

Evaluation of Pier 94 as a potential oyster restoration site



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Project background

The native Olympia oyster (*Ostrea lurida*) has declined from historic levels along the west coast of North America (Baker 1995, zu Ermgassen et al. 2012). These small (<70 mm) oysters once formed beds in many estuaries along the West Coast, where they provided food and habitat for numerous other organisms and provided other ecosystem services such as nutrient cycling. Harvested by Native Americans and then by European settlers (Baker 1995), they were also a part of the cultural history of our coast. Although the exact reason for their decline is unknown and likely varies by estuary, native oysters undoubtedly suffered from overharvesting, pollution, and habitat modifications, including increased siltation (Baker 1995, zu Ermgassen et al. 2012). Once the faster growing and larger Eastern oyster (*Crassostrea virginica*) and the Pacific oyster (*Magellana gigas*) could be successfully imported to the West Coast, human interest in the Olympia oyster as a fishery faded.

Efforts to restore Olympia oysters on the West Coast began in Puget Sound in 1999. Field studies and then small pilot projects started in San Francisco Bay shortly thereafter. Today, there are 40 projects to restore or enhance native oyster populations from British Columbia to Southern California. More information about these efforts is available on the Native Olympia Oyster Collaborative website olympiaoysernet.ucdavis.edu. These projects vary in terms of goals and approaches, with some projects attempting to re-establish locally extinct populations and others enhancing existing populations with the goal of restoring ecosystem functions.

A multi-agency resource management plan, the San Francisco Bay Subtidal Habitat Goals Report (SHGR, California State Coastal Conservancy 2010), articulated a goal of restoring up to 8,000 acres of oyster beds in San Francisco Bay within 50 years. Because Olympia oyster restoration approaches are new (relative to longer-term efforts on the East and Gulf coasts for *C. virginica*), the SHGR recommended a phased approach to restoration in the Bay. This approach included investigating site suitability for new projects by measuring oyster demographics and key environmental parameters, and scaling up from pilot scale to larger projects, using a robust experimental design and monitoring data to inform each step. It also made broad recommendations for suitable regions within the Bay based on a combination of appropriate bathymetry and other environmental conditions and restoration opportunities (i.e., locations where other restoration efforts were underway or planned). Since the publication of the report, further research summarized by Wasson et al. (2014) refined key parameters for site selection within San Francisco Bay. Measurements of existing oyster population at a site, particularly recruitment rate, adult oyster density, and distribution of oyster size classes, were identified as good ways to identify a suitable location for oyster restoration. Some of the factors that could be detrimental to oyster success at a site, according to Wasson et al. (2014), included the presence/abundance of predators (primarily the non-native oyster drill *Urosalpinx cinerea*), risk of exposure to high air temperatures during low tides, and risk of exposure to extended periods of low salinity water (defined as more than 5 days of salinity lower than 10).

In San Francisco Bay small, scattered populations of native oysters can be found on hard substrates in the intertidal zone from just south of the Dumbarton Bridge past the Richmond-San Rafael Bridge into North Bay. In some years and at some locations, densities can be quite high (>100/m²). The northern limit of oysters in the Bay appears to be set by salinity. In dry years oysters may settle far north and into Suisun Bay. In wet years, freshwater input from the

Sacramento-San Joaquin Delta can kill oysters in the North Bay (Cheng et al. 2016). In very rainy years, freshwater input from streams in the South Bay may also kill oysters, restricting them to the central portion of the Bay (Chang et al. 2016, Cheng et al. 2016). Surviving populations in Central Bay may be critical to re-populating the rest of the Bay following extreme flood years. As both more extreme drought and more extreme rain are expected as part of climate change, protecting and enhancing oysters in Central Bay may become key to the long-term survival of Olympia oysters throughout San Francisco Bay.

The Pier 94 Wetlands project is a long-term effort to restore and protect native marsh habitat on land owned by the Port of San Francisco in an industrial area on San Francisco's southern waterfront. Since 2002, Golden Gate Audubon has been organizing volunteer efforts to remove trash and weeds and nurture native plants there. In 2006, the Port of San Francisco, the San Francisco Bay Natural Resources Trust, and the California Coastal Conservancy completed enhancements to the site that included removing fill and debris and regrading the area to a more natural topographic form. This effort improved tidal circulation, which allowed for the creation of 1.5 acres of new wetland on the 5-acre site, a habitat type that is critical for both migratory and resident bird species. However, there are now concerns that the marsh may be eroding behind the rip-rapped shoreline, and a desire to investigate whether the addition of a living shoreline might 1) provide increased shoreline protection and 2) provide habitat for a suite of native subtidal and intertidal organisms at the site.

The term "living shoreline" encompasses a wide variety of approaches to shoreline protection that include some natural components to protect and stabilize a shoreline (<https://oceanservice.noaa.gov/facts/living-shoreline.html>). This concept has been more widely adopted on the East and Gulf coasts than on the West Coast. In a handful of projects in California, including San Francisco Bay, oyster settlement substrates are part of a living shoreline approach, in which eelgrass, marsh plants, and other natural elements are restored together with the goal of both enhancing habitat and protecting shorelines from erosion. Monitoring data from the oldest of these projects, the San Francisco Bay Living Shorelines Project at San Rafael, indicated an increased diversity of invertebrate species in the project area (compared to pre-project and a control site with no project), an increase in the diversity of birds using the project area for foraging and resting, sediment accretion around the oyster substrates, and a reduction of wave energy on the shoreward side of the oyster structures (Boyer et al. 2016). Golden Gate Audubon and the Port of San Francisco are interested in determining whether native oysters could be used as part of a living shoreline at Pier 94.

As adults, Olympia oysters are filter-feeding, bivalve (two-shelled) molluscs that live attached to hard substrates such as rocks, riprap, seawalls and pier pilings. Native oysters are sequential hermaphrodites, beginning life as males, and later developing into females, and switching back again perhaps as frequently as twice in a year. Female oysters take up sperm from the water column through filter feeding; fertilized eggs then develop into tiny larvae inside their mother's mantle over the course of 7 to 12 days. While adult oysters cannot leave the substrate to which they are attached, they begin life as weakly swimming larvae that can feed and drift in the plankton for days to weeks (Fig. 1). Because of this dispersal phase, adult oysters at any given site may have originated from elsewhere, and populations within San Francisco Bay are to some degree connected to one another.

