to the restoration structures.

(2) *Live oysters per square meter*: determined by counting and measuring all live oysters identified within a 0.1-m^2 quadrant.

Table 5. Oyster density expressed in the unit of oysters per square meter at sites classified as Community Reefs: Paerdegat Basin (PB), Coney Island Creek (CIC), Lemon Creek Lagoon (LCL) and Bush Terminal Park (BTP).

Site	Structure Type and Year of Installation	Oyster Cohort	Live Oysters Per Square Meter		% Survival
			Spring/Summer	Fall	
PB	*Cabinet 2018*	PBSOS04182018	**657** ± 58 (n=3)	**220** (n=1)	**33.5**
CIC	*Cabine 2019*	MBSOS05142019	–	**200** ± 110 (n=2)	**n/a**
LCL	*Bagged-Shell 2018*	MBSOS06262018	**450** ± 110 (n=6)	**310** ± 165 (n=6)	**68.9**
	Mini-Gabion 2018	MBSOS06262018	**377** ± 52 (n=4)	**151** ± 47 (n=4)	**40.5**
	ECOncrete® Disc 2018	MBSOS06262018	**17.7** ± 4.1* (n=6)	**19.7** ± 3.0* (n=4)	**130.1**
BTP	*Cabinet 2016*	MBSOS05272016	**340** ± 25 (n=3)	**ND**	**n/a**
	Cabinet 2018	MBSOS06262018 GISOS07252018	**310** ± 107 (n=3)	**ND**	**n/a**
	Bagged-Shell 2018	MBSOS06262018	**633** ± 76 (n=3)	**ND**	**n/a**
	Bagged-Shell 2018	GISOS07252018	**183** ± 189 (n=3)	**ND**	**n/a**

Table 6. Densities of live oysters held in Super Trays that are suspended in the water column at SUNY Maritime (SM). Initial density was assessed on 8/26/2019. % survival is calculated based on data gathered during two monitoring events.

Site	Structure Type and Year of Installation	Oyster Cohort	Live Oysters Per Clump		% Survival
			Spring/Summer	Fall	
SM	*Super Trays 2019*	MBSOS07022019	**11.6** ± 23.4 (n=11)	**2.4** ± 1.3 (n=4)	**20.9**

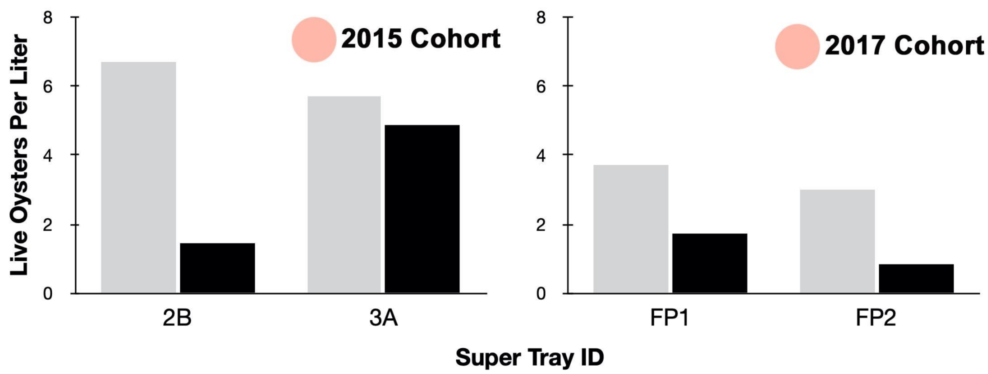

Figure 10. Densities of live oysters from 2015 and 2017 cohorts from Great Kills Harbor based on data collected in 2019.

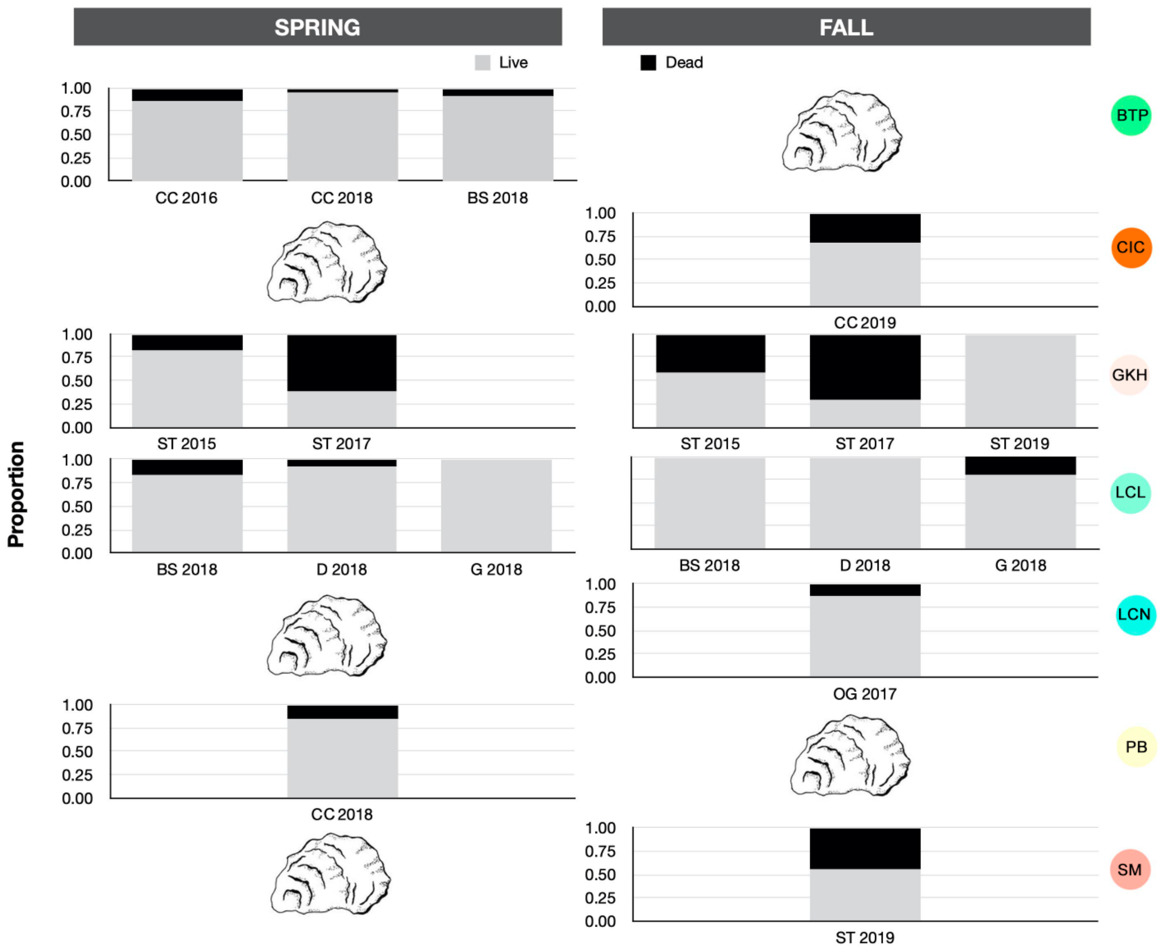

Figure 11. The proportion of live and dead oysters across sites based on the 2019 monitoring. Oyster pictures appear where the measurements were not taken or oysters were not yet installed.

Disease

Dermo (*P. marinus*) and MSX (*Haplosporidium nelsoni*) are parasitic protozoan diseases that can infect oysters, with detrimental effects. In 2019, adult oysters (at least 2 years old) were sampled in spring/summer and fall from select sites. There were 30 large individuals per sample (see shell heights in Fig. 12). Oysters were collected from Brooklyn Navy Yard (only spring), Great Kills Harbor, Bush Terminal Park (only spring), and Lemon Creek Nursery (only fall) and sent to Dr. Bassem Allam at the Stony Brook University Marine Animal Disease Laboratory (SBU MADL) for disease diagnostics. Dermo diagnosis was made using FTM (fluid thioglycollate medium) on mantle and rectal tissues. MSX diagnosis was made using histopathology on formalin-fixed sections. SBU MADL also provided data on shell height, condition index, stage of gonad development, and sex ratio (see below). Samples from June were assumed to best represent the reproductive status of oysters, and samples from October represented the maximum disease loads.

