SAN FRANCISCO BAY SUBTIDAL HABITAT GOALS REPORT

Appendix 7-1: Shellfish Conservation and Restoration in San Francisco Bay: Opportunities and Constraints

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Shellfish Conservation and Restoration in San Francisco Bay: Opportunities and Constraints
Final Report for the Subtidal Habitat Goals Committee

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Executive summary

Little is known about the ecosystem functions of native Olympia oyster (*Ostrea lurida*) and the ecological role it has played in San Francisco Bay before European settlement. While *O. lurida* is different in several ways from its better-studied relative the Eastern oyster, *Crassostrea virginica*, it is reasonable to assume the two oyster species provide similar ecosystem services, and that restoring Olympia oysters to San Francisco Bay could result in the restoration of some of those services. Among these is the provision of complex, hard substrate which provides habitat for many other organisms, including small crustaceans that might be fed on by salmonids. Herring use oyster shell for egg-laying, and eelgrass establishment appears to be facilitated by the presence of oyster shell mounds. Work elsewhere suggests that oysters and oyster-restoration substrate can alter hydrographic regimes, providing shoreline protection. If oysters can be restored in high numbers, the restoration of filter-feeding function to parts of the bay where filter feeders are not present in high numbers is likely to increase nutrient cycling and perhaps contribute to improved water quality in the Bay.

Naturally occurring populations of native oysters can be found throughout San Francisco Bay from Pt. Pinole to south of the Dumbarton Bridge on natural and artificial hard substrate. In the intertidal zone, oysters can be found in highest abundances (80 per m^2) in the Central Bay, but lower densities and scattered live individuals are found over a wider extent. Based on measurements of oyster densities around the Bay in 2006, Grosholz et al. (2007) estimated that there are 300,000 living oysters in the intertidal zone in San Francisco Bay.

Oysters have appeared to do well subtidally in many manmade habitats such as on marina floats and in tidally restricted ponds, lagoons and saline lakes. The population in one such area, Shoreline Sailing Lake in Mountain View, was estimated to be at 10 million (Brian Mulvey, unpubl. data). The extent of the subtidal population in the Bay remains unknown, although limited sampling has failed to reveal any viable populations.

Demographic variables such as recruitment, growth and mortality in naturally occurring populations and in pilot restoration projects vary spatially and temporally, but some patterns are emerging. Sites in Richmond and the Central Bay seem to have consistently higher recruitment rates to standardized intertidal recruitment collectors than those in Richardson Bay and sites further south and north. Adults are largely missing in most parts of the South Bay, yet recruitment to deployed surfaces has been fairly consistent across years. Some sites appear to support source populations of many large adults, but few recruits; other sites may be sink populations with high levels of recruitment but few large adults. Sites in San Pablo Bay and northward appear subject to periodic die offs due to seasonal low salinity events. Sites in the Central Bay and the Richmond area generally seem to have both high recruitment and high growth.

Restoration efforts in San Francisco Bay to date have been carried out on a relatively small scale. Annual recruitment to deployed substrate has been variable, with high recruitment in 2008. Restoration projects have relied almost exclusively on the provision

of hard substrate (mainly Pacific oyster shell) to areas where substrate is lacking. Settlement on the substrate by both native and non-native fouling organisms, burial by sediments and predation by non-native oyster drills have been the major difficulties encountered by these projects.

Restoration of the Olympia oyster elsewhere along the West Coast is still relatively new and methodology is still in the experimental stage. Based on the information we have gathered from research in the Bay, from restoration attempts along the West Coast and elsewhere, we make the following general recommendations:

- **Oyster restoration projects should be located south of China Camp and Point Pinole.** Historical records and our own observations indicate that oyster populations in San Francisco Bay extend northward into San Pablo Bay and move further up into sloughs in South Bay during drought years; with large-scale die offs along these population edges in flood years. Thus, despite the sometimes high abundance of oysters in the northern portion of San Pablo Bay, the majority of large-scale restoration efforts should be concentrated to the south of China Camp and Point Pinole. Central and South bays, which are less subject to seasonal low salinity events, should be considered priority areas which could provide larvae to re-establish populations further north following flood years.
- **Oyster restoration efforts will require the deployment of hard substrate.** Oysters require hard substrate for attachment. The increase in sediment in the Bay that has occurred as a result of human activities has likely resulted in the burial of smaller, naturally occurring substrates oysters once were able to use and necessitates the addition of larger substrate. Substrate does appear to be limiting in locations such as the South Bay where oyster larvae are present and where oysters could survive. Hard substrate also appears to be limited below the zero tide line in many locations where it is present in the intertidal zone. This need will have to be reconciled with the current push to remove hard substrate from the Bay and with regulations that restrict the deposition of “fill” in the Bay.
- **Seeding of substrate is also likely needed.** Recruitment is variable in both time and space, but is consistently low in some locations in the Bay. New recruits are also more vulnerable to physical stresses, competition for space with other sessile organisms and predation by oyster drills. Seeding substrate and/or growing oysters to a certain size in hatchery conditions would provide restoration practitioners with an additional tool to “jump start” populations in areas with little natural recruitment, and to improve oyster survival at restoration sites. Seeding has not been tried on a large scale in San Francisco Bay due to concern about maintaining genetic structure within the Bay. The latest research indicates some population structure, which could be preserved by using adults from a region to generate spat to be planted in the same region. Further research is needed to better understand connectivity among locations within the bay.
- **Design restoration to meet research needs.** Many funding agencies are looking for projects that can meet acreage goals; there is significantly less funding for basic research and for monitoring. Restoration projects can be designed to meet restoration goals and to answer critical questions that will increase our

understanding of the biology and ecology native oysters and thus guide future restoration projects.

- **Incorporate oyster restoration into other restoration/shoreline protection projects.** Where possible, oyster restoration should be incorporated into larger habitat restoration projects and shoreline protection/erosion prevention projects. Many such projects are already in the works. We believe such an approach will attract funding sources, be more cost-efficient than restoring separately, potentially have synergistic positive effects on greater numbers of native species, and improve coordination among the various organizations working to improve habitats in San Francisco Bay.
- **Involvement of the public in oyster restoration projects.** Public support is critical for the success of extensive restoration projects we envision. This is true at every level, from political support for needed funding, to the permitting process, to working out potential user conflicts. Most restoration projects also rely heavily on volunteers to construct oyster "reefs" and to monitor recruitment rates and growth.

Major gaps still remain in our understanding of what limits oyster populations in the Bay and of the best approach to restoration. Our report contains specific research recommendations and stresses the need for long-term monitoring of oyster restoration projects. Among the key unknowns are:

- **The extent of subtidal populations.** Subtidal populations, if they exist, represent a recruitment source that may serve to repopulate intertidal and shallow subtidal locations following low-salinity events and other disturbances, and which could play a significant role in the success of recruitment to restoration projects.
- **Larval delivery and connectedness between populations.** The native oyster population in San Francisco Bay is likely best viewed as a metapopulation, connected to some as-yet-unmeasured extent by larval recruitment between sites within the Bay and perhaps between bays along the coast. Understanding the degree of connectivity is critical to restoration planning on both a local and regional scale.
- **Climate change and its impact on oysters.** Global climate change is likely to affect existing natural populations as well as attempts to restore native oysters. Specifically, more intense storm events are likely to result in greater amounts of sedimentation and longer periods of lowered salinity and thus higher rates of oyster mortality. It would be worth exploring whether some populations of native oysters are better adapted to lowered salinity than others and if so, to consider protecting or enhancing these populations. Warmer air and water temperatures may affect oyster survival and reproduction. Little is known about the tolerance of native oysters to heat stress in field conditions in San Francisco Bay much less what might be done to mitigate it. Ocean acidification is also predicted to interfere with the ability of shell-building organisms to obtain calcium, slowing growth and perhaps interfering with larval development, but the specific effects of

acidification on *Ostrea lurida* under different scenarios of pH change are not known. This ought to be explored and incorporated into planning for oyster restoration.

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I. Introduction

While this document is intended to cover the major species of shellfish in San Francisco Bay, the focus is on information relevant to the preservation and restoration of native Olympia oysters, or *Ostrea lurida.* Of the conspicuous bivalves in the Bay, Olympic oysters are the only native species for which management efforts appear feasible at this time, if we wish to enhance native estuarine species and recover the ecosystem services which they provide. Native California mussels, *Mytilus californianus,* are essentially an open-coast species, and are limited in the Bay, being found only in the most marine habitats. The native bay mussel *Mytilus trossolus* is difficult to distinguish in the field from its non-native congenor, *Mytilus galloprovincialis,* and in fact the two species are hybridizing in the Bay.

Oyster populations in many regions of the world have been devastated due to a combination of overharvesting, habitat destruction, water pollution, increased sedimentation and more recently, disease and introduced predators, competitors and parasites. Interest in oyster restoration has been high for a number of decades on the East and Gulf coasts of the United States as this valuable food source becomes scarce, and as people have become aware of the ecosystem services provided by oysters. Oyster restoration efforts on the West Coast are newer, in part because native West Coast oysters have not recently been an important food source, and significantly less is known about their life stages and ecological requirements.

Here we have summarized the state of knowledge of relevant aspects of the biology and ecology of *Ostrea lurida,* and in particular what is known about extant populations in San Francisco Bay, oyster restoration methods that have been used to date both in San Francisco Bay and elsewhere along the West Coast. Because so little is known about Olympia oysters we have also summarized information from work on Eastern oysters (*Crassostrea virginica*) in sections on ecosystem function and restoration methodology. We do so with the understanding that there are some key differences between these two species, including the shorter planktonic phase (Olympia oysters brood larvae until umbo stage), the fact that West Coast oysters don’t create large, three dimensional reefs and the much lower incidence, at the time of this writing, of disease in West Coast populations. Thus, while restoration efforts are proceeding while key information about Olympia oysters is still lacking, we are optimistic about the potential for successful oyster restoration in San Francisco Bay.

The research and pilot restoration projects in San Francisco Bay that are referred to in this document were funded by the NOAA Restoration Center, and NOAA RC partnership with the Institute for Fisheries Resources, NOAA RC partnership with Restore America’s Estuaries/Save The Bay), USFWS Coastal Program, the State Coastal Conservancy, National Fish and Wildlife Foundation, The Nature Conservancy, and the US Sea Grant.

In addition to summarizing peer-reviewed and gray literature, this document includes information gleaned from interviews with restoration practitioners, unpublished data sets and information presented at West Coast native oyster meetings organized by the NOAA Restoration Center in 2005, 2006 and 2007, a one-day workshop highlighting research and restoration efforts in San Francisco Bay, organized by UC-Davis (ANR) and The Coastal Conservancy in 2007 and one-day Shellfish Restoration retreat in 2008. Abstracts and copies of presentations for the West Coast 2006 and 2007 workshops are available online at http://www.nmfs.noaa.gov/habitat/restoration/publications/tech_glines.html. Articles largely based on material presented at these workshops are also available in volume 28 of the Journal of Shellfish Research.

To reflect the difference in three-dimensional habitat creation by Olympia oysters versus the better-known Eastern oyster, we will refer in this document to naturally occurring clusters of Olympia oysters as "beds," to aggregations of Eastern oysters on the Atlantic Coast as "reefs" and to constructed three-dimensional habitat for oyster restoration on both coasts as "reefs."

II. State of current knowledge of native oysters

A. Historic abundance and distribution of oysters in SF Bay

Ostrea lurida has a long fossil record in the San Francisco Bay area, with fossils found in Pleistocene deposits (Arnold 1903). Oyster shells are present in Native American kitchen middens around the Bay, which date back to 5000 years BP (Ingram 1998). Despite evidence of a long tenure in the bay, we have little reliable quantitative information on the historic abundance and distribution of native oysters. However, there are several accounts which indicate that oysters were at one time highly abundant, and which are informative with regards to the distribution of oysters in the bay.

Townsend (1893) wrote that native oysters were "ever-accumulating" on the shells of live large Eastern oysters, which were planted in the Bay beginning around 1870. So many natives settled on the farmed oysters that they were thought to interfere with the growth of the Eastern oysters (Townsend 1893). Settlement on cultivated oysters by the "remarkably fertile native oysters, naturally adapted to SF Bay" was so great, Townsend wrote, that "when a heap of the [Eastern oysters] have been cleaned for market the accumulated parasites almost equal in bulk the edible species."

Townsend noted that the native oysters were present in high numbers in all the areas in which Eastern oysters were farmed, which was primarily in the western side of the South Bay (see Figure 1) but that live oysters were absent from San Pablo Bay and the creeks and sloughs in the South Bay.

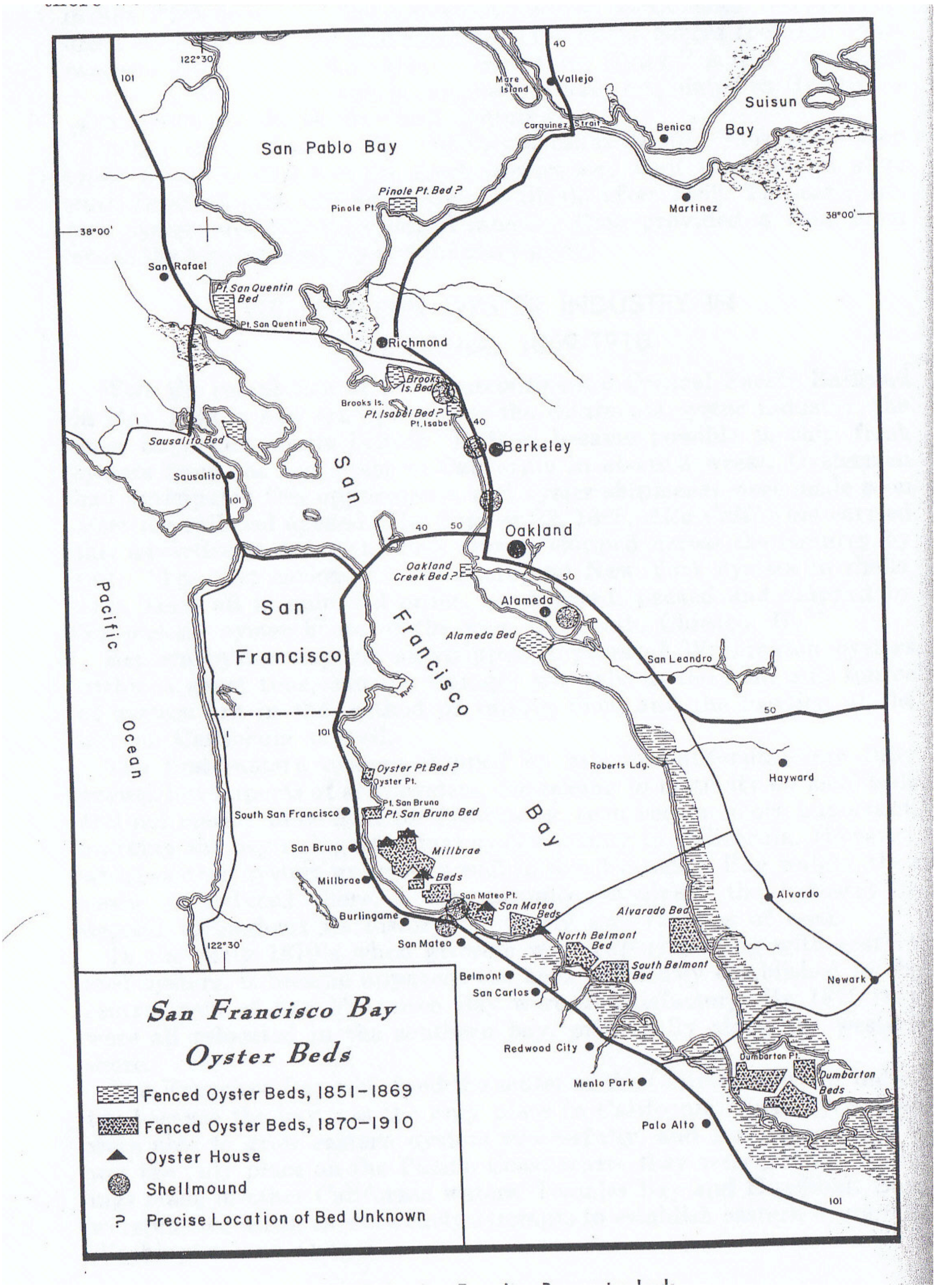


Figure1: Oyster beds in San Francisco Bay (Bonnot 1935).

In contrast to the picture painted by Townsend, very few live oysters were found in an expedition of the *R/V Albatross,* which involved the analysis of 43 dredge hauls in 1912-1913 in North, Central and South Bay (Packard 1918a,b). However, these hauls were mostly made in waters 8 m and deeper, which might explain the virtual absence of live oysters. Hauls which did include live oysters were those made in waters less than 8 m.

Live oysters were found at 17 of the dredge stations, including Southampton Shoal, Point Isabel, the eastern shore of Angel Island, Sausalito, the southern end of Yerba Buena Island and the western side of Alameda. On the southwest side of the bay, live oysters were present at several sites south of Hunter's Point to just south of the current location of the Dumbarton Bridge. Packard also noted that the native oyster was present in shallow water outside of the Golden Gate and that the substrate type he found oysters on was "sand and mud."

Barrett (1963) noted that native oysters extended their range in the Bay in years of light rain, writing that oysters "are now found well up the sloughs and in other places where they were not able to maintain themselves a few years ago." This contrasts with Townsend's note that oysters were absent in the sloughs in the year he surveyed.

Bonnot (1935) noted that native oysters had been used "commercially since the days of the Spaniards but no worthwhile attempt at any form of culture was ever made."

Native oyster shell was abundant in San Francisco Bay in the late 1800s and early 1900s, and it remains so today. Townsend (1893) wrote: "There are extensive deposits of [native oysters] in the shallow waters all along the western part of the bay, and their dead shells washed ashore by the high seas that accompany the strong winds of the winter season have formed a white glistening beach that extends from San Mateo for a dozen or more miles southward. So abundant are they that this constantly increasing deposit of shells covers everything alongshore and forms bars extending into the bay." But Townsend also wrote that the native oyster shell disintegrated rapidly and shifted readily with waves and currents, and thus did not provide suitable settlement substrate for Eastern oysters.

Packard (1918b) also described extensive amounts of oyster shell: "in lower division of the bay the shells literally pave the bottom," he wrote. While it is not possible to say how old the shells described by Townsend and Packard were, Packard (1918b) speculated that some recent change in the environment, perhaps precipitated by human actions, was the cause of the huge numbers of shells he found.

Native oyster shell is still abundant in San Francisco Bay. This shell has been dredged for agricultural uses for well over one hundred years. Jericho Products, which has been dredging native shell in the bay for nearly 40 years, characterizing the shell as "layered in limitless strata" in the bay. Tows in 2007 in the South Bay in particular brought up lots of oyster shell, but it is nearly completely clean (Zabin, Attoe, Grosholz, pers. obs.).

Commercial oyster farming in San Francisco Bay

At the time of the Gold Rush, native oysters were also brought to San Francisco Bay from elsewhere on the West Coast: from Tomales Bay, from Netarts and Yaquina in Oregon, and from Mazatlan, Mexico, but principally from Willapa Bay, Washington (then known as Shoalwater Bay). Oysters from Washington were preferred by European settlers, as they were larger and milder in flavor than oysters from California. It is not clear from the available literature, but perhaps already by this time local oysters were becoming harder to find.

In his article on the trade in Shoalwater oysters in San Francisco Bay, Bonnot notes that the first successful importation from Washington State was made in 1851, with 600 bushels brought from Puget Sound. However, 90 percent of the imported oysters in the 1850s-1860s were from Willapa, and this trade was so large that six sailing vessels were used exclusively to supply San Francisco Bay with oysters from Washington State. While some of the oysters went to market directly upon arrival, 2,000 to 5,000 baskets (no volume denoted) per ship were placed in beds in the Bay to maintain a steady supply of fresh oysters (Bonnot 1935). Most of the oysters were kept in Central Bay, where oystermen had to contend with annual flooding from the Sacramento and San Joaquin rivers which both in lowered salinity and deposited silt on the oyster beds. San Pablo Bay was largely avoided, as these problems were even greater there. South Bay was also largely avoided as described as access to the mudflats where oysters could be placed was through “extensive marshlands.” At that time, South Bay was also considered too far from the major markets in San Francisco.

The Shoalwater trade diminished rapidly once the transcontinental railway was completed and live Eastern oysters could be shipped to California. Both adult and seed oysters were imported, and commercial oyster beds were shifted to the western shore of South Bay, where conditions were better for these oysters (Bonnot 1935). San Francisco rapidly became the center of commercial oyster trade in California. While data are incomplete, most sources according to Bonnot (1935) estimate that some 100 carloads of oyster seed were imported annually from 1875 through the turn of the century. Records from Wilcox (1895) show annual imports of Eastern oyster seed weighing between 1.5 million and 3 million pounds for the years 1887 through 1895. Eastern oyster production peaked in 1892 at ~15 million pounds, but by 1908 oyster production had dropped by 95 percent due to pollution in the Bay.

In 1931, Japanese seed oysters were imported to California, but San Francisco continued to decline in oyster production, as Pacific oyster culture took off at other less polluted locations such as Tomales Bay, Drakes Estero and Bodega Bay (Skinner, 1962).

Historic abundance and distribution: research recommendations

USGS has a number of cores from the Central Bay that are likely to contain oyster shell from various strata; most of these are unprocessed. These samples are a promising source of information about the historic distribution of native oysters in San Francisco Bay. If the relative abundance of native oysters in the cores can be correlated with physical parameters, these data could be valuable in furthering our understanding of the conditions under which native oysters do best and perhaps in reconstructing a picture of earlier ecosystems in San Francisco Bay. For this reason, we recommend that this work be done.

However, we caution against using historical distributions as a blueprint for restoration. Today's conditions are greatly changed from pre-contact Bay and even from Thompson's day. Global climate change will bring additional changes to the Bay and surrounding watershed. Restoration projects can be informed by the past, but goal-setting and planning will have to focus on current and anticipated future conditions.

B. Current distribution and abundance of native oysters

Several surveys and studies of San Francisco Bay or portions of the Bay have been made over the last 10 years (Figure 2). The most recent and extensive one was carried out by UC Davis in 2006-2007. Highlights are summarized below.

Oyster Distribution: UC Davis Study

From July 2006 to June 2007, Grosholz et al. (2007) surveyed most of the accessible rocky shoreline of San Francisco Bay for the presence of native oysters. A variety of information sources, including unpublished reports and anecdotal observations of oyster presence were used to guide survey site selection. In addition, various shoreline maps to determine substrate types and accessibility of potential sites were consulted. Sites were generally visited once, by 1-3 researchers, with appropriate substrate searched for at least half an hour. GPS points were recorded and qualitative notes on each site were taken. In addition, at a subset of sites, density was measured by counting oysters in 5-10 randomly placed 0.25 m^2 quadrats.

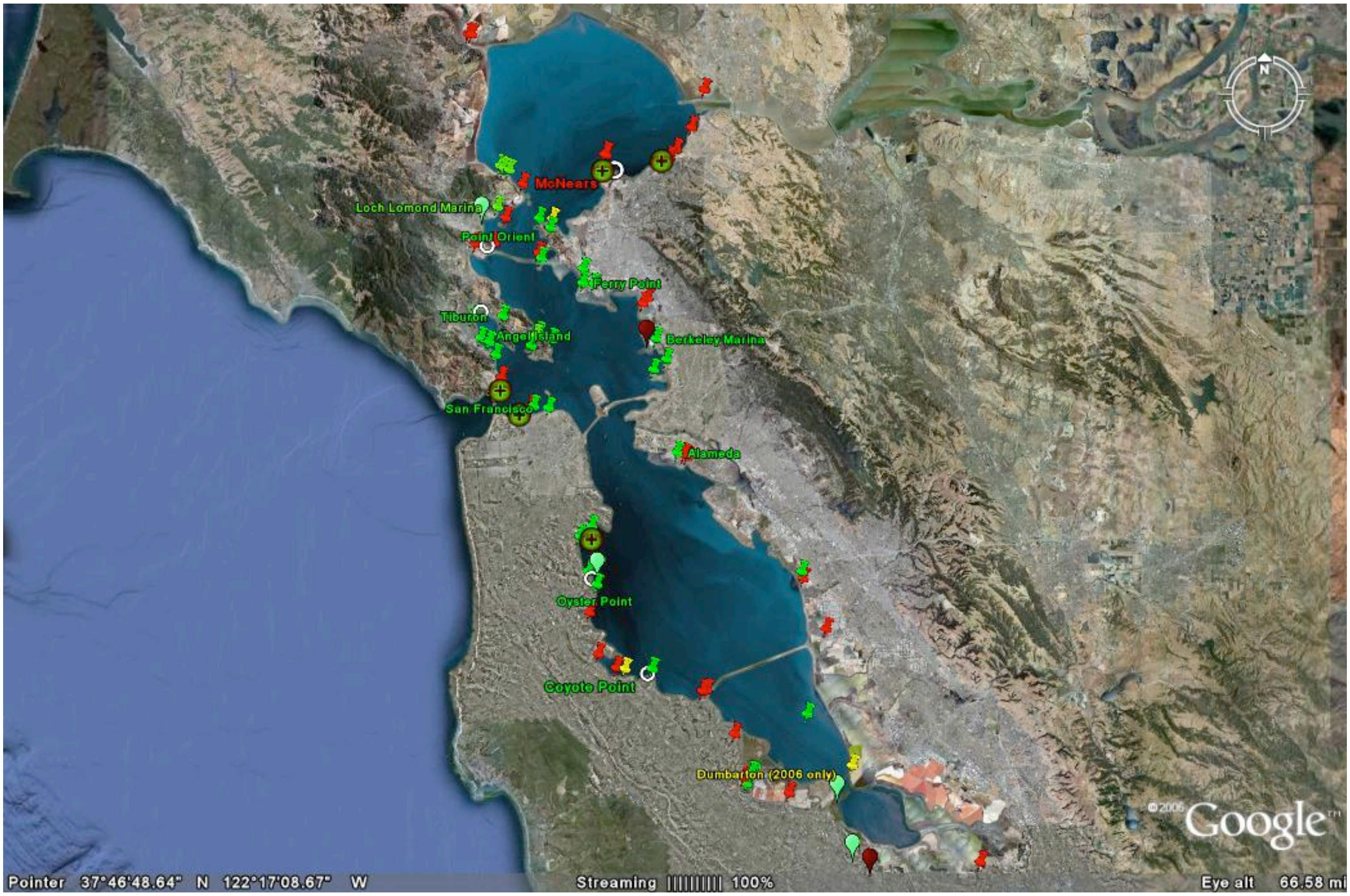


Figure 2: Intertidal survey sites. Green pushpin indicates UCD survey, oysters present, Red pushpin indicates UCD survey, oysters absent. Green balloon indicates Save the Bay survey, oysters present. Red balloon indicates Save the Bay survey, oysters absent. Green circle indicates Harris survey, oysters present. White circle indicates other project, oysters present.

While a few oyster scars were found at many locations in the Bay, most live oysters were found between the Richmond and San Mateo bridges. It was obvious that many oyster populations, especially in the northern portion of San Francisco Bay and San Pablo Bay had experienced a recent massive die-off within the past several months (Table 1). This was likely due to the extreme low salinity in many parts of the bay after later spring rains (Table 2). Oyster shells with both valves still intact were abundant, while live oysters were few. Subsequent work indicated that upper valves do not remain intact for more than a few months indicating that these sites had live oysters recently. At some of these sites, numbers of live, recently dead (top valve still intact) and scar (bottom valve only) oysters in 5-10 randomly placed 0.25 m^2 quadrats were recorded (Table 1, below, from Grosholz et al 2007).

Table 1: Examples of the densities per 0.25 2m^2 qudrats of live oysters, recently dead oysters, and oyster scars at a subset of San Francisco Bay sites, fall 2006-spring 2007.

Site	Live	Dead (both valves)	Scar
China Camp	0	2.6	4.8
South of Richmond Bridge	0	0	6.4
Point San Quentin South	0	3.2	5.0
Keller Beach	0.4	1.2	0.8
Angel Island Harbor	4.4	0.2	1.6
Brickyard Park, Strawberry	1.2	0.4	0.2
Earl F. Dunphy Park, Sausalito	3.6	0	1.8
Candlestick State Park	2.6	1.4	0.2
Sierra Point Yacht Club	2.4	1.2	2.3
Bayfront Park, Millbrae	1.8	0.2	0
Bayside Park, Burlingame	0.2	0.2	0
Port of Redwood City	0.2	0.2	0

Table 2: An example of the monthly surface water salinity (ppt) during the late winter and spring of 2006. Marin Rod and Gun Club Pier, San Rafael, CA (N 37°56.694, W 122°28'769). Data from Obernolte & Abbott.

Date	Salinity	Date	Salinity
Jul-05	26.5	Apr-06	5.6
Aug-05	27.7	May-06	12.5
Sep-05	28.3	Jun-06	15
Oct-05	31.3	Jul-06	24
Nov-05	26.8	Aug-06	28
Feb-06	13.4	Sep-06	30
Mar-06	7.3	Oct-06	31

Oysters have subsequently returned to the intertidal zone at Pt. Pinole, Loch Lomond Marina, China Camp, and Pt. San Quentin south (Chela Zabin, Caitlin Coleman-Hulbert, Sarikka Attoe, Rena Obernolte, Brian Cheng, pers. obs., 2008 and 2009). The images below were taken at Pt. San Quentin south in September 2008 and were typical of the densities observed there.

Figure 3: Top: Only dead oysters were found at Point San Quentin South in the summer of 2006. Bottom left: two years later, oysters and isopods on the underside of a rock about the zero tide mark. Bottom right: Oysters settled on the underside of a lower intertidal rock. Photos: Chela Zabin.

Oyster Distribution: Harris Thesis

In 2002-2003, Harris carried out a series of intertidal surveys for oysters. She reported oysters present from a number of sites in San Pablo Bay, including Pinole Bayfront Park and China Camp in relatively high numbers, where no live oysters were found in 2006. The southern limit of the oyster population found by Harris was not different from that of the UC-Davis study. The sites for which she provided complete GPS data are included in Figure 2.

Population Density of Native Oysters: Polson Study

In 2005-2006, Maria Polson surveyed for *O. lurida* in the intertidal zone along its entire known distribution. At each location, she carried out a 2 hour timed survey to locate the highest density patches. These densities were then measured by counting oysters in 10 .25-m2 quadrats. Polson had one site in San Francisco Bay, Point San Quentin. With a mean density of 36.7 ± 11.6 per quadrat, this site had some of the highest densities of any location along the West Coast. The next most dense sites were Mission Bay, CA (mean =22.8 ± 3.4) and Bahia de San Quintin, Baja, Mexico (mean = 20.7 ± 6.5). Links to Polson's work can be found in the 2006 West Coast Native Oyster Workshop Proceedings (http://www.nmfs.noaa.gov/habitat/restoration/publications/tech_glines.html).