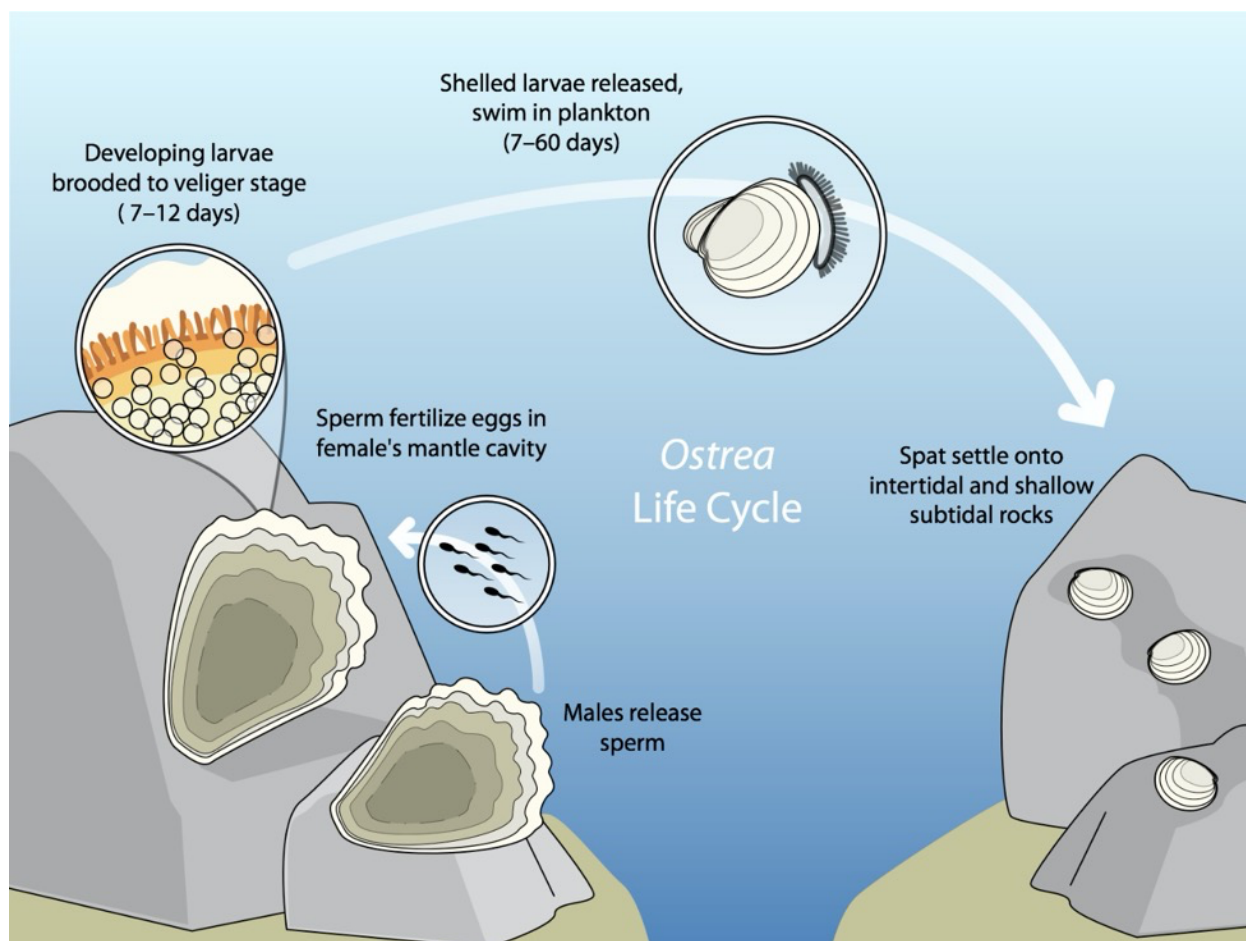


Figure 1. The life cycle of the native Olympia oyster *Ostrea lurida* by Julia C. Blum. Licensed under the Creative Commons Attribution—NonCommercial 4.0 International License. To view a copy of this license, visit <http://creativecommons.org/licenses/by-nc/4.0/>. Image source: <http://www.flickr.com/photos/juliablum/13316182434/>.

Project goals and objectives

The goal of our project was to investigate key aspects of the existing oyster population at the Pier 94 site to determine the site's suitability for an oyster restoration project and/or a living shorelines project that would include oysters. Our project was broadly aligned with the stepwise approach for site selection recommended by the 2010 Subtidal Habitat Goals report, combining elements of the report's Phase 1 and Phase 2 actions. We also took into account the findings of Wasson et al. (2014, 2015) who further refined critical data for site selection and highlighted key factors to oyster restoration success. All of these documents recommend gathering population-level data on oyster recruitment, adult densities, other biotic factors such as potential predators and abiotic factors such as temperature and salinity.

Specifically, we aimed to measure several parameters: 1) the current distribution and abundance of adult oysters at the site; 2) oyster recruitment to two tidal elevations; 3) the presence and abundance of the Atlantic oyster drill *Urosalpinx cinerea*, which, when present in high densities can decimate oyster populations; 4) the presence and abundance of the native

rockweed *Fucus distichus*, which may protect oysters from heat stress during low tides; 5) air and water temperature at tidal elevations to which oysters are recruiting. As salinity can also be a critical factor in oyster survival; data on salinity at the site were gathered by Golden Gate Audubon, and data from USGS at two nearby survey stations were also reviewed.

These data were to be entered into a site evaluation table to generate an overall score for the likelihood that oyster restoration would be successful at Pier 94. The evaluation table was developed by SERC staff and collaborators at the San Francisco Bay National Estuarine Research Reserve (NERR) and Elkhorn Slough NERR (Wasson et al. 2014, further refined by Wasson et al. 2015). It uses several key attributes of existing oyster populations and a suite of environmental and biological parameters to score potential restoration sites and rank them relative to one another. Further details about the selection and ranking of the various metrics used in the table are available in Wasson et al. 2014 and associated appendices. Some of these data are challenging and costly to obtain, but others are easily measured, and the tool can be used with a smaller number of factors, albeit with less certainty in the overall score.

We also aimed to involve volunteers in this project, in the shoreline surveys and examination of recruitment tiles. Volunteers worked with us in 2019, but the global COVID-19 pandemic made this unviable in 2020.

Methods

Field surveys. We made three surveys of the shoreline at Pier 94 in two consecutive summers (August 2019 and July 2020) and one spring (April 2020). At each time point, we surveyed two 30-m segments of the rip-rapped shoreline. One transect ran along the site's southern shoreline and one along the western shoreline; both transects started at the edge of the rip-rap on either side of the small sandy beach in the southwestern corner of the site (Fig. 2). We worked during daylight low tides, placing the transect tape over the substrate close to the water's edge (~0 MLLW, estimated based on tide predictions for NOAA's Hunters Point tide station).