“Prevalence” refers to the percentage of the population that tests positive for a given disease. “Intensity” refers to the degree to which an individual oyster is infected with a given disease. Dermo intensity is reported on the Mackin scale from 0 to 5, with 5 being the highest intensity. Rankings of 3 or higher typically indicate lethal intensities that are presumed to cause mortality. MSX intensity is reported as “low,” “medium,” or “high.”

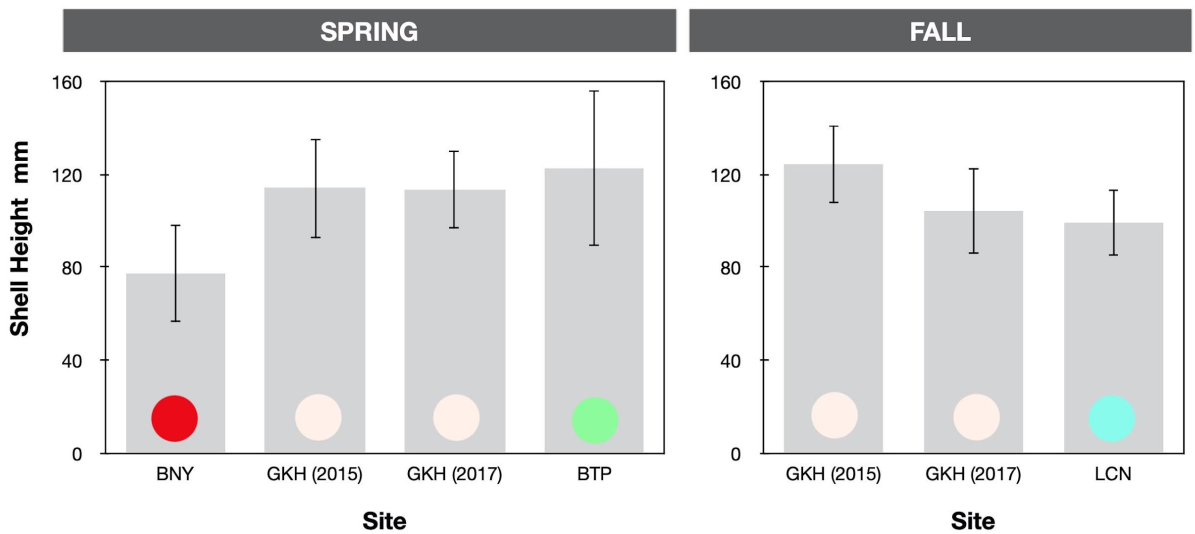

Figure 12. Mean shell heights of oysters that were tested for disease (see data in Table 5 and Figure 24). Error bar = standard error (n = 28 - 30 oysters). Oysters sampled at BTP represented the 2016 cohort.

In 2019, Dermo was the primary disease of concern. According to the Mackin scale, the intensity above 3 indicates lethality. Prevalence was highest in fall (Fig. 13). A comparison of two oyster cohorts from Great Kills Harbor showed that the older oysters were more severely impacted. In fall 2019, 13.6% of the tested individuals from the 2015 cohort and 3.3% of the 2017 cohort reached or exceeded level 3 at this site. About a third of the oysters collected from the Lemon Creek Nursery tested positive for Dermo but had relatively low-intensity levels, suggesting minimal mortality risks due to this disease. Among the various oyster groups that were tested, the only group that was impacted by MSX was from the Lemon Creek Lagoon. The prevalence of MSX was, however, low and intensity moderate (Table 7).

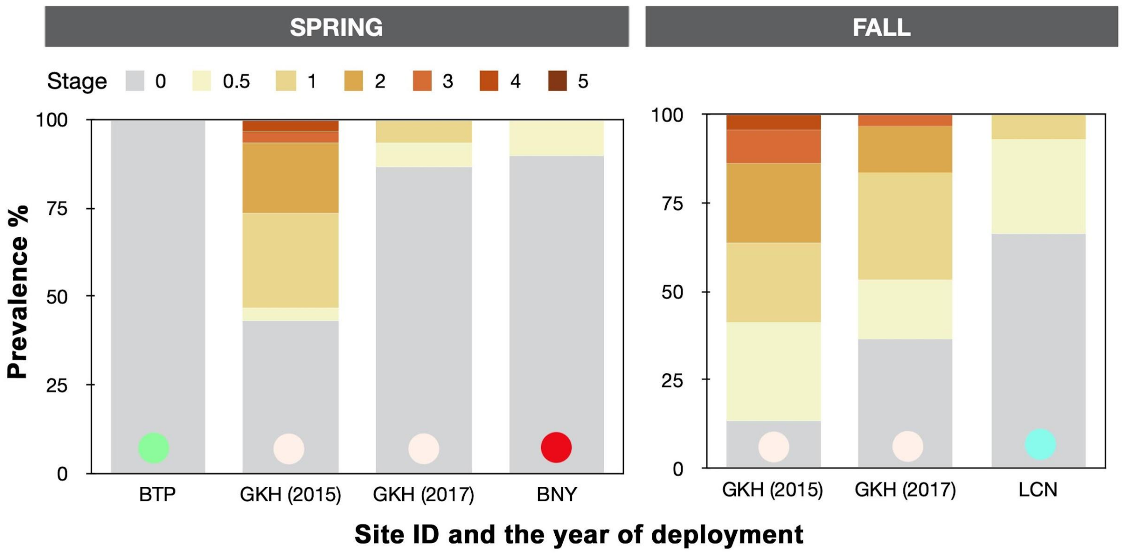

Figure 13. Dermo (*P. marinus*) prevalence (%) and intensity (stages) in oysters from three of Billion Oyster Project's field stations sampled in June and October of 2019. Stage 3 and higher is considered lethal.

Table 7. MSX (*H. nelsoni*) prevalence (%) and intensity at select sites for which oysters were tested (n = 30 individuals per site in June and October). Brooklyn Navy Yard (BNY), Great Kills Harbor (GKH) (2016 and 2017), Lemon Creek Nursery (LCN), and Bush Terminal Park (BTP) in June and October 2019. NT = oysters not tested.

	June		October	
Site	**Prevalence (%)**	**Intensity**	**Prevalence (%)**	**Intensity**
BNY	0	0	NT	NT
GKH (2016)	0	0	0	0
GKH (2017)	0	0	0	0
LCN	NT	NT	11	Moderate
BTP	0	0	NT	NT

Reproductive Status

Monitoring the reproductive status of adult oysters provides us with information about the reproductive timing and capability of a restored oyster population. Oysters have separate sexes and can switch sex (male to female) at the time of sexual maturity (typically ~2 years after settlement). In addition, oysters maintain gonads to produce gametes (eggs and sperm) only during warmer seasons when they are preparing to spawn. Because of these factors, we were able to assess oysters (1) sexual maturity and (2) readiness to spawn by determining their stages of reproductive development (Table 6) and assess the population's long-term capacity to grow by determining its sex ratio.

Typically, oysters with gonads that are categorized as gametogenic (G1–G2) or developing (D1-D2) are preparing to spawn, while those that are ripe (R) or spawning (S1–S4) are actively reproducing. Oysters in inactive (I) or undetermined (U) stages are either not ready to spawn or have recently spawned (Fig. 14). Since oysters can change sex from male to female, equivalent (50:50) or female-skewed sex ratios indicate that a population has reached sexual maturity and that conditions are optimal for successful fertilization.