Population Density of Native Oysters: UC Davis Study

In addition to the above-mentioned survey, a series of population measurements at 8-13 study sites was carried out by UC-Davis from 2006-2008. Sites were chosen to represent four broad geographical areas in San Francisco Bay: 1) North Bay; 2) Central Bay West; 3) Central Bay East; 4) South Bay. Sites were selected after the initial survey and represented areas with the most abundant oyster populations within each of region. In the North Bay, there were no sites with many live oysters. Here, and at one site in South Bay, sites with high numbers of recently dead oysters and/or oyster scars, which indicated that the site had at one time been good habitat, were selected. The oyster densities at the 13 sites in fall 2006 are represented graphically (Figure 4).

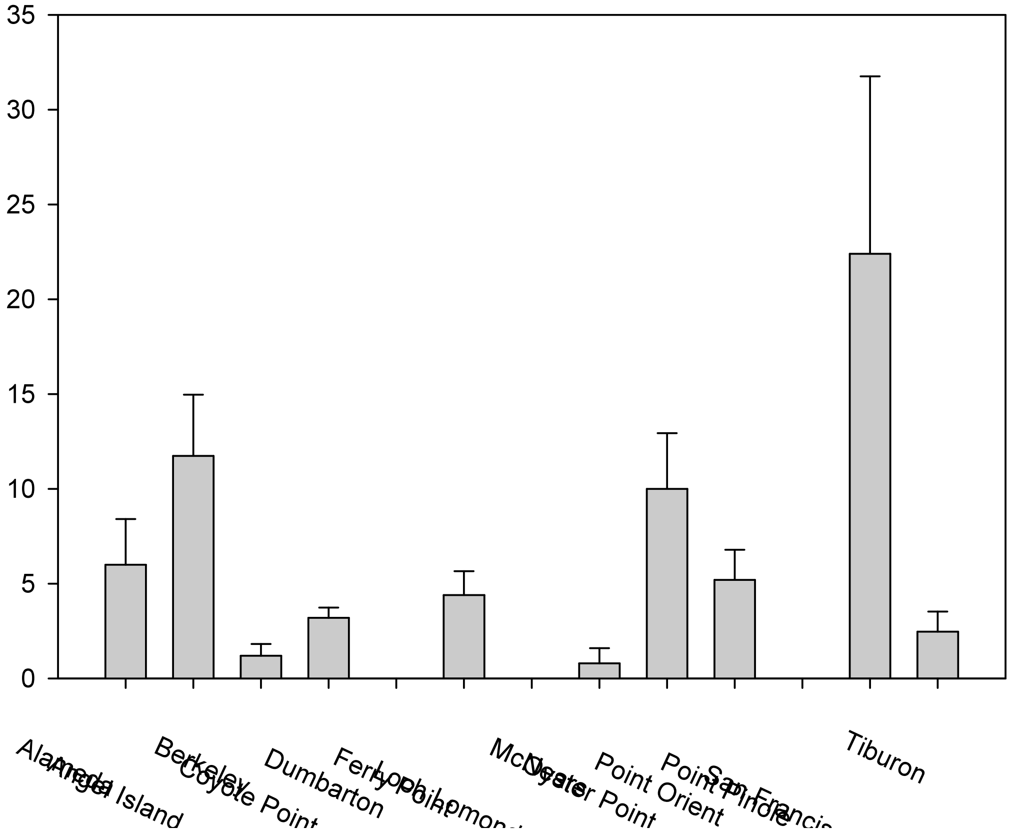


Figure 4: Oyster population density in 2006 by site within San Francisco Bay.

Population Density of Native Oysters: Harris Thesis

In 2002-2003, Harris carried out a series of surveys for oysters along the shoreline recorded relative densities as number of oyster per minute searching. She recorded the highest relative densities at San Leandro and Berkeley marinas. Additionally, she recorded densities of oyster in quadrats from both intertidal shorelines and marina floats (Figure 5).

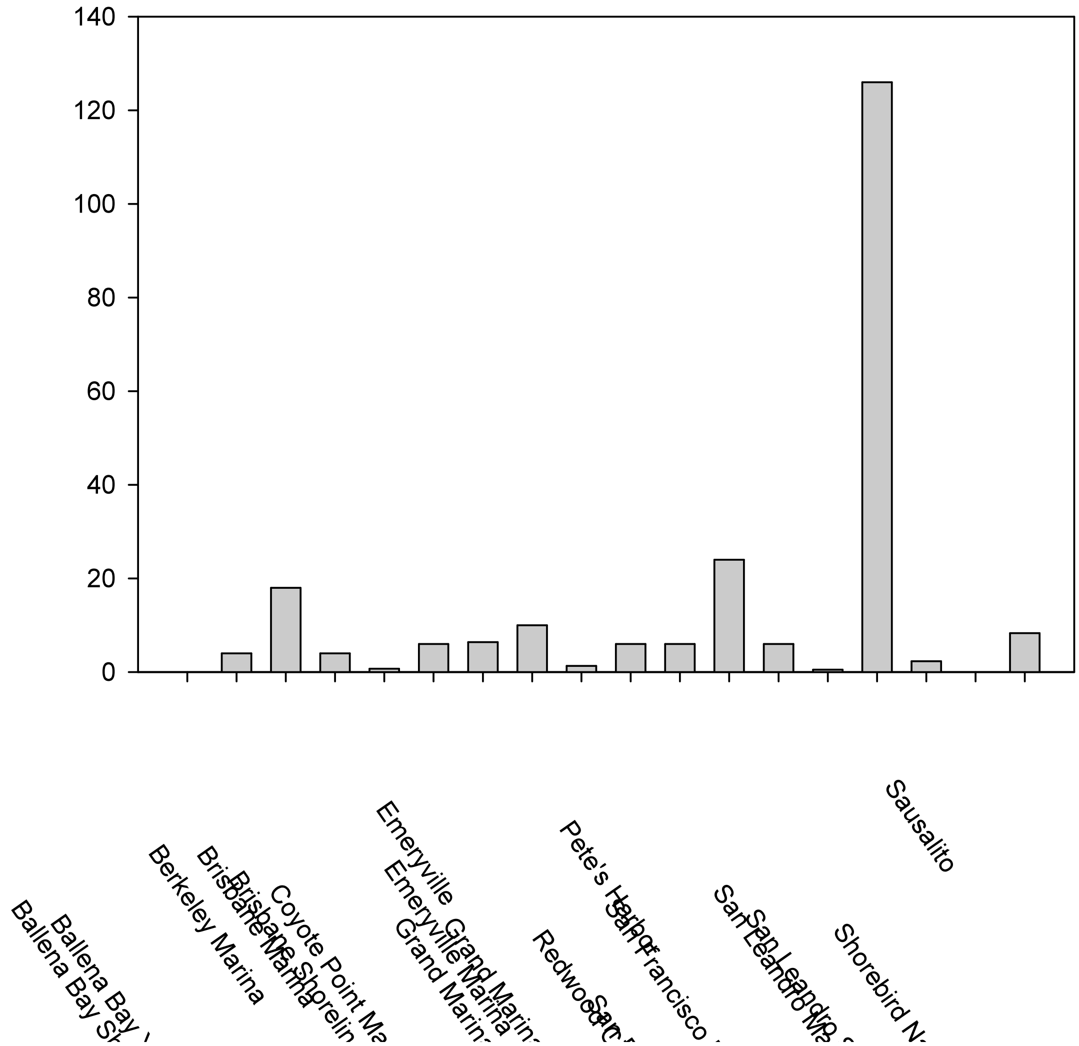


Figure 5: Oyster densities from 10 docks and 10 intertidal shorelines (Harris 2004).

Additional shoreline surveys at single locations

Richardson Bay Audubon Center

A survey along the shoreline in front of the Richardson Bay Audubon Center was made in 2007, but a difference in methodology does not allow us to directly compare densities between this and other surveyed sites. These data are attached as Appendix 1. A second such survey is planned for 2009.

Oyster Point Marina

As part of a mitigation effort, the shoreline and breakwater at Oyster Point Marina was surveyed by Abbott and Obernolte in 2007. These data are attached as Appendix 2.

Point Pinole

Obernolte and Mulvey surveyed oysters at Point Pinole Park in 2007 and 2008. Numbers of live, recently dead oysters, and oyster scars were recorded along with the sizes of live and recently dead oysters. These surveys showed exceptionally high densities and oysters overall of larger size classes (Table 3).

Line #	Date	Average/m^2			Live Sizes			Dead Sizes		
		Live	Dead	Scars	Avg	Min	Max	Avg	Min	Max
1	8/28/07	20.8	11.2	41.6	20.9	5.0	33.0	40.0	29.0	52.0
1	11/23/07	38.4	1.6	88.0	22.2	10.0	41.0	52.0	52.0	52.0
2	11/23/07	48.0	17.6	118.4	23.5	9.0	42.0	38.2	30.0	45.0
1	6/19/08	84.8	3.2	36.8	25.8	6.0	46.0	34.0	28.0	40.0
2	6/19/08	84.8	4.8	70.4	26.0	6.0	44.0	27.3	15.0	43.0
1	8/1/08	19.2	3.2	19.2	25.5	11.0	45.0	29.5	13.0	46.0
2	8/1/08	6.4	0.0	6.4	27.5	22.0	33.0	0.0	0.0	0.0
3	8/1/08	41.6	4.8	38.4	26.6	13.0	38.0	15.0	11.0	19.0

Table 3. Dates, sizes and densities of live and (recently) dead (top valve attached) oysters and oyster scars at Point Pinole (Obernolte and Mulvey, 2008).

Marina Bay (Richmond)

The armored and rip-rapped shoreline at Marina Bay in Richmond was surveyed for native oysters in 2008 in preparation for the addition of rip rap. Most oysters were between 11 and 25 mm with no new recruits. Figure 6 shows areas (reaches) surveyed in Marina Bay. Figure 7 shows oyster density at each reach (Attoe, 2008). Oysters were then located and removed to an area that fill was not being placed.

Figure 6: Areas (reaches) surveyed at Marina Bay in Richmond, CA (Attoe 2008).

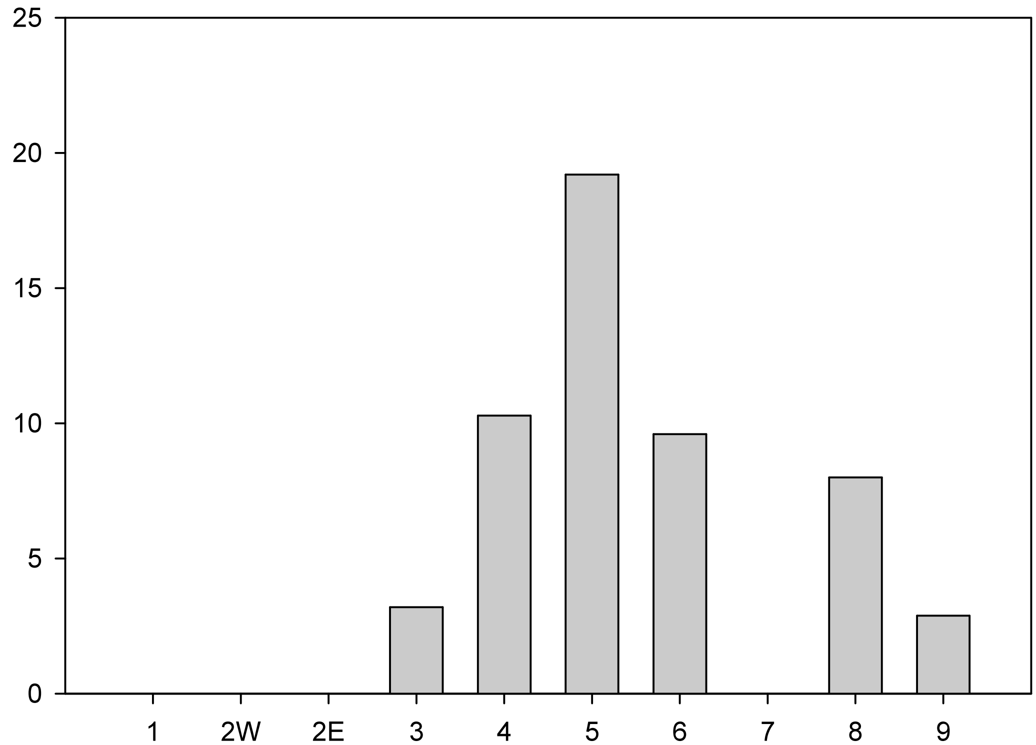


Figure 7: Oyster density at 9 sites (reaches, on X axis) in Marina Bay (Attoe 2008).

Subtidal Oyster Presence: UC Davis Study

The presence of oysters in San Francisco Bay may be significantly influenced by remnant subtidal populations. Intertidal areas may be in part maintained by recruitment from subtidal habitats if in fact oysters are present in abundance. Based on evidence from restoration pilot projects and from their presence on floating docks, we know native oysters can live in the shallow subtidal in San Francisco Bay. Although historical records suggest the presence of subtidal populations, there is only casual mention and minimal evidence suggesting the current presence of significant subtidal populations. Other than the tidally restricted human-created Sailing Lake site in Redwood City, an anomalous site with very restricted flow and consequently very high larval retention, no other subtidal populations have been identified. Subtidal survey methods to date have been limited by equipment and funding and the possibility exists that more intensive and better funded efforts may yield evidence of such populations in the future.

Grosholz et al. (2007) relied on several different methods to survey the presence or absence of subtidal populations of native oysters in the same regions of San Francisco Bay (north, central and south) as the intertidal surveys. The surveys were conducted at several locations in each of the three regions of the bay using a variety of methods that depended on the availability of the appropriate instruments, boat support, and the applicability of the instruments in habitats typical of each part of the bay.

In collaboration with the Gulf of the Farallones National Marine Sanctuary and Moss Landing Marine Laboratories, side-scan sonar was used to identity subtidal structures within the bay that looked like oyster beds and/or rocky reefs that might provide good oyster habitat. The sonar was used in several locations in the Central Bay (offshore of their San Francisco study site, around Angel Island, offshore of Sausalito) and South Bay (offshore of their Coyote Point and Oyster Point sites). These survey sites are included in Figure 2. Side-scan sonar is inaccurate and often unworkable in depths and topography of much of the South Bay, particularly in areas less than 3 m deep. This method was used only within the deeper, dredged channel areas. In some cases, the steepness of the channel sides made image resolution impossible. Several structures were found in the Central Bay that appeared to be solid and topographically complex.

These locations were returned to and an oyster dredge was used to investigate the areas imaged with the sonar. Several tows were made with the dredge around these structures and in several other locations in Central Bay and Richardson Bay. The features imaged by the sonar device turned out to be shell piles. Native oyster shells were present but not abundant, along with the shells of other bivalves, but no living bivalves were found.
A limited number of tows were also conducted using the oyster dredge from aboard the R/V *Brownlee,* a research/education vessel owned by the Marine Sciences Institute. As guests of the MSI, UC Davis was only able to make tows during MSI's scheduled bottom trawl – twice on each of two days. A single living native oyster was hauled up by Zabin in a dredge in the Redwood City area in the summer of 2007 as part of a study of bryoliths (free-living bryozoan colonies). The oyster was growing on a bryolith and was in turn being overgrown by the bryozoan colony (C. Zabin, pers. obs.).

The UC Davis group also investigated the feasibility of using a high resolution sonar imaging device DIDSON (Dual frequency IDentification SONar). On loan from Sound Metrics, Inc., the DIDSON device was tested for its ability to detect oyster shells in a swimming pool. It was found that images of objects the size of native oysters can only be visualized when the device is firmly anchored or moored to a fixed location. Even the tiny wind waves in the swimming moved the DIDSON device too much to resolve an image clearly when it was held by hand. It was clear that deploying this device from a boat or other non-stable platform in field conditions would be unworkable.

In addition, oysters were looked for on rocks and maritime structures in and around Oyster Point Marina using an underwater camera mounted on a pole. The pole-cam belongs to a local water district and was being tested for use in a project at the marina. In clear water, such as shallow water (less than 1 m) over rocky rip-rap and on seawalls, oysters could be seen. In more turbulent conditions and over muddy bottoms, visibility was poor and one couldn't see well enough to determine whether oysters were present. This technique could be useful for looking at specific structures in relatively shallow water under calm conditions, but not for a widespread visual survey of the bay.

Subtidal Oyster Presence: Harris Thesis

Harris used a dredge to survey 16 sites for subtidal oyster populations from about the R/V Questuary in 2001. Her sites covered a wide north to south extent from Pinole Point to Redwood Creek. Although she hauled up clam and oyster shells in many of her samples, she found only one live native oyster, off of Point Pinole.

C. Current population dynamics of native oysters

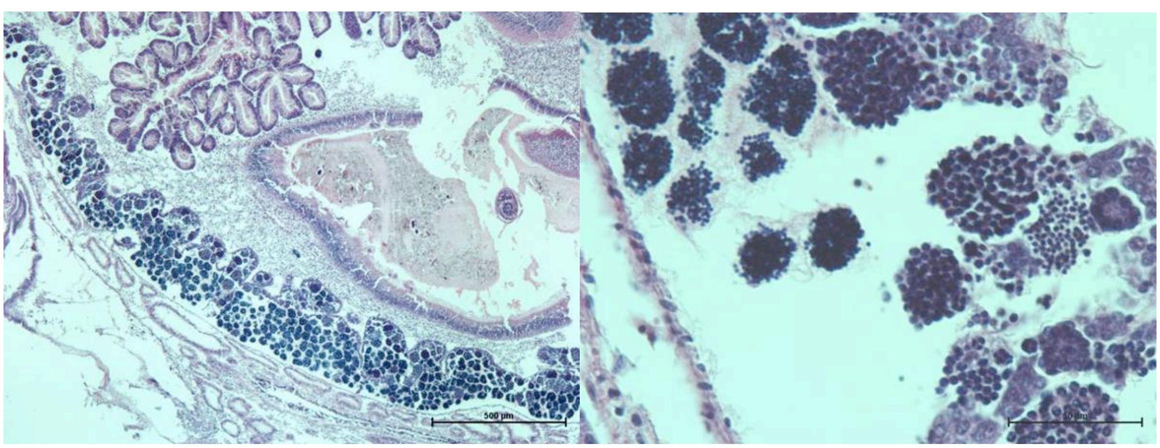
Fecundity

Direct measures of fecundity in *Ostrea lurida* are not straightforward due to the fact that these oysters are hermaphrodites, with both male and female gametes in various stages of development. The development of a method for scoring fecundity is in the beginning stages (Jim Moore, pers. comm.). Moore and Obernolte collected oysters monthly for one year from a set of spat outplanted in June 2007 at the Marin Rod and Gun Club to investigate reproductive development. Slides have been prepped but not yet scored. When analyzed, these data will assist us in the development of population models for native oysters.

A pilot data set of 3 month old oysters (N=22, size range 5 to 22 mm) collected in November 2006 is included below (Table 4 and Figure 8). Moore has found oysters at this site are reproductive sooner than previously reported in the literature.

Table 4. Results of a preliminary study of reproductive development.

Qualitative reproductive stage	# individuals	Percentage of individuals
Undeveloped/no gonad observed	4	18.2%
Early male	12	54.5%
Early male + earlier female	4	18.2%
Apparently mature sperm present	2	9.1%



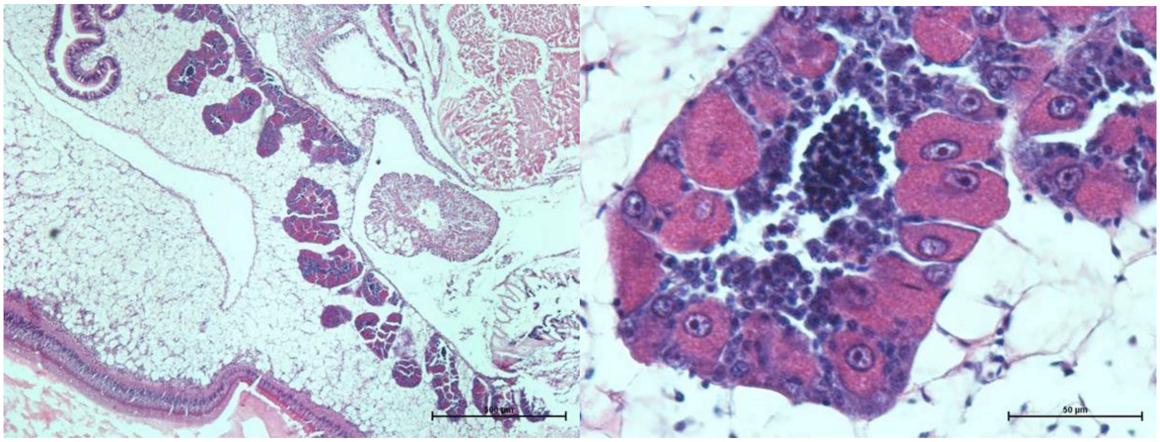


Figure 8. Clockwise from top left: Male with mature-appearing sperm balls. Close-up view of same. Hermaphrodite with developing male and earlier developing female gonads. Close-up of hermaphrodite with developing male and earlier developing female gonads. Photos by Jim Moore.

Recruitment

Measurements of native oyster recruitment have been made in San Francisco Bay by a number of organizations and individuals on a semi-regular basis beginning in 2001.

Oyster Recruitment: Save The Bay/ San Francisco State University Study
In 2001-2002, Save The Bay (Marilyn Latta, staff, volunteers) and San Francisco State University researchers (Professor Micheal McGowan, Aimee Good, Tripp McLandish, others) partnered with five community-based restoration and education organizations to survey intertidal oysters at five sites in San Francisco Bay. Simple shell strings made with Pacific oysters (*Crassostrea gigas*) were hung from docks and piers in 1-3 feet of water and monitored bi-monthly for presence/absence of native oyster settlement and other invertebrate species settlement. Water quality data was collected, including temperature, pH, dissolved oxygen, and salinity. The five sites included the north end of Richardson Bay in Tiburon (with Richardson Bay Audubon's Bayshore Studies Volunteers), the mouth of San Pablo Creek in Richmond (with The Watershed Project's San Pablo Area Watershed Awareness and Education and Restoration program); the mouth of Sausal Creek in Oakland (with the Friends of Sausal Creek), the mouth of Redwood Creek in Redwood City (with the Marine Science Institute), and at the Coyote Point Marina in San Mateo (with the Coyote Point Museum docent group). Native oysters were found at all sites except the mouth of San Pablo Creek. The project raised public awareness about native oyster presence in the bay, and generated media interest in the topic of native oyster restoration.

Figure 9a: Save The Bay/ SFSU 2001-02 study: Native oysters settled at the mouth of Sausal Creek, near the Fruitvale Bridge.

Oyster Recruitment: Save The Bay/ San Jose State University Study
In 2006-2007, recruitment data were generated by Save The Bay (Marilyn Latta, staff, volunteers) and San Jose State graduate student Sumudu Welaratna (Figure 9b). Four types of substrate were deployed, including 1) shell strings, 2) shell bags, 3) pvc plates attached to brick, and 4) collectors made from native oyster shell material mixed with Portland cement. Six sites were monitored bi-monthly, including the San Rafael Canal, Berkeley Marina, Oyster Point Marina, Palo Alto Baylands, the mouth of Permanente Creek, and the Ravenswood Pier. The south bay sites and the shell bag method had the highest recruitment densities.

Figure 9: San Jose State University graduate student Sumudu Welaratna prepares to deploy two types of recruitment substrate at Berkeley Marina. Left shell string. Right shell bag.

Oyster Recruitment: UC Davis 2006-08 Study
From 2006-2008, UC Davis deployed standardized recruitment collectors at between 7 and 13 sites; in 2007 and 2008 members of the San Francisco Bay Native Oyster Working Group coordinated efforts with UC Davis to use similar methodology so that recruitment could be compared across more locations. These data are summarized below.

Recruitment collectors (sets of 10 PVC tiles) were first deployed by UC Davis in July 2006 at the zero tide mark at 13 study sites. Seven oysters recruited to two sites, Berkeley (Shorebird Park) and Alameda (Encinal Boat Launch) (Figure 10). New recruits were seen in the late fall and winter at the UCD field sites after recruitment collectors had been removed. The lack of recruits was not surprising given the massive die-off of oysters earlier in the year. Recruitment was significantly higher in 2007, when recruitment collectors were placed at eight sites beginning in July. Recruitment collectors were checked every 2 months and left out continuously. Recruits first appeared in September in 2006 and August in 2007 and 2008.

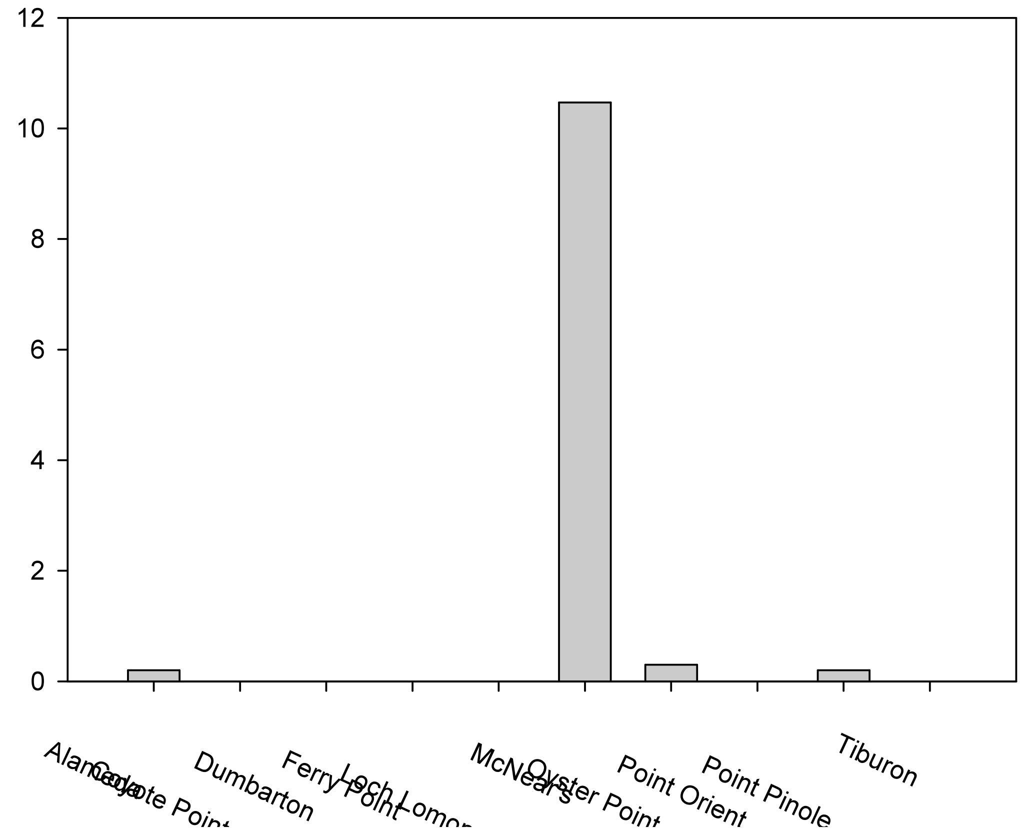


Figure 10: Recruitment of native oysters in 2006

In 2008, recruitment collectors (cement pavers and shell bags) were placed at the 0 tide mark and at two tidal heights (0 tide mark and to -2 to -3 feet). These were over two 3 month periods: Winter (January-March), Spring (March-June), Summer (June-August), and Fall (August-November). We present the 2008 data here in more detail as it is the most recent and complete data set available.

Oysters recruited best in 2008 during the summer (mean 6.483; SE =1.6 oysters/collector) and fall (mean 8, SE =0.2 oysters/collector) versus the winter (0 oysters/collector) and spring (mean 0.579; SE =0.2 oysters/collector) (Figure 11).

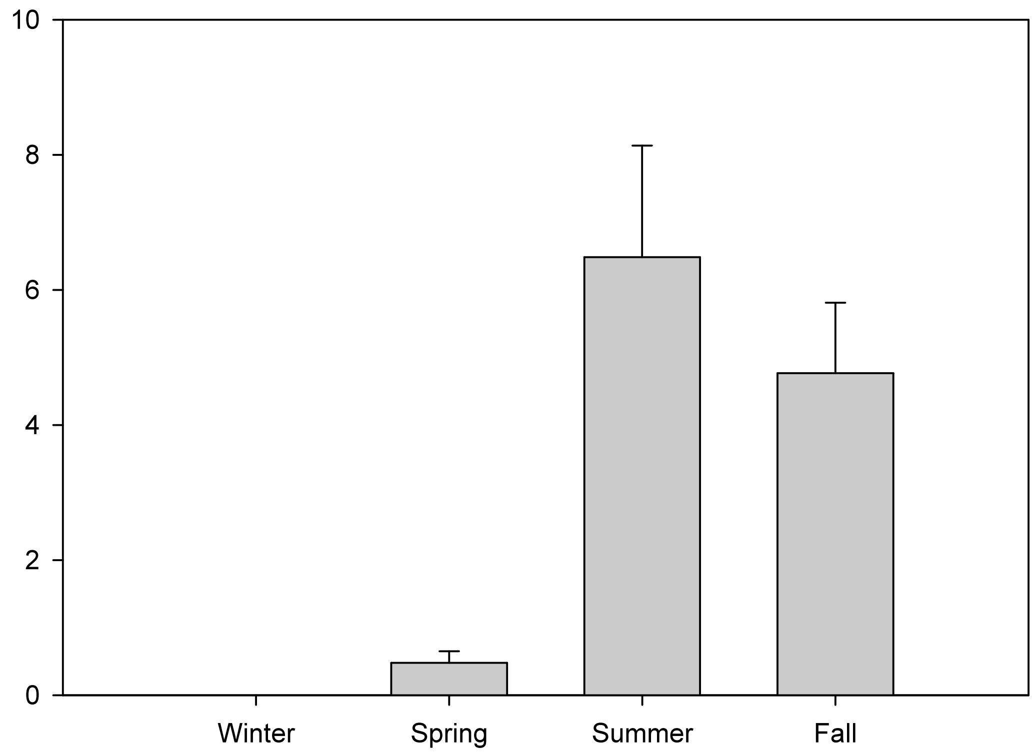


Figure 11: 2008 recruitment across all sites and depths.

Summer 2008 recruitment was best at Berkeley (mean 19.6, SE =3.3 oysters/collector) followed by Angel Island (mean = 8.200, SE 6 oysters/collector) (Figure 12). In the fall Ferry Point had the highest recruitment (mean = 13.2, SE =3.2 oysters/collector) followed by Angel Island (mean =4.200, SE =2.5 oysters/collector), Oyster Point (mean = 4.00, SE =2.0 oysters/collector), and Point Orient (mean = 4.000, SE =1.4 oysters/collector) (Figure 13).