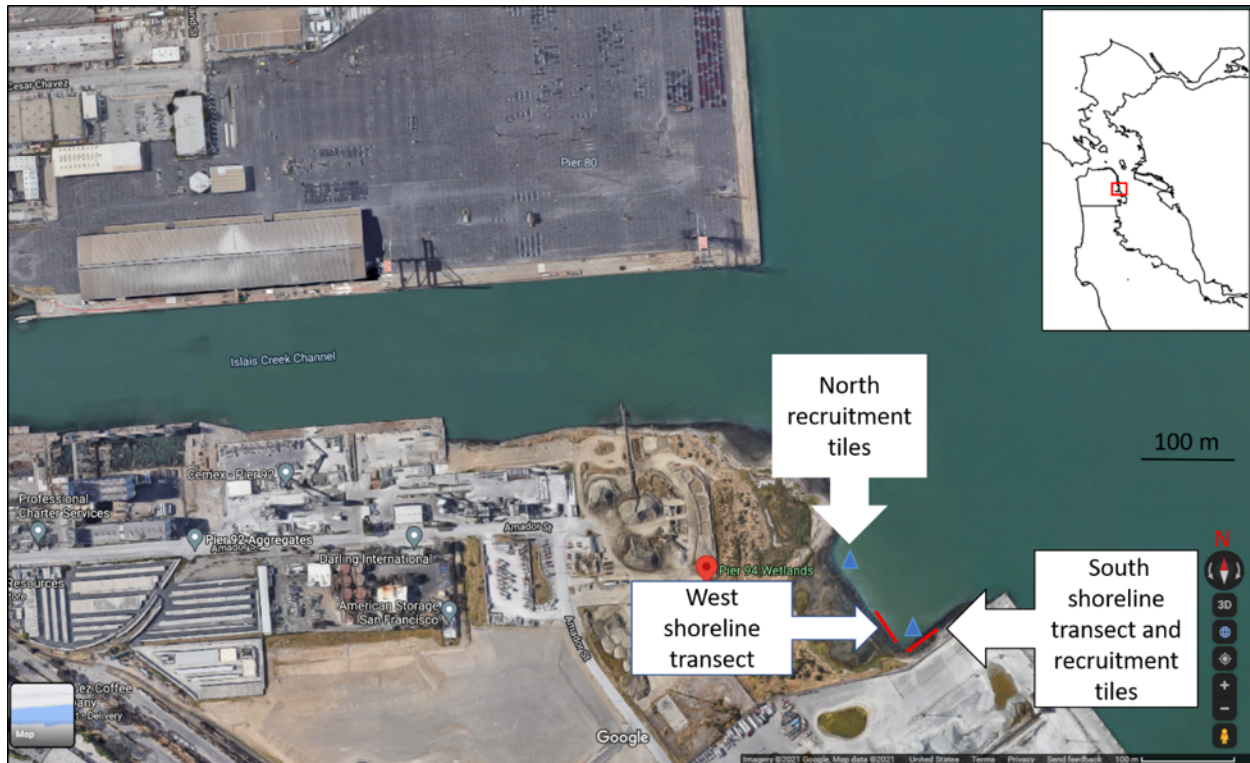


Figure 2. Map of the Pier 94 study area. Thirty-meter transect locations indicated by red lines; recruitment tile locations indicated by blue triangles.

To estimate densities of the oyster population at Pier 94, we counted all oysters within ten 25 x 25 cm quadrats in each transect. We used a stratified random approach to determine the placement of the quadrat along the transect, with 5 points randomly selected in the 0 to 14.9 m section of the transect and 5 in the 15 to 29.5 m section. We alternated placement of the quadrat to either the bay side or the shore side of the transect to estimate abundances along a 0.5 m swath of the shoreline. We counted all oysters within the quadrat, including those on the sides of rocks and the undersides of cobbles. We enumerated both live oysters and recently dead oysters (top shell still attached). Oyster “scars” or the bottom shell, which is attached to the rock, can persist for a long time and thus don’t provide a good picture of recent mortality in a population. We also measured oysters in each quadrat, using calipers and measuring the longest dimension to the nearest 1 mm. To prevent bias, we always began making measurements in the upper left-hand corner and then moved to the right side and down the quadrat until we had recorded the sizes of up to ten oysters.

We searched for the Atlantic oyster drill within the quadrats and examined oyster shells for signs of drill predation. The snails attack their prey by using their tongues and acidic secretions to create a distinctive, perfectly round hole in shells (see Fig. 17). In addition, we made visual estimates of cover of *Fucus distichus* (percent cover in bins of 5%). At this site, we noted that the most dense *Fucus* patches were higher in the intertidal than the oyster zone. We made some additional measurements of *Fucus* cover at this tidal elevation (~61 cm +MLLW). For educational purposes, we also photographed other intertidal organisms found at the site and shared these with Golden Gate Audubon.

Recruitment. To measure recruitment (settlement and early survival) of oysters to the site, we used 10.8 x 10.8 cm white ceramic tiles (Datile Bright White wall tile) suspended above the benthos, retrieved and replaced with new tiles three times a year (in April, July/August and November). This timing allows us to detect the spring, early summer, late summer-fall pulses of oyster recruitment that earlier studies indicate exist in San Francisco Bay. Three tiles were attached to each of four PVC frames using stainless steel bolts and nylon wingnuts. Because oysters prefer to settle on the undersides of surfaces and on surfaces with rough texture, we oriented the tiles horizontally with the unglazed side facing the benthos. We attached the frames to reinforcing bar driven into the mud. Two frames were placed in the northwest and the southwest corners of the site (Fig. 2). Buoys and flags were used to mark the frames. We attempted to set the tiles out at -30 and +30 cm mean lower low water (MLLW) to look at the potential effects of tidal elevation on oyster recruitment. Previous work in the Bay indicates the highest densities of intertidal oysters tend to be within this range.

We used temperature loggers (Onset HOBO Pendant temperature/light loggers model #UA-002-64) attached to the recruitment frames to record temperatures likely to be experienced by oysters at the tidal elevations of the frames. These were set to record every 15 minutes.

Spot measurements of salinity were made periodically by Golden Gate Audubon from April 2020 to January 2021 using a handheld refractometer. Time, temperature and tide were also noted. For 2019-2020, we analyzed temperature data from the two water quality stations nearest Pier 94, monitored by USGS (Stations 22 Potrero Point and 23 Hunter's Point, which are to the north and south of the site [Schrage et al. 2018]). USGS water quality measurements are made once a month with a submersible CTD and capture a depth profile with readings every 1 m to a depth of 18 m at Station 22 and 1 m to 20 m at Station 23.

We used the data collected to populate the Site Evaluation Table, an Excel spreadsheet that converts raw data into scores that range from 0 to 100 and uses weighted multipliers to generate an overall score. The table below summarizes the data we used in the evaluation tool.

Table 1. How data collected for Pier 94 were used for the Site Evaluation Table.

Measurement/units	Method
Adult oyster density on existing hard substrate: mean # oysters/m ²	Surveys in 30 x 0.5 m transects: 10 sub-samples per transect using 25 x 25 cm quadrats
Size of largest oysters: mean length in mm	Mean of the upper quartile of oysters measured in the above surveys
Oyster recruitment: mean # oysters/m ² across recruitment season	Counts on 10 x 10 cm recruitment tiles, which were retrieved and replaced every four months
Density of oyster drills: mean #oyster drills/m ²	Surveys in 30 x 0.5 m transects: 10 sub-samples per transect using 25 x 25 cm quadrats
Risk of high air temperatures: number of days with temps above 30° C during warm season	Data from temperature loggers attached to recruitment frames.
Salinity range: % of salinity measurements <25	Spot measurements made by GG Audubon and USGS

Risk of low salinity events: % of years with salinity <5 ppt for 4 or more consecutive days	Used data from Wasson et al. 2014: these data were from long-term regional sondes in Central Bay
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Data analysis. Statistical analyses were performed in R software (version 4.0.3: R Core Team 2020). Generalized linear models (GLM) were developed using the glmmTMB package (Brooks et al., 2017). A mixed-effects model (GLMM) was used when appropriate by designating timepoint of data collection as a random-effect variable.

A modified Gini-Simpson index was used to characterize the diversity of oyster size classes at the site. The Gini-Simpson index is a measure of species diversity based on the proportional abundance of each species in a sample relative to the total number of species in that sample (Kiernan 2020). Diversity can be calculated by the formula $D = 1 - \sum_{i=1}^R p_i^2$ where R is the total number of species in a sample and P is the proportional abundance of each species. The index is scaled from zero (no diversity) to one (maximum diversity). For purposes of the Site Evaluation Table, abundance of species was replaced by abundance of oysters in a size class. Size classes were binned in 10 mm intervals.