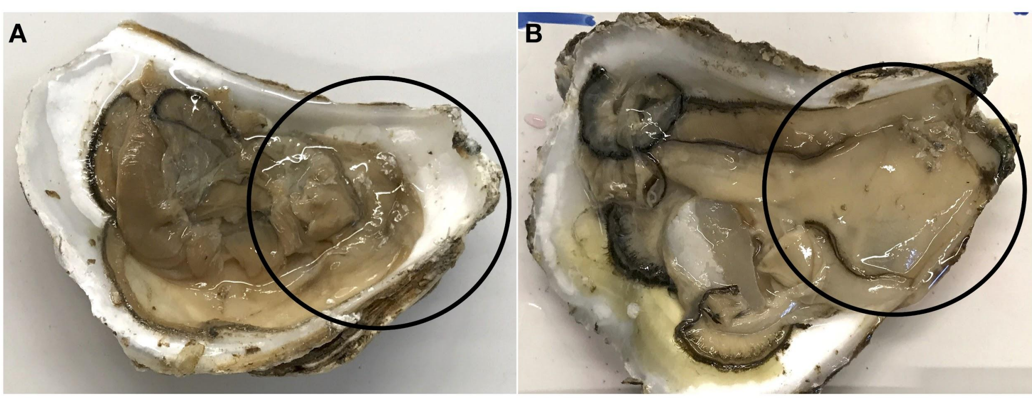

Figure 14. These pictures compare gonad development (circled) in (A) inactive or "unripe" and (B) "ripe" oyster tissue. (Photos Courtesy of Dr. Elizabeth Burmester and Dr. Michael McCann)

Table 8. Stages of reproductive development in oysters as assessed by the Stony Brook University Marine Animal Disease Lab

	Stage	**Description**
I	Inactive	No gonadal activity, resting
G1	Gametogenic I	Gametogenesis has begun; no ripe gametes visible
G2	Gametogenic II	First ripe gametes appeared; gonad developed to about one-third of its final size
D1	Developing I	Gonad increased in mass to about half the fully ripe condition; each follicle contains about equal proportions of ripe and developing gametes
D2	Developing II	Gametogenesis still progressing; follicles mainly contain ripe gametes
R	Ripe	Gonad fully ripe, early stages of gametogenesis rare; follicles distended with ripe gametes; ova compacted into polygonal configurations; sperm with visible tails
S1	Spawning I	Active emission of gametes has begun; gamete density reduced
S2	Spawning II	Gonad about half empty
S3	Spawning III	Gonadal area reduced; follicles about one-third full of ripe gametes
S4	Spawning IV	Only residual gametes remain; some may be undergoing cytolysis
U	Undetermined	Gonad tissue rudimentary (completely undeveloped, as is the case in very young oysters) or absent

Sexual differentiation and stages of gonad development among the tested individuals were performed by Dr. Basse Allam. Samples from summer (i.e., collection in June) were assumed to represent oysters' reproductive status because, after spawning, oysters resorb their gonads. Spawning season is not well understood for NY Harbor, but it is safe to assume that oysters no longer reproduce in October. To assess the reproductive status of the Great Kills Harbor oysters, the 2015/2016 cohort was sampled on June 18th, 2019, and the 2017 cohort was sampled on June 26th, 2019. Oysters from the Bush Terminal Park (2016 cohort) were sampled on June 19th, 2019 and from Brooklyn Navy Yard on June 18th. We found that oysters from the Brooklyn Navy Yard were male-skewed (only 34% were females). Among these oysters, only 27.6% were sexually mature. Oysters from Great Kills Harbor were at even sex ratios for both tested cohorts. Gametes of some of the oysters were in early stages of development, and some oysters were spent (Fig. 15, Table 4). Bush Terminal Park was the only site at which oysters were at an even sex ratio and spawning (Fig. 15, Table 4).

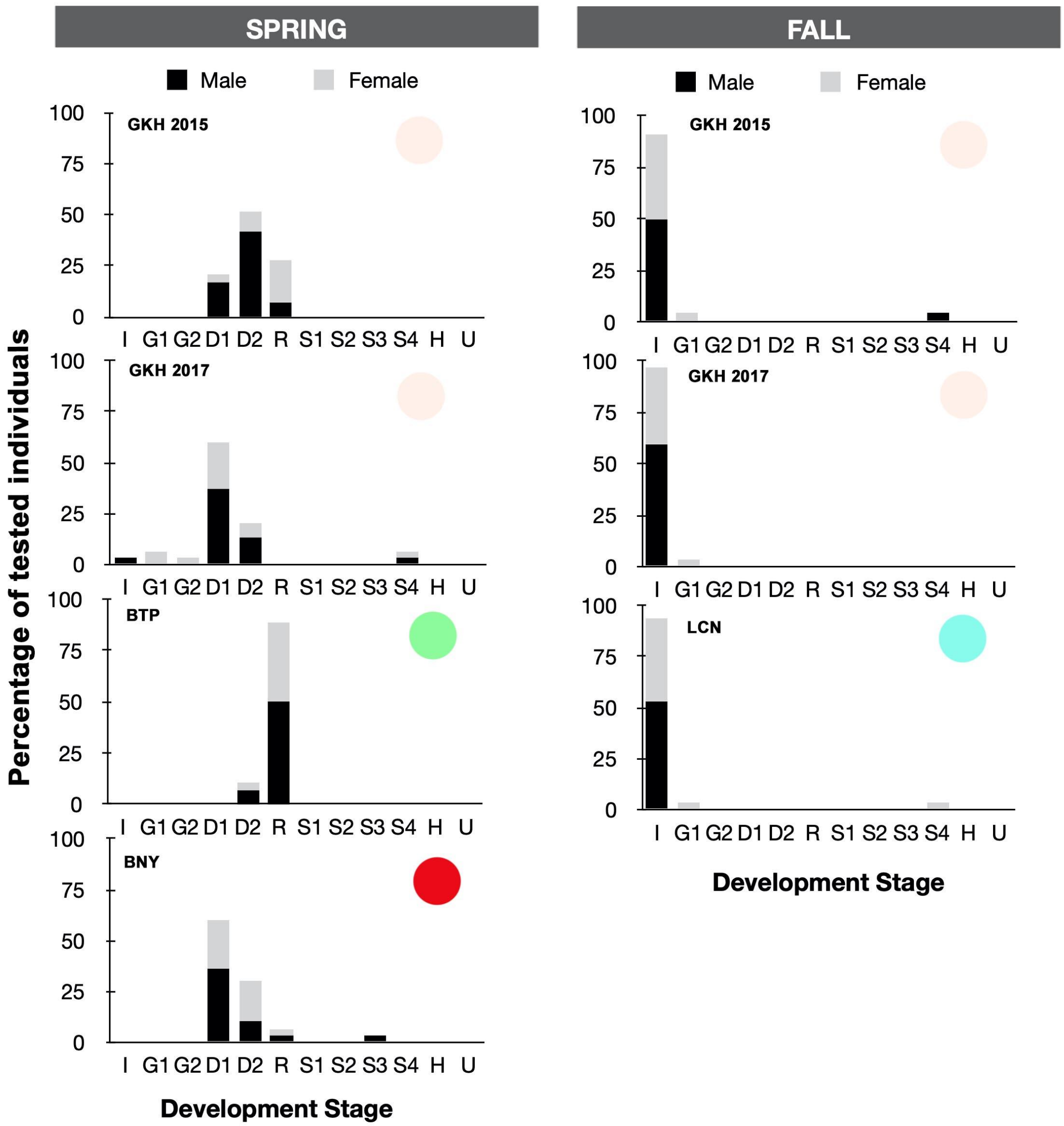

Figure 15. Sex and stage of reproductive development (I - Inactive, G1 - Gametogenic Stage I, G2 - Gametogenic Stage II, D1 - Developing Stage I, D2 - Developing Stage II, R - Ripe Stage, S1 - Spawning Stage I, S2 - Spawning Stage II, S3 - Spawning Stage III, S4 - Spawning Stage IV, U - Undetermined) of oysters from four of Billion Oyster Project's field stations (30 oysters from each site). Color dots correspond to the color code of a site, as displayed in Fig. 1. Refer to Table 8 for a full description of the reproductive stages.

