CHAPTER SEVEN

Shellfish Beds

THIS CHAPTER ADDRESSES SHELLFISH BEDS on hard substrate such as rock or shell aggregates, or mud/shell mix, together with the associated water column. (Shell hash areas in soft substrate are addressed in Chapter 4.) Shellfish beds are defined as locations where a shellfish species occupies more than 50% of an area of more than a few square meters (Schaeffer et al. 2007). Five species of shellfish occur in San Francisco Bay: native Olympia oysters (*Ostrea lurida*), California mussels (*Mytilus californianus*), hybridized Bay mussels (*Mytilus trossulus/galloprovincialis*), and non-native ribbed horsemussel (*Geukensia demissa*) and green bagmussel (*Musculista senhousia*). The latter two species are common in the estuary but do not occupy hard-bottom habitats and are not discussed further in this report. There are also small populations of the non-native Pacific oyster (*Crassostrea gigas*) in the South Bay, where eradication efforts are underway. Much of this discussion is based on Schaeffer et al. (2007), Grosholz et al. (2007), and Appendix 7-1.

Multiple age classes of native oysters can be found in rocky intertidal areas.

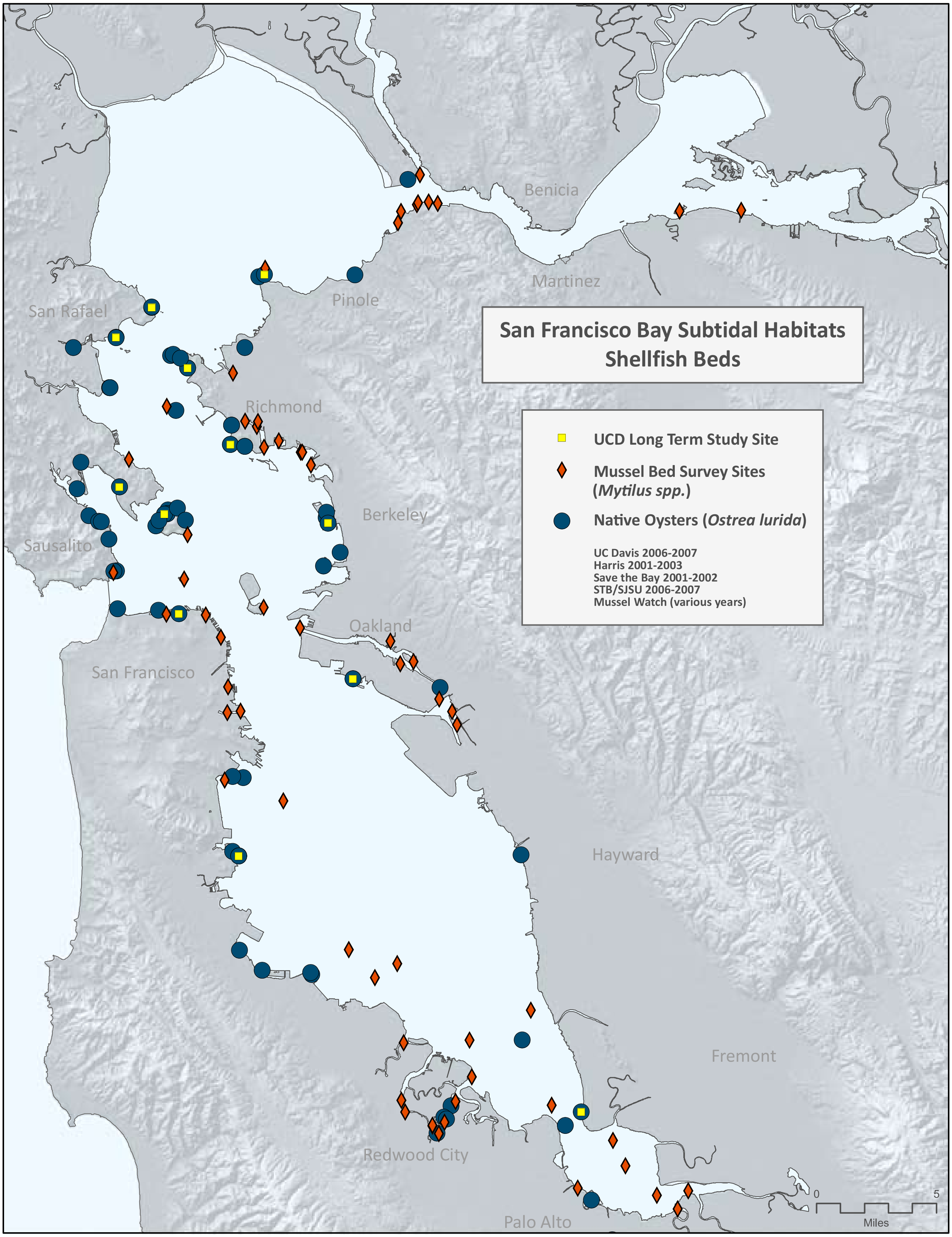


Figure 7-1: Distribution of Shellfish Habitat in San Francisco Bay.