Results

Density of adult oysters on existing hard substrate. Abundance of adult oysters varied across survey time periods and was 29% higher on average on the west shore compared to the south shore (Fig. 3, Table 2), although the shorelines were similar in summer 2020. This difference was statistically significant (GLMM: $z = 2.05$, $p = 0.04$; GLM: $Z = 5.89$, $p < 0.001$). Across both transects and all timepoints, average abundance of oysters was 47 m², which generated a weighted score of 100 (out of a potential 200) in the Site Evaluation Table.

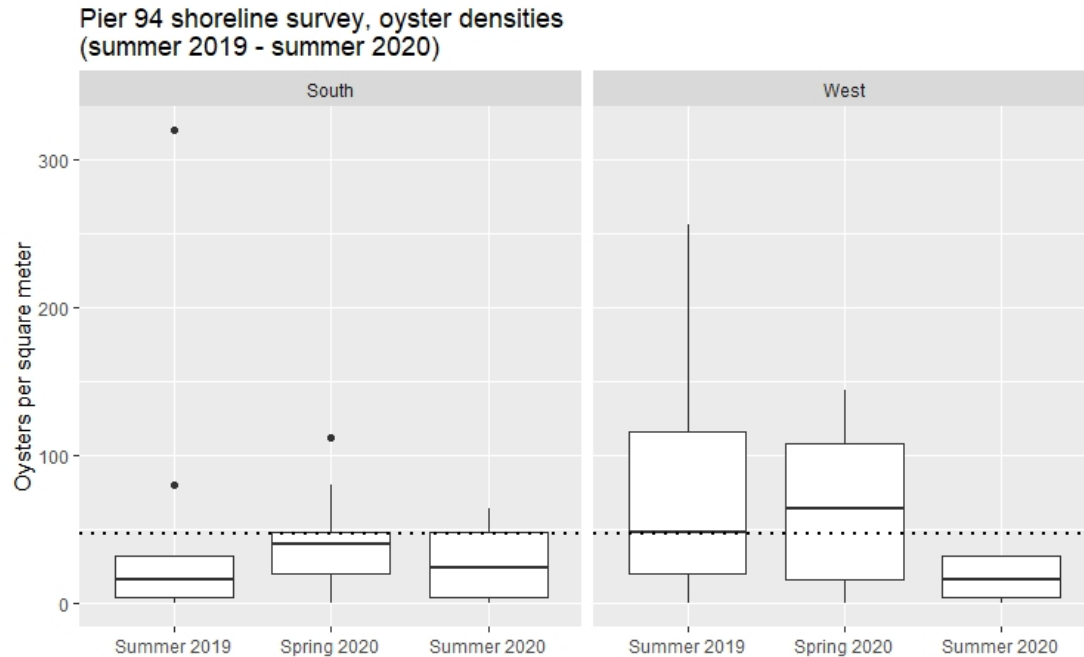


Figure 3. Oyster density (oysters per square meter) at three timepoints along two transects, one each along the south and west riprap-lined shore of the Pier 94 site. The dotted line shows the overall mean density (47 oysters per m^2) across all time points and both shorelines. This mean density was used for the “Adult Oyster Density” category of the Site Evaluation Table.

Table 2. Results of shoreline oyster surveys at the south and west shorelines of Pier 94, summer 2019 - summer 2020.

Transect location	Avg. oysters per m^2	Standard error
South shoreline	41	10.92
West shoreline	53	11.09
Site overall	47	7.76

Adult oyster size and diversity of size classes. Oysters on the south shore were 31% larger on average across all timepoints (Fig. 4, Table 3). The effect of location on oyster size was statistically significant (GLMM: $z = -6.52$, $p < 0.001$; GLM: $z = -2.04$, $p = 0.04$). The average size of the largest oysters (upper quartile) of oysters at the site was 31.1 mm. This resulted in a weighted score of 62.5 out of 125 potential points in the Site Evaluation Table.

The south shore consistently had a greater proportion of oysters in the largest size class (Fig. 5). Very small oysters were present in summer 2019 and spring 2020 but not summer 2020, with slightly more on south shoreline in summer 2019 and nearly twice as many in spring 2020 on the western shoreline. In spring 2020, these most likely represent oysters that recruited in 2019, while the small oysters in summer 2020 were likely new recruits from that year. The Gini-

Simpson score for diversity of size classes was 0.67. This generated a weighted score of 112.5 out of a potential 150 in the Site Evaluation Table.

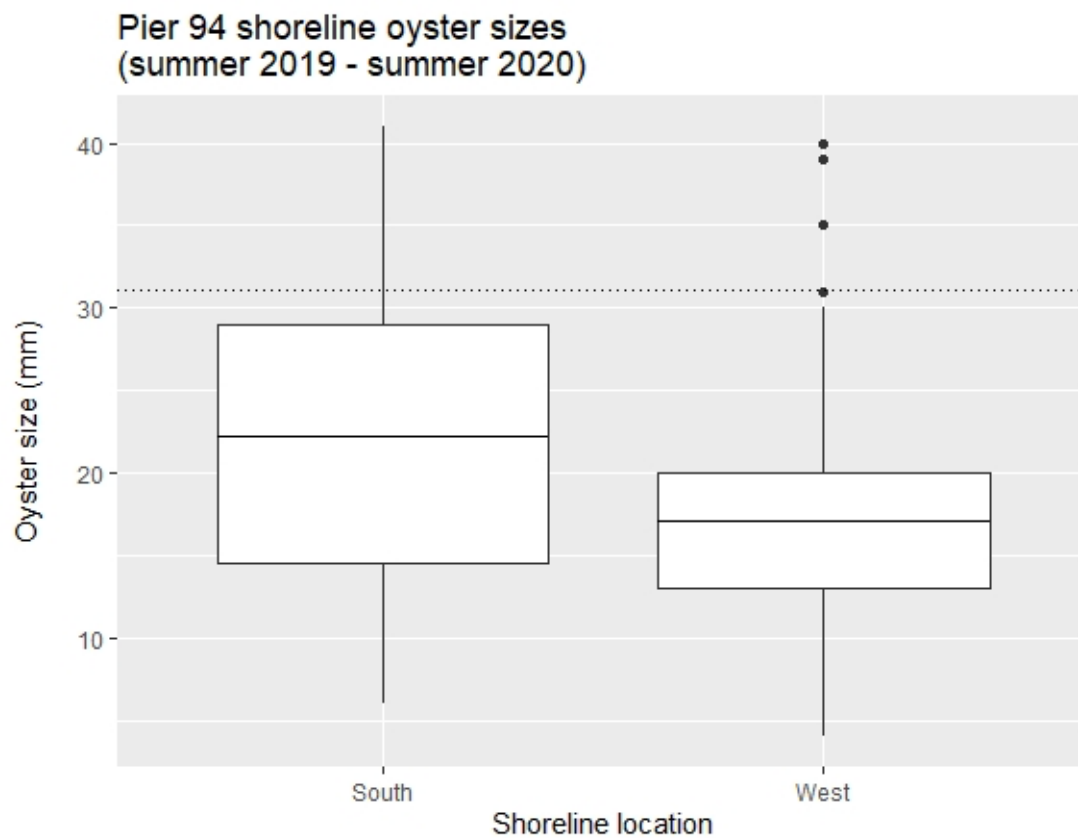


Figure 4. Sizes of all oysters observed during Pier 94 shoreline surveys separated by shoreline location, all time points combined. Box edges represent the interquartile range of sizes; solid horizontal lines represent average sizes; dots represent outliers. The dotted horizontal line shows the mean size (31.1 mm) of the largest oysters (upper quartile) for both shorelines combined. This mean was used for the “Adult Oyster Size” category of the Site Evaluation Table.