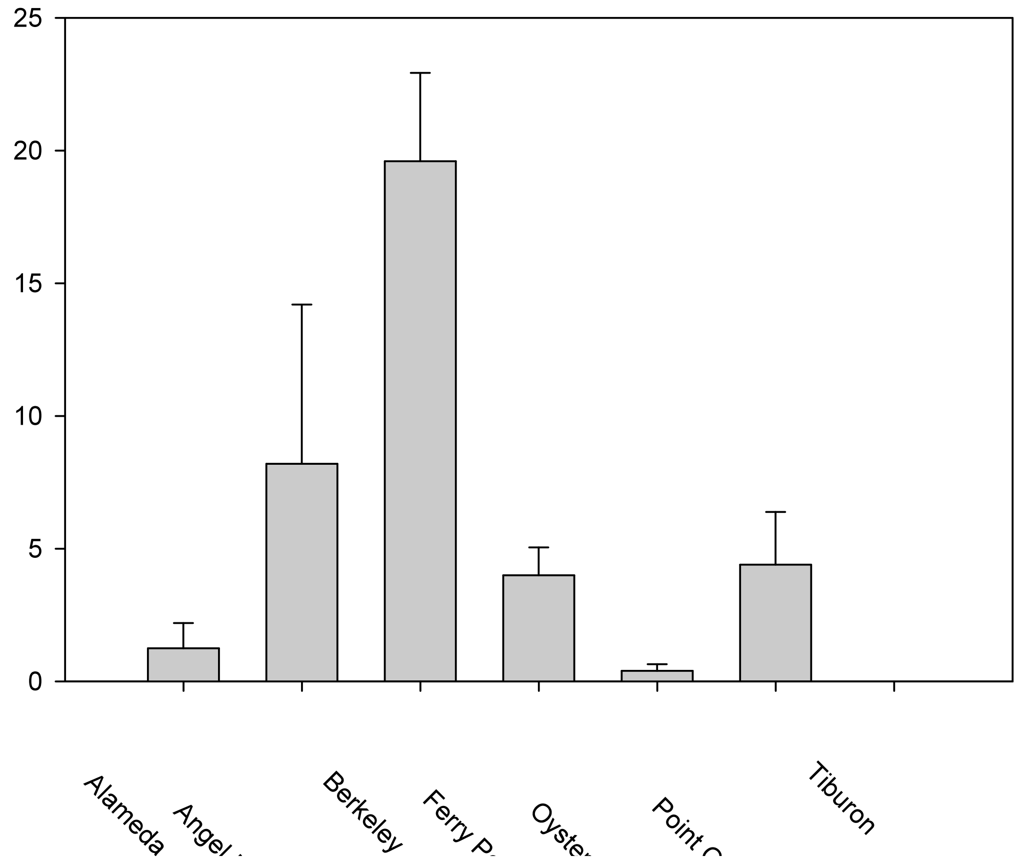


Figure 12: Summer 2008 recruitment.

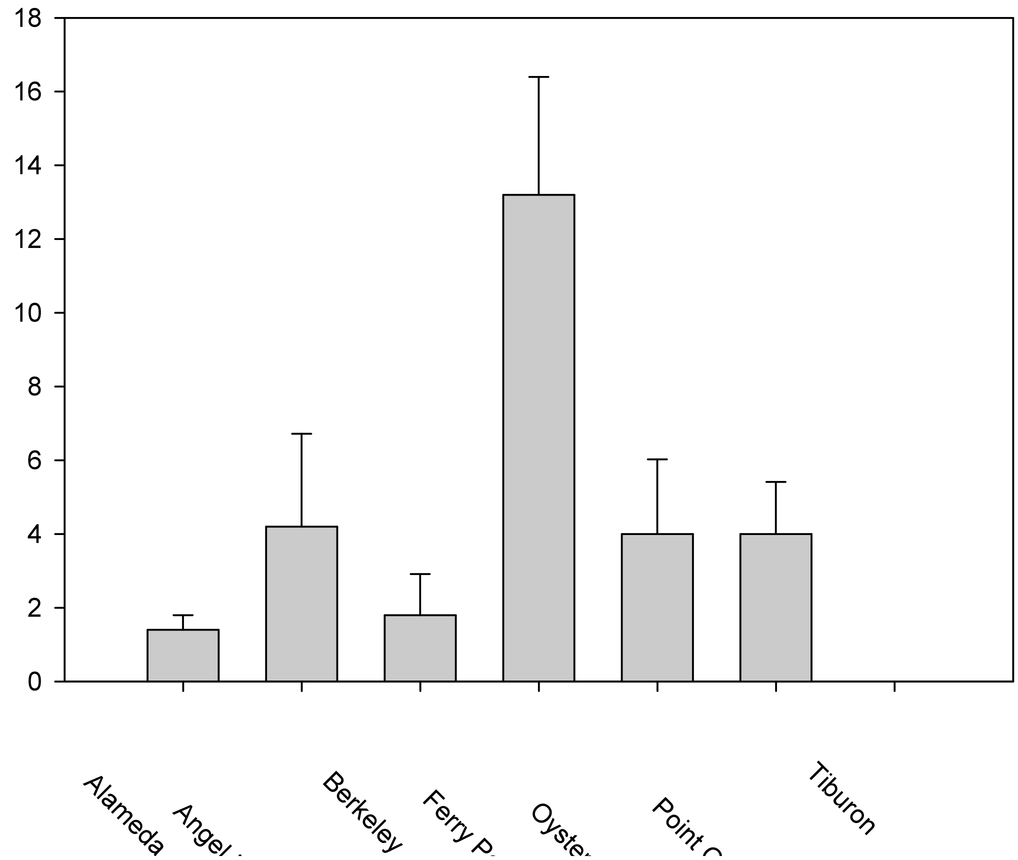


Figure 13: Fall 2008 recruitment.

Recruitment was higher at the -2 to -3 ft depth (mean = 26.0, SE = 5.0 oysters/collector) than at 0 tide (mean= 6, SE =1.4 oysters/collector). This difference (Figure 14) was statistically significant (p=0.000, df=1, chi-square =21.098).

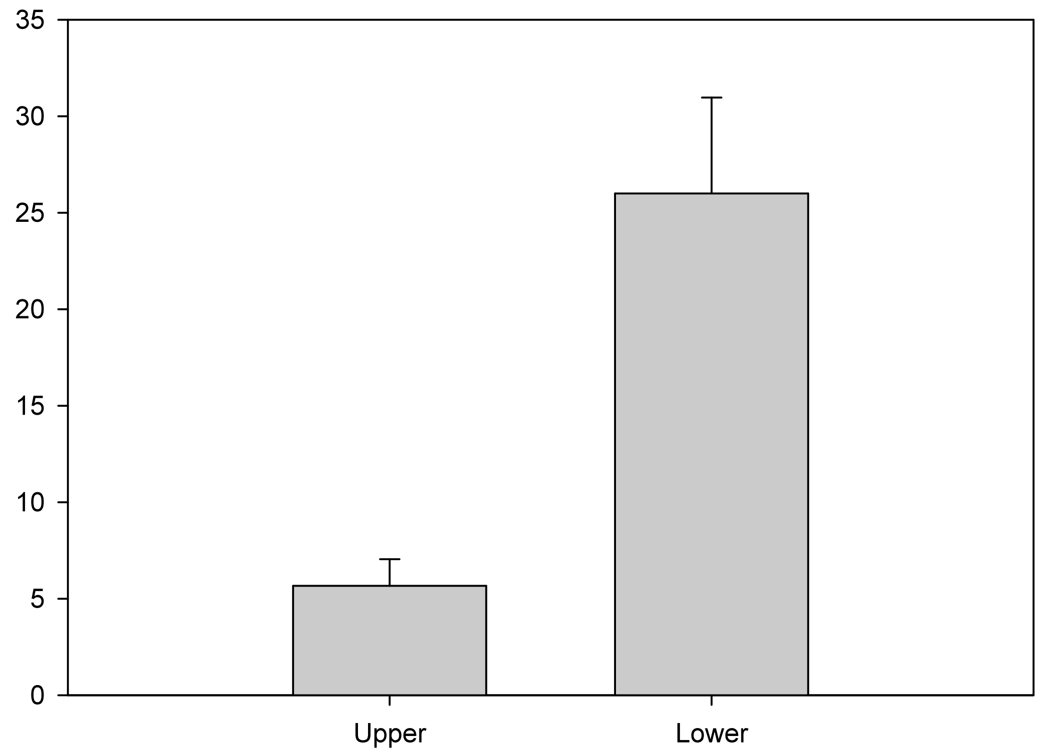


Figure 14: 2008 recruitment, upper vs. lower collectors. Upper tidal height was 0 (MLLW), and lower tidal height was -2 to -3 feet (MLLW).

Recruitment: San Francisco Bay Shared Oyster Protocol

In both 2007 and 2008 the San Francisco Bay Native Oyster Working Group (SFNOWG) conducted a recruitment study with a shared protocol.

In 2007 SFNOWG compared the recruitment efficacy of shell, PVC plates and oyster "seameant." Shell consisted of 5 quart bags of shell, with an average shell surface area of 100 cm^2. PVC plates were 100 cm^2 sanded gray PVC. Oyster "seameant" was made by twice dipping 100 cm^2 burlap in a cement mixture of 1 part Portland cement, 1 part ground native oyster shell (Jericho brand Pearl Powder), and 2 parts water. There was no significant difference in the number of recruits between the substrate types (Kruskal Wallis non-parametric test, p=0.277). There were differences between sites, but these might have been due to the fact that this study was conducted in a variety of ways including fixed versus floating substrate and varying depth of substrate (Figure 15, Table 5).

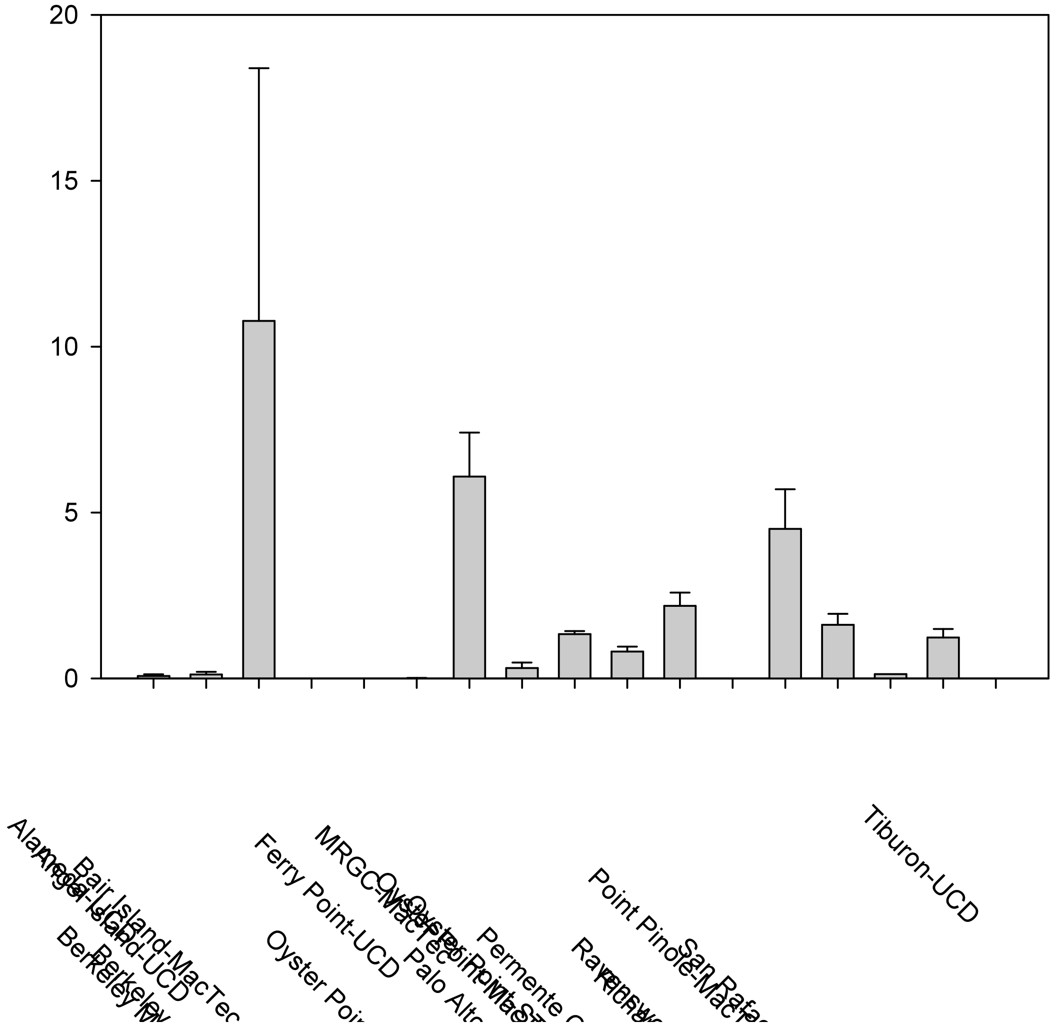


Figure 13: Mean number of oyster recruits for the recruitment season 2007 (all substrate types combined after being approximated to a standard size).

Table 5: 2007 shared oyster protocol of SFBNOWG.

Research Group	Site	Depth	Fixed or Floating	Shell Bags	PVC tiles	Seameant
MacTech	Point Pinole	0 m	Fixed	X	X	
MacTech	Oyster Point Marina	0 m	Fixed		X	
MacTech	Marin Rod and Gun Club	0m	Fixed		X	
MacTech	Marin Rod and Gun Club	-1 m	Fixed	X	X	
MacTech	Oyster Point Marina	-1 m	Floating		X	
Richardson Bay Audubon Center	Richardson Bay	0 m	Fixed	X	X	X
Richardson Bay Audubon Center	Richardson Bay	-1 m	Fixed	X	X	X
Save the Bay and San Jose State	Permanente Creek	-1 m	Fixed	X	X	X
Save the Bay and San Jose State	Ravenswood Pier	-1 m	Fixed	X	X	
Save the Bay and San Jose State	Palo Alto Baylands	-1 m	Floating	X	X	
Save the Bay and San Jose State	Oyster Point Marina	-1 m	Floating	X	X	X
Save the Bay and San Jose State	Berkeley Marina	-1 m	Floating	X	X	X
Save the Bay and San Jose State	San Rafael Canal	-1 m	Floating	X	X	X
UC Davis	Oyster Point Shoreline	0 m	Fixed	X	X	X
UC Davis	Ferry Point	0 m	Fixed	X	X	X
UC Davis	Angel Island	0 m	Fixed	X	X	X
UC Davis	Alameda	0 m	Fixed	X	X	X

In 2008, a second shared protocol study was conducted in a more uniform way. Substrates being compared were shell bags and cement bricks, which some groups had used as support for the PVC plates in the previous study and noticed that these attracted oyster settlers. The cement bricks were 5”x5”x2” gray garden pavers. Only the front of these was monitored. Shell bags consisted of 10 approximately 10 cm long Pacific oyster shells. Collectors were placed at MLLW and -1 to -2 feet. Collectors were deployed for 2 3-month periods during the summer and fall (June to November). In calculating settlement, the total number of oysters spat per bag was divided by the number of shells. Bricks were significantly more successful at recruiting oyster spat than shells (Mann-Whitney U Test $p<0.0005$). The sides of the bricks and surface area of one shell was approximately the same area, 160 cm^2. Bricks at the lower tidal height recruited more oyster spat than those at MLLW (Mann-Whitney U Test $p<0.0005$); shells at MLLW and the lower tidal height did not experience significantly different recruitment.

Recruitment: San Francisco Bay Marinas

UC Davis graduate student Andrew L. Chang deployed recruitment panels from floating docks at 1 m below the waterline at a number of marinas in San Francisco Bay from June 2006 to January 2008. He has observed a "band" of oyster recruitment that moves up and down the estuary and expands and contracts depending on water conditions. For example, during a wet season, the band would be near the mouth of the Golden Gate Bridge and be very narrow in its north-south extent, while during a dry season, the band could extend far into the bay. Table 6 shows the recruitment patterns during wet and dry years. Long term panels that were deployed from the summer of 2006 to February 2008 from the mouth of the Bay into the Delta recruited oysters at Presidio Yacht Harbor, San Francisco Marina, Sausalito Marina, Richmond Marina Bay, Loch Lomond Marina, Glen Cove Marina, and Benicia Marina (Andrew Chang, pers. comm.).

Table 6: Short-term recruitment collectors deployed for 3 month periods between June 2006 and January 2008. Glen Cove Marina (GCM), Loch Lomond Marina (LLM), Richmond Marina Bay (RMB), and San Francisco Marina (SFM).

Date Deployed	Date Recovered	Sites With Oysters	Sites Without Oysters
6/2006	9/2006		GCM, LLM, RMB, SFM
9/2006	12/2006	RMB, SFM	GCM, LLM
6/2007	9/2007	GCM, LLM	RMB, SFM
9/2007	12/2007	SFM	GCM, LLM, RMB
6/2008	9/2008	GCM, LLM, SFM	RMB
9/2008	12/2008		GCM, LLM, RMB, SFM

Recruitment: Sailing Lake Study

In July 2005, 14 bags of Pacific oyster shell (~1.2 m long and 20 cm wide) were deployed at Sailing Lake in Mountain View. The bags were hung at three depths below the surface of the water in this tidally restricted lake: 3 bags at 1 m, 8 bags at 2.5 m and 3 bags at 4 m. The trend of spat settlement on the bagged shells was an increase with depth in the mean number of spat per shell: 3.8, 2.1 and 1 for the deepest to shallowest, respectively. Interestingly, mean spat size was smaller at the deepest depth at 9.4 mm, vs. 12 mm for the two shallower sites.

Growth

Oyster Growth: UC Davis Study

Oysters were tagged during 2006, 2007, and 2008 using cyanoacrylic or marine epoxy and Floy shellfish tags. Initial sizes of oysters were taken, and sites were revisited periodically to remeasure oysters. Many tagged oysters were lost due to mortality and the difficulty of refinding mud-covered oysters. New oysters were tagged each visit to keep the number of total tagged oysters near 50. The residual proportional growth rate was calculated as actual growth rate-expected growth rate divided by the initial size. The residual proportional growth rate was used because smaller oysters grow more than larger oysters and the initial size of oysters was significantly different at each site.

Oyster growth varied among years. Warm season growth (March-October), which is consistently higher than cold season growth (November-February) was higher in 2006 and 2008 than 2007, with data from all sites combined (Figure 14).

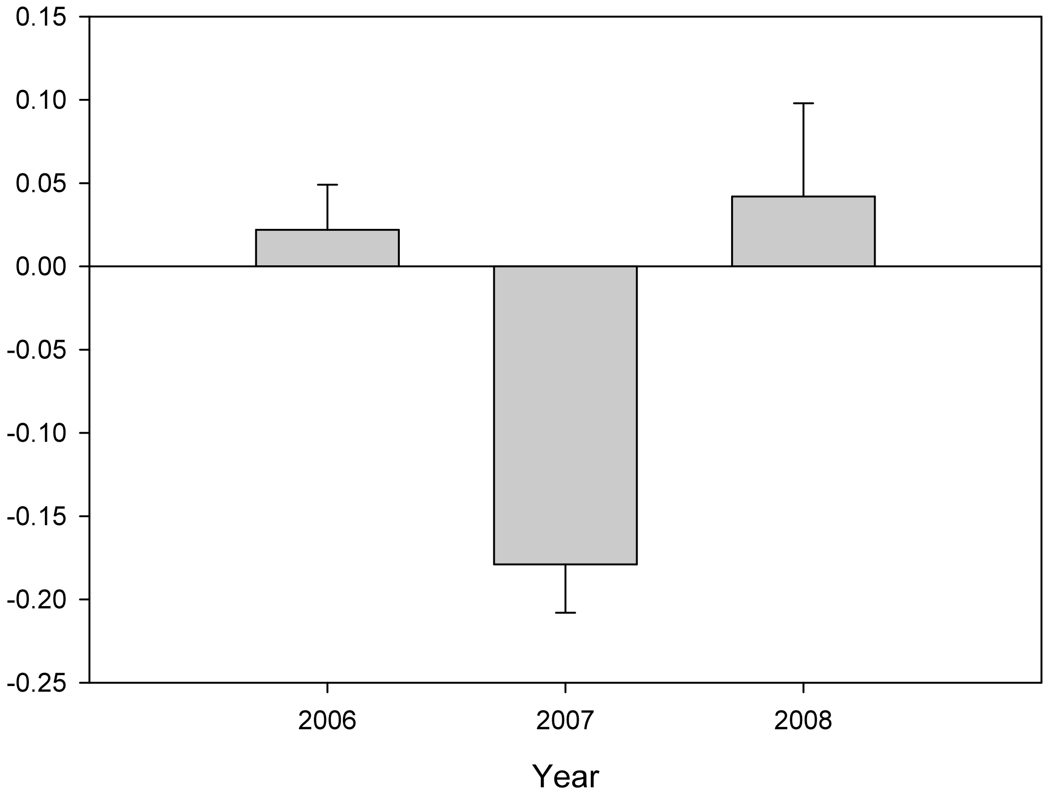


Figure 14: Residual proportional growth rate of the warm season (May-November). Expected proportional growth rate was calculated using the equation y=-0.0374x+1.3786, where x is the initial size (mm) and y is the expected proportional growth rate (mm/season), where the season is May-November. Residual proportional growth rate was calculated as actual growth rate-expected growth rate. Means and standard errors are as follows: 2006 (0.022 $\pm$ 0.027 mm/season), 2007 (-0.179 $\pm$ 0.089 mm/season), and 2008 (0.042 $\pm$ 0.056 mm/season).

Growth also varied between sites in 2007 and 2008. At the five sites for which we could confidently calculate growth in 2008, warm season growth was highest at Ferry Point (Figure 15). The difference in growth rate between Ferry Point and both Tiburon and Oyster Point was statistically significant.

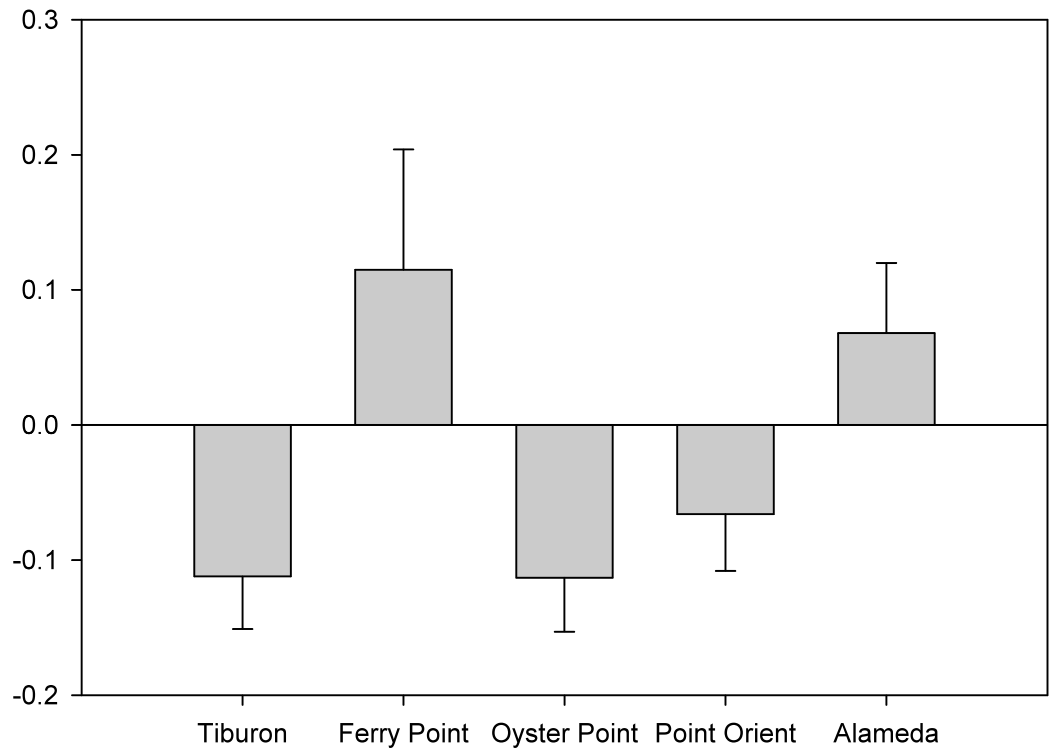


Figure 15: Residual proportional growth rate of the warm season (May-November). Expected Proportional Growth Rate was calculated using the equation y=-0.0374x+1.3786, where x is the initial size (mm) and y is the expected proportional growth rate (mm/season), where the season is May-November. Residual proportional growth rate was calculated as actual growth rate-expected growth rate. Means and standard errors are as follows: Tiburon (-0.112 $\pm$ 0.039 mm/season), Ferry Point (0.115 $\pm$ 0.089 mm/season), Oyster Point (-0.113 $\pm$ 0.040 mm/season), Point Orient (-0.066 $\pm$ 0.042 mm/season), and Alameda (0.068 $\pm$ 0.052 mm/season).

Oyster Growth: Bair Island/Greco Island Study

Growth was measured using a different method in at two pilot restoration sites in 2005-2006. Oysters of known maximum age were measured on shell substrate placed in the shallow subtidal. Growth rates were calculated as being 10 mm month in summer (for newly settled spat) and 2 mm month after November. Maximum size after 1 yr (May 2005 to May 2006) was up to 55 mm at the Bair Island site and 50 at the Greco Island site.

Mortality

Mortality: UC Davis Study

Mortality rates were measured during the 2006-2008 study at each of the long term study sites. The total number of tagged oysters found was noted for each visit. The size of tagged live and dead oysters was measured to the nearest mm. Using a binomial logistic regression where:

$$F = if(x>0, y)+a*\ln(abs(x),o)$$

it was found that smaller oysters died at higher rates than larger oysters, suggesting stress as opposed to senescence kills most oysters (Figure 16). Stresses may include, low salinity, high temperatures, or selective predation on smaller oysters.

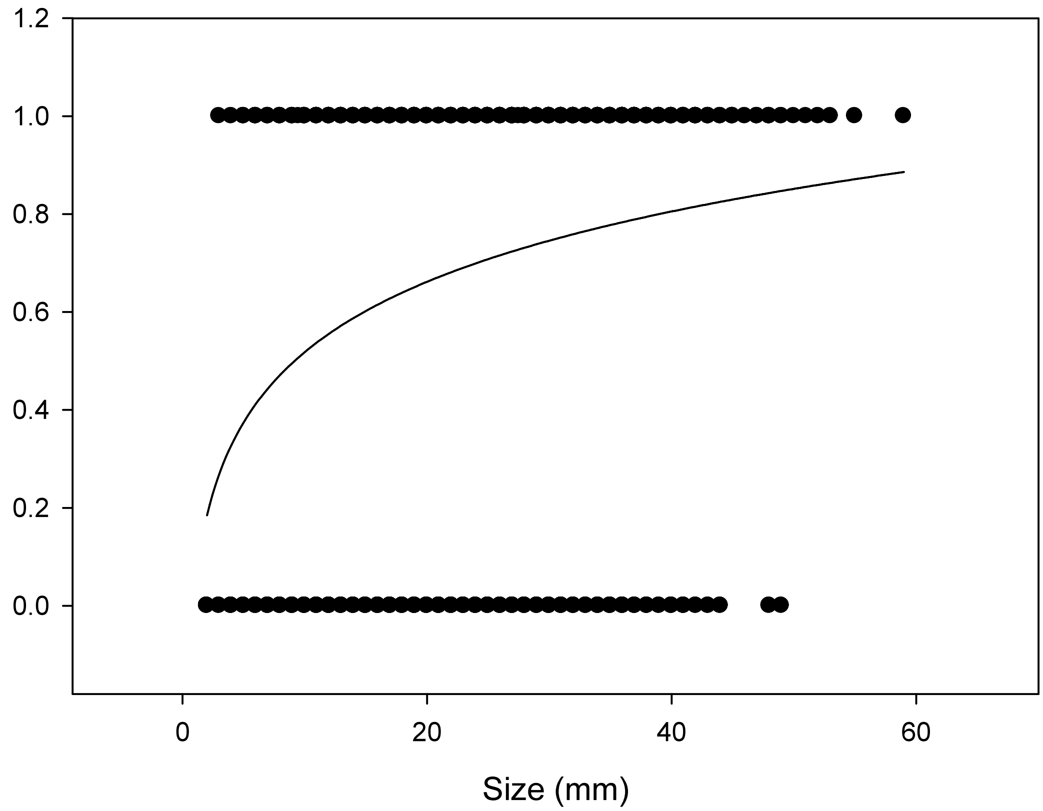


Figure 16: Logistic regression of probability of survival. Dead oysters=0, Live oysters=1.

There was no significant difference between warm and cold percentage mortality (p=0.162, df=1, chi-square =1.966). Mortality was higher in 2007 and 2008 than in 2006 (Figure 17). However, these results are likely skewed because in 2006 oysters were marked on the top of their valve, which usually falls off after an oyster dies, thus we likely missed many oysters that had died. After 2006, oysters were tagged on the rock next to the oyster, resulting in a greater ability to track dead oysters.