Of these species, the Olympia oyster is by far the most abundant and is the only species that is a native confined to estuaries. Recent surveys for oysters in the intertidal zone have found numerous individuals on hard substrates in the Central Bay and to a lesser extent in the San Pablo and South Bays (Figure 7-1; Zabin, et al. 2009). The abundance of oysters in the subtidal zone is unknown because methods for surveying them are inadequate. Oysters settle on natural soft substrate such as mud/shell mix (Chapter 4), hard substrate such as rock outcrops (Chapter 5), and some artificial structures (Chapter 6).

Declines in extent of these rock habitats due to lowering for vessel traffic safety have been offset by the installation of artificial substrates (Chapter 6) such as riprap and seawalls.

The intertidal rocky shoreline is covered in sea lettuce and native oysters.

Shells of native oysters occur in the vast shell middens at various sites around the bay along with those of mussels and clams, attesting to the pre-European settlement presence of the native oyster. However, the actual historical abundance of oysters is poorly known, in part because of confusion between native oysters and *Ostrea lurida* brought from Washington or Oregon and planted in the bay. Townsend (1893) referred to native oysters as very abundant and overgrowing the shells of eastern oysters which had been introduced for aquaculture. Commercial harvest was important "since the days of the Spaniards" (Bonnot 1935), and native oyster reportedly made up about 15% of the total oyster harvest from San Francisco Bay in the late 1800s to early 1900s, producing up to 150 tons of meat per year during 1888-1904 (Barrett 1963).

The vast majority of available information on native shellfish species is on native oysters, and most of the following discussion addresses native oyster beds. Many of these issues would also apply to other hard-bottom shellfish beds, although there may be less interest in restoring them at this time than there is for oyster beds.

Various species of mussel can be abundant enough to form beds; most are confined to the more saline regions in and near the Central Bay where rocky substrates are common (Schaeffer et al. 2007). San Francisco Bay is marginal habitat for the native *Mytilus californianus*. The two native mussels (*M. californianus* and *M. trossulus*), and *M. galloprovincialis*, introduced in 1947, are common along the outer coast and presumably the bay populations are linked to the outer coast populations through larval exchange. The introduced Pacific oyster *Crassostrea gigas* may be completing its life cycle in the bay (C. Zabin, 2009, pers. comm.).

ONGOING OYSTER RESTORATION PROJECTS

Interest in restoring and maintaining oyster beds is demonstrated by the numerous restoration and research projects underway in San Francisco Bay, Elkhorn Slough, and the Pacific Northwest.

- http://www.bioone.org/toc/shre/28/1
- http://www.elkhornslough.org/research/conserv_oysters.htm
- http://www.habitat.noaa.gov/media/publications.html