Condition Index

Condition index was calculated as (dry mean weight / dry shell weight) x 100 with higher values indicating higher quality oysters (i.e., more internal body meat relative to shell). If the condition index of the same stock is measured repeatedly over the course of a season, a sudden drop in condition index can indicate spawning or other events. Because staff sampled oysters only once during the reproductive season, it is not possible to link the CI data to the status of reproduction. The condition index is available only for oysters collected in June 2019.

In June of 2019, the average CIs of oysters from the three sites were similar, ranging from 3.5 at Brooklyn Navy Yard to 4.1 at Bush Terminal Park (Fig. 16). The level of variability was relatively high within the site, possibly resulting from differences in spawning status among individuals.

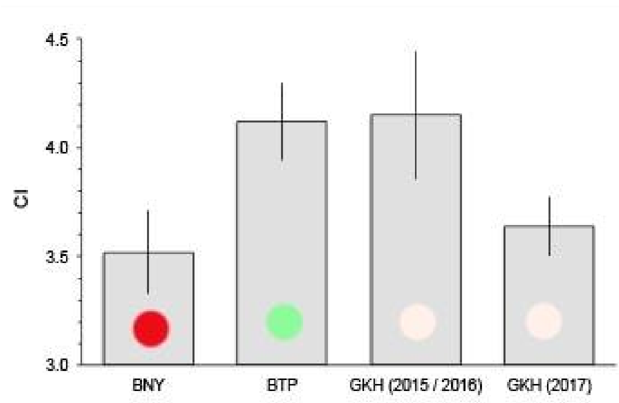

Figure 16. Condition Index (CI - y-axis) of oysters from Brooklyn Navy Yard (BNY), Great Kills Harbor (GKH) 2015 and 2017 cohorts, and Bush Terminal Park (BTP) collected in June 2019. Sites are indicated on the x-axis. CI data displayed in this figure on the y-axis represent mean values (n = 28 - 30). Error bars = standard error.

Figure 17. (A) Thinner morphology oysters growing through files at the Sunset Park, Bush Terminal Park Community Reef, and (B) thicker morphology oysters collected from an Oyster Research Station at the Canarsie Community Reef. (Photos courtesy of Finola Fung-Khee)

Water Quality Measurements

Oysters both influence and are influenced by the water quality conditions of their environment. Water quality is measured to identify environmental conditions that favor oyster reproduction, survival, and growth. Beginning with 2017, each field season, Billion Oyster Project deployed HOBO loggers that recorded temperature, salinity, and dissolved oxygen data every 15 minutes. Additional snapshot measurements are taken with hand-held sonde (Horiba U-52; Fig. 19). Measurements by the hand-held sonde are essential and are used to check whether the loggers produce reliable data. Figure 21 shows the average values for temperature, dissolved oxygen concentrations, salinity, and pH, measured on four site visits during the 2019 field season. It is important to note that the snapshot measurements cannot describe the suitability of conditions for oysters or other biota because they miss demonstrating the high variability in parameter values that constantly change. 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), and this is why high-frequency measurements are required (Figures 20-22).

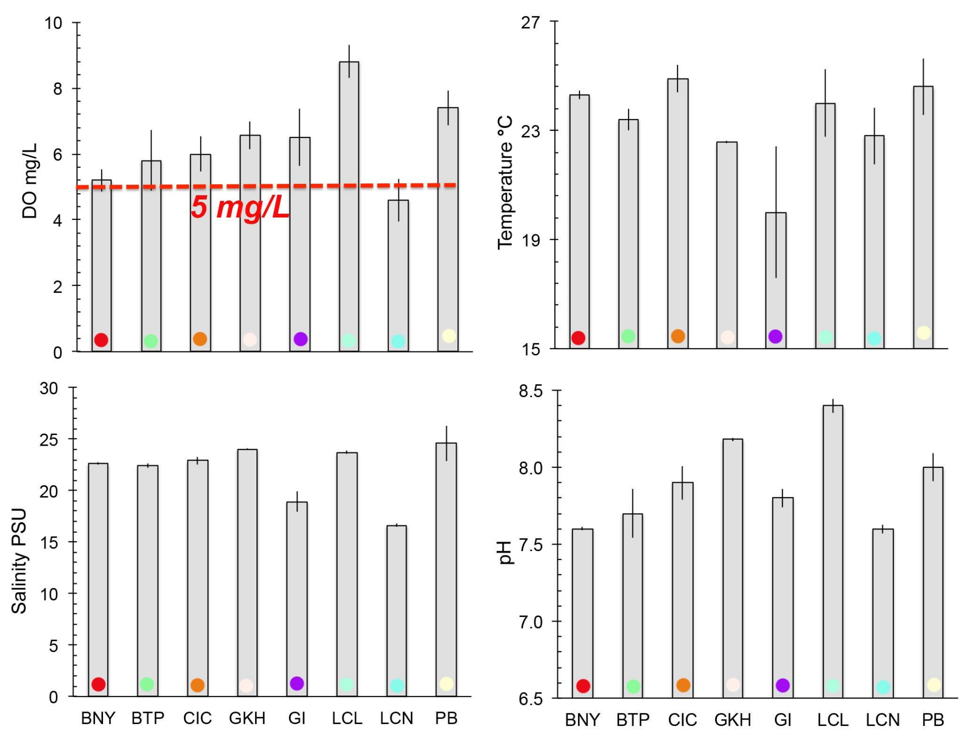

Figure 18. Average values of temperature, dissolved oxygen (DO), salinity and pH from June through September 2019, based on discrete point sampling. Measurements were performed three times at each specific date and time and each site was visited 2 (site BTP), 3 (sites BNY, CIC, GI), 4 (sites GKH, LCL and LCN), or 5 (e.g. PB) times. Sampling sites were: Brooklyn Navy Yard (BNY) (n = 3), Bush Terminal Park Community Reef (also referred to as the Sunset Park Community Reef) (n = 4),Coney Island Community Reef (CIC) (n = 5), Governors Island (GI) EcoDock (n = 6), Great Kills Harbor (GKH) (n = 4), Lemon Creek Lagoon (LCL) (n = 5), Lemon Creek Nursery (LCN) (n = 4), Canarsie Community Reef in Paerdegat Basin (PB) (n = 4). Error bar = standard error.