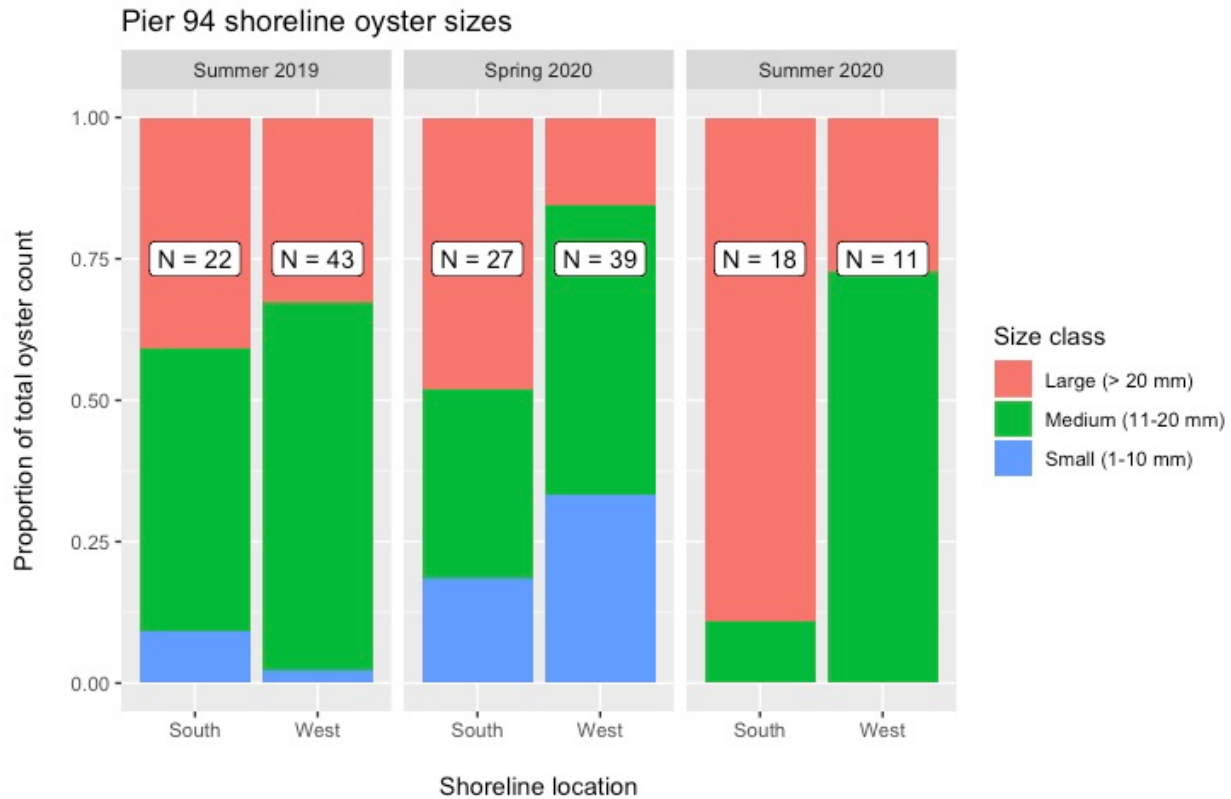


Figure 5. Sizes of oysters observed during Pier 94 shoreline surveys, separated by time point and shoreline location, summer 2019 – summer 2020. Oyster sizes are classified as small, medium, or large. The number of oysters of each size class are shown as a proportion of the total number of oysters observed during each seasonal survey.

Table 3. Pier 94 shoreline oyster sizes across all timepoints.

Transect location	Maximum size (mm)	Minimum size (mm)	Average size (mm)	Standard error (mm)
South	41	6	22.27	1.09
West	40	4	17.04	0.75
Total	41	4	19.23	0.66

Recruitment density. Recruitment equipment on the south end was regularly damaged: on three occasions, one of the frames was knocked down and found lying on its side in the benthos. On two occasions, a frame was missing completely, and on one occasion, both frames were intact but 3 of the tiles were missing. Entanglement in drift algae was common. Equipment on the north end mostly fared better, although one of the frames was missing during the spring retrieval. Because of these losses, we were unable to evaluate recruitment to two tidal elevations, and instead combined tile data to generate overall recruitment to the site.

Oysters recruited to our tiles in fall 2019, spring 2020, summer 2020 and fall 2020. We omitted the counts of recruits from spring 2020 our analyses due to heavy losses of tiles. Recruitment was highest at the fall timepoints (Fig. 6, Table 4). On average, across recruitment

seasons (summer and fall tiles) there were 6827 new oyster recruits per m² at Pier 94. This resulted in a top score in the Site Evaluation Table: 125 points out of 125 potential points.

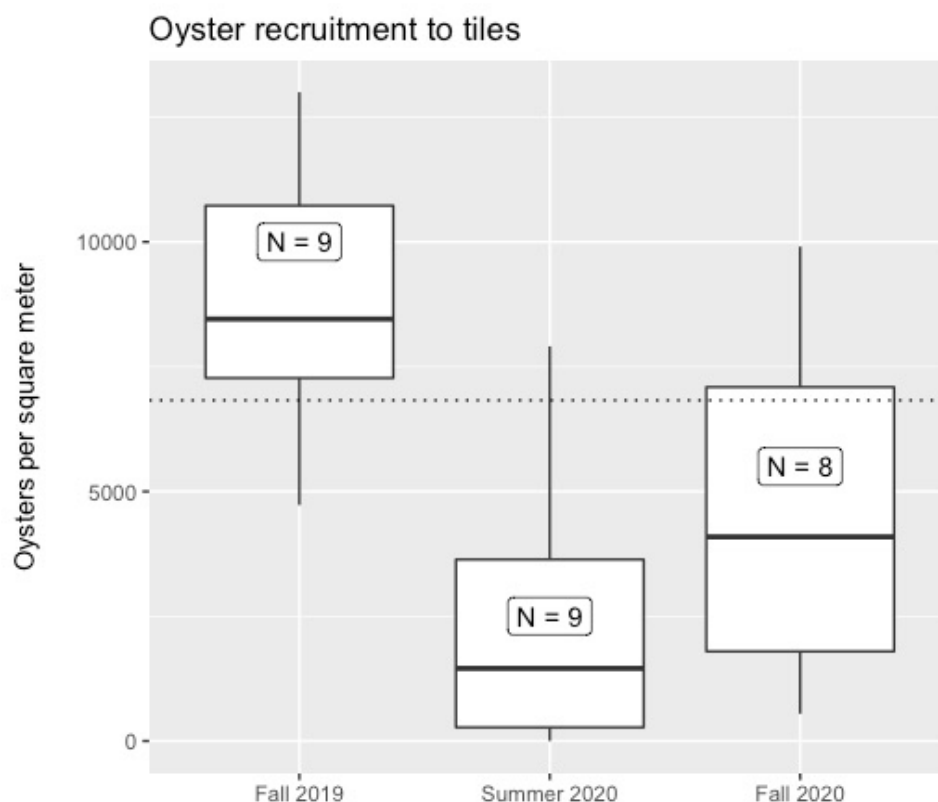


Figure 6. Recruitment to settlement tiles by season, 2019-2020. Spring data not shown due to loss of tiles. The dotted horizontal line represents the mean across all tiles.