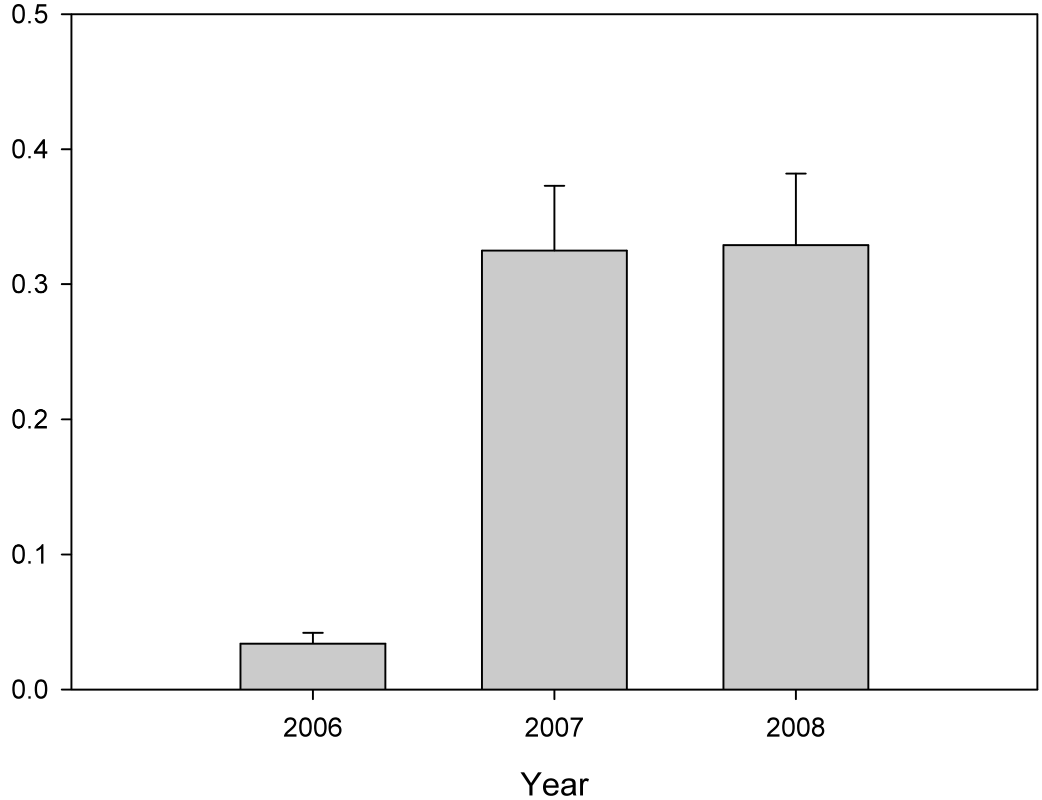


Figure 17: Percent Mortality. Means and standard errors are as follows: 2006 (0.034 $\pm$ 0.008 proportion mortality), 2007 (0.325 $\pm$ 0.048 proportion mortality), and 2008 (0.392 $\pm$ 0.053 proportion mortality).

Mortality rates varied by site across all years, with the highest mortalities noted at the San Francisco Aquatic Park site and the lowest at Berkeley and Ferry Point (Figure 18). The difference between mortality at the San Francisco site and these two sites was statistically significant (for both comparisons, Mann-Whitney U <0.0005, p <0.025, df =1).

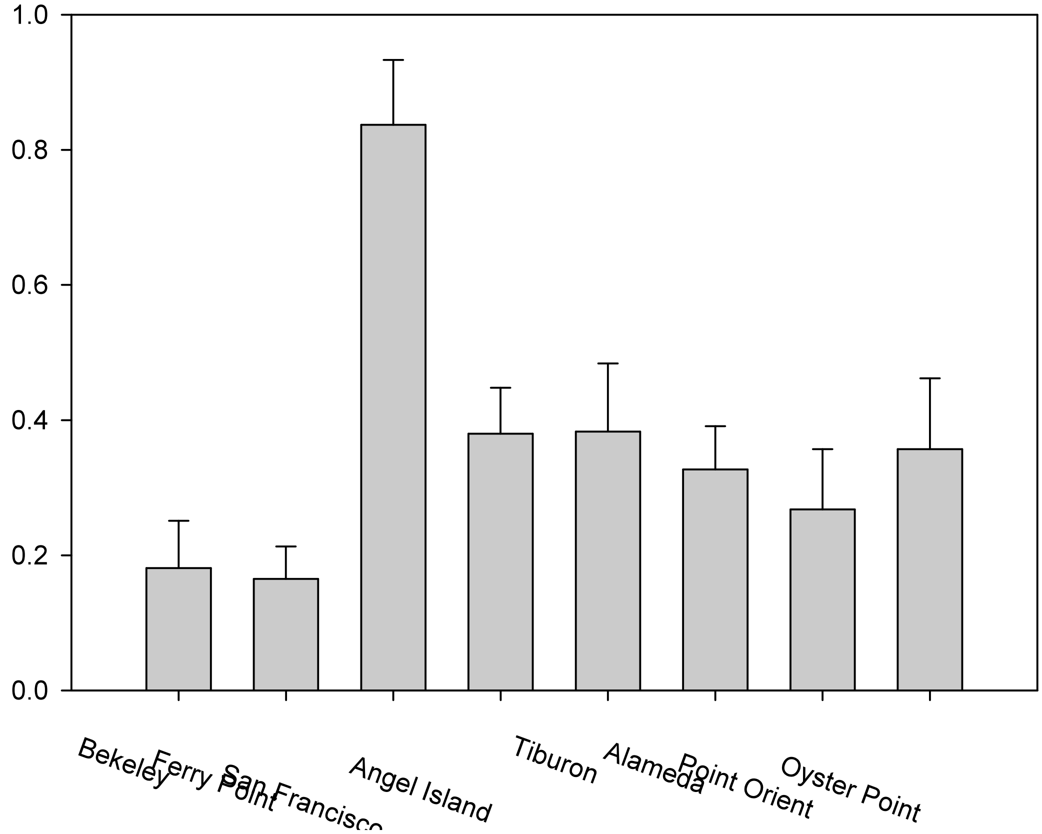


Figure 18: Percent mortality. Means and standard errors are as follows: Berkeley (0.181 $\pm$ 0.070 proportion mortality), Ferry Point (0.165 $\pm$ 0.048 proportion mortality), San Francisco (0.837 $\pm$ 0.096 proportion mortality), Angel Island (0.380 $\pm$ 0.101 proportion mortality), Tiburon (0.383 $\pm$ 0.101 proportion mortality), Alameda (0.327 $\pm$ 0.064 proportion mortality), Point Orient (0.268 $\pm$ 0.089 proportion mortality), and Oyster Point (0.357 $\pm$ 0.105 proportion mortality).

Summary

Native oysters in the intertidal zone can be found in highest abundances (up to 20 per .25 m^2) in the Central Bay, but lower densities and scattered live individuals are found over a wider extent. Based on our observations after the major low salinity event in the spring of 2006, as well as from historical observations, it seems clear that both the northern and southern edges of the oyster population shift over time as salinity fluctuates. Extrapolated from estimates of oyster densities around the Bay in 2006, Grosholz (2007) estimated that there are 300,000 living oysters in the intertidal zone in San Francisco Bay.

Oysters have appear to do well subtidally in many manmade habitats such as on marina floats and in the tidally restricted Sailing Lake in Mountain View, where they may have continuous access to a food supply, are protected from heat stress, and have some level of release from crawling predators. The population in Sailing Lake from 2002 was estimated to be at 10 million (Brian Mulvey, pers. comm.). The extent of the subtidal population in the Bay remains unknown.

Although all demographic variables measured varied across time and space, some patterns are emerging. For example, sites in Richmond and the Central Bay seem to have consistently higher recruitment rates to standardized intertidal recruitment collectors than those in Richardson Bay and sites further south and north. Adults are largely missing in most parts of the South Bay, yet recruitment to deployed surfaces has been fairly consistent across years. Coyote Point has had large oysters throughout the entire span of the UC Davis study, but new recruits were rarely seen there. Oyster Point, just to the north of Coyote Point, has had consistently good recruitment, but low growth, and generally smaller oysters. The same was true of Angel Island and is generally true of Point Orient. Ferry Point and Berkeley have consistently had both high recruitment and high growth.

Based on the work to date, it appears that recruitment season in San Francisco Bay generally begins in June and continues through November. (An exception to this was in the flood year 2006, when recruitment was delayed and continued through February 2007.) Oysters also generally appear to recruit in higher numbers to substrate lower in the intertidal (or shallow subtidal) zone. Although we do not have sufficient sample size to accurately determine this, it appears that substrates left out longer collect proportionately more larvae, suggesting that a certain amount of conditioning and/or the presence of other oyster spat promote settlement.

Not surprisingly, growth appears to be higher during the warm season (March-October) than in the cold season. Growth of individuals in natural populations varies widely, but growth of newly settled spat on clean substrate has been calculated at about 10 mm/month in summer and 2 mm after November. Maximum sizes at the end of a year in the shallow subtidal zone are around 50 to 55 mm.

Across several years of study, smaller oysters died at higher rates than larger oysters in the intertidal zone, suggesting stress and/or differential predation, as opposed to senescence, kills most oysters. We did not, however, see a difference in mortality rates between seasons, suggesting that heat stress is not an overriding source of stress for intertidal oysters. We also did not see much evidence of predation in the intertidal zone and in the central and northern portions of the Bay (see Limiting Factors below). The overall mortality rate in the intertidal zone at long-term study sites was fairly low at about 35 percent at most sites. Sites with the highest survival rates were Berkeley and Ferry Point, two sites with high recruitment and high growth.

Research recommendations

1. Subtidal populations

The question of whether extensive subtidal populations exist in the Bay is still unanswered. Subtidal populations, if they exist, represent a recruitment source that may serve to repopulate intertidal and shallow subtidal locations following low-salinity events and other disturbances, and which could play a significant role in the success of recruitment to restoration projects. As such, this represents a major gap in our understanding of native oyster population dynamics in San Francisco Bay.

2. Multi-year, multi-site population studies

Besides the obvious need to carry out more complete surveys for subtidal oyster populations, an extensive intertidal survey like the one carried out by UC Davis ought to be made during a normal rainfall or drought year to better assess the current status of oysters in San Francisco Bay. There is some indication that lagoons and managed ponds (such as Sailing Lake) around the Bay may be good habitat for oysters, providing hard substrate in areas of the South Bay were substrate appears to be limiting and offering some amount of protection from predators and perhaps from heat and other physical stresses. These habitats ought to be surveyed in a more focused manner and recommendations for their management should be generated.

In addition to surveys for adult oysters, regular surveys which include deploying standardized recruitment collectors, such as the cement pavers and small shell bags used by SFBNOWG, and making density and size-class measurements ought to be made at key shoreline areas on an annual or biannual basis. It is clear that oyster populations in the Bay are dynamic, shifting in extent and density depending on climatic conditions, recruitment and potentially other factors such as disease and predators, and a better understanding of these dynamics would be gained with multi-site, multi-year data. Such surveys are not difficult to do and could be carried out by trained volunteers, which would have the dual advantage of providing scientists and decision makers with needed data and involving and educating the public about Bay ecosystems.

3. Larval delivery and connectedness between populations

The native oyster population in San Francisco Bay is likely best viewed as a metapopulation, connected to some as-yet-unmeasured extent by larval recruitment between sites. Understanding the degree of connectivity is critical to restoration planning. Among the most pressing research needs of direct relevance to native oyster restoration is the understanding the movement of larvae in the bay. To date, restoration projects in San Francisco Bay have relied on natural recruitment of larvae to deployed substrate (see Restoration Methods, below). This approach may work in some parts of the Bay but not in others.

Recruitment patterns seem to suggest that larvae are retained in certain areas, perhaps due to eddies created by geographic features. For example, recruitment seems to be consistently quite high in the Richmond/San Rafael area. Larvae that are likely released further north seem to be retained in South Bay.

On the other hand, recruitment has been consistently low in Richardson Bay, which seems like it ought to retain larvae. Low recruitment there could be due to insufficient numbers of adult oysters in local populations and not enough influx of larvae from elsewhere, current patterns which remove larvae from Richardson Bay or high mortality of larvae and/or new settlers. Understanding which of these factors is driving low recruitment is essential to the development of restoration approaches in Richardson Bay.

Methods for studying larval movements include the deployment of drifters, plankton tows, assays involving PCR-based sampling, the release of chemically marked larvae and trace element analysis might be able to distinguish between larvae produced in different locations in the Bay. In contrast to *Crassostrea virginica,* little is known about the swimming behavior of the larvae of *Ostrea lurida.* Studies focuses on larval behavior and response to waterborne cues may be critical to understanding the movements of larvae in the bay as well as substrate selection and settlement patterns.

Population viability analyses

Knowledge of native oyster population parameters in San Francisco Bay is nearly at a point at which a formal population viability analysis could be carried out. Such an analysis would be particularly informative in identifying life stages that are the most vulnerable and/or the most critical to the viability of the population. This information could be used to prioritize management actions.

D. Limiting factors to existing populations/restoration projects

Biotic Factors

Predatory Drill Abundances: UC Davis Study

As mentioned above, high mortality among small size classes might be suggestive of increased predation on young oysters. The Atlantic oyster drill *Urosalpinx cinerea* (Figure 19) and a native whelk *Acanthina spirata* are two snail species known to prey on native oysters and are considered a limiting factor in some West Coast estuaries (Kimbro et al. 2009).

Figure 19: The Atlantic oyster drill *Urosalpinx cinera.*

The UCD group surveyed for oyster drills (whelks) at its long-term (see Appendix 3) study sites over the course of two minus-tide series in late Sept-early Oct 2006 and late May-early June 2007. At each site, they searched for drills in ten 1-m^2 quadrats randomly placed along our permanent transects. They turned small cobbles within each quadrat to check for the snails on the sides and undersides of rocks. Drills were only found at five locations. The native drill was the only drill found at the San Francisco site; the Atlantic drill was the only drill found at the remaining sites (Figure 20).

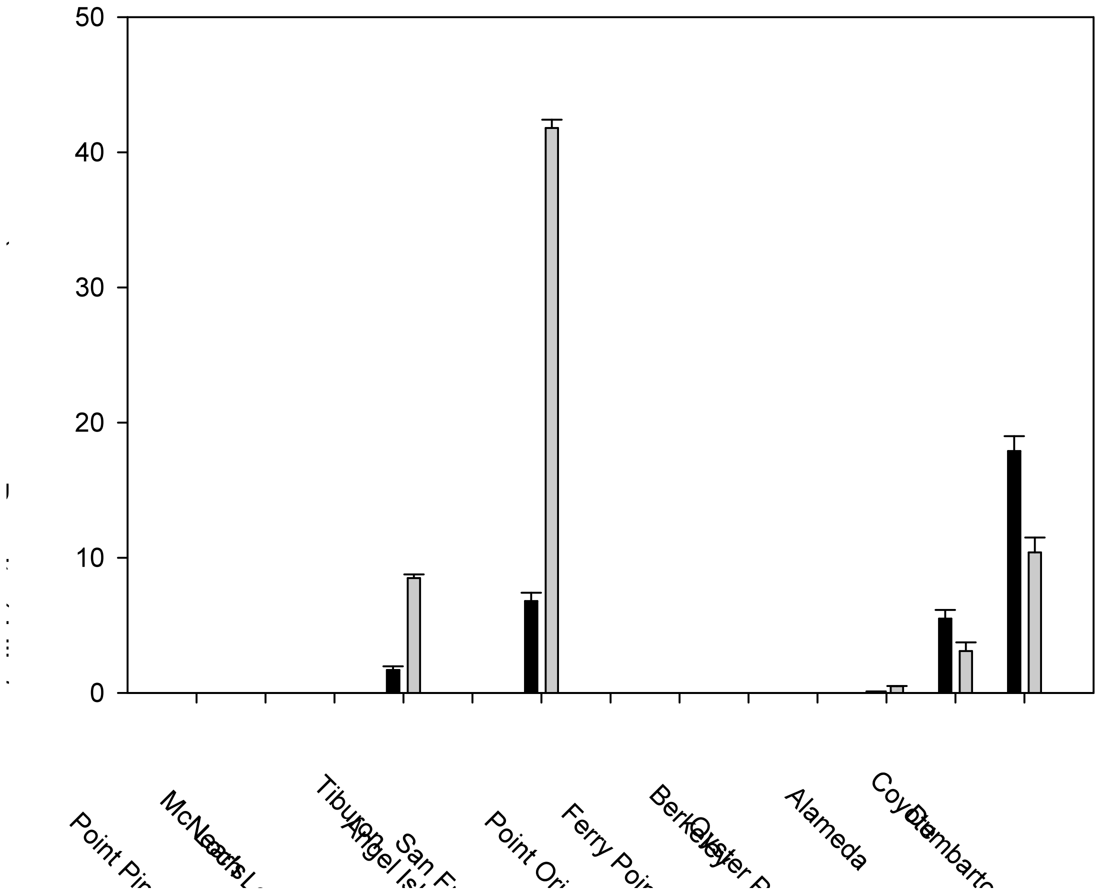


Figure 20: 2006/2007 Density of oyster drills by site. Black bars indicate fall densities. Gray bars indicate Spring densities. All sites except San Francisco have only *U. cinera*. San Francisco only has *A. spirata.*

Other predators are known to prey on native oysters including birds and fishes (Barnett 1963, Baker 1995). Bat rays (*Myliobatus californica*) and some other sharks and rays are known to be significant oyster predators. Predatory crabs, including both native *Cancer* spp. and introduced European green crabs (*Carcinus maenas*) are also known to consume oysters under some circumstances. We have not observed these other predators on a regular basis or seen evidence of predation on oysters at our intertidal study sites (S. Attoe & C. Zabin, pers. obs.), but data were collected only on oyster drills. Experiments with crabs and whelks in Tomales Bay strongly indicate that oyster drills are much more important consumers of oysters than crabs (Kimbro et al. 2009). Drills and their eggs were abundant on the oyster shell deployed for the pilot restoration projects at Bair and Greco Islands; many drilled oysters, including many drilled dead juveniles, were observed (Rena Obernolte, Robert Abbott, Brian Mulvey, pers. comm.). Drills were more plentiful at Greco Island than at Bair Island. Mulvey and Abbott (B. Mulvey, unpubl. data) noted that oysters larger than 20 mm were rarely drilled or had only incomplete drill holes, suggesting a size refuge from predation.

Space competitors

To determine whether competition for space might be a limiting factor for native oysters at our study sites, we assessed the abundance of other sessile organisms in the oyster zone using photoquadrats. In September 2006 and January and June 2007 we photographed the organisms inside 10 cm^2 photoquadrats randomly placed along our permanent transects. The images were downloaded and percent cover of each type of organism was determined by projecting 25 points onto the computer screen. Mussels, barnacles and algae were the major organisms in the oyster zone. At most sites and most time periods, more than 40% of the hard substrate in oyster zone was bare (Figure 21).

These results suggest that space may not be currently limiting native oyster populations, at least in the intertidal zone in Central Bay and some areas of the North Bay. However, in the South Bay and areas of the North Bay, where hard substrate is rare, space may be among the factors limiting recruitment and population growth generally. Space limitation may also be more of a factor for subtidal populations, as hydroids, sponges and tunicates are more abundant in the subtidal than the intertidal zones. Indeed, restoration and recruitment monitoring projects from around the bay have recorded numerous species of these fouling organisms on oyster substrate deployed in the subtidal zone (Marilyn Latta, Rena Obernolte, Sumudu Welaratna, pers. comm.).

Disease

In 2006-2007, J. Moore (CA Dept. of Fish and Game) looked for disease in native oysters. Generally, infectious disease did not appear to be having a dramatic impact on these populations, although the high prevalence of disseminated neoplasia in the January 2005 sample from Candlestick Point suggests that this disease may be significant in some locations (see Grosholz et al 2007. for details). To conclude, of the potential obstacles for restoring native oysters, parasites and pathogens appear to be relatively unimportant. Diseases appear to have little influence on population growth and are very unlikely to be responsible for the lack of recovery of native oysters since the cessation of harvest pressure. This contrasts sharply with the important role of disease in confounding restoration of *Crassostrea virginica* is the eastern U.S. However, with native Olympia oysters, this does not appear to be a concern for current or future restoration planning.

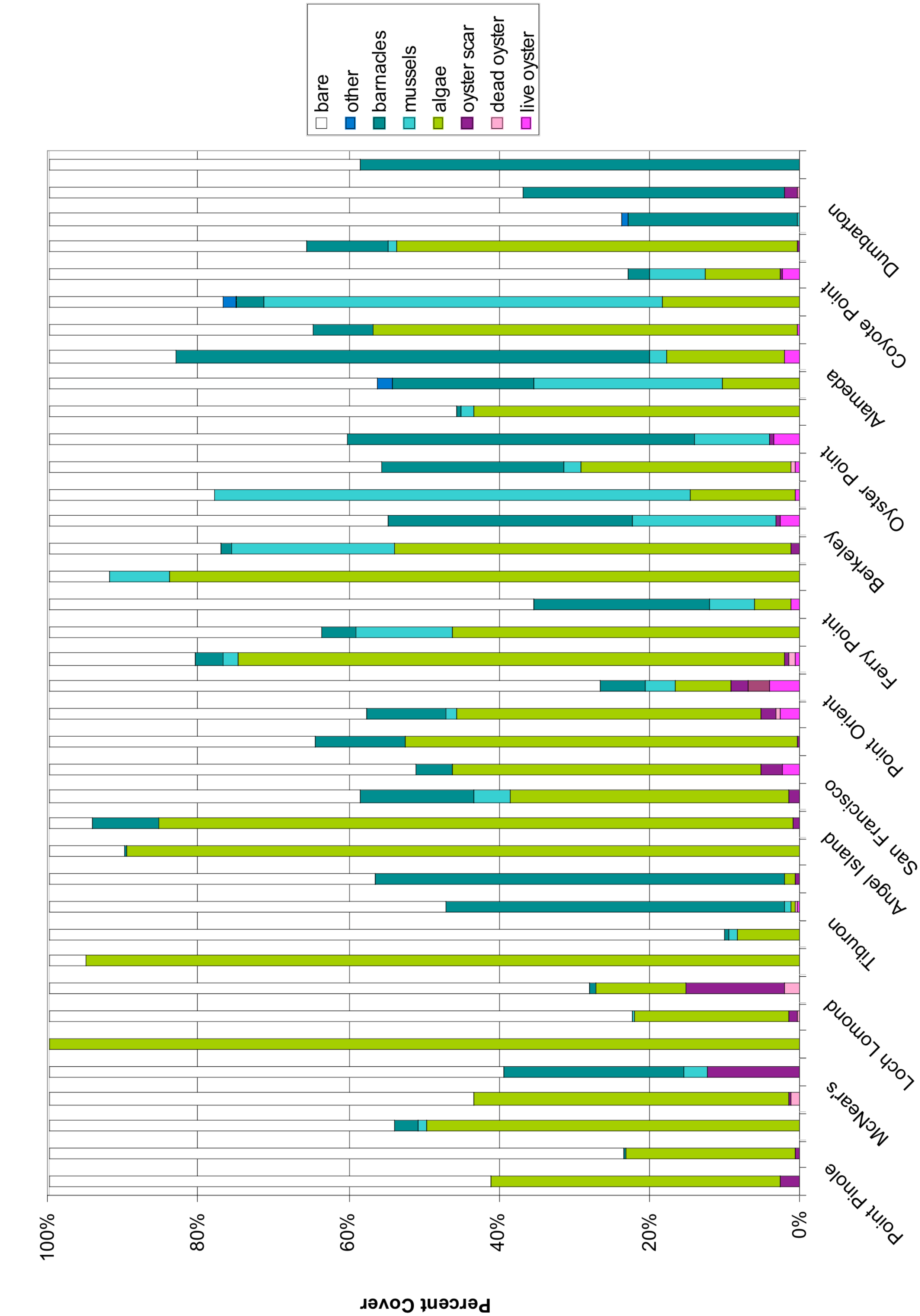


Figure 21: Seasonal variation in cover of space competitors by taxa in photo quadrats.

Each group of three bars represents cumulative cover of various taxa for each season.
Food supply

Chlorophyll a was sampled at each of the 13 UC Davis sites monthly to account for local food abundance. These samples were concentrated by filtering then analyzed using a fluorometer. Analysis is forthcoming.

Abiotic factors

Lack of appropriate substrate

Olympia oysters require hard substrate for settlement, and while they are able to use tiny bits of shell and small pebbles, in muddy locations these small substrates are likely to get buried (see Sediment Deposition below). Oysters in San Francisco Bay are found on seawalls, rip-rap, cement portions of floating docks, boulders, cobbles, tires, metal and hard plastic debris, pebbles and shells of both living and dead molluscs. Hard substrate is lacking in many parts of the Bay, particularly in the South Bay, where there is little naturally occurring in the mudflats and marshes and where there is less shoreline armoring. Substrate for oysters also appears to be lacking in the shallow subtidal in many locations where intertidal substrate is found. Restoration projects in the Bay to date have focused on the deployment of hard substrate in locations where it is not present or in low abundance. The successes of these projects in attracting oyster settlers is suggestive that substrate is a key limiting factor in these locations.

Salinity

Various researchers have reported low salinity limits for Olympia oysters. Gibson (1974) reported 80 percent survival at 15 ppt for 49 days. Hopkins (1936) wrote that adults cannot withstand prolonged salinities below about 15-25 ppt and that the ideal salinity for settlement is 20 ppt. But throughout their range Olympia oysters may vary in salinity tolerances, indeed, oysters in Puget Sound are reported to be limited by 23-24 ppt (Hopkins 1936), while oysters in British Columbia have been reported near the mouths of rivers where salinity is certainly lower than that (Quayle 1941).

As noted by some of the earliest studies of oysters in San Francisco Bay and in the more recent studies outlined above, salinity is clearly a limiting factor in native oyster populations in the Bay. In addition to the already-mentioned observations of a major die off during the spring of 2006, researchers noted a 29 percent decrease in spat between April 1 and 30 at the Bair Island project site, where salinity dropped to 14 ppt in April and was recorded at 11 ppt in May. Mortality in 2006 following the low salinity events was substantially higher at the Marin Rod and Gun Club (80%), where salinity was in the single digits, than at the Bair Island-Greco Island sites (25%).

A lab-based salinity study examining the effects of salinity on adult oyster mortality and growth was conducted by Attoe and Grosholz in 2008. They set up 50 tanks, with 10 replicates at each of 5 levels of salinity (5, 10, 15, 20 and 25 ppt); into which were placed between 10 and 30 lab-reared oysters of the same age and size. Oyster broodstock were obtained from one site that was destroyed by the 2006 extreme low salinity event, and one that was not. There were no differences in growth or survival between sites. Survival and growth rate were monitored weekly for six weeks. Low salinities (less than 15 ppt) caused significant oyster mortality over a matter of weeks (Attoe and Grosholz, 2009). The steady downtrend of survival for both groups suggests that other factors were stressing the oysters. There was also an abnormal die off at between weeks 5 and 6. Temperatures were suddenly very high, and oysters may have experienced anoxia, before the water was changed (every 2-3 days). Lowered salinity was impacting oysters more than they were naturally dying in suboptimal conditions (Figure 22).

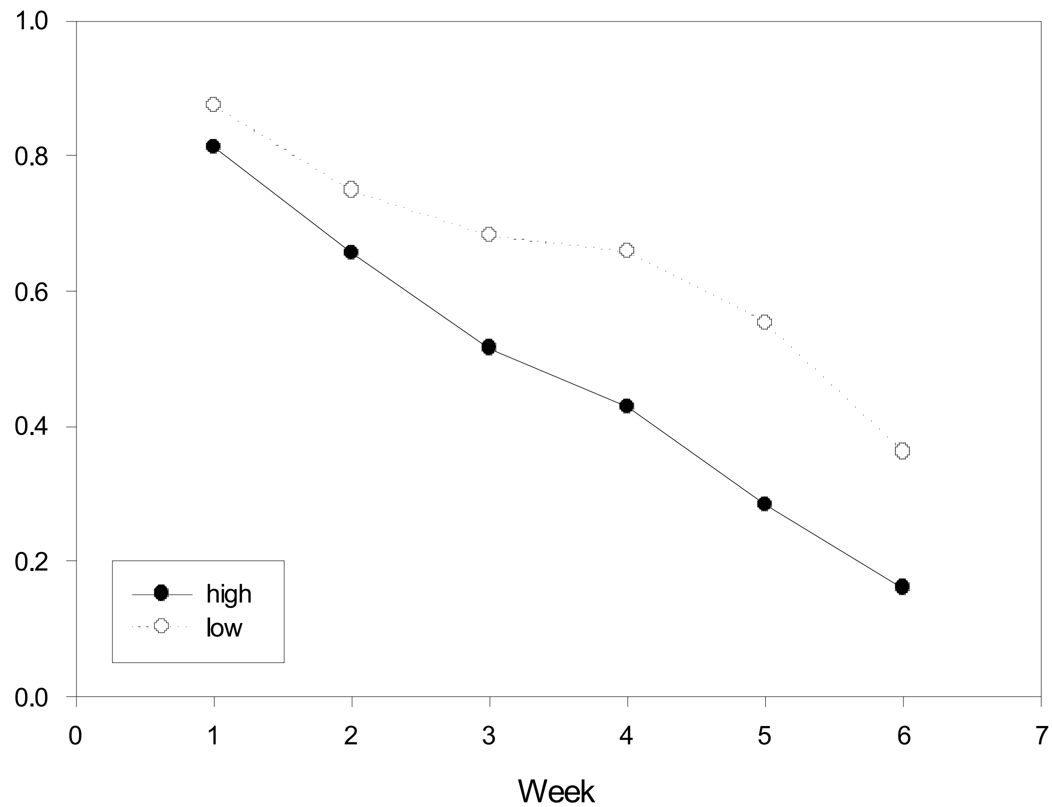


Figure 22: The proportional survival of oysters at low (5, 10 or 15 ppt) or high (20 or 25 ppt) salinities. The difference in mortality at weeks 4 (p=0.014) and 5 (p=0.017) are statistically significantly. Week 6 experienced a strange die off, so is anomalous.

The US Geological Survey. The USGS samples bay salinity along a 145 km transect through the Bay. Samples are taken of surface water and of water 1 m off the bottom. Data collected during two of the area's recent wet winters are pictured below (Figure 23). In both of these time periods, salinity remained the highest in the Central Bay, while salinity was quite low particularly in the shallow water in San Pablo Bay. In the higher rainfall year (1997), the South Bay also experienced extremely low salinity.