Figure 19. TNC Marine Science Technician Tatiana Castro-Gallego and Billion Oyster Project Summer Intern Lisette Mejia monitor water quality with HORIBA water quality meters and maintain HOBO logger equipment. (Photo courtesy of Elizabeth Burmester)

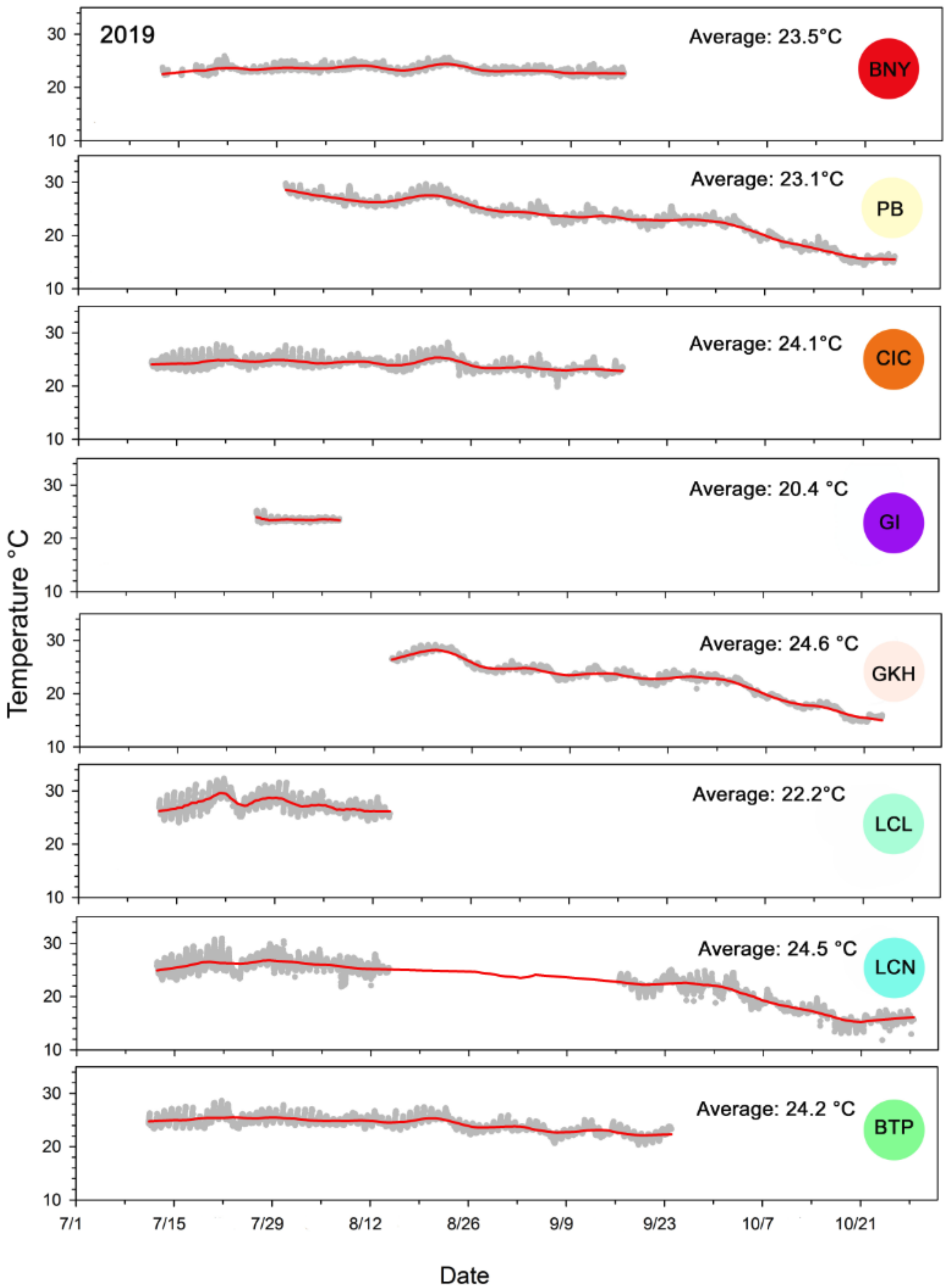

Figure 20. High-resolution (recorded every 15 minutes) temperature data for Brooklyn Navy Yard (BNY), Paerdegat Basin (PB), Coney Island Community Reef (CIC), Governors Island EcoDock (GI), Great Kills Harbor (GKH), Lemon Creek Lagoon (LCL), Lemon Creek Nursery (LCN), and Bush Terminal Park (BTP).

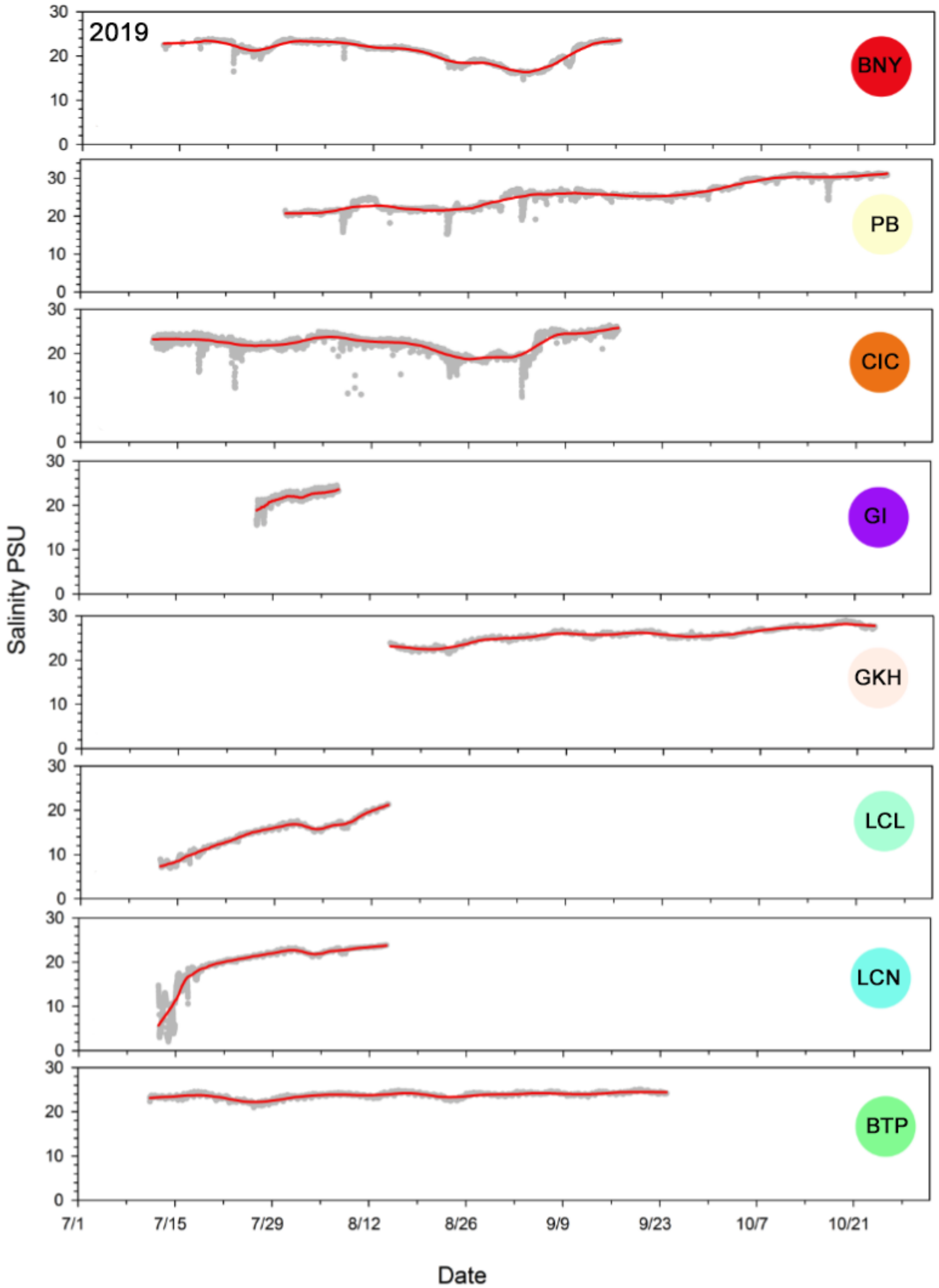

Figure 21. High-resolution (recorded every 15 minutes) salinity data for Brooklyn Navy Yard (BNY), Paerdegat Basin (PB), Coney Island Community Reef (CIC), Governors Island EcoDock (GI), Great Kills Harbor (GKH), Lemon Creek Lagoon (LCL), Lemon Creek Nursery (LCN), and Bush Terminal Park (BTP).