Table 4. Recruitment of oysters to Pier 94.

Timepoint	Avg. oysters per m ²	Standard error	Number of tiles
Fall 2019	8950	835	9
Summer 2020	3803	1270	9
Fall 2020	6636	1099	8
Site overall	6827	740	26

Drill predation. We found zero oyster drills and no evidence of drill predation in our surveys. This resulted in a top score in the Site Evaluation Table, a weighted score of 150 out of 150 total possible points. We note that drills were found at a site to the south of Pier 94 (Candlestick Park), and at multiple points along the shoreline from there to Oyster Point in 2020 (author's unpublished data).

Salinity range and risk of low salinity events. The lowest salinity reading made at the site was 24, and this was measured by Golden Gate Audubon from the shoreline in September and

October 2019. Readings of 25 were recorded in April, May, October and December 2020. The lowest readings from the USGS were 27-28 in the winter months: January, February and March 2020. Spot measurements can't be easily converted into the parameter required by the Site Evaluation Table (percent of days when salinity is lower than 25). Since two days of a reading of 24 represent less than 1% of our total readings; we placed Pier 94 in the category of 1 to 9% of days below 25. This generated a weighted score of 112.5 out of a total potential score of 150.

For scoring Pier 94 in the “risk of low salinity events” category, we relied on long term data for this sub-Bay region (based on data in Wasson et al. 2014). For this category, we are scoring based on percent of years in which salinity goes below 5 for 4 or more consecutive days. This had not occurred for this portion of the Bay during the years for which Wasson et al. (2014) had data. This resulted in a score of 150 points of out a potential 150.

Risk of high air temperature. The maximum air temperature we recorded was 27.17 °C on May 7, 2020 (Fig. 7) on one of the higher elevation recruitment frames. This temperature is below the Site Evaluation Table parameter, Risk of High Air Temperature threshold of 30 °C. Zero days above 30 °C generated a top weighted score of 125 out of 125 on the Site Evaluation Table.

Although there were days during the study when air temperatures surpassed 30 °C, the temperature loggers were underwater during those periods, and so oysters at the target elevations would not have been exposed to those high air temperatures. Recruitment elements at the low elevation (-0.3 m MLLW) experienced more moderate temperature extremes than the elements at the high elevation (+0.3 m MLLW) because they spent more time underwater and at greater depth and so are less influenced by air and surface water temperatures (Table 5). Because air has a lower heat capacity than water, higher elevation temperature loggers with more air and shallow water exposure will register greater temperature fluctuations (higher highs and lower lows) than deeper temperature loggers.

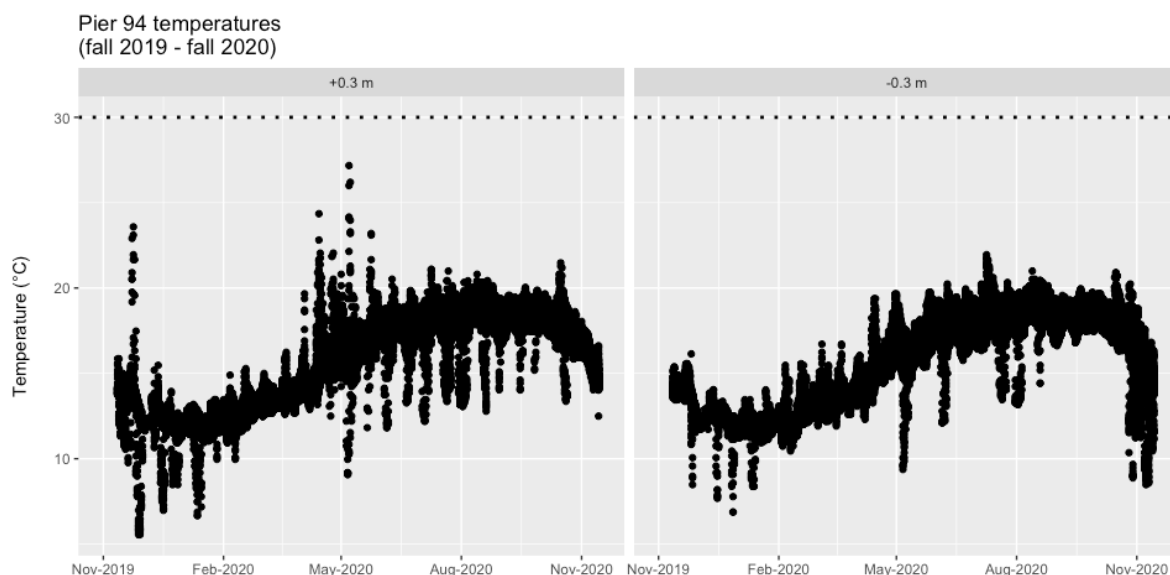


Figure 7. Temperature time series of high (0.3 meters above MLLW) and low (0.3 meters below MLLW) elevations measured on recruitment tile frames. Dashed line indicates 30 °C, the threshold for high temperature days on the Site Evaluation Table.

Table 5. Summary of temperatures at Pier 94 by elevation. Longer exposure to air at the higher elevation accounts for the higher temperature maximum and lower temperature minimum.

Elevation	Average Temperature (°C)	Maximum Temperature (°C)	Minimum Temperature (°C)	Standard error
High (+0.3 m)	16.13	27.17	5.55	0.01
Low (-0.3 m)	16.14	21.95	6.88	0.01

Site evaluation score. With all of the data noted above added into the Site Selection Table, Pier 94 received an overall weighted score of 80% (117.2 out of a possible 146.9). This places Pier 94 in the highest ranked category for oyster restoration sites (Fig. 8).

Tool for evaluating appropriateness of site(s) for Olympia oyster restoration, reliant on natural recruitment

Instructions: You must fill in the green boxes with your raw data and their conversion to scores.