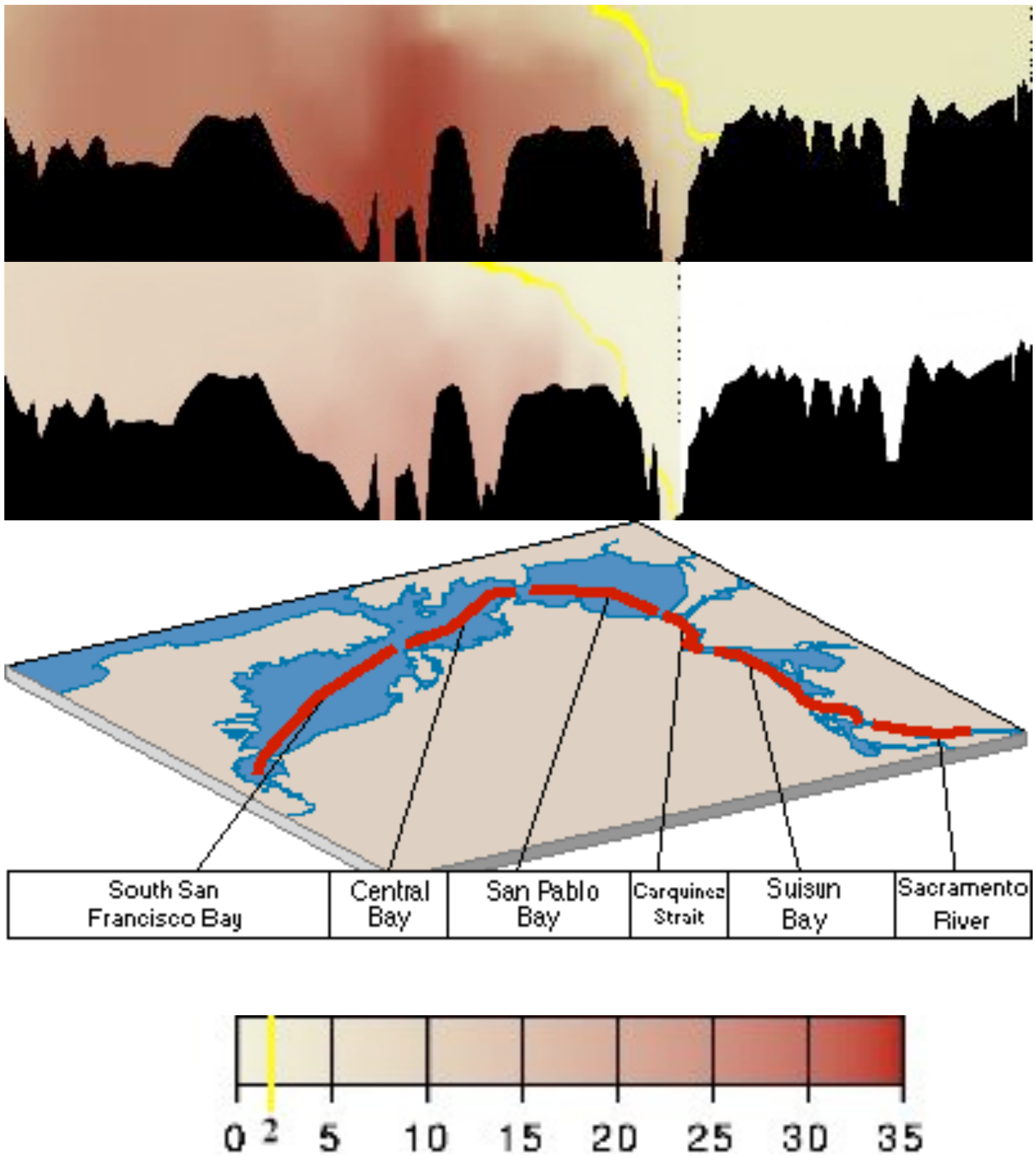


Figure 23: Salinity profile from San Francisco Bay USGS transect. Top plot shows salinity from January 13, 1997. Bottom plot shows salinity from March 15, 2006. Black shaded areas indicate bottom contour. Source: http://sfbay.wr.usgs.gov/access/wqdata/index.html

Other water quality parameters

Losses of oysters in Puget Sound have been attributed to contaminants, specifically sulfates, from paper mills in the area (Baker 1995). To our knowledge, no work has been done specifically testing native oysters for sensitivity to other forms of pollution, and anecdotal information is lacking as well. Oysters at the Marin Rod and Gun Club were tested for heavy metals by researchers at the Smithsonian Environmental Research Center in 2005 (Robert Abbott, pers. comm.). They were found to have particularly high levels of nickel and copper, and yet appeared to be healthy. This along with observations of apparently healthy native oysters in many contaminated areas of San Francisco Bay, including the Richmond shoreline, the area around Candlestick Park and the airport and many marinas, suggests they have fairly broad tolerances for chemical contaminants (Zabin, Attoe and Grosholz, personal observations).

We did not observe mass mortality of oysters following the Cosco Busan oil spill in November 2007 (Zabin, Attoe, personal observations), but subtler effects such as decreased resistance to disease, growth, reproduction and recruitment success were not adequately studied. Among the difficulties in ascertaining impacts on oysters and on intertidal organisms in general following this spill was the lack of long-term data sets over a sufficient spatial scale to have adequate control (non-impacted) sites and the inherently patchy nature of data such as recruitment and cover. This spill and the subsequent smaller spill in 2009 underscore the need for long-term monitoring. We have been unable to find published accounts of the effects of oil on Olympia oysters, so their sensitivity to this contaminant remains largely unknown. Further investigation into the effects of PAH's on oysters is needed.

Figure 24: An oyster at Ayala Cove, Angel Island covered in oil following the Cosco Busan spill in November 2007. Photo: Chela Zabin.

Barrett (1963) reported that native oysters are vulnerable to turbidity, but it is not clear whether the mechanism is interference with oyster feeding or sediment deposition that buries oysters (see Sedimentation below). Oysters in the Bay certainly appear to be able to live in highly turbid conditions.

Hypoxia can affect benthic invertebrate communities, but it is unknown what the tolerance of native oysters is for different oxygen levels. Oysters on portions of our recruitment collectors that have been buried in anoxic mud have died, but we know little more than this.

Sediment deposition

High levels of sediment deposition in the intertidal zone in some locations around the bay clearly limit native oysters. Although deposition rates in the intertidal zone have not been formally measured, recruitment surfaces, along with tagged oysters on cobbles, were buried by sand and mud at three of the long-term study sites where UC Davis researchers worked. The highest amount of sedimentation was recorded at San Francisco Aquatic Park, over 0.3 m of sand was deposited over a one-month period in the summer of 2007, as recruitment collectors with rebar of that height were completely buried (Figure 25). Some recruitment collectors were buried at the Point Orient site, along with tagged oysters that were lost and not found again until nearly a year later at Berkeley Marina and Point Orient. Where oysters were buried for short periods of time <1 month, many survived (Zabin & Attoe, pers. obs.). How long oysters can withstand burial is not known, but certainly oysters can not recruit to buried substrate.


Figure 25. A recruitment collector (cement paver attached to a piece of rebar) is buried by sand at San Francisco Aquatic Park. A second set of collectors was put out and subsequently buried.

Activities which increase sedimentation, such as dredging, waterfront construction and the creation of wakes by ferries, can be considered stressors to native oysters.

Hinchley et al (2006) tested the effect of sedimentation on juvenile *Crassostrea virginica*. They found that with low levels of overburden, or burial stress, for short time. *C. virginica* were highly tolerant to sedimentation, and it was assumed that the oysters switched to anaerobic metabolism. Anoxia tolerance in juvenile oysters is 6 days with 100% mortality at 7 days (Widdows et al 1989). High sedimentation resulting in burial for longer times would reduce recruitment and increase mortality in these oysters (MacKenzie 1983, Lenihan 1999).

In Elkhorn Slough, in Monterey County, the size of substrate settled on by native oysters has a negative correlation with deposition rates (Kerstin Wasson, pers. comm.) oysters recruit on small pieces of gravel and shell in portions of the slough in which fine sediment does not settle, in areas of high deposition, oysters are only found on large cobble and rip-rap.

While northern portions of the Bay have shifted from depositional to erosional systems as a whole, clearly sedimentation remains a factor for oysters.

Temperature Stress

Temperature stress is assumes to be critical to oyster survival. Oysters at sites with high temperatures, and little algal protection or long exposure periods have higher mortality rates. The best site for oyster recruitment changed from Berkeley (19.600 $\pm$ 3.326 oysters/collector) in the summer to Ferry Point (13.200 $\pm$ 3.200 oysters/collector) in the fall. This can be expected because summer temperatures in San Francisco Bay are typically milder than fall temperatures. Ferry Point has more algal cover to protect oysters from heat stress than Berkeley, thereby allowing for the survival of more juvenile oysters in the fall than Berkeley (1.800 $\pm$ 1.114 oysters/collector). Waves from wind and boats can negatively affect oyster presence (Blockley and Chapman 2008), but may positively affect presence when mortality due to thermal stress is critical (Dayton 1975, Menge 1978.

Summary

Our understanding of the potential of biotic factors to limit oyster populations is certainly not complete, however, it appears that the relative importance of these factors varies by location in San Francisco Bay. For example, drill predation on oysters did not appear to be affecting populations at any of the long-term intertidal study sites in the UC Davis study, but predation by drills especially on juvenile oysters was high at the Bair Island-Greco Island restoration sites. At the time of this writing, drills are primarily restricted to the South Bay. With the exception of Richardson Bay, only a few individuals of drills have been found north of the San Mateo Bridge.

Similarly, competition for settlement space did not appear to be a limiting factor at the UC Davis study sites, which are all intertidal. For most locations at most times, bare space was still available in the oyster zone. However, subtidal substrate at the Marin Rod and Gun Club becomes heavily fouled over time, with little room remaining for new oyster settlers within a few years.

Disease does not appear to be a limiting factor at this time in San Francisco Bay. Even at the sites where diseased animals were found, overall incidence is low.

Based on the work to date, it appears that three abiotic factors are important in the distribution and survival of native oysters in the bay. Several lines of evidence, from historic reports to recent field observations and laboratory experiments, indicate that oysters in San Francisco Bay are affected by periodic lowered salinity. While oysters may be able to extend their range into the northern part of the Bay and up into San Pablo Bay as well as into the sloughs of South Bay during dry years, it does not make sense to locate restoration projects far into these areas (ie north/east of China Camp and Point Pinole); although these would be ideal sites to carry out studies of oyster resistance and resilience to lowered salinity events. Although we recommend restoration projects over a greater area, particularly to take advantage of what appear to be larval retention zones to the north and south, as well as good community support for projects in these areas, we also suggest prioritizing projects in the Central Bay (~Oyster Point to Richmond); these populations could serve to help rebuild populations further north and south following flood years. Sedimentation of substrate and burial of both substrate and oysters also appears to be a major issue at least for some of sites studied in San Francisco Bay, although it is unknown at this time how long oysters can withstand burial and specific spatial and temporal patterns of sedimentation in the Bay are not known. Hard substrate also appears to be a limiting factor in some locations.

Research needs and recommendations

More detailed studies, including manipulative field studies are needed before the importance of factors such as predation, competition and food supply as potential limiting factors of native oyster populations can be fully understood. Such studies can make major contributions to the success of restoration projects. For example, even in locations where drill predation is evident, predation may not actually preclude successful restoration, but this is currently unknown. Conversely, drill populations might increase as oyster populations do, and predation might in time become a limiting factor. Increases to the distribution of oyster population through multiple and/or large-scale restoration projects could also serve to spread the drill further north.

Similarly, while disease is not a major factor at this point, its incidence might increase with an increase in oyster densities. These points underscore the need to continue to monitor oyster populations and associated fauna as restoration continues.

In addition to the above ideas, we have several specific research commendations with management implications:

1. Oyster drills

The prevalence of the drill in Richardson Bay is unknown. If the drill is present in only a few locations, an eradication attempt might be successful in reducing drill numbers and preventing or slowing the spread of the drill further north. Doing so may be critical to the future success of oyster restoration in the Central Bay.

2. Other predators

To date, predation studies have focused on oyster drills. Rays were major predators of oysters in the days when oysters were commercially farmed in San Francisco Bay. Crabs, both native and introduced species, may also be preying on oysters.

3. Competition for space

Fouling organisms are obscuring the substrate at the Marin Rod and Gun Club site. It may be feasible to clean the substrate with high pressure hoses; this ought to be tested.

4. Control of fouling organisms

Fouling organisms are not universally a problem at all locations. For example, shallow subtidal substrates in Tomales Bay stay relatively clean, as do intertidal substrates in San Francisco Bay. This suggests that factors such as periodic air exposure and/or the presence of grazing organisms can benefit restoration efforts. While it is likely not feasible to add grazing organisms to a restoration site adding features such as eelgrass might encourage the presence of grazers on oyster reef. These ideas ought to be tested more formally. In addition, despite lower recruitment and slower growth in the intertidal zone, it may make sense to locate some restoration projects intertidally to discourage some foulers.

5. Food supply

Differences in growth rates at different locations are suggestive of a difference in availability of food. This might be due to actual abundance of food items or to difference in currents delivering food. This connection should also be explored formally.

6. Sedimentation/burial by sediment

Burial by sediment for long enough periods of time may kill oysters, but sedimentation of settlement substrate certainly affects settlement in both existing populations and in restoration projects. Sedimentation rates in the oyster zone are clearly not the same everywhere in the bay (Attoe & Zabin, personal observations). Research on sediment dynamics should be a high priority. In addition, the relative sediment collection rates of different types and configurations of restoration substrate should be explored. We recommend that at the very least sediment traps, which can indicate potential substrate burial rates, be deployed for a year prior to the location of new oyster restoration projects.

7. Climate change-related research

Climate change as it relates to efforts to restore native oysters should also be a priority. Global climate change is likely to effect existing natural populations as well as attempts to restore native oysters. Specifically, more intense storm events are likely to result in greater amounts of sedimentation and longer periods of lowered salinity and thus higher rates of oyster mortality. It would be worth exploring whether some populations of native oysters are better adapted to lowered salinity than others and if so, to consider protecting or enhancing these populations. In addition, studies of the recolonization of these sites by oysters following low salinity events are important to understanding larval supply in the Bay and predicting return times following such disturbances.

Warmer air and water temperatures may affect oyster survival and reproduction. Little is known about the tolerance of native oysters to heat stress in field conditions in San Francisco Bay much less what might be done to mitigate it. Ocean acidification is also predicted to interfere with the ability of shell-building organisms to obtain calcium, slowing growth and perhaps interfering with larval development, but the specific effects of acidification on *Ostrea lurida* under different scenarios of pH change are not known. This ought to be explored and incorporated into planning for oyster restoration.

III. Ecosystem functions of oyster beds

An extensive search of the peer-reviewed scientific literature revealed virtually no studies on ecosystem functions of Olympia oysters. Eastern oysters (*Crassostrea virginica*) and other large oyster species have been studied much more extensively. Olympia oysters might be expected to play similar roles in West Coast estuaries, although many of the ascribed ecosystem functions are not likely to be significant when populations are low. Several key differences exist between Eastern oysters and Olympia oysters, including the significantly larger size of Eastern oysters and their ability to big large, three dimensional reefs. With these caveats in mind, we can draw on what is known about ecosystem functions of other oyster species to infer the ecosystem functions or potential ecosystem functions of Olympia oysters.

Oysters affect the ecosystem through their filter-feeding activities, deposition of feces and pseudofeces and the provision of three dimensional structure represented by their shells and by the reefs or beds formed by aggregates of oysters.

Research elsewhere has shown that oyster habitat degradation contributes to increased sedimentation and turbidity (Cooper and Brush 1993), increased hypoxia and anoxia (Elmgren 1989, Officer et al 1984, Cooper and Brush 1993), loss of seagrass beds (Orth and Moore 1983), change of primary production from benthic to planktonic (Cooper and Brush 1993), euthrophication (Elmgren 1989, Officer et al 1984, Nixon 1995), increase microbes (Jonas 1997), increase algal and dinoflagelate booms (Jonas 1997), increase jellies (Newell 1988), and fish kills (Buckholder et al 1992).

Filter-feeding

Through their filter feeding, oysters have been shown to improve water quality (Geritson et al. 1994, Brumbaugh et al 2000, Mann 2000), remove seston from the water column (Gerritson et al. 1994, Brumbaugh et al 2000, Mann 2000), reduce chlorophyll a concentrations (Dame et al 1984; Nelson et al 2004), increase water clarity (Lenihan 1999, Meyer and Townsend 2000), decrease the deposition of fine grained sediments, and decrease ammonium concentrations and TSS (Nelson et al 2004), and prevent hypoxia, harmful algal blooms, and parasitic diseases (Newell 1988, Jonas 1997, Jackson et al 2001).

In the past, reasons for oyster restoration on the East Coast were reduction of public health risks through improved water quality (Coen et al 2005). Oysters transfer material from the water column to the benthos. Decreased chlorophyll a levels downstream of oyster reefs are as high as 25% (Cressman et al 2003), 37.4% (Grizzle et al 2006), and 27.9% (Grizzle et al 2008).

Historical densities of oysters were so high as to filter the whole of Chesapeake Bay in 3.3 days compared to a current 325 days (Newell 1988).

Structure: physical and chemical effects

Through their structure-building function, oysters have been shown to alter hydrodynamic conditions (Nelson et al. 2004), provide erosion control (Meyer et al 1997), alter both physical and biological parameters (Lenihan 1999, Dame 1999, Dame et al. 2000, Mann 2000), and increase flow, larval retention, resuspension of seston, biodeposition, and particle settling rates (Haven and Morales-Alamo 1966, Dame 1999). Through shell-building, they sequester carbon in the form of calcium carbonate (Hargis and Haven 1999).

High velocity flows from high relief structures may negatively impact filtration and growth (Nelson et al 2004). This suggests that our very flat beds should have better survival than reefs, enhancing restoration.

Enhancement of benthic diversity

Oyster reefs are key marine habitats (Jackson et al. 2001). Reefs create biological diversity (Posey et al 1999, Brietburg et al. 2000). Oysters are responsible for higher densities of macro invertebrate species for crabs and predatory fish species than unstructured mud (Summerson and Peterson 1984, Lenihan and Peterson 1998). Macroinvertebrate density and species richness are positively correlated with structural complexity (Crowder and Cooper 1982, Diehl 1988, Diehl 1992). Enhanced habitat structure increases prey for crabs and predatory fish survival (Heck and Thomas 1981, Crowder and Cooper 1982, Schriver et al. 1995, Beukers and Jones 1997, Grabowski 2004). Oyster beds made of disarticuated shell (versus mud) increased resident fish, bivalve, and decapod crustacean populations (Plunket et al 2005).

While Olympia oysters do not make reefs, there is evidence that even small-scale physical structure increases biodiversity (Kimbro & Grosholz 2006). In Lousiana, as in San Francisco Bay, oysters are present in beds not reefs. Despite lacking this, oyster beds have been shown to be a valuable refuge and foraging habitat for fish and decapod crustaceans (Plunket et al 2005).

In San Francisco Bay, structure in the form of oyster restoration substrate has been anecdotally shown to enhance eelgrass recruitment, attract salmonids, and generally increase the numbers and diversity of fish species (R. Abbott, personal communication). Researchers involved with oyster restoration at the Marin Rod and Gun Club site in San Rafael have documented use of oyster shell as egg-laying substrate for herring and gobies.

Research needs and recommendations

Restoration of native oysters is considered a priority on the assumption that Olympia oysters play an important ecosystem role similar to that of better-studied oyster species elsewhere. However, reasonable goals and expectations for the outcome of restoration cannot be set with a better understanding of the current ecosystem functioning of these oysters in San Francisco Bay. We recommend lab and field experiments and carefully designed restoration projects as an approach to answering some of these key questions.

1. Oyster/eelgrass interactions

A critical issue for restoration of eelgrass -- another species for which restoration plans are underway -- and native oysters is that restoring one habitat may have impacts on the other. For example, putting out structures to encourage native oyster recruitment could reduce water flow, oyster filtering could decrease turbidity and the input of pseudofeces could influence nitrogen availability. Conversely, eelgrass restoration could also influence adjacent oyster beds by reducing water flow, increasing particulate detritus, etc. However, virtually nothing is known regarding the effects of one habitat on the other. And though virtually all current restoration projects involve a single species, multispecies restoration programs may be needed in the future so this information may be critical to future projects. Researchers at the Richardson Bay Audubon Center have already begun examining the effects of eelgrass on oyster recruitment. A comprehensive understanding of the reciprocal effects of eelgrass and native oysters on one another is needed and could be accomplished through a series of laboratory mesocosm and field experiments.

2. Oyster enhancement of habitat for species of interest such as herring and salmonids

Anecdotal evidence indicates that constructed oyster "reefs" in San Francisco Bay provide habitat for salmonids and egg-laying substrate for herring. At the time of this writing, two reefs have either been constructed or are being constructed for the combined purpose of enhancing oyster settlement and creating salmonid habitat. We recommend that future projects be designed in ways that specifically allow for experimental tests of the use of oyster reefs or beds by fish species.

3. Enhancement of biodiversity

Further studies on the effects of oysters and oyster-restoration structure on the diversity of invertebrates, algae, submerged aquatic vegetation and fish are needed. We recommend that all future restoration efforts incorporate measurements of diversity into their design (see Monitoring section, below).

4. Erosion control

On the East and Gulf coasts, oyster reefs historically played a role in estuarine hydrodynamic regimes, affecting currents, wave impacts, and sedimentation rates. On those coasts, oyster restoration has been incorporated into erosion-control projects. It is not clear whether or to what degree, Olympia oysters, which do not build large three-dimensional reefs, might serve the same function. However, the provision of structure for native oyster restoration *is* likely to alter flow and sediment movement. We recommend that future restoration projects be designed to test some of these ideas (see Monitoring section below).

5. Filtering capacity

Much has been made of the ability of oysters to improve water quality, but to our knowledge, no tests have been made of the filtering capacity of native oysters, or of what size particles they remove.

IV. State of current knowledge for five additional bivalve species in SF Bay

Mytilus californianus

Native to the west coast of the United States, the range of *Mytilus californianus* stretches from Baja California to the Aleutian Islands of Alaska. Predominantly located in the wave exposed rocky intertidal areas of the open coast, these mussels extend into central San Francisco Bay. Their distribution appears to be from eastern Tiburon peninsula to Angel Island, Alcatraz, and Yerba Buena Island. There have been no population or density studies within San Francisco Bay (Schaeffer et al. 2007).

M. californianus has been shown to provide many ecosystem services on exposed coasts. *M. californianus* beds are home to 300 species (Suckanek 1992). These beds have been shown to be stable in the long term (Paine 1974; Paine & Levin 1981). Pfister (2007) was able to show that *M. californianus* increases the available supply of inorganic nitrogen and phosphorus which directly increased primary productivity.

Smith (2006) suggests southern California *M. californianus* beds have decreased substantially in recent years and speculated that climate change, human visitation, and pollution may be causes for this decline. One method for the preservation of these beds is establishing a marine reserve with a “no take” regulation. Upon investigation, Smith (2008) suggests this may not be enough to preserve these crucial beds. No other studies were found detailing conservation methods.

Mytilus trossulus/galloprovincialis

Introduced into San Francisco Bay, *Mytilus galloprovincialis* and its native cousin, *Mytilus trossulus* were both reported as *Mytilus edulis* until the early 1990s. Before the discovery by McDonald and Koehn (1988) that there were actually two different species in California, all studies examined them as one. Since then *M. galloprovincialis* has been noted as one of the most widespread marine invaders, inhabiting coasts throughout the world (Lowe et al. 2000). In San Francisco Bay *M. galloprovincialis* and *M. trossulus* hybridize. An extensive literature and internet search turned up no information about the current population of *M. trossulus*, *M. galloprovincialis*, and their hybrids in San

Francisco Bay. These mussels (reported by their various current and previous names) are found from the northern part of the South Bay to the southern part of San Pablo Bay although there have been sightings near the Dumbarton Bridge, Port Sonoma, and Martinez (Hopkins 1986, Cohen & Chapman 2005, A.N. Cohen unpublished data). It has been observed that they range from intertidal to 40 m (Crowles 2005).

M. galloprovincialis/trossulus provide a variety of ecosystem services. They have been used as a bioindicator of toxins in San Francisco Bay for many years (Phillips 1988; Rasmussen 1994) as they have the ability to filter up to 340 L of water daily (Moles & Hale 2003) and bioaccumulate toxins. These mussels create extensive beds, providing large amounts of habitat and therefore biodiversity. *Mytilus* larvae are an important source of food for carnivorous zooplankton and herring larvae (Seed & Suchanek 1992). Also, bivalves are generally known to increase nutrient and organic carbon turnover (Dame 1996). Mussel beds also provide critical food sources for estuarine birds (Nehls & Thiel 1993).

M. galloprovincialis has had lasting and evolving effects on *M. trossulus* due to competition and hybridization. In San Francisco Bay *M. galloprovinicalis* outcompetes *M. trossulus* in sites with warmer water and with more consistent salinity (Geller 1999). A South African study suggests *M. galloprovincialis* typically grows faster, is more tolerant of air exposure, and has great reproductive output (Van Erkom Schurink & Griffiths 1993, Branch & Stephanni 2004).

Geukensia demissa

First collected in San Francisco Bay in 1894 (Stearns 1899), *Geukensia demissa* has been studied inconsistently and current information is hard to come by. De Groot reported in 1929 that *G. demissa* reached large densities, stating, "countless millions of these small mussels cover the edge and sometimes the entire bottoms of the gutters and creeks of the west Bay marshes." The mussel is commonly found in the lower salt marshes of San Francisco Bay, attached to cordgrass and other solid objects partially protruding from the mud. It has been reported from the Petaluma River in San Pablo Bay to the southern tip of South San Francisco Bay (Cohen 2005).

There has been very little contemporary research conducted on *G. demissa* in San Francisco Bay, making accurate abundance and distribution estimates impossible. Densities reported from other locations include up to 10,000 per square meter on the Atlantic coast (Puglisi 2008) and 0 to 35 per square meter in the Estero de Punta Banda, Baja California Norte, Mexico (Torchin et al. 2005).

As for impacts on native species, De Groot (1927) concluded that *G. demissa* is responsible for many deaths of the endangered clapper rail. While this interaction has been studied several times since, the results were less conclusive. In 1961 Kuenzler suggested that *G. demissa* can remove up to a third of the particulate phosphorus from suspension, depositing it on the mud surface, thereby effecting nutrient cycles in Atlantic salt marshes which would have inevitable effects on native species.

G. demissa is not perceived as pestiferous and there have not been any known control efforts, which many expect would be overwhelmingly difficult (J.T. Carlton, personal communication).

Mya arenaria

Since its introduction to San Francisco Bay circa 1870 (Carlton 1979), the distribution and abundance of *Mya arenaria* has varied widely. Throughout this time, individuals have been found from Collinsville, on the far northern coast of Suisun Bay, to the south shore of South San Francisco Bay (Cohen 2005). Data from a long term sampling location near the middle of San Pablo Bay that the California Department of Water Resources has been monitoring shows consistently low numbers of clams with the exception of two periods in the last 25 years. The first is in the mid-80s when densities reached 2,840 clams per square meter and the second is in the summers of 2000, 2001, and 2002 when densities reached 3,360 per square meter. Monthly sampling since then has produced low to no *M. arenaria*. Unpublished data from Janet Thompson of USGS for the South Bay shows a regular bloom of small individuals (1-2 cm) in June dropping to nearly zero during the winter throughout the 1990s. Currently she is seeing fewer than one 3-cm long individual at many sites in the South Bay.

Because of this annual and seasonal variation, plus its ability to live as deep as 30 cm below the surface, it is difficult to estimate population size. In the fall of 1999, Poulton et al (2004) found densities ranging from present but negligible to 119.7 individuals per square meter at six sites around San Pablo Bay. Using the same methods at the same sites, no *M. arenaria* were found in the spring of 2000. The Exotics Guide states densities from 100 to over 1000 per square meter in the greater San Francisco Bay (Cohen 2005).

The cause of this variation appears complex. One well-supported explanation of some of the variation in Suisun Bay following consecutive dry years is that *M. arenaria* larvae travel up stream from San Pablo Bay into Suisun Bay on the saline bottom current (Nichols 1985). Other speculations include predation, especially by birds (Thompson personal communication) and the impacts of fresh water input (Poulton et al. 2004).

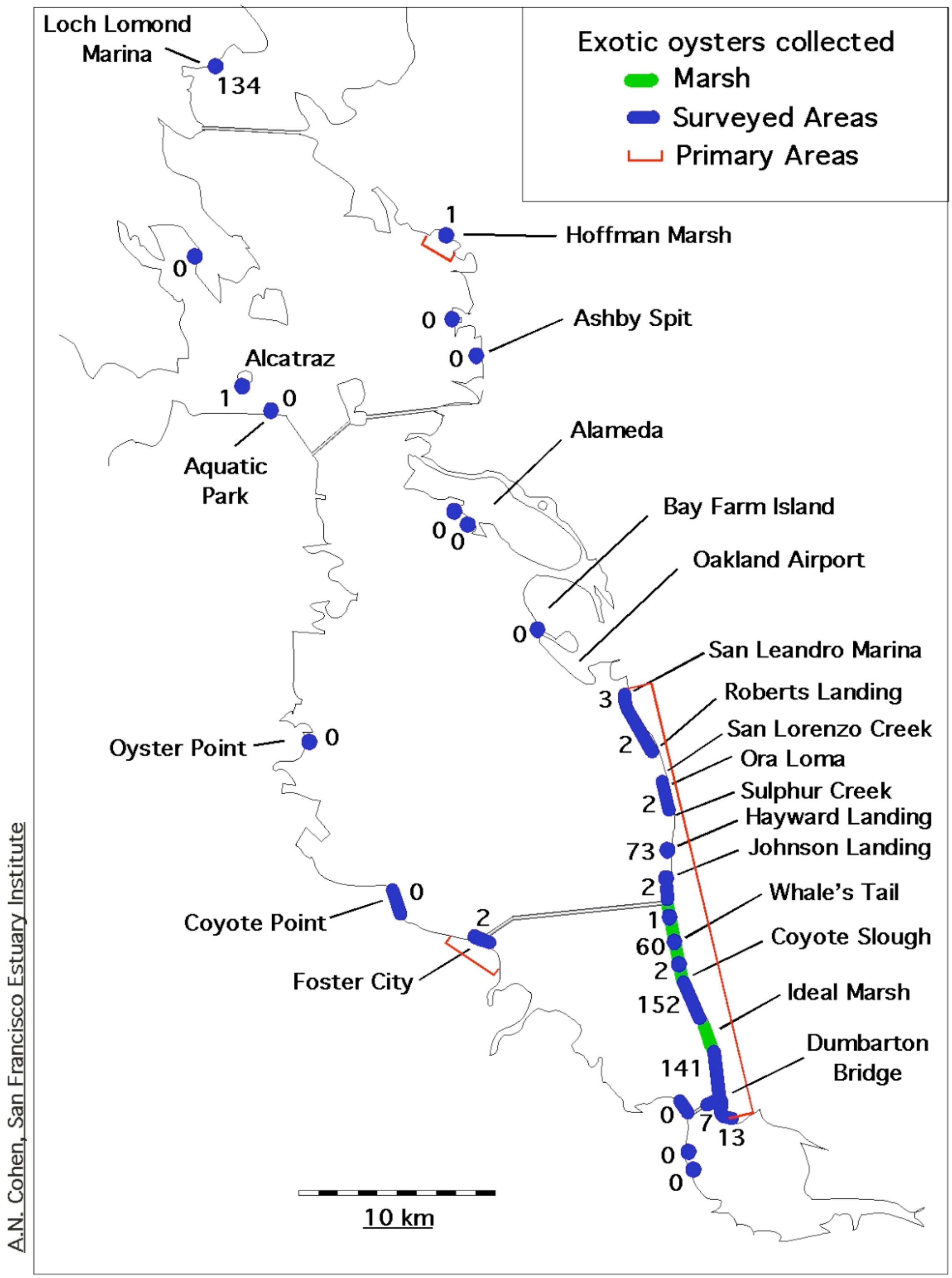
Upon arrival, *M. arenaria* had large impacts on the native clams, becoming the only form marketed by 1919 (Weymouth 1920).