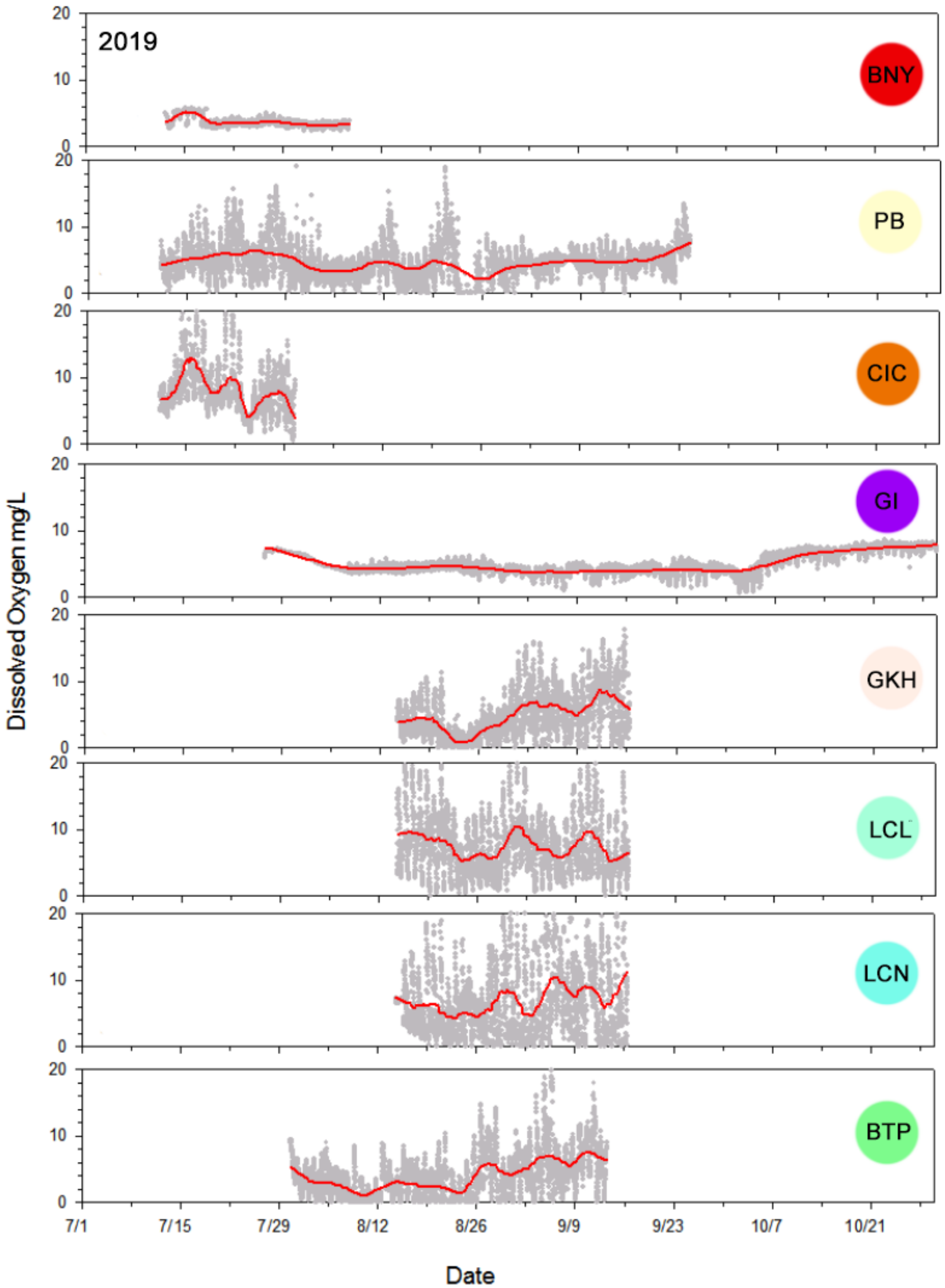

Figure 22. High-resolution (recorded every 15 minutes) dissolved oxygen data for Brooklyn Navy Yard (BNY), Paerdegat Basin (PB), Coney Island Community Reef (CIC), Governors Island EcoDock (GI), Great Kills Harbor (GKH), Lemon Creek Lagoon (LCL), Lemon Creek Nursery (LCN), and Bush Terminal Park (BTP). Red lines indicate dates when loggers were cleaned, calibrated, and redeployed. Levels below 5 mg/L are considered stressful for oysters.

Biodiversity

Oyster beds and reefs increase the three-dimensional complexity of the bottom environment and typically support greater biodiversity than adjacent, non-structured habitat, such as muddy or sandy bottoms. Most of the research on biodiversity enhancement by oyster beds comes from other estuaries, such as Chesapeake Bay, bodies of water in the southeastern United States, and the Gulf of Mexico (Peterson et al. 2003, zu Ermgassen et al. 2016). The degree to which restored oysters enhance populations of fish, crabs, and shrimp depends on biogeographic context, as different estuaries are home to different species. Therefore, in 2017, we initiated a study to understand the role of oyster restoration activities on species abundance and composition at the Sunset Park Community Reef at Bush Terminal Park in Brooklyn and Lemon Creek Lagoon in Staten Island. In 2018, we continued the study at these sites with some modifications to our sampling methodologies. As in 2017, we primarily relied on minnow traps to capture organisms at on- and off-reef sites (Fig. 23). Off-reef sites were at least 10 m away from reefs and had a similar depth as reef sites. In 2018, we continued to use minnow traps but also deployed traps with and without oyster shell inside (those with shell were roughly 50% full) and deployed traps for 48 hours. This approach is also used by Meredith Comi and Dr. Allison Fitzgerald of NY/NJ Baykeeper at the reefs at Naval Weapons Station Earle in New Jersey and Soundview in the Bronx.

At the Sunset Park Community Reef at Bush Terminal Park, in addition to placing minnow traps, we also assessed the organisms residing in and around the community reef files (i.e., cages). To do this, we quickly removed the cages from the reef and transferred them to plastic trays to collect all of the contents, including organisms that fell off the outside of the file. We then rinsed the cage with 25–30 gallons of seawater from the site and collected all the organisms that fell off. This approach allowed us to document organisms residing in and around the reef that may not enter the minnow traps. Biodiversity assessments were performed at both sites in June. Additionally, biodiversity was assessed in August and October at the Lemon Creek Lagoon. There was no access to the Bush Terminal Park site later in the summer and fall of 2019.

Table 9 reports the taxa encountered at both sites (Fig. 24 shows examples of animals found in association with the Billion Oyster Project oyster reefs). A total of eight taxa were captured at Bush Terminal Park. There were eleven taxa at the Lemon Creek Lagoon. All species are summarized in Table 10. Among the various organisms, there were some oyster predators, including Oyster toadfish. Blue crab was also present at the reef sites. This is a species valued commercially and commonly harvested by recreational anglers. According to a recent report, oyster restoration should enhance the population of Blue crab (Knoche et al. 2020).

Table 10 summarizes the abundance values of different organisms caught in minnow traps. We found more species on the reef at both sites than off the reef (Bush Terminal Park: 7 vs. 4; Lemon Creek Lagoon: 7 vs. 6). In most cases, the addition of shells to the minnow traps attracted fewer taxa, except at the "Off reef" location at the Bush Terminal Park (Table 11). The empty minnow traps attracted six different types of organisms, but those filled with shells attracted either five (at BTP) or three types of organisms in Lemon Creek Lagoon's "On reef" and "Off reef" locations (Table 11). Total abundances of organisms show that the reef at Bush Terminal Park attracted ten times more individuals than were present away from the reef (870 vs. 87). The difference in the number of animals at the Lemon Creek Lagoon was minimal "On reef": 369 vs. "Off reef": 300; Table 11).

As the access to the Bush Terminal Park was interrupted during the 2019 summer, biodiversity data collection occurred only once at this site but three times at the Lemon Creek Lagoon site (Table 12). Animals were most abundant at the end of May.