You can tinker with the weights in the grey boxes if you like.

	parameter unit of measurement	scoring	Weight of parameter	Pier 94 raw data	Pier 94 score	Pier 94 weighted score	Maximum score Site could have received
oyster attributes	ADULT OYSTER DENSITY oysters/m ²	0 = 0 <10 = 25 10 to 99 = 50 100-999 = 75 >1000 = 100	2	47	50	100	200
	ADULT OYSTER SIZE length in mm***adjusted for SF Bay	<20 = 0 20 to 29 = 25 30 to 39 = 50 40-49 = 75 >50 = 100	1.25	31.1	50	62.5	125
	DIVERSITY OF SIZE CLASSES diversity index	<0.25 = 0 0.25 to 0.44 = 25 0.45 to 0.64 = 50 0.65 to 0.84 = 75 >0.84 = 100	1.5	0.67	75	112.5	150
	RECRUIT DENSITY average number/m ² (July 2019 - Nov 2020)	0 = 0 1 to 99 = 25 100 to 499 = 50 500 to 999 = 75 1000 or more = 100	1.25	7793	100	125	125
	RELIABLE RECRUITMENT coefficient of variation June - October	>2.6 = 0 2.0 to 2.6 = 25 1.3 to 1.9 = 50 1.2 to 1.0 = 75 <1.0 = 100	1				
	LARVAE EXPORTED estimated	0 = 0 1 to 5,000,000 = 25 5,000,001 to 10,000,000 = 50 10,000,001 to 20,000,000 = 75 >20,000,001 = 100	1.25				
	SURVIVAL RATE mean % surviving previous quarter* modified from previous version	0 = 0 1 to 25 = 25 26 to 50 = 50 51 to 75 = 75 >76 = 100	1.5				
	GROWTH RATE mm/day	<0.050 = 0 0.05 to 0.09 = 25 0.10 to 0.25 = 50 0.26 to 0.40 = 75 >0.40 = 100	1				
	DRILL PREDATION number snails/m ²	>5 = 0 3 to 5 = 25 1 to 2 = 50 <1 = 75 0 = 100	1.5	0	100	150	150
	SALINITY RANGE % days/yr average <25 ppt	>40 = 0 25 to 40 = 25 10 to 24 = 50 1 to 9 = 75 <1 = 100	1.5	N/A	75	112.5	150
environmental parameters	RISK OF LOW SALINITY EVENTS % yrs with salinity <5 ppt for 4 or more consecutive days	>50 = 0 26 to 50 = 25 15 to 25 = 50 0 to 15 = 75 0 = 100	1.5	0	100	150	150
	WATER TEMPERATURE average daily warm season °C	<12 = 0 12 to 13.9 = 25 14 to 15.9 = 50 16 to 18.9 = 75 >19 = 100	1.25				
	RISK OF HIGH AIR TEMPERATURE days above 30°C	>7 = 0 5 to 7 = 25 3 to 4 = 50 1 to 2 = 75 0 = 100	1.25	0	100	125	125
	CHLOROPHYLL warm season µg/L	<5 = 0 5 to 10 = 25 10 to 15 = 50 16 to 20 = 75 > 20 = 100	1.25				
	LOW DISSOLVED OXYGEN average difference of observed values from 9.25 mg/L	>3.9 = 0 3 to 3.9 = 25 2 to 2.5 = 50 2.6 to 2 = 75 1 to 1.9 = 100	1.25				
	OYSTER RESTORATION SCORE	(Note that score is 0 if recruitment is 0) 0 to 25 = LOW 26-50 = MEDIUM LOW 51-75 = MEDIUM HIGH 76-100 = HIGH			80%	117.2	146.9

Figure 8. The Site Evaluation Table with data from Pier 94 filled in. Light green boxes indicate data that were not available.

Fucus abundance and observations of other intertidal organisms. *Fucus* is abundant at Pier 94 (Fig. 9), but *Fucus* density is relatively low in the zone in which oysters are most abundant, so it is unlikely to be important in providing microhabitat for oysters. Percent cover of *Fucus* in our oyster transects was rarely in the double digits, while quadrats placed at about +61 cm MLLW often had canopy that covered 50% of quadrats (Fig. 10).



Figure 9. *Fucus distichus*, the native rockweed, in the mid-intertidal zone at Pier 94.

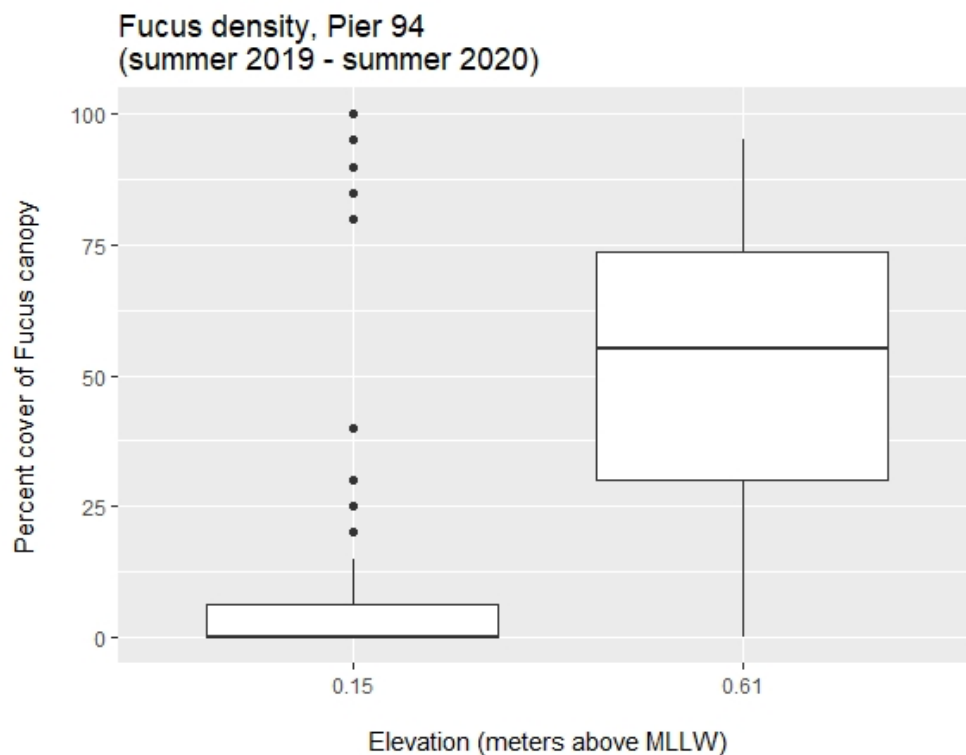


Figure 10. Abundance of *Fucus* at two tidal elevations at Pier 94.

While we did not quantify abundance of species other than native oysters, *Fucus* and oyster drills, we made several observations of interest at the site. First is the presence of a non-native mudsnail, *Batillaria attramentaria*, which has been present in San Francisco Bay since at least 2005, but had been thought to be limited to a single location in San Rafael (Fig. 11). The mudsnail, commonly known as the Japanese mudsnail or false cerith, is native to the Northwest Pacific Ocean, and was accidentally transferred to North America when Pacific oysters were introduced to West Coast estuaries for aquaculture. The non-native mudsnail can attain high densities on mudflats, where it outcompetes the native mudsnail, *Cerithidea californica* (Byers 1999, Byers 2000). The shells of the mudsnail, which can attain high densities, provide hard substrate which allow other non-native species (and some natives) to settle on what would otherwise be mudflats, and it can further modify the environment in ways that benefit other non-natives (Wonham et al. 2005). At Pier 94, *B. attramentaria* is abundant on gravel in the pools than drain from the marsh into the Bay.