We conducted an extensive literature review, but were unable to find information on control efforts for this bivalve. This may be because *M. arenaria* is not perceived as a problem species. The Department of Environment and Heritage, Australia by Commonwealth Scientific and industrial Research Organization marine Research has categorized *M. arenaria* as a ‘low priority’ (Hayes et al. 2005). The Prince William Sound Regional Citizens’ Advisory Counsel states “there are currently no effective eradication efforts in use for the Softshell Clam.” There’s a perception that such attempts would be unsuccessful (JT Carlton pers. comm.).

M. arenaria reportedly prefers areas with clean, fast-flowing water and is usually found from the upper intertidal zone to deep waters, 190 m beneath the surface ocean (Tyler-Walter 2003). It may be that conditions in San Francisco Bay are not consistently optimal for the clam.

Crassostrea gigas

Single individuals of the Pacific oyster *Crassostrea gigas* have been found in San Francisco Bay occasionally for several years (Andrew Chang, Jim Carlton, pers. comm.). In late July 2006, a population of these oysters was found near the Dumbarton Bridge by Rena Obernolte (identity subsequently confirmed by Andrew Cohen). Pacific oysters had been commercially grown in San Francisco Bay in the 1930s and tried again experimentally in 1981, but had never reproduced successfully in the Bay. However, these oysters have become nuisance species in Europe and in parts of the Pacific Northwest where they have been raised for many decades. The San Francisco Estuary Institute (SFEI) thus took the lead in an effort to remove this population. In an initial sweep in August 2006, some 250 large Pacific oysters were removed from hard substrate near Dumbarton Bridge (Cohen & Weinstein 2008). These oysters did not look like typical Pacific oysters and several dozen native oysters which also looked unusual were collected in this eradication effort. Molecular testing later confirmed that the large oysters were *C. gigas,* and the small oysters were *O. lurida.* Since this time, SFEI has continued to survey and collect large oysters over 70 mm (greater than the maximum size reported for *O. lurida*). To date, SFEI has collected more than 500 Pacific oysters from various sites around the Bay, not including oysters they removed from an illegal *C. gigas* planting north of the Loch Lomond Marina (Figure 26). SFEI had planned some genetic analysis work to attempt to trace the source of the Bay populations and has identified priority sites for survey. However, these plans have stalled due to funding cuts.



Note: One exotic oyster was collected at Vallejo, which is not shown on this map.

Figure 26. Sites surveyed by SFEI and number of exotic oysters collected. Used with permission.

Management recommendations for additional bivalve species

Of the bivalve species mentioned above, only two species are native to California. Of these, *Mytilus trossulus* is indistinguishable in the field from its non-native congenor and in fact hybridizes with it, making differential management efforts for these two species impossible at this time. We do not recommend management action for the other native, *Mytilus californianus,* as there is no indication that this species is in need of such action and every indication that San Francisco Bay is not prime habitat for this largely open-coast organism.

At this time, little is known about the potential impacts on native species and habitats of the non-native species *Guekensia demissa* and *Mya arenaria*. These organisms are well-established in the bay, making eradication efforts likely impossible, and we were unable to find any information about such attempts elsewhere. We recommend further research on interactions between these organisms and native species.

Crassostrea gigas, were it to become widespread in San Francisco Bay, poses perhaps the greatest risk to native oysters and oyster restoration efforts as both oysters. Finding additional funding for SFEI's efforts to monitor and remove this invasive oyster and to attempt to determine the possible source is of utmost importance.

V. Restoration techniques for native oysters

1. Substrate enhancement

Oysters require hard substrate to settle. Naturally occurring hard substrate has likely declined in most estuarine systems. Anthropogenic changes in hydrological regimes in have resulted in increased sedimentation, which increases the burial and loss of native hard substrata such as bivalve and gastropod shells and smaller pebbles and cobbles that wash into estuaries from rivers and streams. In addition, the decline of oyster populations itself has contributed to the loss of appropriate hard substrate. As oyster populations decrease, habitat for oysters, which includes both live oysters and empty shells, also decreases. When the rate of shell production does not exceed the rate of shell loss (through burial or deterioration), the result is the negative feedback loop elucidated by Mann and Powell (2007) which makes it increasingly difficult for populations to recover without substrate addition. In San Francisco Bay, in addition to likely loss of native hard substrate through increased sedimentation, natural rocky outcroppings were removed by the Army Corps of Engineers as navigation hazards (Chin et al. 2004). Many of the populations of native oysters found in San Francisco Bay today occur on manmade structures such as bridge supports, seawalls, tide gates and rip-rap. While it may be desirable to remove artificial hard substrate from the Bay for a number of environmental and aesthetic reasons, this needs to be balanced against the need to ensure that oyster populations do not suffer further from a decrease in appropriate substrate.

Based on our research, it appears that substrate enhancement is by far the most commonly used method of oyster restoration worldwide. Mann & Powell (2007) indicate that enhancement of oyster resources by the placement of hard substrate has been used since the Roman times. Substrate enhancement is clearly the method of choice where oyster populations appear to be limited by appropriate substrate and but by not by recruitment or other demographic factors. It is the least costly of the suite of methods available to restoration practitioners. With one exception, it is the only method that has been tried in San Francisco Bay to date.

Currently any hard substrate deployed in San Francisco Bay is considered “fill” and requires a permit from the San Francisco Bay Conservation and Development Commission (BCDC). Conditions of permits for current projects also require the eventual removal of such substrate, thus limiting the size, type and configuration and potential longevity of restoration substrate.

A wide variety of substrate types have been employed in restoration attempts worldwide. These include: Pacific oyster shell, other bivalve shell, tires, old concrete, pebbles and cobbles of various types, used porcelain bathroom fixtures, etc. The most widely accepted method is the use of cleaned oyster shell (= hash or cultch). On the West Coast cultch has generally come from farmed populations of Pacific oysters, as it is relatively available and as well as being a natural, biodegradable substrate readily settled on by native oysters. Bags, piles, or mounds of oyster shell also create interstitial space which can provide a refuge for young oysters from heat stress and predation as well as provide living space for other organisms. Here we review the use of various substrate types and configurations in restoration projects in San Francisco Bay and elsewhere.

Pacific oyster shell

Cleaned and dried Pacific oyster shell has been the main material used in oyster restoration and in oyster recruitment research in San Francisco Bay. Most of the shell used in the Bay has come from Washington State, purchased by the NOAA Restoration Center. More recently, shell from Drakes Estero has been donated by oyster grower Kevin Lunny (see Table 1 in Cohen & Zabin 2009 for further details). Shells placed in mesh bags have been used for restoration purposes at two locations: Bair Island/Greco Island (near Redwood City) and the Marin Rod and Gun Club (in San Rafael). Loose shell piled in rows has also been tried at Marin Rod and Gun Club. Other shell configurations have included shell “necklaces” (shells strung on string and suspended from docks or piers), shell “stakes” (shells affixed to wooden stakes), and small hanging shell bags. These three configurations are most useful in small-scale experiments to measure recruitment and growth but are not feasible for large-scale restoration projects.

San Francisco Bay

Bair Island and Greco Island pilot restoration projects

These two sites were selected based on their historical importance as oyster culturing sites. There were scattered native oyster shells at both sites, but no live oysters were found. The Bair Island site was located on the mudflats north of the Port of Redwood

City shipping channel at a depth of approximately -2.0 ft at mean low low water (MLLW). The Greco Island site was located on the mudflats south of the Port of Redwood City shipping channel at a depth of approximately -3.0 ft at MLLW.

In 2005, bags of Pacific oyster shell were placed on two wooden pallets at each site. Small monitoring bags were hung from PVC at each site. Seeded bags from Shoreline Sailing Lake were placed at each site in Sept 2005 (see "Seeding" section for more details). In 2006, two additional pallets were placed next to the 2005 pallets, to create a row of four pallets and new frames and monitoring bags were added. Ten bags of Pacific oyster shell were stacked in a pyramid on each. The cultch bags were tied together and to the pallets with long cable ties. The pallets were attached to the bottom with two iron bars sunk 3 feet into the mud.

Pallets from 2005 completely disintegrated by fall 2006 due to shipworms.

Once a month, one of the bags of shells was removed to quantify spat settlement and the presence of potential space competitors. Additionally, each month two new bags were added and one of the previous month's bags was removed to quantify settlement over the previous month. This allowed for the measurement of cumulative and monthly recruitment. Monthly samples of about 24 shells were removed from the large cultch bags attached to the pallets in 2005. All pallet bags from 2005 and 2006 were sampled in November 2006. Bair Island overall did better than Greco Island in terms of predation from oyster drills and numbers of oyster settlers.

In 2006, recruitment in the "cumulative" monthly bags spat negligible before August, reaching high of 7 per shell in November. Recruitment to the "monthly" bags occurred from May on with rates highest in June and July (~8 per shell) dropping off to zero after September.

Marin Rod and Gun Club

The project at the Marin Rod and Gun Club in San Rafael is in its fourth year of existence. In 2005, 10 bags of Pacific oyster shell clutch were stacked in a pyramid shape on top of wooden loading pallets. Eight such pallet and pyramid configurations were deployed in two rows at -2.5 and -3.4 feet. At the end of 2008, these pallets were still in good shape. In June 2006, three 75-foot long reef rows were set up parallel to shore at three depths (~0, -2 ft and -4 ft below MLLW) separated by 6 feet. One-third of each row consisted of loose oyster shell in an elongated mound; the rest stacked cultch bags anchored with rebar hooks. Within 6 months, the loose shell was becoming scattered and buried by sediment, while the bagged shell was still stable. Average set rate on the reef rows was 3.4 spat per shell. In 2007, shell was stacked into 26 mounds made up of 30-35 bags and held in place with rebar hooks at -2.5 ft. Four rows running parallel to and in between the most shoreward reef row and the middle reef row. Average set rate on these mounds was 13.8 spat per shell. In 2008, an additional 18 mounds were added. Average set rate was 7 spat per shell.

Figure 27. Constructing a “reef” using bagged Pacific oyster shells at the Marin Rod and Gun Club, San Rafael. Top: Robert “Bud” Abbott and Rena Obernolte bend rebar, which will be used to stabilize the bagged shell. Bottom: Bagged shell is moved to the site on a boat and lowered into the water where it is stacked and tied in place.

Table 6. Summary of restoration projects using Pacific oyster shell as substrate enhancement in SF Bay.

Location	Marin Rod & Gun Club	Bair Island & Greco Island
Year	2005, 2006, 2007, 2008	2005, 2006
Substrate tried	Pacific oyster shell	Pacific oyster shell
Configuration	2005: 8 10-bag pyramids in two rows parallel to shore; 2006: 10-bag pyramids and Lincoln-log stacks on wooden pallets and rows of loose shells, laid out in three 75-foot rows parallel to shore; 2007: 26 "reefs" (mounds of 30-35 bags) in between the first and second row created in 2006; 2008: 18 reefs and 4 reef balls (~2.5 ft diameter) on pallets. Reef ball cement 80% ingredients from SF Bay	Per site: 2 10-bag pyramids on wooden pallets; 2 more added in 2006
Depths	2005: -2.5, -3.5 ft 2006: 0, -2 and -4 ft 2007: -2.5 ft 2008: -2.0 ft	-2 and -3 ft
Monitoring method(s)	Shells collected ~monthly from stakes, strings and bags, by 2008: ~quarterly checks of bags. These were all cumulative counts.	Shells collected monthly from small hanging bags some of which were 1) retrieved with replacement monthly to examine monthly set rates and 2) set out at beginning of recruitment season and allowed to accumulate spat to examine monthly cumulative settlement. Shells from pallet also retrieved and checked monthly.
Spat observations	Ave spat settlement 2005-2006: approx 3 per shell, including those from strings, which had fewer	More settlement and greater survival at Bair Island. Mean cumulative settlement per shell in

	than those in bags. 2007: 13 per shell 2008: 7 per shell; reef balls deployed after recruitment season	2006: 7. Predation by drills higher in southern site.
Structural observations	Wooden pallets from 2005 still in good shape in 2008; loose shell rapidly lost to currents and burial	Wooden pallets disintegrated within 1 ½ years
Other observations	Heavy cover of encrusting organisms on shell strings	Heavy cover of hydroids at Bair Island; heavy cover of sponges at Greco

Other West Coast projects

Tomales Bay, CA

In 2003, a pilot oyster restoration project was established at Tomasini Point by researchers at UC Davis. Two sites were established, each of which had two sublocations. Four mounds of Pacific oyster shell in mesh bags were placed at each sublocation. The bags were stacked in a pyramid formation on 2 x 2 m wooden pallets. The project was monitored monthly until 2005. Each month, two bags were removed from each pallet and all shells were checked for spat. Recruitment was low initially, but then fell off completely following heavy settlement by barnacles and other fouling species.

Humboldt Bay, CA

The southern portion of Humboldt Bay is a designated oyster preserve, but few restoration activities have occurred there. In 2005 David Couch (Couch, pers. comm.) placed rock and bagged cultch shell on pallets over 3-4 acres, but had no settlement, so this method could not be evaluated.

TNC Puget Sound

Loose Pacific oyster shell has been used in a number of oyster and habitat restoration projects elsewhere along the West Coast, including several locations in Puget Sound, where The Nature Conservancy's efforts are focused on enhancing habitat. These habitat enhancement projects have been conducted at Liberty Bay, Dogfish Bay, Woodard Bay, Frye Cove, Fidalgo Bay and Raab's Lagoon, among others. Bags are being specifically avoided because they are not biodegradable. Recruitment has been much higher where there is a higher source population, but even at sites with very small populations recruitment has occurred (Betsy Lyons, pers. comm.). It is unknown what the life of the loose shell is in these locations.

Grays Harbor

In Grays Harbor 1991, loose oyster shell was placed on mudflats as habitat enhancement for Dungeness crabs (*Cancer magister*). Shell was laid down in 30 by 30 m plots with a thickness of 15 cm. Most of these plots were lost due to burial or sinkage within a few months (Armstrong et al. 1992).

East Coast loose shell

Burial and loss of loose shell has also been noted in numerous restoration projects on the East Coast (Bartol & Mann 1997). To compensate for this loss, restoration professionals are using thicker layers of shell. For example, in Chesapeake Bay, the Virginia Marine Resource Commission constructed a 210 by 30 m intertidal reef consisting of numerous hummocks, some of which rose 3 meters from the estuary floor. The hummocks were exposed at MLLW and varied from 2 to 20 square m. These were constructed using a high pressure water cannon to shoot shells into the water from barges. The reef remained intact and attracted oyster spat for the two years it was monitored (Bartol & Mann 1997).

Shell Research Needs

Oyster shell that is taken from one bay and placed in another or taken from one location and placed in a second location within the same bay has the potential to transport non-native species, including pathogens. Most states require that shell that is to be deployed in a bay other than where it originated sit above the high tide level for some period of time. Such regulations have typically been set with the aim of preventing the spread of specific organisms (Cohen & Zabin, 2009). Experimental testing of the ability of a broad suite of organisms to withstand air exposure needs to be done in order to determine safe drying times; this is likely to vary between geographic locations and within a given location in a shell pile.

Further research also needs to be done to understand the rate of loss of shell placed in San Francisco Bay for oyster restoration and methods for reducing such loss. The rate at which shells are buried by sediments or otherwise destroyed in the bay is likely to vary both spatially and temporally. These data are needed to determine whether oyster restoration projects employing shell will be sustainable in the long term. At the very least, we recommend the deployment of sediment traps for at least one year prior to considering a site for restoration.

Surprisingly, despite the long history of shell deployment for oyster restoration projects on the East Coast, no work has been done to date on shell loss rates. Powell & Klink (2007) argue that habitat enhancement with there shell is not sustainable: rates of shell production are far outpaced by the loss of shell to burial, dissolution by boring sponges and sulfide-rich soils, oyster harvesting, and disease-caused mortality. In fact, Mann & Powell (2007) argue that restoration goals for Eastern oysters are not being met and are likely to be. While some of the issues they raise are relevant in San Francisco Bay, the situation here differs in two major aspects: native oysters are not harvested and disease is minimal.

Reef balls

Reef balls, dome-shaped cement structures, have been used in a wide variety of coastal restoration projects. The "balls" are hollow inside and have round openings like a Whiffleball. Molds for the balls are produced by the nonprofit organization Reef Ball Foundation and are available in a variety of sizes. Over the past decade, they have been used for shoreline stabilization, and oyster, mangrove and coral reef restoration. Here we outline a few of the projects that have employed reef balls.

San Francisco Bay

In the fall of 2008, 4 2.5 ft diameter reef balls at the Marin Rod and Gun Club site were deployed. The balls were created from a cement mixture using native oyster shell powder and sand dredged from San Francisco Bay; native material made up 80 percent of the mixture. Four additional reef balls will be deployed at the Rod and Gun Club site and at a new site in Berkeley in 2009 (R. Abbott, personal communication). The cement mix will be made up 100 percent native materials this year. The balls were set out after the recruitment season, so their success as recruitment collectors at Marin Rod and Gun Club is unknown.

East and Gulf Coast projects

Reef balls have been used in a number of projects involving Eastern oysters. In some cases, the balls have been seeded with juvenile oysters in aquaculture facilities. In many instances reef balls are deployed for oyster restoration as part of bigger "living shoreline" projects (see below). We were unable to find evaluations of projects using reef balls in the scientific literature. The following examples, which are included to give a sense of the scope at which reef balls are being used, are from the Reef Ball Foundation's website and from conversations with people who have used reef balls.

Memorial Stadium Oyster Reef Sanctuary

In 2002 14 reef balls were seeded with oysters in a culture facility and placed in the upper Chesapeake as part of a 6-acre oyster reef sanctuary within the ~40-acre Memorial Stadium Sanctuary, along with 10,000 cubic yards of rubble. Since then, dozens of reef balls have been added yearly to the sanctuary by a salt-water fishing club and local school groups. Growth of oysters on the balls is being monitored by volunteer divers from a scuba club.

NOAA Restoration Center, Anapolis, MD

In conjunction with the Chesapeake Bay Foundation and a number of other community-based organizations, has been using Reef Balls in restoration projects in the Chesapeake

Bay for eight years. NOAA has deployed both seeded and unseeded balls. Oysters do well on the balls that have been seeded; but spatfall has been low on unseeded balls, due to low salinities and low recruitment rates at the restoration sites (Rich Takacs, NOAA, personal communication 2009). A Nature Conservancy project near on the Virginia coast (Smith Island), where salinities are higher, has had good natural spatfall (TNC: Restoring the Native Eastern Oyster: http://www.nature.org/initiatives/marine/files/va_smith_is_oyster_april_2008.pdf), so it's clear oysters will settle on reef balls. At the NOAA sites, there has been no evidence to date of an increase in local recruitment due to the presence of large healthy oysters on reef balls; Takacs believes conditions don't favor the retention of larvae at local sites. However, the balls are colonized by mussels and other fouling organisms and have high value as fish habitat, according to Takacs. While they have not used balls for shoreline stabilization, Takacs says reef balls definitely dissipate wave energy.

NOAA has primarily used two sizes: "low pro" and "bay balls," which are about 2 feet high, 3 ft diameter at the base and 3 feet high, 4 ft diameter at the base, respectively. Even smaller balls "oyster" balls which are 1.5 ft in diameter and 1 ft high are available (Reef Ball Foundation) for use in settings where an even lower profile is desired. NOAA has avoided placing the balls on soft sediment, setting them down on either sandy or shell-covered bottoms. Wooden pallets have also been used to help keep the balls from burial/sinkage. They have also used reef balls primarily in subtidal habitats (4-20 feet below MLLW). They have been using lift bags to raise the balls for monitoring purposes as low visibility makes working underwater unfeasible. NOAA has also successfully used "fish havens," which are pyramid-shaped cement and rebar reef-building structures and got good oyster spatfall during a high-salinity period. One advantage of reef balls over fish havens is that community groups can produce the reef balls once the molds are purchased; fish havens are sold fully manufactured.

Tampa Bay

Tampa Bay used in living shoreline projects (see below).

Reef Ball Research Needs

Reef balls placed in the subtidal will be more difficult to monitor than shell bags. In San Francisco Bay turbidity prevents accurate underwater counts on reef balls. Bringing a 300-pound reef ball to the surface for monthly spat counts is unfeasible. R. Abbott (pers. comm.) is exploring the feasibility of making small sampling plates of the same material as the reef balls. The plates will be attached to the balls upon deployment, and would be removable. Divers could retrieve and redeploy plates, which would be used to estimate spat settlement on the reef ball. The longevity of reef balls made with SF Bay materials is also unknown.

Other substrate

Other substrate types have been tried in a variety of locations on the Atlantic and Gulf coasts, in part because supplies of shell are running low.

Nelson et al (2004) created PVC frames with hardware cloth bottoms to reduce subsidence to create oyster reefs. This was a small scale experiment to see if reefs provided more habitat than mud, but would be a potential restoration technique.

O'Beirn et al. (2000) explored the feasibility of using clam shells and coal ash pellets as substrate and compared settlement and survivorship on these substrates to oyster shell near Fisherman's Island, Virginia at the mouth of the Chesapeake. Survival on oyster shell was higher than on the other two types of substrate. They concluded that the greater amount of interstitial space provided by the oyster shell was key to the survival of settled spat.

Soniat and Burton (2005) compared recruitment to quartzitic sandstone and to siliceous limestone, placing ~1 in diameter rocks of each type into mesh bags and setting these out in the field in South Sister, North Sister and Bay Junop in Terrebonne Parish, LA. Bags were placed in two locations which varied both in salinity and in larval abundance. Recruitment was significantly higher to the limestone rocks. As the texture of the two types of rock is similar, they concluded that the chemical makeup of the rocks, particularly the presence of calcium carbonate, may have been an important factor in oyster settlement rates.

Rocks, both seeded and unseeded, are frequently a part of living shore line construction (see below).

Other Substrate Research Needs

Rock type is one of the factors that seem to be important in the selection of substrate by competent larvae and/or survival of recruits in a number of benthic organisms. Further research on oyster settlement and survival rates across different rock types needs to be done if rock is to be considered for substrate enhancement. Rock size is also important. Small rocks are likely to be lost to burial or removed by waves and currents, just as shells are. In places with low sedimentation rates, smaller rocks are potentially useable substrate for oysters (Wasson, in press); rocks will have to be larger in locations with higher amounts of sedimentation. Optimal rock size thus needs to be determined on a site by site basis.

Living shorelines

Living shorelines use a suite of techniques to achieve bank stabilization, slow coastal erosion and restore habitat. The methods employed vary by habitat type, but typically include combinations of soft and hard elements. Soft elements include terrestrial vegetation, submerged aquatic vegetation, "biologs," which are made of coconut fiber held together with netting. Hard elements include sand and low-profile hard structures such as rocks, low stone groins and "living breakwaters" for oysters to live on. Such breakwaters have been constructed with marl limestone, granite and reef balls. Construction of living shorelines typically involves regarding a shoreline area to create a soft slope, removing debris, replanting with coastal/riparian plants and/or submerged aquatic vegetation and the addition of soft and hard materials.

NOAA has been involved for many years in living shoreline projects and has a grant program specifically aimed at the creation of living shoreline. More information about living shorelines and NOAA's program is available on the agency's website (http://habitat/noaa.gov/restorationtechniques/public/shoreline_tab1.cfm).

To date, it appears that most living shoreline projects have been done on the East and Gulf coasts. NOAA lists 20 such projects in the Chesapeake Bay, 16 along the North Carolina shore, 16 in Florida and 10 in states on the Gulf of Mexico. We highlight three projects that featured oyster restoration as part of their living shoreline project.

Fantasy Island, Tampa Bay

Fantasy Island is an artificial island that was starting to erode. A living shoreline project that ran from 2001 to 2002 was set up there as erosion control and habitat enhancement. The project involved the planting of 7000 plugs of salt marsh grasses, the deposition of 12 cubic yards of loose oyster shell and the placement of reef balls. The shell was piled over 144 linear feet to a height of 18 inches; reef balls were 2 feet in diameter and 18 inches tall. The shell piles scattered fairly rapidly, although continued to provide some living space for oysters and other mobile organisms. The reef balls maintained their integrity, and within 2 years were covered with adult oysters.

MacDill Airforce Base Salt Marsh and Oyster Restoration, Tampa Bay

At this site, in 2004, 4.1 acres of oyster habitat were restored using 910 oyster domes and 25 tons of oyster shell plant in mesh bags. Another acre of marsh was restored with the planting of 5,000 plugs of marsh grass.

Figures 28 and 29. Top: reef balls at low tide. Bottom: three months after deployment. NOAA photos.

Green Shores Oyster Reef and Salt Marsh, Florida (Gulf Coast)

The goals of this two-part project were to restore 3 acres of oyster reef, improve water quality, and protect 12 acres of salt marsh and submerged aquatic vegetation. In 2001-2002 three acres of oyster habitat were enhanced with the addition of limestone rock. Shell necklaces were hung in other locations in the bay until they were seeded with oysters. These were then added to the newly created habitat. In 2003 and 2005, 5 acres of salt marsh and seagrass were planted and 7 additional acres of oyster habitat were set up.

2. Seeding

Seeding of hard substrate, in particular clutch, has been widely used in oyster restoration projects. In Chesapeake Bay, the Oyster Recovery Partnership has planted over 1 billion spat on cultch in the bay. Seeding is typically used when natural recruitment is absent or low, or in locations where disease is a major issue (i.e. Milbury et al 2004), to stock an area with disease-resistant individuals. Other reasons to consider seeding include letting oysters grow out to a size that is less vulnerable to predation or to space competition/smothering by other sessile organisms or to more rapidly build a population.

Seeding can be done in a laboratory or aquaculture facility or by deploying substrate in a location with high natural recruitment and then transferring the seeded substrate to the restoration area.

One of the concerns with seeding is the potential loss of genetic diversity if the number of individuals being used for brood stock is too low or has low genetic diversity for other reasons. In most locations, including San Francisco Bay, little is known about the population structure of existing populations. Within a bay and certainly between bays it is possible that oysters are adapted to local conditions.

Although the degree to which oyster populations are adapted to local conditions is unknown at this point, there are new data regarding levels of genetic differentiation among native oyster populations in San Francisco Bay. These most recent data (M. Camara and D. Stick, Oregon State University, unpubl. data) using DNA extracted from a small number of populations with modest sample sizes shows some evidence of population genetic structure (hence differentiation) within the bay based on Fst values. Sailing Lake is significantly different from all other sites within the bay, South Bay sites (Candlestick and Redwood City) are not significantly different from each other, and there are slight but nonsignificant difference between the South Bay sites and the North Bay site Pt. Orient. At this point, assuming little or no inbreeding depression (this has not be investigated) or local adaptation, the recommended approach would be to use oysters from the local site to produce seed for restoration plots. But additional study of these issues should be a high priority.

Another concern with the use of seeded substrate is the spread of disease. Disease incidence can be highly localized; thus the movement of spat within a bay could potentially transport pathogens to disease-free locations.

To deal with these issues, restoration practitioners generally try to use broodstock from locations near where spat are to be redeployed, if this is possible (Peter-Contesse & Peabody 2005).

San Francisco Bay

To our knowledge, there has been only one example of seeding for restoration purposes in San Francisco Bay. In 2005, 14 bags of Pacific oyster cultch were hung in the Shoreline Sailing Lake, a tide controlled artificial “lake” near Redwood City. Abundant oyster populations had been found at Shoreline Sailing Lake earlier. The bags were set out a 3 tidal heights (1, 2.5 and 4 m below the surface) in July. Six weeks later, 4 seeded bags were then placed at the restoration sites at Bair Island and Greco Island and 4 at the Marin Rod and Gun Club. The seeded oysters grew out successfully. While sample size was too small for statistical tests, there were twice as many oysters at the end of the year on bags that had been seeded compared to non-seeded bags.

Oysters in Sailing Lake were examined for disease and found to be disease-free prior to being moved to the restoration sites.

Other locations on the West Coast

Netarts Bay, Oregon

The Nature Conservancy, in partnership with several other agencies studied the reestablishment of Olympia oysters and the effect on the restoration of eelgrass in Netarts Bay, Oregon. Various densities of seeded cultch were outplanted into different eelgrass treatments. In 2005, 5 million larvae were outplanted; 8 million in 2006 and 13 million in 2007. Oysters grew and reproduced. The medium cultch treatment experienced the highest oyster density with the lowest eel grass destruction (Archer, 2008).

Washington State

Currently, hatchery seeding of oysters is no longer allowed in the state of Washington, due to concerns over maintaining genetic diversity of different subpopulations. Seeding is allowed when seed is captured from natural set and moved within the same inlet. The Restoration Fund in Puget Sound is working with WDFW to develop protocols that will allow for the production of multiple family crossing in order to supplement wild seed to be spread within the inlet from which the brooding oysters were collected (B. Peabody, pers. comm.).

Previously, oyster restoration in Washington State included seeding, and millions of cultured spat have been deployed as part of restoration efforts. The Olympia Oyster Restoration Project, beginning in 1999 in Puget Sound, seeded more than 5 million oysters at 80 experimental sites. Sites include: Brownsville, Dogfish Bay, Poulsbo, Discovery Bay, Sandy Hood, Lemolo Shore, Belfair State Park.

A partnership of non profits has been planting seeded cultch in Fidalgo Bay since 2002. The current strategy in Fidalgo Bay was to enhance settlement where there is limited structure but adequate recruitment, outplant natural set at nearby locations, and where natural set is not available, produce genetically diverse seed to outplant (B. Peabody, pers. comm.). Survival and growth for these projects have been good, with the emergences of a sustainable bed (spawning and natural recruitment) at least one site. Loose shell has been continually added for additional substrate. There are plans to outplant new seed, which may or may not occur based on seeding restrictions (Paul Dinnel, pers. comm.).

East Coast

Brumbaugh et al. 2000 involved high and middle school students in grow out of brood stock oysters in Great Wicomico River in the Cheasapeake. They placed 65,000 hatchery reared oysters placed in floating cages and kept in cages from spring to summer. Students then transplanted them onto constructed reefs. Spatfall over the reefs had increased by order of magnitude from the previous year and was higher than nearby reference reefs. Additionally, larval abundance over the artificial reef was several orders of magnitude higher than any recorded in Virginia subestuaries in the previous three decades (Southward & Mann 1998). Drifters released near the reef suggested that there was strong local retention of larvae at the artificial reef.

3. Addition of broodstock to restored oyster reefs

This method involves adding adult oysters from one location to a restoration site to increase reproductive output. In San Francisco Bay this would have to be done with lab-reared oysters, as there few easily-moveable adult oysters at any given location to use to enhance another.