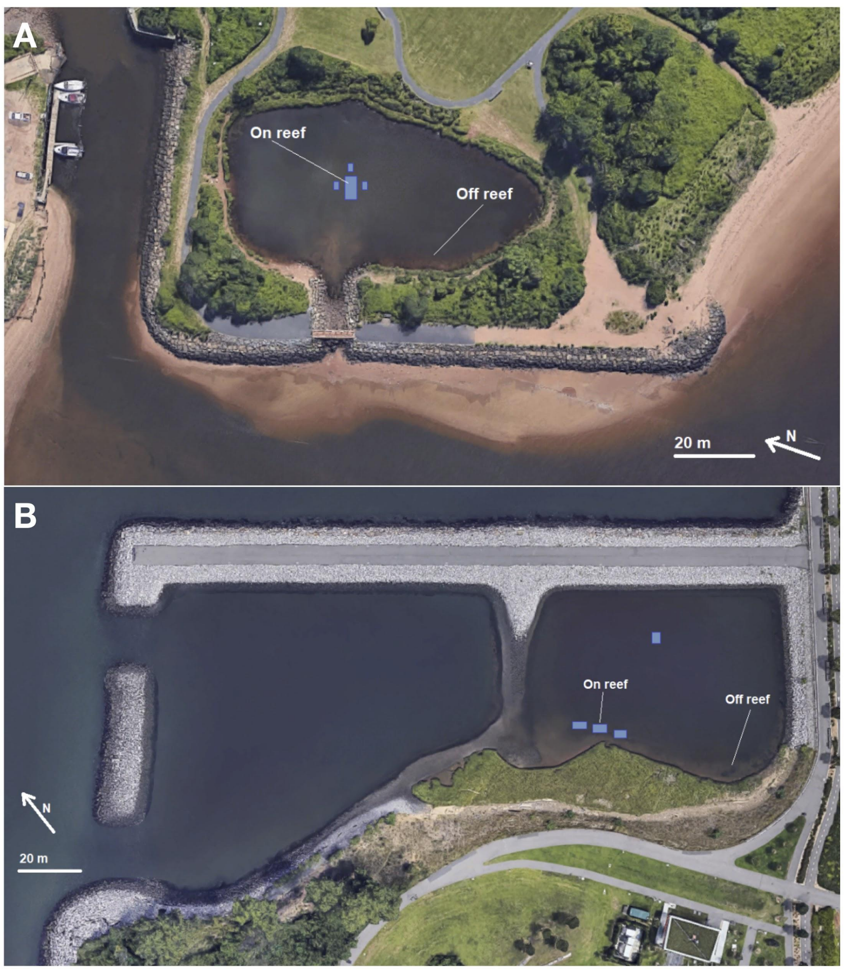

Figure 23. Aerial view of biodiversity study sites at (A) Lemon Creek Lagoon and (B) Sunset Park Community Reef at Bush Terminal Park. Blue polygons indicate approximate size and location of oyster restoration projects. (Diagrams courtesy of Dr. Michael McCann).

Table 9. Taxonomic richness at Lemon Creek Lagoon and Bush Terminal Park, May - October 2019.

Vertebrates			
Scientific Name	**Common Name**	**Lemon Creek Lagoon**	**Bush Terminal Park**
Anguilla rostrata	American eel	x	
Apeltes quadracus	Fourspine stickleback	x	
Cyprinodon variegatus variegatus	Sheepshead minnow		
Fundulus heteroclitus	Mummichog	x	
Fundulus majalis	Striped killifish	x	
Gobiosoma bosc	Naked goby	x	x
Menidia menidia	Atlantic silverside		
Morone saxatilis	Striped bass		
Opsanus tau	Oyster toadfish	x	x
Paralichthys dentatus	Summer flounder		x
Pseudopleuronectes americanus	Winter flounder		
Syngnathus fuscus	Northern pipefish		
Invertebrates			
Scientific Name	**Common Name**	**Lemon Creek Lagoon**	**Bush Terminal Park**
Order Amphipoda	Amphipod	x	
Callinectes sapidus	Blue crab	x	x
Carcinus maenas	Green crab		x
Crangon septemspinosa	Sand shrimp		
Geukensia demissa	Atlantic ribbed mussel		
Hemigrapsus sanguineus	Asian shore crab		
Mercenaria mercenaria	Hard clam (quahog)		
Mnemiopsis leidyi	Sea walnut	x	
Mytilus edulis	Blue mussel		
Nephtys sp.	Red-lined worm		
Nereis spp.	Clam worm		
Palaemonetes spp.	Grass shrimp	x	x
Panopeus spp.	Mud crab		x
Class Polychaeta	Polychaete worm(s)		
Tritia obsoleta	Eastern mud snail	x	x
Urosalpinx cinerea	Atlantic oyster drill	x	

Table 10. A summary of data on total abundances. Animals were collected by minnow traps, which were deployed on ("On-reef") and off the restored bagged shell reef ("Off-reef") at Lemon Creek Lagoon and Bush Terminal Park for two days.

	Bush Terminal Park				Lemon Creek Lagoon			
	Off reef		On reef		Off reef		On reef	
Taxon	Shells Absent	Shells Present	Shells Absent	Shells Present	Shells Absent	Shells Present	Shells Absent	Shells Present
Amphipoda								3
Anguilla rostrata							1	
Apeltes quadracus					1			
Callinectes sapidus		2			1		3	
Carcinus maenas			1					
Fundulus heteroclitus					1	3	8	
Gobiosoma bosc		2	2	6	1			
Opsanus tau			3	1			2	
Palaemonetes spp.	4	49	15	60	25	16	5	15
Panopeus spp.				1				
Paralichthys dentatus			1					
Tritia obsoleta	3	27	613	167	169	83	184	148
Total Abundance	7	80	635	235	198	102	203	166
Taxonomic Richness	2	4	6	5	6	3	6	3
Total Taxonomic Richness	4		7		6		7	
Total Abundance at Site	87		870		300		369	

Table 11. Temporal patterns in abundance of different organisms were collected in minnow traps (data combined for traps with and without oyster shells) set out on the reef ("On-reef") and off the reef ("Off-reef") at the Lemon Creek Lagoon (LCL) in Staten Island. Billion Oyster Project staff and interns assessed animal abundances in May, August, and October of 2019.

Sampling Date	Taxon	Location within the site		Ratio of individuals off vs. on reef
		Off reef	On reef	
5/29/19	*Amphipoda*		3	
	Anguilla rostrata		1	
	Apeltes quadracus	1		
	Callinectes sapidus	1	3	
	Fundulus heteroclitus	4	8	
	Gobiosoma bosc	1		
	Opsanus tau		2	
	Palaemonetes spp.	41	20	
	Tritia obsoleta	252	332	
	Total Abundance	300	369	1.2
8/12/19	*Apeltes quadracus*		1	
	Fundulus heteroclitus	5	25	
	Gobiosoma bosc		2	
	Mnemiopsis leidyi		1	
	Palaemonetes spp.	10	13	
	Tritia obsoleta	60	141	
	Total Abundance	75	183	2.4
10/22/19	*Anguilla rostrata*		1	
	Fundulus heteroclitus	120	87	
	Fundulus majalis		1	
	Gobiosoma bosc	4	3	
	Palaemonetes spp.	9	44	
	Tritia obsoleta		2	
	Total Abundance	133	138	1.0