*Figure 11. Top, the non-native mudsnail *Batillaria attramentaria* on a Swiss army knife for scale. Bottom, the snail is highly abundant in the creek that drains to the Bay.*

Secondly, the overall diversity of intertidal organisms and the abundance of macroalgae at the site is quite striking (Figs. 12-16). In addition to *Fucus*, a red alga, *Mastocarpus* sp., is highly abundant, along several other native algal species that are present both on the shoreline and washed up on the beach in the wrack. Our team and volunteers from the Golden Gate Audubon center documented a number of invertebrate taxa, both native and non-native, from the site.



Figure 12. Abundant seaweeds along the rip-rapped shoreline at Pier 94.

Figure 13. Seaweeds at the Pier 94 provide food and shelter for many organisms, such as this isopod crustacean (right), that in turn provide food for fish and birds.





Figure 14. Grazers, which are importantly ecologically, at Pier 94 include limpets (above) and chitons (right). The slipper limpet (above right) may be mistaken for an oyster but can be distinguished by its very symmetrical shape and smooth edge; oyster shells are often more fluted and irregular by comparison (see Fig. 17 top left).



*Figure 15. The hermit crab *Pagurus hirsutiusculus* in a turban snail shell (left) and a red rock crab, *Cancer productus*, are examples of the crustaceans found at the site.*



Fig. 16. *The native nudibranch Dialula sandiegensis in a crevice with a non-native colonial tunicate (orange/brown) and purple sponge.*

Discussion

Data collected by our team and incorporated into the Site Evaluation Table indicate that from a biological perspective Pier 94 is an excellent site for oyster restoration. The site ranked high due to a combination of supportive environmental parameters (both biotic and abiotic), such as being at low risk for extreme low-salinity events, having cooler maximum air temperatures, and absence of the oyster drill. The recruitment rate to the site was also high and the diversity of size classes indicated a relatively high level of survivorship of oysters over time. For comparison's sake, the Site Evaluation Table scored Giant Marsh at Point Pinole Regional Shoreline, the site of a major living shorelines project that includes oyster restoration, at 65% (= medium high category) based on data collected in 2014-2015 (Zabin et al. 2017). Using data collected in 2012-2013, Wasson et al. (2014) used the Table to evaluate 12 San Francisco Bay sites, with only four receiving the highest rank. Those sites were Point Pinole, the San Rafael shoreline (where a living shorelines project had recently been deployed), Brickyard Park in Strawberry and Berkeley Marina (Wasson et al. 2014). It is important to note that environmental conditions and oyster populations in the Bay vary over different years, such that scores generated by the Table can fluctuate depending on when (and for how long) data were collected. While conditions at Pier 94 currently appear to be supportive, it will be important to continue to

monitor key parameters (such as the presence/abundance of the non-native oyster drill) before commencing with a restoration project. Based on this report's findings, we recommend Pier 94 as a site where oyster restoration efforts that deploy additional hard substrate for oysters to settle on is likely to be successful.

An oyster restoration at Pier 94 may also benefit oysters throughout the Bay. Intertidal sites around San Francisco Bay vary enormously in terms of local environmental parameters and these impact oyster populations (Wasson et al. 2014). Sites farther from the mouth of the Bay tend to be more influenced by freshwater following rain events, as they are closer to rivers and large creeks. Sites in areas that have less fog are more likely to experience hotter air temperatures during summer daytime low tides. In wet winters, oyster populations exposed to prolonged low salinity can suffer mass mortality (Cheng et al. 2016). While less well-documented, heat waves, such as one that occurred in June 2019 that resulted in mass mortality of intertidal mussels on the open coast and a die-back in *Fucus* in San Francisco Bay (personal communication, K. Nielsen), may also cause mortality of oysters, particularly higher in the intertidal zone (Zabin et al. 2021). Sites like Pier 94 that have more moderate conditions may thus act as a refuge from these stressors; oyster larvae produced at these sites may help repopulate other sites in the Bay following extreme events. Under future climate change scenarios, more fog-free (and thus hotter) days are predicted for the Bay Area. More extreme droughts but also more extreme flood years are also predicted. Thus, sites like Pier 94, particularly those free from oyster drills, may play an increasingly important role in supporting native oyster populations throughout the entire Bay. Enhancing oyster populations at these sites is one approach to bet-hedging against increasingly stressful environment conditions.

In addition, the diversity of intertidal species and general accessibility of the site provide a great opportunity for increased volunteer engagement and educational opportunities for nature-focused community groups like the Golden Gate Audubon and the Heron's Head EcoCenter. There is good potential for community members to be involved in oyster restoration and/or a living shorelines project at the site.

One potential challenge is that the site appears to be a high-energy system, as evidenced by the damage to our recruitment frames and the large amount of algal wrack on the beach and floating in shallow waters. Projects will need the design guidance of a coastal engineer and pilot tests of the structural integrity of any proposed oyster structures. We were also never completely able to determine whether some of the damage to our gear might have been due to vandalism. Any projects moving forward in the intertidal/near shore area at the site will need to consider outreach to the fishing community and to the homeless people who may be using the site.

We are happy to report that we did not encounter oyster drills during our study period. However, the presence of drills at nearby sites, such as Candlestick Park, is worrisome. Drills can have devastating impacts on native oyster populations (Wasson et al. 2014) and other intertidal fauna (authors' personal observations) and can thus stymie restoration projects. We strongly recommend continued monitoring for oyster drills (see Fig. 17), and the development of a rapid response plan to eradicate drills should they be detected. Care needs to be taken to not accidentally move drills from other sites to Pier 94 (i.e. on boots, gear, or other materials that will be placed in or near the water).

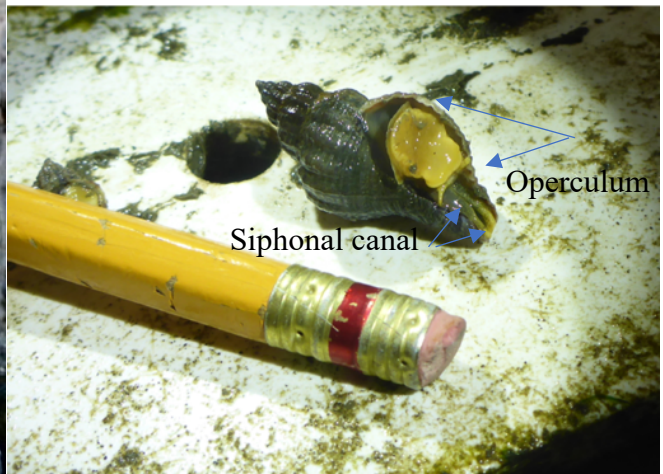


Figure 17. Top, the round holes in this oyster indicate that it has been attacked by the oyster drill (shown just above the oyster). Bottom left, several oyster drills attack a clam. Bottom right, the underside of an oyster drill, with some of the characteristic features that help with identification. Note the whorled, ridged shell, the shape of wide operculum (opening) and siphonal canal. Both the shell and the foot of the snail can vary in color.

Similarly, we recommend that volunteers, researchers and others working at Pier 94 take care not to spread the non-native mud snail *Batillaria attramentaria* from the site to other sites. Both the oyster drill and the mudsnail do not have pelagic larvae and so are limited in their ability to spread naturally. Thus, there is an opportunity through volunteer trainings, and perhaps through interpretive signage at the site, to reduce their spread within the Bay through education and outreach.

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