VI. Recommendations for native oyster restoration

Introduction

Critical gaps remain in our understanding of the factors that limit native oysters in the Bay, in best restoration methods and in the ecological role they once played in the Bay and the role they may be able to play in a Bay that will continue to change in ways that are unpredictable. The San Francisco Bay Area is not unique in this: that restoration projects elsewhere have moved forward faster than the theoretical and conceptual bases that support them has been noted by many others (i.e., Allen et al. 1997, Palmer et al. 1997). Our best hope is to use good experimental design in establishing projects and monitor these appropriately so that we can learn from failures as well as successes.

In moving forward with plans for oyster restoration, we are working under the assumption that native oysters can provide important ecosystem services to the Bay, among those the provision of a native habitat type that is important to a community of invertebrates and to fish. Along with the restoration of another critical habitat type, eel grass (*Zostera marina*), we expect that these restoration projects will enhance the Bay in a number of important ways.

Based on the current state of knowledge, our general recommendations are to:

1. Take steps to protect existing oyster populations, particularly the higher density, persistent populations of the Central Bay.
2. Survey portions of the Bay that have not received thorough study, including lagoons and other entrained water bodies, such as Lake Merritt, which might serve as refuges for oysters, and protect and/or enhance these areas if warranted
3. Proceed with restoration projects in a stepwise fashion based on level of knowledge at a given site
4. Locate oyster restoration projects primarily in Central Bay where salinity fluctuations are not as extreme
5. Continue to experiment with substrate type and configuration and integrate oyster restoration projects into larger habitat restoration projects where feasible

6. Include seeding as a restoration technique where recruitment levels are low, or where it may be advantageous in terms of predation and/or competition to deploy oysters at larger sizes.

Adaptive management will be needed, considering the level of unknowns, including the effects of several aspects of global climate change such as ocean acidification, sea level rise, and increases in storm severity. While our recommendations focus on specific segments in the Bay, steps that can be taken on a watershed level to reduce erosion, sediment flow and freshwater run off into the Bay will improve conditions for oysters.

Strategy for research and restoration

Organizational needs

We strongly recommend that native oyster research and restoration projects in the Bay proceed in a collaborative manner, with information generated by these projects shared among those involved and interested members of the community. This is already happening to a great extent through the San Francisco Bay Native Oyster Working Group (SFBNOWG), an informal group of restoration practitioners, academic researchers, agency personnel and non-profit conservation and community outreach groups. The SFBNOWG would be more effective if it had a permanent paid staff person who could organize meetings, distribute information among members, collect, store, and analyze data collected by group members, create a website for members and the public, and find funding for research and restoration projects. This level of organizational work is now being done by group members who are already stressed for time and funding. Undoubtedly, potential funding opportunities are being overlooked as a result.

Incorporation of oyster restoration into existing enhancement/restoration projects

Wherever feasible, we recommend incorporating oyster restoration into projects that seek to restore habitat for other bay organisms. We believe such an approach will attract funding sources, be more cost-efficient than restoring separately, potentially have synergistic positive effects on greater numbers of native species, and improve coordination among the various organizations working to improve habitats in San Francisco Bay. In particular, we strongly recommend the integration of oysters into a living shoreline approach to erosion control and shoreline protection.

Involvement of the public in oyster restoration projects

Public support is critical for the success of extensive restoration projects we envision. This is true at every level, from political support for needed funding, to the permitting process, to working out potential user conflicts. Most restoration projects also rely heavily on volunteers to construct oyster “reefs” and to monitor recruitment rates and growth.

Figure 29: Volunteers monitoring oyster settlement and growth at Marin Rod and Gun Club.

We recommend increasing public awareness of native oysters in several ways;

1. through the creation of a website that would feature information on native oysters and projects in San Francisco Bay and would include a listing of volunteer opportunities
2. encouraging/assisting local aquariums, nature centers and museums to include native oysters in their exhibits, along with interpretive information about the history of oysters in San Francisco Bay, their likely ecosystem services and current restoration efforts;
3. writing curricula that could be used in local schools and/or community-based environmental groups and involving such groups in oyster restoration and/or research projects; and
4. creative collaborations, which might include ideas such as working with artists who would create sculptures that could be used for oyster recruitment substrate and seafood focused cookoffs with local chefs.

Design projects to meet research needs

Many funding agencies are looking for projects that can meet acreage goals; there is significantly less funding for basic research and for monitoring. We believe that it is possible to design restoration projects to answer critical questions that will increase our understanding of the biology and ecology native oysters and thus guide future restoration projects (see Goal #8 and Table 7 below).

Oyster restoration goals

While each restoration project will likely have its own set of specific goals, here we lay out a broad set of goals which we expect to be achieved by restoration projects and make suggestions about how these ought to be measured as well as the scale and timing over which these measurements ought to be made. It should be noted that unlike efforts on the East and Gulf coasts creating a fishery is not one of the goals of native oyster restoration in San Francisco Bay.

1. Habitat creation or enhancement

The major goal of oyster restoration efforts is to increase or improve habitat for native oysters, in recognition of the value of these native organisms as foundation species and providers of ecosystem services. At this time, the reestablishment of a native oyster fishery is not one of the goals of restoration.

2. Development self-sustaining populations of native oysters.

Simply put, survival must at least match mortality, although size-class structure also needs to remain stable as smaller oysters are more prone to stress-related mortality and are less fecund than larger ones.

3. Ecosystem function: Increased diversity of mobile invertebrates and small fishes.

One of the expected outcomes of oyster bed restoration is the increase in diversity of associated mobile invertebrate animals and small fishes. While Olympia oysters do not make reefs like Eastern oysters, invertebrate diversity and the use of oyster shells and interstitial space by small fish is expected to increase due to the increased structural complexity of both the oyster substrate and the oysters themselves (Kimbro & Grosholz 2006; Abbott et al. 2007).

4. Ecosystem function: Increased use of area by larger fishes.

Evidence from San Francisco Bay suggests that herring will use oyster shells as spawning areas (R. Abbott, personal communication). In addition, it has been suggested that oyster beds provide habitats that attract prey organisms eaten by salmonids. Early evidence based on the detection of tagged salmon indicates the use of the Marin Rod and Gun Club oyster restoration area by salmonids resting and/or feeding (R. Abbott, pers. comm.). Results from fishing derbies at the Marin Rod and Gun Club are also suggestive; fishing is better over the "reef" areas than over mudflat areas (Abbott et al. 2007).

5. (Potential) Ecosystem function: Enhancement of eelgrass recruitment.

The potential interactions between eelgrass (*Zostera marina*) and native oysters are not fully understood. Studies in San Francisco Bay and elsewhere have indicated 1) negative effects of eelgrass on oyster recruitment (Wendy Norton and Lara Martin, pers. comm.); 2) no effects and 3) positive effects. However, there is anecdotal evidence that the creation of oyster "reefs" at least in areas of high current flow can retain eelgrass seed and thus enhance recruitment of eelgrass (R. Abbott, pers. comm.). Monitoring programs ought to consider measuring eelgrass response to oyster restoration whenever feasible.

6. Shoreline stabilization/erosion control.

Oyster "reefs" have been used as part of shoreline stabilization projects in bays and estuaries elsewhere (see Living Shoreline section above) and oyster restoration projects elsewhere have reduced wave impacts and changed sediment deposition regimes (Thayer et al. 2005; NOAA Restoration Portal https://habitat.noaa.gov/restoration/.)

7. Water quality improvement.

The often-quoted estimation of the former ability of Eastern oysters to filter the equivalent of the Cheseapeake Bay in 3 days has no doubt contributed to idea that oyster restoration can have positive effects on water quality. South San Francisco Bay is expected to experience massive eutrophic blooms due to high residence time and sewage outflow, yet the filtration by bivalves, mostly invasive clams, which exist in high numbers, prevents this (Officer et al. 1988). Native oyster biomass would have to increase considerably before this ecosystem service could be provided by native species. At this point, water quality effects resulting from oyster restoration are likely to be very localized, on the scale of a few feet from the restoration project. Effects of oyster filtering on water quality may include changes in turbidity, addition of nutrients. Restoration managers typically expect restored reefs to provide water quality improvements soon after construction, but the impact is determined by oyster size and population density relative to flow characteristics (Coen et al 2007, Newell et al 2007).

It is instructive that the water at Sailing Lake in 2002 was reported as being "generally opaque" with a visibility of just a few inches (Mulvey, pers. comm.) despite extremely high numbers of oysters. Most of the turbidity in San Francisco Bay is the result of suspended sediment (Kimmerer 2004) not high amounts of phytoplankton; thus oyster filtering may actually have little effect on water clarity.

8. Increased knowledge of native oyster biology, population dynamics, ecology, appropriate restoration methods.

As suggested throughout this document, there are still major gaps in our understanding of some of the basics of oyster biology and of population dynamics and ecology in San Francisco Bay as well as the most effective methods for restoration. Restoration projects ought to be designed with the specific intent of advancing this knowledge. Some examples of the types of information that can be gained from restoration projects were nicely illustrated by Breitburg et al. (2000, their Table 1), adapted and included below. The authors noted that their table was meant to illustrative, not exhaustive of the potential ways restoration projects could be set up to inform restoration practices and increase basic knowledge.

Table 7: Restoration goals.

Restoration Action	**Improvement in Restoration Practices**	**Improvement in Understanding of Oyster Reef Function**
1. Reefs constructed at different depths	Importance of reef depth to successful restoration	Relationship between depth and recruitment, growth and survival of oysters and associated biota
2. Reef constructing using different base materials	Evaluation of alternative materials for successful restoration	Relationship between construction material and development of oyster populations and associated biota
3. Reef construction with varying spatial dispersion patterns	Aid in the placement and spatial arrangements of restoration projects	Evaluation of the role of reef spacing patterns in maximizing oyster recruitment and providing habitat for mobile species
4. Position constructed reefs in varying proximity to other landscape elements	Aid in the placement and spatial arrangements of restoration projects	Evaluation of the importance of reef placement within a landscape for achieving restoration goals
5. Reefs constructed in areas with different tidal ranges and water quality	Aid in the successful restoration and protection of habitats that might otherwise not be protected or restored successfully	Enhance appreciation of EFH or critical habitat roles; provide better understanding of biogeographic differences among sites differing in physical regimes
6. Reefs constructed with varying shapes and vertical structure	Aid in the placement and construction of restored reefs	Evaluation of reef morphology relationships for habitat goals

9. Educational outreach

Public support for restoration is critical to sustaining efforts to restore oysters and other habitat to San Francisco Bay. Oyster restoration projects offer an opportunity to directly involve the public in construction and monitoring efforts. Volunteers have been involved in all of the efforts in San Francisco Bay to date and community groups such as fishing organizations, scuba clubs, service organizations and schools have played key roles in oyster restoration projects elsewhere. Whenever possible, we recommend that oyster restoration project include an education/outreach component. We also recommend a coordinated effort to increase public awareness of native oysters (see Strategy below), which will benefit individual restoration projects

Stepwise approach to restoration

We recommend a stepwise approach to restoration for native oysters, with methodology, goals, and scale depending on how much is known for a given site. The information gained from the initial steps will be critical in determining whether a site is appropriate for a full-scale restoration attempt. This approach is outlined below:

Phase 1 action: no prior knowledge

Definition: No prior restoration, surveys or monitoring
Recommended action: Basic site survey

a. Shoreline survey for abundance of oysters, oyster drills and substrate type and size
b. An extreme low tide survey should also be done to gather information on the area bordering the shallow subtidal

Phase 2 action: limited site knowledge

Definition: There has been minimal monitoring and/or anecdotal information that oysters are present. Phase 1 has been completed.
Recommended Action: Additional monitoring to gather some basic demographic information and physical characteristics of the site

a. Recruitment collectors, use standardized method (Appendix 4)
b. Monitor growth/mortality
c. Measure abiotic factors such as sedimentation/salinity/temperature

Phase 3 action: testing site for restoration

Definition: Phase 2 actions completed; good recruitment, growth, survivorship of oysters indicated
Recommended Action: small-scale pilot site selection technique:

a. Install a limited number of shell bags/other restoration substrate
b. Install this configuration at 2 depths
c. Replicate across area of interest. Use good experimental design to evaluate recruitment, growth, mortality across depths.
d. Continue to record salinity, temperature, sedimentation
e. Monitor for 1 year
f. Evaluate

Phase 4 action: starting pilot restoration

Definition: Phase 3 completed with positive outcome
Recommended Action: small restoration project (1/10 acre or less)

a. Use knowledge gained in Phase 3 to guide design
b. Use good experimental design to evaluate project success
c. Monitor for 3 years
d. Evaluate

Phase 5 action: larger restoration project

Definition: Phase 4 completed with positive outcome
Recommended Action: larger restoration project (One acre or greater, as feasible within site or funding constraints)

a. Use knowledge gained in Phase 4 to guide scaling up
b. Use good experimental design to evaluate success of oyster restoration and community-level impacts
c. Monitor for 5 years
d. Evaluate

Recommended methodologies

Substrate addition

Lack of appropriate hard substrate appears to be a limiting factor in some locations and perhaps especially below the tide line. In the South Bay, where few existing populations of oysters are evident, the addition of substrate has resulted in sometime high levels of spatfall. We recognize the reluctance to deploy additional hard substrate in San Francisco Bay, but suggest that 1) much natural larger hard substrate has likely been lost 2) sedimentation rates have changed in ways that make settlement on the kinds of small substrates that probably were once more abundant unfeasible for oysters today. If oysters are to be restored, substrate addition will have to happen.

The existing regulations regarding the addition of “fill” to the Bay should be reviewed and revised to make it easier and less costly to obtain a permit for the placement of hard substrate for research and restoration purposes. In our own experience, the process of obtaining a permit to deploy four small-scale experimental floating recruitment collectors in the Bay was so onerous that we were unable to proceed with a planned experiment.

Shell placed in mesh bags and stacked on wooden pallets or other surfaces to prevent or slow sinking/sediment burial seems to have worked relatively well for current projects. Loose shell is too easily lost due to current action and sediment burial. Pacific oyster shell is still readily available on the West Coast and provides more surface area than the native shell currently being dredged from the bay. As mentioned above, steps need to be taken to ensure that non-native species are not transferred with the shell.

We also recommend the incorporation of Reef Balls and other such structures into restoration projects, particularly where these can be made using native Bay materials. The feasibility of using an all-native material mix is being explored (R. Abbott, pers. comm.) This is an avenue that should be explored and used in place foreign materials wherever possible. Reef Balls have been used successfully in a number of locations. While the molds run about $1500 a piece, the materials are relatively inexpensive and many East Coast projects involve volunteers groups in creating Reef Balls to cut down on costs.

Both shell bags and reef balls along with other materials such as native rock can be incorporated into the structural portions of living shoreline projects, which can double as breakwaters and natural seawalls. We highly recommend exploring the feasibility of incorporating oysters into these types of multi-purpose, multi-habitat restoration projects. A matrix of soft and hard elements looks more natural and is likely to result in fewer aesthetic objections than a project that deploys only hard substrate.

Best methods for configuration and depths of the above substrate are not yet known and may vary by site. We recommend incorporating various configurations into restoration projects to determine best practices.

Seeding

We think that seeding ought to be tried at least experimentally to supplement areas where recruitment is low or highly variable and where there is high cover of other sessile organisms. As the goal of seeding would be to increase local population size, research on current dynamics at a proposed seeding site is an important first step. An ideal site is one that will retain larvae. While currents can be tracked using passive drifters such as drogues and predicted to some degree using current models, we also need a better understanding of larval behavior to be able to better determine whether a site will retain larvae.

There is some suggestion that oysters are less vulnerable both to predation and to physical stresses at larger sizes; this ought to be explored by deploying oysters at different size classes. The pilot work at Sailing Lake suggests that seeding can increase the number of oysters that survive the first year.

Current analysis indicates little population structure in Olympia oysters at the within Bay level. Until we better understand the genetic structure of oysters in the bay, broodstock ought to be collected from the subsection of the bay where the seeded oysters will be placed. Broodstock should also be inspected for disease.

Monitoring: Metrics for measuring success

The importance of monitoring

Monitoring is systematic data collection that provides information on changes that can indicate problems and/or progress towards target criteria or performance standards, which, when met, indicate that established ecological goals have been reached (Thayer et al 2002).

We cannot emphasize enough the importance of monitoring to successful restoration projects. Among the risks inherent in NOT monitoring are (adapted from Thayer et al 2005, our addition in italics):

1. the inability to determine that a project is not developing as expected
2. the inability to assess whether project goals are being met
3. the inability to determine what measures might need to be taken to better achieve goals
4. decreased project coordination and efficiency
5. *the inability to learn lessons that can be applied to future restoration projects*

Monitoring Plans

Before a monitoring plan can be formed, the project goals need to be clearly defined. Ideally the plan should include a means of documenting progress toward project-specific targets (such as an increase in fish use of the area) as well as regional goals (such as progress towards the acreage goals laid out in this document). Ideally, project goals should be stated in terms of testable hypotheses. Measurement methods, appropriate statistical analyses, and plans for using/disseminating the data should be clearly spelled out.

Monitoring ought to be integrated into the project design. The schematic below (Thayer et al. 2003, their Figure 11) illustrates the ways in which a monitoring program and a restoration project are linked throughout all phases.

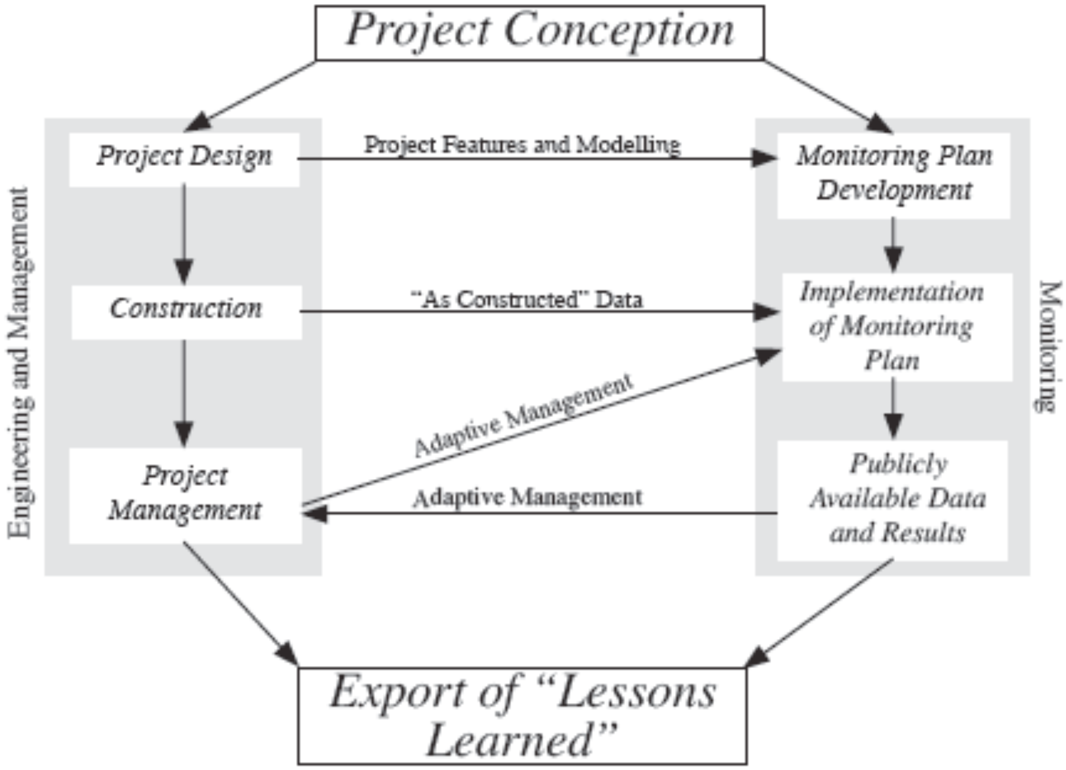


Figure 30. A flow diagram illustrating the interface of a monitoring program with all phases of restoration project design, construction and management.

Reference sites

Whenever possible, an oyster restoration project should identify a reference site to which the project can be compared. In the ideal, a reference site would be a relatively undisturbed site with a healthy oyster population; it would provide an illustration of the targets to be achieved in terms of oyster demographics and ecosystem functioning. San Francisco Bay has been changed so completely since European contact it is unlikely that any site could be viewed as undisturbed. At this point in time, we do not know what pre-contact oyster populations looked like in the bay (see Historical Information). However, it is possible to choose a disturbed reference site to serve as a control or illustration of how oyster populations would fare *without* restoration, and we recommend doing this whenever possible. We recommend monitoring of a proposed restoration site and the reference site for one year prior to the commencement of an oyster project as well as during the construction phase and post-construction for the time periods indicated in the chart below.

Below, we have constructed a matrix for measuring the success of projects in meeting biological/ecological goals. For specific field methodology, see references contained in Thayer et al. (2005).

Table 8. Matrix for measuring restoration success.

Goal	Measurements	Methodology	Timing
Increase/improve habitat for native oysters	Acreage or linear feet of hard substrate	Snorkeling/wading measurements of perimeter	During construction phase and immediately following construction phase, determine that substrate configuration is holding
	Topographical complexity	Chain transects	At least annually, pre-settlement season
	Percentage of hard substrate/surface area available for settlement space	Determination of percent cover of other sessile organisms on sample substrate	At least annually, pre-settlement season; determine whether maintenance is needed
Self-sustaining populations of native oysters	Oyster density	Counts of live oysters per unit area; compare to reference site	At least annually, for 3-5 years after construction.
	Size class structure	Measurements of oysters in above counts: compare to reference site	At least quarterly, for 3-5 years after construction.
	Recruitment	Number of spat on samples of material used for restoration; compare to reference site	At least annually, for 3-5 years after construction. If recruitment is low over 2-3 years, consider seeding
	Growth	Repeated measures of growth of marked individuals; compare to reference site	At least two times year, for 3-5 years after construction
	Reproduction	Plankton tows for larval abundance around restoration site; laboratory examination of sacrificed individuals; compare to	At least two times year immediately preceding and during recruitment season for 3-5 years after construction

		reference site	
	Mortality	Tracking marked individuals; counting recently dead individuals; counting number of drilled individuals; compare to reference site	Quarterly, for 3-5 years after construction
	Disease	Pathology of sacrificed animals; compare to reference site	Annually, for 3-5 years after construction
Increased diversity	Species richness and abundance of invertebrates, algae and small fishes	Counts of individuals in samples of oyster restoration material; compare to reference site	Quarterly, for 3-5 years after construction; may be up to 2 years before community is fully assembled (Meyer & Townsend 2000)
Increased use of area by larger fishes.	Numbers and species of fish at restoration site; time individuals are spending at site	Counts of individuals caught via samping in nets and traps; presence of acoustically tagged fish on reef; where appropriate CPU for recreational fishing; compare to reference site	At least annually, for 3-7 years after construction. Counts may need to be coordinated with seasonal appearance of target species.
Enhancement of eelgrass recruitment/other impacts on eelgrass	Abundance and distribution of eelgrass; density; blade density; growth; # of reproductive individuals	Presence/absence of eelgrass at restoration site; counts of plants where possible; other measures of eelgrass health as appropriate; compare to reference site	At least annually, for 3-7 years after construction.
Shoreline stabilization/changes to sediment deposition regime	Shoreline erosion measures; changes in wave fetch; measures of sedimentation	Sediment traps; sediment cores; grain size measurements; measures of	Sediment measures quarterly; erosion measures annually, 3-5 years after construction.

	rates; changes in grain size, bulk density, organic content, silt/mud/clay; nutrients in sediment	changes in shoreline shape and slope; compare to reference site	
Water quality improvement	Changes in turbidity; chlorophyll A, PAR, phytoplankton diversity and abundance; DO; nutrients in water column	Secci disks or turbidity meters; water column sampling for key nutrients, chl A; PAR meter; DO meter	At least quarterly, from construction to 7 years. Measurements should be taken at various distances from restoration site. Effects likely very localized; on site flow through plastic tunnel (Dame et al 1984) can be used to evaluate oyster filtering capacity

Restoration Costs

Costs for establishing oyster restoration plot using shell mounds and reef balls are derived from B. Abbott, Environ (pers. comm.). Permitting is determined to be a significant cost off deploying restoration structures (although state agencies may be able to seek reductions). Currently the per acre costs including requirements to secure bonds, special insurance, consulting labor needed for NEPA/CEQA requirements and other expenses is approaching $10,000 per acre (B. Abbott, pers. comm.). The costs of deployment for reef mounds assuming 200 mounds per acre and 400 hours of bagging at $20 /hr ($8000) and associated costs for pallets ($1000), trucks ($3000), forklifts ($600) and other miscellaneous costs is approximately $15,000 assuming no additional project management costs. For reef balls, assuming 200 reef balls per acre, $3000 for materials (concrete, sand) and 600 hours of labor for construction at $20 per hour produces an estimate of about $15,000 per acre of reef balls.

The costs of follow up monitoring depend greatly on the level of detail and the type of work needed for the monitoring. With this noted, the cost of quarterly sampling involving two persons and requiring one week of work for both at $20 per hour would be $6,400 per year.

Estimates of the costs of seeding restoration plots are developed from estimates using hatchery produced oyster spat on shell cultch using very detailed cost estimates for eastern oysters (*Crassostrea virginica*) (Congrove 2009). These estimates are based on a very similar process involving spawning adult oysters, hatchery rearing of larvae, settling larvae on shell cultch and outplanting newly settled oysters onto restoration structures. Although these estimates may vary somewhat based on the differential costs of inputs and some differences in life history of Olympia oysters, we feel estimates for eastern oysters provide a useful approximation of cost of seeding plots in San Francisco Bay for Olympia oysters.

The summary costs of including extensive and detailed estimates of all the cost inputs (production, facilities, etc.) suggests that the cost per bushel of cultch shell is $20-25 dollars. Assuming 700 shells per bushel with 100 larvae set per shell and a planting density of 1000 oysters per m^2, this would be ten shells per m^2. Assuming a little more than 4,046 m^2 in an acre, this would be about 40,000 cultch shells per acre or about 55 bushels given 700 cultch shells per bushel. So the total cost of producing seeded cultch per acre would be approximately 55 x $25 = $1375. These costs do not include any of the labor estimates involved in this process for which there are no estimates currently available.

VII. Site-specific recommendations for protection, restoration and research

The following recommendations are based largely on the recommendations of participants in a one-day workshop on shellfish restoration held in Tiburon, CA in December 2008. The participants included representatives from most of the organizations involved in oyster restoration and research in SF Bay. Participants discussed the state of knowledge of oyster populations, known and potential stressors and research and restoration opportunities for each segment of the shoreline. They were also asked to suggest next steps, including goals for restoration in terms of acreage and time. These goals were discussed as ideals based on our best understanding of what habitat is appropriate for native oysters as well as opportunities for collaborations with community groups, agencies and broader restoration projects. Notes from the workshop were entered into a spreadsheet which we have amended and added to here (Appendix 5). In addition, to the recommendations made at the workshop, we added other potential sites based on 1) our direct experience with the site and/or 2) conversations with other researchers or restoration groups which indicated good oyster habitat and restoration opportunities. Each entry in the spreadsheet includes a shoreline segment designation (which correspond to those used in other Subtidal Goals project documents), a location description, GPS coordinates for the beginning and end points of the segment, a summary of work to date and proposed actions. Not all of the shoreline segments outlined in other Subtidal Goals projects were included here as they fall outside of the areas we recommend for oyster restoration. For areas that seem promising for restoration, we estimate total *potential* acreage, which is defined simply as the area defined by the shoreline segment out to 2 m depth. We do not suggest that all of this area should be used for restoration. Instead, where we have sufficient information to do so (Phase 3 work to date or higher), we recommend acreage goals over 5, 10 and 50 year time spans. The acreage goals are meant to indicate a footprint in which restoration activities should occur: they should not be interpreted to mean completely covering an area in oyster shell! In addition, we have summarized opportunities and potential constraints for oyster research, protection and/or restoration at each shoreline segment.

Below we highlight the some of the shoreline segments that participants thought ought to receive some level of protection due to the persistent presence of oyster populations, potential restoration sites, opportunities for expanding current projects, and critical research in support of restoration. Further details can be found in Appendix 5. We realize that many factors, such as funding and access to sites, will ultimately set limits on oyster restoration in the bay.

For a number of shoreline segments, where little was known about oyster populations, we recommended surveys (or resurveys) or small-scale experimental studies. In the text below, we highlighted areas for which we had more information as follows:

Protection

A survey of oysters prior to activities that could damage habitat or oysters, such as seawall repairs/rebuilding, shoreline construction, ferry terminal construction, dredging, marina expansion, etc. If a qualified marine invertebrate biologist finds a significant population (i.e. high densities, large adults, or multiple size-classes), developer should attempt to protect oysters/oyster habitat or provide mitigation for loss of oysters.

Potential restoration areas (further study warranted phases 2 & 3)

These are sites that appear to be good locations for oyster restoration and in some cases represent opportunities to collaborate with willing partners or with larger restoration projects.

Restoration areas (phases 4 & 5):

These are sites where smaller scale projects have been successful and/or research has indicated that they are appropriate for restoration.

Research

Specific research opportunities or needs, explained in text below.

South Marin/Central Bay (Segment I) and North Marin (Segment G) in part

Western edge of central San Francisco Bay extending from McNears Beach around Point San Pedro to the Golden Gate

Protection

Sausalito shoreline; Brickyard Park (Strawberry); Richardson Bay shoreline in front of the Audubon Center; the Tiburon Peninsula; Angel Island; Point San Quentin south and north of the Richmond-San Rafael bridge.

Potential restoration areas

Earl F. Dunphy Park: fairly high densities of oysters were seen in 2006 (Grosholz et al 2007); herring eggs frequently seen in the intertidal zone (C. Zabin, pers. obs.).

Brickyard Park (Strawberry): large oysters in fairly high densities; park setting might offer an opportunity for community participation.

Angel Island: UCD's long-term study site at Ayala Cove had good recruitment, growth, survivorship. The cove has heavy usage by boaters and beachgoers, which might be in conflict with a restoration project. We recommend a survey for other areas on the island which might be better suited to such a project. Park setting a potential opportunity for community/multi-agency participation.

Richardson Bay: Following further study of larval supply and drill abundances, this area should be considered for restoration projects, with a goal of gradually restoring up to 1/10 of area of the bay (80 acres) within 50 years. Substrate may need to be seeded, depending on outcome of larval supply study (see Research). Location of the Richardson Bay Audubon Center and the inclusion of Richardson Bay in the San Francisco Bay National Estuarine Research Reserve Area make logistics of protection and habitat restoration feasible.