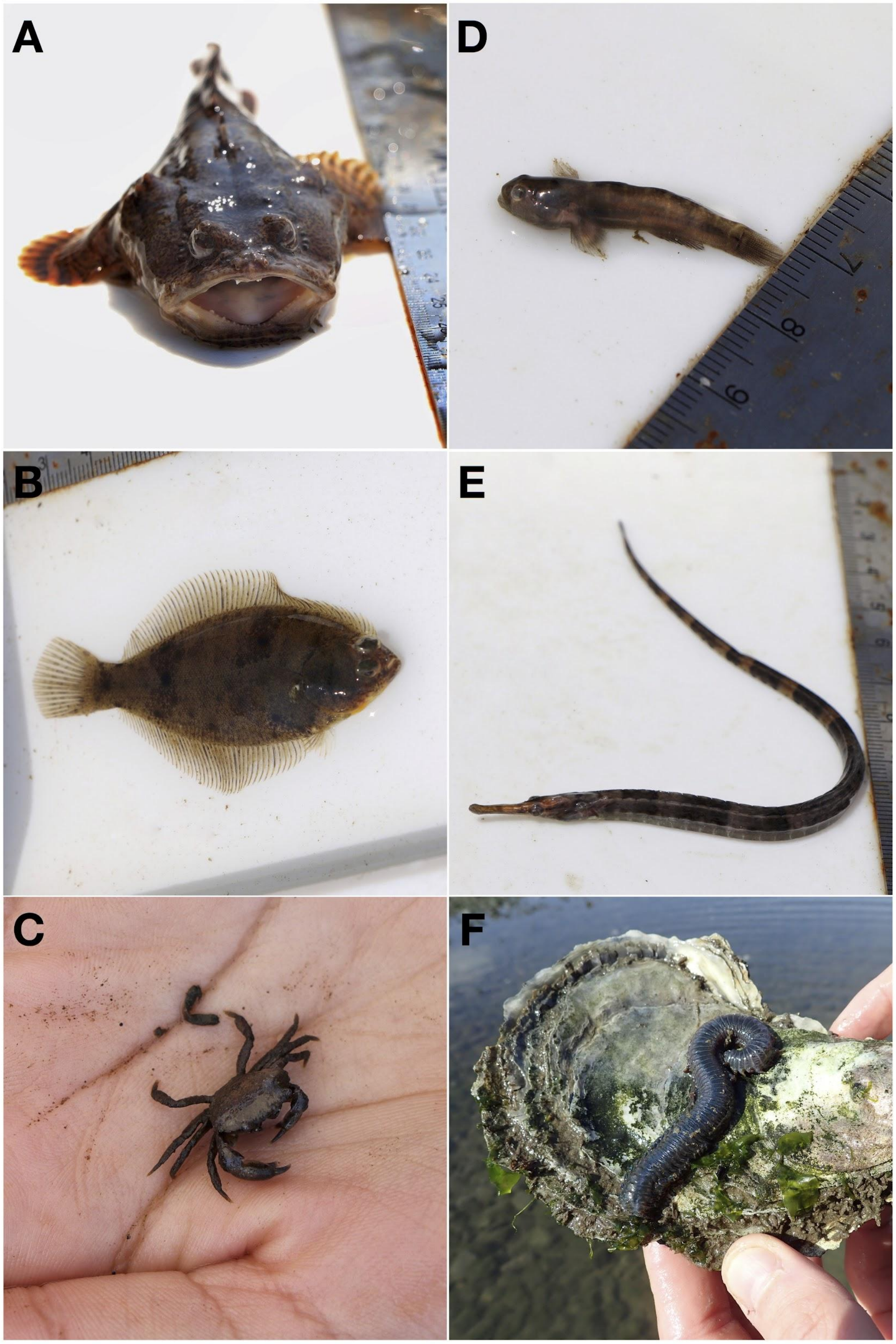

Figure 24. Examples of organisms inhabiting restored reefs: (A) Oyster toadfish (*Opsanus tau*), (B) Winter flounder (*Pseudopleuronectes americanus*), (C) Mud crab (*Panopeus sp*.), (D) Naked goby (*Gobiosoma bosc*), (E) Northern pipefish (*Syngnathus fuscus)*, and (F) Clam worm (*Nereis* sp.). (Photos courtesy of Elizabeth Burmester)

References

Baumann, H., Wallace, R., Tagliaferri, T., and Gobler, C. 2015. Large Natural pH, CO_2 and O_2 Fluctuations in a Temperate Tidal Salt Marsh on Diel, Seasonal, and Interannual Time Scales. Estuaries and Coasts 38(1): 220-231.

Brown, JR, EB Hartwick. 1988. A habitat suitability index model for suspended tray culture of the Pacific oyster, *Crassostrea gigas* Thunberg. Aquaculture and Fisheries Management 19: 109–126.

Hoellein, TJ, CB Zarnoch. 2014. Effect of eastern oysters (*Crassostrea virginica*) on sediment carbon and nitrogen dynamics in an urban estuary. Ecological Applications 24: 271–286.

Knoche, Scott, Thomas F. Ihde, Giselle Samonte, Howard M. Townsend, Douglas Lipton, Kristy A. Lewis, and Scott Steinback. 2020. Estimating Ecological Benefits and Socio-Economic Impacts from Oyster Reef Restoration in the Choptank River Complex, Chesapeake Bay. NOAA Technical Memorandum NMFS-OHC-6, 68 p.

Long Island Sound Study: https://longislandsoundstudy.net/about/our-mission/management-plan/hypoxia/

McCann, MJ. 2018. New York City Oyster Monitoring Report: 2016–2017. The Nature Conservancy, New York, NY.

McCann, MJ. 2019. Restoring Oysters to Urban Waters: Lessons Learned and Future Opportunities in NY/NJ Harbor. The Nature Conservancy, New York, NY.

Newell, RIE, CJ Langdon. 1996. Mechanisms and physiology of larval and adult feeding. In The Eastern Oyster *Crassostrea virginica*, ed. VS Kennedy, RIE Newell, AF Eble. A Maryland Sea Grant Book: College Park, MD, pp. 185–229.

Peterson, CH, JH Grabowski, SP Powers. 2003. Estimated enhancement of fish production resulting from restoring oyster reef habitat: Quantitative valuation. Marine Ecology Progress Series 264: 249–264.

Shumway, S.E. 1996. Natural Environmental Factors. In The Eastern oyster Crassostrea virginica. Edited by V.S. Kennedy, R.I.E. Newell and A.F. Eble. Maryland Sea Grant College, College Park, Maryland. pp. 467-513.

Starke, A., Levinton, J., and Doall, M. 2011. Restoration of Crassostrea virginica (gmelin) to the Hudson River, USA: a spatio-temporal modeling approach. Journal of Shellfish Research 30,671–684.

Talmage, Stephanie C., and Christopher J. Gobler. 2009 The effects of elevated carbon dioxide concentrations on the metamorphosis, size, and survival of larval hard clams (*Mercenaria mercenaria*), bay scallops (*Argopecten irradians*), and Eastern oysters (*Crassostrea virginica*). Limnology and Oceanography 54(6): 2072-2080.

Tappan Zee Constructors LLC. 2013 Oyster Material Collection and Placement Report for Tappan Zee Hudson River Crossing Project

Theuerkauf, SJ, RN Lipcius. 2016. Quantitative validation of a habitat suitability index for oyster restoration. Frontiers in Marine Science 3: 64.

Tomasetti, S.J. and Gobler, C.J., 2020. Dissolved oxygen and pH criteria leave fisheries at risk. Science, 368(6489), pp.372-373.

Wallace, R.B., Baumann, H., Grear, J.S., Aller, R.C., and Gobler, C.J. 2014. Coastal ocean acidification: The other eutrophication problem. Estuarine, Coastal and Shelf Science 148: 1-13

Waldbusser, George G., Ryan A. Steenson, and Mark A. Green. 2011. Oyster shell dissolution rates in estuarine waters: effects of pH and shell legacy. Journal of Shellfish Research 30(3): 659-669.

zu Ermgassen, PSE, JH Grabowski, JR Gair, SP Powers. 2016. Quantifying fish and mobile invertebrate production from a threatened nursery habitat. Journal of Applied Ecology 53: 596–606.