Arambaru Island (Richardson Bay): A restoration project is planned for Aramabaru Island, including regarding and planting of native vegetation. This is an excellent opportunity for a living shoreline approach which would include oyster restoration. Substrate may need to be seeded, depending on outcome of larval supply study (see Research). We strongly recommend a pilot oyster restoration project, which, if successful would lead to a larger scale project at the island within a 5-10 year timeframe.

San Rafael Shoreline north from Marin Rod & Gun Club to south of canal area: Space for additional restoration projects is limited at the Marin Rod & Gun Club, but the area to the north appears to be equivalent habitat (R. Abbott, pers. comm.). We recommend, following successful small-scale studies, phasing up to 50 acres within a 50 year time frame along this shoreline.

San Rafael Shoreline from north of the canal to McNears Beach: following high mortality in 2006, oysters have recruited in high numbers to locations along this shoreline. These populations are still abundant at the time of this writing. Following small-scale pilot studies, we recommend phasing up to larger scale projects within a 50-year time frame in the 1,870 acre footprint along this shoreline.

Marin Islands: In 2006 many oysters were seen at the low tide mark (M. Latta, pers. comm.). The islands are under joint control of California Department of Fish and Game and the US Fish and Wildlife Service. Their isolated nature makes them potentially a good site for oyster restoration/protection. Oyster densities, recruitment and growth rates need to be investigated as well as the logistics of working with plans for the islands that these two agencies may have.

Research in support of restoration

Larval delivery/retention in Richardson Bay: recruitment has been low in Richardson Bay for the last few years that it has been monitored. A study of current patterns and/or direct measurements of larval delivery, sources and sinks needs to be done before large-scale restoration.

Survey for oyster drills in Richardson Bay and consider eradication/management action: Richardson Bay represents the northernmost extent of the Atlantic oyster drill in San Francisco Bay – in fact only a few individuals are found in surveys north of Oyster Point. The drill may impact oyster restoration attempts in Richardson Bay and if it spreads north throughout the Central Bay, could threaten oysters in what is currently their best habitat. We recommend a survey for the drill along the shoreline. Eradication or control actions should be carried out if feasible.

Point Pinole area (Segment H)
Southeastern side of San Pablo Bay between Point San Pablo and Point Pinole

Protection

Hard substrate along the entire shoreline of this segment.

Potential restoration areas

Point Pinole Regional Shoreline. Community-based monitoring of oyster recruitment is ongoing in this area, generating data and local enthusiasm for native oyster work. East Bay Regional Parks controls much of this area and may be interested in restoration projects involving oysters. This area periodically experiences low salinity events which can result in massive oyster die-offs; however oysters appear to return rapidly and in high abundance. This factor would have to be taken into account in evaluating the success of oyster restoration projects.

Berkeley Area/Central Bay (Segment L)

Eastern edge of San Francisco Bay between the Oakland Outer Harbor and Point San Pablo.

Protection

Entire shoreline of this segment.

Potential restoration sites

Richmond Bridge north to Point San Pablo: High density intertidal populations can be found from Point Molate to Keller Beach and these were among the first to recover after the low salinity event of 2006. Population parameters for recruitment, growth, disease and survivorship are all positive. Much of the habitat integrity of this area appears to have been retained, including some of the Bay's largest eelgrass beds, which range into the intertidal, high numbers of juvenile Dungeness crabs, and high algal diversity. Much of this area is under East Bay Regional Parks control and environmental groups are active in this area, providing an opportunity for cooperative and community-based projects.

Point Isabel & Albany Dog Park: These sites appear to be appropriate habitat for oysters and may represent restoration opportunities in conjunction with local parks and community groups. We recommend a resurvey and studies of recruitment, growth and survivorship at these sites.

Berkeley Shorebird Park: There are high density intertidal oyster populations at this site and good recruitment in the years it has been monitored. There are potential user conflicts (sail boarders and sailing groups) with a restoration project at this site, which would need to be worked out, perhaps by limiting the scope of the project to less than 1 acre. The nature center would be a good portal for community involvement in such a project.

Ashby Spit to Emeryville Crescent: This area appears to be good native oyster habitat. If surveys and subsequent population studies are positive, we recommend moving to pilot scale restoration projects in this area within 5 years.

Restoration

North Cesar Chavez Park: a small-scale restoration project is under way at this site. If this project is successful, we recommend scaling up to 1 acre within 5 years, 5 acres in 10 years and up to 30 acres in 50 years.

Oakland Area/Central Bay (Segment K)

Eastern edge of San Francisco Bay between Oakland Outer Harbor and the San Leandro Marina.

Protection

Alameda shoreline and marinas in this segment.

Potential restoration sites

There are several sites for which we believe there is good community and agency support for restoration projects, however, much of this area has not been surveyed or has not been surveyed recently. We recommend restoration projects at these sites if surveys and smaller scale experimental work indicate that they are appropriate for oysters.

Lake Merritt: An opportunity exists to incorporate oyster restoration into the Lake Merritt Channel opening project and interest in this from the project managers. This would also represent an opportunity for a highly visible project which could involve the community.

Oakland Middle Harbor enhancement: This project may provide some opportunities for restoration as part of mitigation.

San Leandro Marina and nearby shoreline. The San Leandro harbormaster and the marina community are supportive of other environmental projects and may be interested in a small-scale or demonstration project.

Baumberg area/Eden Landing/South Bay (Segment S)

Eastern edge of San Francisco Bay between the Alameda Flood Control Channel and Highway 92

Potential restoration site

Eden Landing Ecological Reserve: Like much of the South Bay, appropriate substrate for oysters is scarce at this site. However, based on recruitment studies nearby, it is clear that oyster larvae are present in high numbers. We recommend a survey of existing hard substrate in this area and small scale experimental deployment of substrate as part of living shoreline as salt ponds in this area are breached and habitat restored. Such projects have good support from the relevant agencies.

Mountain View Area (Segment O)

Western edge of San Francisco Bay between Dumbarton Bridge and Alviso Slough

Protection

Shoreline Sailing Lake: A large population of native oysters can be found in this tidally managed “lake.” It is not clear why this habitat is so good for oysters, but the lake may provide a refuge for oysters from heat stress (having no tides) and predation (no drills present). The lake has provided a natural seeding area for pilot restoration projects, and could play this role again. This population may also be the source of some of the larvae in the South Bay.

Potential restoration sites

Ravenswood Pier/SF2: Larval recruitment to substrate placed in these areas was high, despite the absence of adult oyster populations nearby. We recommend pursuing a restoration project here as part of a larger project aimed at restoring habitat for shorebirds. Thirty to 40 islands are to be constructed in the former salt ponds, leaving deeper “borrow” ditches where shell bags and small reef balls could be placed. We recommend the initial placement of 10 pairs of reef balls and shell bags in the borrow ditches and an additional 10 in the deeper channel.

Palo Alto Baylands: Larval recruitment to substrate placed here was also high, despite the apparent absence of appropriate oyster substrate and thus naturally occurring oyster populations. The park and surrounding area need further surveying and assessment, however there is good access to the water here and local interest in oyster restoration.

Redwood City Area (Segment N)

Western edge of San Francisco Bay between Steinberger Slough and the Dumbarton Bridge

Potential restoration sites

R1 pond: There may be an opportunity at this site to incorporate oyster restoration into a living shoreline project which would also serve to prevent levee erosion, a large and costly problem in this area. Plans for levee breaching and habitat restoration are in the works, and may provide opportunity for oyster restoration. We recommend a recruitment study at this site to determine natural recruitment levels.

West Point Harbor: The harbormaster of West Point Harbor, a newly built 26 acre marina that is a former bittern pond, has expressed interest in oyster restoration projects. We recommend a recruitment study at this site.

Restoration projects:

Bair Island: Despite some challenges at this site, oyster recruitment and growth were high at the 1/10 acre pilot project at this site. This area is a historic oyster farming location, with massive shell piles remaining and there is multi-agency support for restoration projects here. The Marine Science Institute in Redwood City was involved in monitoring the pilot project and is an excellent opportunity to educate and involve the public. We recommend several 1/10 acre plots in this area; but future projects may need to be deployed from a larger, more stable platform to make working in this area easier and safer.

Research in support of restoration

Predator/prey dynamics: The Atlantic oyster drill is patchily abundant throughout the South Bay. Predation, especially on young oysters, was a major issue at the Bair Island/Greco Island pilot restoration projects. Whether predation by the drill is currently enough to limit native oyster populations is not known. It is also not known whether the populations of the drills might increase in response to an increase in oyster populations. There may also be some strategies that could be employed to reduce the impact of this predator. This research is extremely important in the consideration of restoration projects in this part of the bay.

Non-native fouling organisms: As at the Marin Rod and Gun Club, oyster shell substrate deployed as part of the Bair Island-Greco Island restoration project was quickly settled on by a number of non-native fouling species, and the wooden pallets on which the shell bags were placed disintegrated after a year due to infestations of shipworms. Further research into the ability of different types and configurations of restoration substrate to deter settlement by other organisms is warranted, as well as various methods to keep the substrate clean.

Larval supply/retention: Despite the apparent absence of significant oyster populations, recruitment has been consistently high in many locations in the South Bay. It appears that the South Bay retains larvae, which could be a critical feature in building a self-sustaining population in the area. We recommend studies of current flow and larval supply to better understand where larvae are coming from and how long they are retained in the South Bay.

San Mateo Area (Segment M)

Western edge of San Francisco Bay between Coyote Point and Steinberger Slough

Protection

Coyote Point shoreline and jetty.

Potential restoration sites

Coyote Point: Large oysters are present both in the Coyote Point Marina and in the intertidal zone along the marina jetty (facing the airport). The area in front of the seawall is typically wind-whipped and not conducive to a restoration project, but further exploration of Coyote Point for restoration is warranted. The interpretative center in the park is an opportunity to involve the public in oyster restoration and research/monitoring.

Research in support of restoration

See Predator/prey dynamics above. High drill densities at Coyote Point may offer an opportunity to study predation impacts on native oyster populations.

San Francisco area/Central Bay (Segment J)

Western side of Central San Francisco Bay between the Golden Gate and Coyote Point

Protection

Shoreline segment from Candlestick Park Point to Oyster Point, where there is a persistent and relatively high density population..

Potential restoration sites

The area from Oyster Point to Sierra Point Marina should be considered for a series of pilot restoration projects which would enhance existing populations by providing additional intertidal and shallow subtidal substrate. We need to ensure that these projects do not interfere with boating activities, but we otherwise anticipate support from the harbor and the local community. Oyster Point in particular is well-used by walkers and joggers and others who live nearby for its view of the water. A project here could increase community involvement in the Bay. We recommend several small projects to determine most appropriate tidal heights and substrate (oyster shell vs. Reef Ball) for this area. If these projects are successful, we recommend scaling up to 10 acres within 10 years and 50 acres within 50 years.

Research in support of restoration

The population along this segment needs to be periodically monitored for disease. While overall disease incidence was low, it was higher at Candlestick Park than at any other site in the Bay, and may increase if the oyster population increases significantly.

VIII. Summary

There is relatively little quantitative data on the ecosystem functions of native oysters and thus the potential ecosystem services restored populations might provide in San Francisco Bay. However, it is reasonable to assume that the Olympia oyster plays similar role to that of the Eastern oyster, and that if restored, oysters would improve the functioning of the Bay ecosystem in several ways. Key among these is the provision of complex, hard substrate which provides habitat for a suite of other organisms, including small crustaceans that might be fed on by salmonids. Herring also use oyster shell for egg-laying and eelgrass establishment appears to be facilitated by the presence of oyster shell mounds. Work elsewhere suggests that oysters and oyster-restoration substrate can alter hydrographic regimes, providing shoreline protection. Finally, the restoration of filter-feeding function to parts of the bay where filter feeders are not present in high numbers is likely to increase nutrient cycling and perhaps contribute to improved water quality in the Bay. As mentioned earlier, this function is not likely to be restored over large spatial scales without a significant population increase.

On this basis, interest in restoring oysters in San Francisco Bay is high. However, knowledge of how best to proceed is hampered by a lack of understanding of what limits existing oyster populations in the Bay and how to best overcome some of the limiting factors of which we are aware. For this reason, we have included many research recommendations in this report, and strongly recommend a stepwise approach to restoration, testing potential sites at a small scale to determine feasibility and best approach for each area. In addition, we suggest that restoration projects can be set up to meet both restoration and research goals. Monitoring is an essential part of any restoration project; it allows for adaptive management as well as for the collection of data that can inform future projects.

The few oyster restoration efforts in San Francisco Bay to date have not yet achieved the goal of creating self-sustaining oyster populations, but have demonstrated that the provision of hard substrate, particularly in the lower intertidal and shallow subtidal, will result in significant oyster populations. One of the major hurdles for oyster restoration at these tidal heights appears to be space competition with both native and non-native organisms. For the South Bay projects, predation by non-native oyster drills, particularly on small oysters, has been a major obstacle. However, recent research indicates that space competition and predation are not limiting factors throughout the bay, and that these obstacles are not necessarily insurmountable.

While oysters appear to be somewhat robust to at least some types of water pollution, they do not appear be able to withstand heavy siltation or burial by sediment. While some parts of the Bay are now experiencing a net loss of sediment, research indicates that oysters in the intertidal zone (and presumably the shallow subtidal) in some locations, are buried for months at a time by mud and sand. In other locations, heavy siltation may reduce the ability of oysters to feed. The amount of sediment in the Bay has undoubtedly increased since European contact, and these sediments are moved around through a combination of natural forces such as wave, tides and currents, and anthropogenic activities include dredging, ferry wakes, and land-based erosion and run-off. Heavy siltation has likely resulted in the burial of smaller, naturally occurring hard substrates for oyster settlement. Current restoration efforts have attempted to solve this problem by providing large substrate and elevating it off of the mud bottom. Sedimentation regimes also differ between locations in the Bay, and some of these problems may be avoidable by a better understanding sediment movement in the Bay.

Climate change is likely to present oyster restoration efforts with challenges in the future. Among these are increased heat stress due to warmer air and water temperatures; sea level rise, which could result in loss of oyster habitat if there is a net loss of hard substrate at appropriate depths; increased fluctuations in salinity due to cycles of droughts and floods; and ocean acidification which could interfere with the production of shells and thus the development and growth of oysters. The significance of these changes to oyster populations in the Bay is still largely unknown.

Despite these obstacles, native oyster populations in San Francisco Bay are in many ways better off than populations of East Coast oysters in locations such as the Chesapeake Bay, where restoration efforts, mostly unsuccessful, have been ongoing for decades. Specifically, disease, which is a major factor in the Chesapeake, is at this time, not likely to be an issue in restoration of oysters in San Francisco Bay. Secondly, restoration efforts on the East and Gulf coasts are more difficult in that they are attempting to restore populations and a fishery simultaneously. Eastern oysters are suffering in large part due to loss of habitat, particularly decimation of the large reefs formed by a combination of living and dead oysters. These reefs have been destroyed, perhaps below a critical threshold level, by the fishery itself. Creating a fishery is not one of the goals of oyster restoration in San Francisco Bay, greatly simplifying the objective and approach. Finally, recruitment appears to be extremely low to nearly absent throughout much of

Chesapeake. Although recruitment in San Francisco Bay is variable in time and space, and is certainly impacted by such events as the heavy rains in spring 2006, it has been more consistent over the past five years than it has been at two nearby estuaries, Tomales Bay and Elkhorn Slough.

Finally, interest in habitat restoration in San Francisco Bay appears to be increasing, and there are numerous opportunities to incorporate oyster restoration into larger restoration projects in the Bay. To date, interactions between organizations and agencies working on oyster research and restoration in the Bay have been positive and have resulted in coordinated efforts such as the shared recruitment protocol, which allowed critical data collection over a greater scale than any single organization could have managed alone. There also appears to be strong community support for oyster projects. Volunteers working on oyster projects through Save The Bay, the Marin Rod and Gun Club, the Natural Heritage Institute, The Watershed Project and Richardson Bay Audubon Center have expressed ongoing excitement and enthusiasm for these projects. Public involvement has been an essential part in the various pilot projects and studies in the Bay and public support will be critical to moving these projects forward in the future.

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Native Oyster Proposed Restoration Site Table
Chela Zabin et al UC Davis 12/15/09
For the San Francisco Bay Subtidal Habitat Goals Project

			Work to Date							Proposed Action								Acreage Goals			Notes	
Segment	Location	GPS	None	Shoreline Survey (Phase 1)	Recruitment Collectors (Phase 2A)	Monitor Growth, Mortality and Abiotic Factors (Phase 2B&C)	Test for Restoration (Phase 3)	Small Scale Pilot Restoration (Phase 4)	Large Scale Restoration (Phase 5)	None	Shoreline Survey (Phase 1)	Recruitment Collectors (Phase 2A)	Monitor Growth, Mortality and Abiotic Factors (Phase 2B&C)	Test for Restoration (Phase 3)	Small Scale Pilot Restoration (Phase 4)	Large Scale Restoration (Phase 5)	Protection	5 year	10 year	Potential acreage (50 year goal)	Opportunities	Constraints
I	Sausalito shoreline	37.8611,-122.4858 to 37.8617,-122.4879		x													x				Oyster population widespread and persistent.	Developed, urbanized area. Ferry terminal. Deep.
I	Earl F. Dunphy Park	37.8613,-122.4873		x								x	x	x			x				Oysters present.	
I	Brickyard Park, Strawberry	37.8827,-122.5041 to 37.8810,-122.5041		x								x	x	x			x	1	10	20	County park. Good access. Lots of bricks. Large oysters. May not experience low salinity.	Unusually large oysters should be genetically tested to ensure they are *O. lurida*. Recruitment may be low.
I	Richardson Bay Audubon Center	37.8943,-122.4999 to 37.8939,-122.4949		x	x								x	x	x	x	x				Richardson Bay Audubon Center support. Protected subtidal. Eelgrass research ongoing. Good volunteer base for oyster drill eradication if necessary. Some oysters on shoreline. Large oysters present. Oyster recruitment data from inside and outside eelgrass beds. Eelgrass and herring present.	Oyster drills present. Low recruitment in years studied. Possibly low circulation. Large scale reseeding might be necessary.
I	Arambaru Island	37.8950,-122.5032 to 37.8935,-122.5029	x								x	x	x	x				1	10	32	Potential restoration site as part of island restoration. Living shoreline approach probably most applicable.	Reseeding might be necessary.
I	East Richardson Bay	37.8861,-122.4988 to 37.8772,-122.4971		x	x	x				x												Poor site for oysters. Virtually no recruitment. Oyster drills present.
I	Richardson Bay	37.8938,-122.4997 to 37.8590,-122.4642											x								See individual sites above.	Need to survey for oyster drills. Oyster drill eradication might be necessary. Need to understand delivery, circulation, and retention in bay. Reseeding might be necessary.
I	Angel Island	37.8599,-122.4462 to 37.8715,-122.4306		x	x	x					x						x				Studies done at Ayala Cove. State Park. Lots of oysters on North side. Need to survey North and East sides.	Potential user conflicts at Ayala Cove. South and West sides too unprotected coast and have strong currents.
I	Tiburon Peninsula	37.8772,-122.4730 to 37.9207,-122.4877	x								x						x	5	60	310	Planning department proposes oyster restoration as mitigation for building.	Lack of public access.
I	Keil Cove, Tiburon	37.8761,-122.4434 to 37.8799,-122.4393	x								x	x	x					1	5	16	Supportive landowners. Oysters present.	Lack of public access.
I	Romberg Tiburon Center	37.8894,-122.4456 to 37.8930,-122.4478	x								x										Landowner supportive.	Large seawall. Strong current. Deep.
I	Paradise Drive at Trestle Glen Road, Tiburon	37.9044,-122.4760	x								x	x	x					1			Owner support.	
I	Corte Madera/Larkspur shoreline	37.9207,-122.4877 to 37.9439,-122.5046	x							x												Little appropriate substrate. Sediment and freshwater input from creek. Ferry terminal.
I	Point San Quentin	37.9439,-122.5046 to 37.9437,-122.4797		x													x				Lots of oysters.	Periodic low salinity.
I	Marin Rod and Gun Club, San Rafael	37.9447, -122.4806		x	x	x	x	x								x	x	1	1	1	Recruitment good at MRGC. Eelgrass restoration also at site. Supportive landowners. Successful small restoration projects.	Periodic low salinity. Running out of space for projects.
I	San Rafael Shoreline (MRGC to McNears)	37.9452,-122.4814 to 37.9704, -122.4945	x								x	x	x	x	x		x	8	100	1,870	Habitat and conditions similar to MRGC. Oysters present	Periodic low salinity.
I	San Rafael Canal	37.9697,-122.4950			x						x											User conficts. Periodic low salinity.
I	Marin Islands	37.9650,-122.4707	x								x	x	x								Oysters present. High recruitment in summer and fall following flood year, and persistence of high numbers over several years.	
G	China Camp	37.9979,-122.4570 to 38.0173,-122.4986		x							x						x				NERR controlled area. Oysters sometimes present.	Many dead oysters found in 2006 survey; oysters returned by 2008. Low salinity. High current. Soft sediment.
G,F, ED, BA, C,H	San Pablo Bay	37.9810,-122.4505 to 37.9640,-122.4269		x						x												Regular seasonal low salinity makes this segment extremely marginal oyster habitat.
H	Point Pinole to Point San Pablo	38.0038,-122.3437 to 37.9925,-122.3594		x	x						x	x	x				x	10	200	3,664	Local community positive. Oyster studies might be a good public education opportunity.	Low salinity.
L	Point Orient	37.9556,-122.4222 to 37.9549,-122.4207		x	x	x								x	x	x	x	10	50	100	3 year UCD study indicates good recruitment even following low salinity event. No oyster drills. High density of oysters. Eelgrass and juvenile dungeness crabs present. Good access. Reef balls might be good. Method needs to provide sufficent topographical relief.	High sedimentation. Close to Chevron and other potential sources of chemical pollution. Salinity needs to be measured during major storm.
L	Richmond Bridge to Point San Pablo (including Brothers Islands)	37.9329,-122.4098 to 37.9648,-122.4289									x			x	x	x	x			191	Hydrologic models done. Good marine input. Similar to Point Orient.	Periodic low salinity flushes. Similar to Point Orient.
L	Richmond Bridge to Keller Beach	37.9329,-122.4098 to 37.9224,-122.3908	x								x						x					
L	Keller Beach	37.9224,-122.3908 to 37.9096,-122.3908		x								x	x				x	5	20	71	High oyster density. Population rebounded after low salinity event.	Periodic low salinity.
L	Ferry Point	37.9092,-122.3904 to 37.9087,-122.3877		x	x	x											x				Good oyster density.	Poor access. Lots of algae.
L	Brooks Island	37.9005,-122.3713	x								x						x				Eelgrass present.	No oyster information. Poor access.
L	Richmond	37.9087,-122.3877 to 37.9014,-122.3252		x													x				Oysters present. Protect in marinas and on hard substrate.	Highly industrialized. Possible contaminants. Parts of shoreline lack hard substrate.
L	Point Isabel	37.9010,-122.3251 to 37.8986,-122.3158		x							x	x	x				x	5	20	196	Oysters present.	
L	Albany	37.8986,-122.3158 to 37.8842,-122.3157	x								x						x				Good access. Firm mud. Many oysters at Albany Dog Park. Albany Bulb Lagoon looks like a good oyster site. Good access.	May have contaminants.
L	Berkeley Beach (Race Track to Schoolhouse Beach)	37.8842,-122.3157 to 37.8706,-122.3172	x								x						x				Good public access. Oyster data available.	
L	East Cesar Chavez Park (Basin)	37.8706,-122.3172 to 37.8757,-122.3184		x													x				Lots of oysters on rip rap. City of Berkeley Park.	Oysters wiped out occasionally by sedimentation.
L	North Cesar Chavez Park	37.8757,-122.3184 to 37.8743,-122.3246		x				x								x	x				City of Berkeley. Eelgrass present.	Proposed ferry terminal.
L	West Cesar Chavez Park and Berkeley Marina	37.8743,-122.3246 to 37.8587,-122.3163		x													x				Some oysters present in the marina.	Exposed shoreline. Few oysters present.
L	Shorebird Park	37.8587,-122.3163 to 37.8638,-122.3112		x	x	x								x	x		x	1	5	10	UCD study indicates good recruitment, growth, and survival. Possible site for public education and small scale demonstration of restoration.	User conflicts from small craft launch. Sedimentation. May be a bad place for large scale restoration.
L	Berkeley (from Shorebird Park to Ashby Spit)	37.9638,-122.3112 to 37.8469,-122.3006	x								x						x					
L	Ashby Spit	37.8469,-122.3006 to 37.8459,-122.2994		x								x	x	x	x	x	x	1	3	6	Easy public access. Some oyster data available.	
L	Emeryville Crescent	37.8459,-122.2994 to 37.8245,-122.3205		x							x	x	x	x			x	5	100	559	Large area. Possible mitigation opportunities.	Potential user conficts with Bay Bridge.
L	Yerba Buena/Treasure Islands	37.8224,-122.3637	x								x						x				Looks like good oyster habitat. Herring present.	
K	Oakland Area	37.8245,-122.3205 to 37.7128,-122.1979		x							x										Oysters present at bay-facing marinas in Alameda.	
K	Middle Harbor Enhancement, Oakland	37.8049,-122.3328 to 37.7890,-122.3253	x								x										Possible mitigation opportunities.	
K	Lake Merritt, Oakland	37.8028,-122.2578	x								x										Lake Merritt channel opening project. Restoration opportunities. Interest from Lake Merritt channel opening manager, and others including the City of Oakland. Preconstruction survey needed. Community support. Oysters present.	
K	Fruitvale Area	37.7688,-122.2298			x								x								Educational opportunities. Dock owners supportive.	
K	Encinal Boat Ramp, Alameda	37.7693,-122.2907		x	x	x											x				UCD study indicates persistent oyster population.	Jetty with big boulders. Difficult to work. Oyster drills present.
H	San Leandro to Hayward Shoreline	37.7128,-122.1979 to 37.6257,-122.1512		x							x						x				Historic commercial oyster company.	Lots of marsh.
H	San Leandro Marina	37.7005,-122.1901 to 37.6911,-122.1853		x							x										Harbor master support. NOAA survey from new dock installation.	Survey in 2006 indicated few oysters present. Hydrocarbons present. Oyster drills present.
S	Hayward Shoreline to Dumbarton Bridge	37.6257,-122.1512 to 37.4969, -122.1082		x							x						x				Good site to test reef balls and living shoreline to reduce fetch, protect existing levees and marsh, and look at ability to form habitat. Support form EBRP Hayward Shoreline manager.	Steep levees. Lots of fetch. Shallow long mudflats. Oyster drills. Access difficult for much of the shoreline stretch.
S	Eden Landing Ecological Reserve	37.5756,122.1391 to 37.5923,122.0923	x								x	x	x	x							Breached salt ponds. Future breaches planned. CDFG interested in monitoring ponds. Managed ponds. Recruitment collectors would be good. Could build wave breaks and islands for birds from oyster shell. Historic oyster farm.	Baumberg pond may be too far from the bay. No public access (CDFG). Levees are hard to drive on in winter.
Q,P, O	South of Dumbarton Bridge	37.5097,-122.1113 to 37.4982,-122.1282		x	x						x										Salt pond breaches and restoration planned. Some oyster recruitment. Creek mouths might be a good place to look for oysters. Permanente Creek and Charleston Slough should be checked for oysters because they feed into Sailing Lake. Ducks Head (A6) will soon be breached.	C. gigas present and oyster drills present. Duck's Head has a gull problem. Lack of suitable substrate. Poor recruitment at Permanente Creek.
O	Sailing Lake, Mountain View	37.4227,-122.0917		x	x												x				Good for broodstock. Pop size estimated at 10 million. After lake drainage, oysters died back but rebounded. Highest known densities of oysters in Bay. Oysters at depths of 8 in to 15 ft. Disease free. Spat have been moved to MRGC. Salinity 20 ppt.	Possible user conflicts.
O	Palo Alto Baylands	37.4581,-122.0967 to 37.4615,-122.1054			x						x	x	x	x				10	100	601	Good access. Willing partners. Good settlement.	Poor water quality. Muddy. Marsh. Some fill. Need to look for drills.
O	Ravenswood Pier	37.4752,-122.1222 to 37.4981,-122.1279			x						x		x	x	x			10	80	424	Good oyster recruitment.	
O	SF2	37.4890,-122.1347	x									x	x	x							Former salt pond. Create living shoreline in borrow ditches. 30-40 islands to be built for bird habitat.	
N,M, J	Dumbarton Bridge to Oyster Point	37.4994,-122.1282 to 37.6804,-122.3796		x	x	x															Good oyster recruitment to substrate placed in this region. Large oysters where substrate is present. Westpoint Harbor is new and has harbormaster support.	Little appropriate substrate. Large currents. Shallow mud.
N	R1	37.5015,-122.1393	x								x	x		x							Reef balls and living shoreline might be good here. Good oyster recruitment nearby. Salt pond breaching and restoration planned for near future.	Large and costly erosion problem.
N	Bair Island	37.5346,-122.948						x								x					Lots of shell offshore. CDFW, MSI, POST supportive. Historic oyster farm. Features could benefit sturgeon and salmonids. Good recruitment.	High drill density. High abundance of fouling organisms and drills. Difficult conditions. Large currents. Shallow mudflats. Maintenance may be difficult.
M	Coyote Point	37.5895,-122.3159		x		x											x				Large oysters. Settlement inside marina. Oysters present on North Jetty facing SFO. Easy access. Harbor master supportive.	Few oysters, large swells and currents. Oyster drills present. Rats, raccoons, and skunks present along shoreline.
J	Oyster Point to Candlestick Point	37.6604,-122.3797 to 37.7081,-122.3744		x	x	x					x			x	x	x	x	10	80	408	Lots of oysters where hard substrate is present. Few drills. Willing partners. Salmon, herring, and sturgeon present. Good recruitment. State Park at Candlestick. Golden Gate Audubon supportive and potential island restoration at Candlestick. Oyster Point harbor master supportive. Possible mitigation.	Ferry terminal to be built at Oyster Point. Possible contamination. Disease present at Candlestick. Landfill at Candlestick.
J	San Francisco	37.7081,-122.3744 to 37.8108,-122.4766		x		x					x						x				Literacy for Environmental Justice is interested.	Urban area. Safety concerns on east side. Contamination. Armored shoreline difficult to survey.
J	Aquatic Park, San Francisco	37.8069,-122.4251		x		x											x				Dense patches on rip rap. Easy access. Good visibility.	Sediment burial. Lots of public use.
J	Alcatraz	37.8266,-122.4226	x								x	x	x								Looks like good oyster habitat. NPS.	
J	Crissy Field Lagoon, SF	37.8045,-122.4573	x								x	x	x	x							NPS. Lots of restoration in park. Good for public education.	
																		85	844	8479		