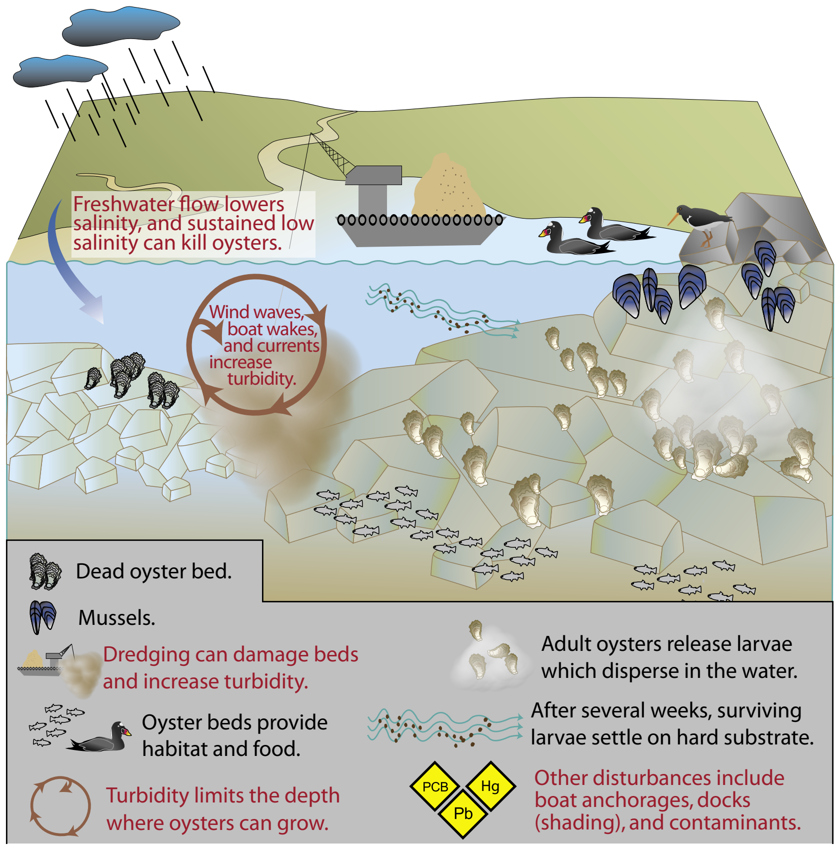


Figure 7-2: Conceptual diagram for shellfish beds in the San Francisco Estuary. This diagram displays processes that occur in and on shellfish beds, some of the ecosystem services these habitats provide, and threats to shellfish beds.

A native oyster on cobble at the Emeryville Crescent.

Conceptual Model for Shellfish Beds

Shellfish beds (Figures 7-1 and 7-2) provide several ecosystem functions and support several ecosystem services. The native oysters do not commonly form tall, three-dimensional reefs, as do Virginia oysters, although they can add structure to hard substrates and may be able to colonize and overgrow soft substrates. In this sense they can be considered a "foundation species" or ecosystem engineer, altering their environment by increasing bottom roughness, reducing current speeds, and as a result, trapping sediments. Oysters also increase physical heterogeneity, which can increase diversity of other marine invertebrates and also result in higher fish diversity and abundances than in neighboring, less complex habitats. Increased abundance of native oysters can locally increase the number of other benthic invertebrates (Kimbro and Grosholz 2006 for Tomales Bay). With their associated invertebrates, oysters provide food for fish, birds, and crabs.

Not all the functions attributed to oyster beds are applicable in the San Francisco Estuary. One key function of bivalves in many estuaries and lakes is increasing water clarity. In locations such as the Chesapeake Bay, turbidity results mainly from high phytoplankton biomass, which can be severely

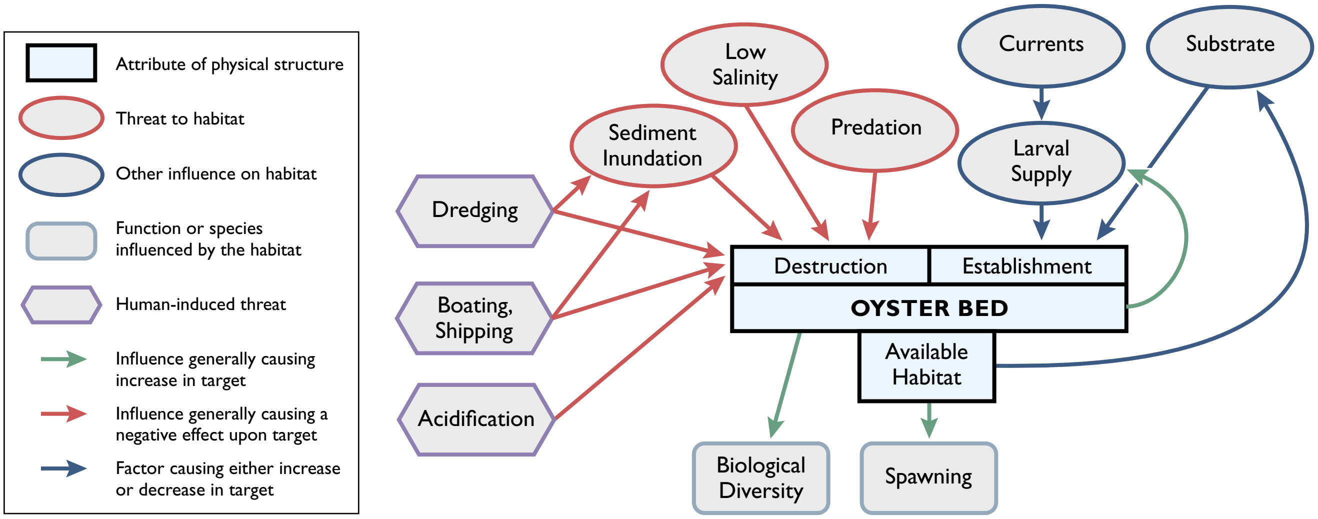


Figure 7-3: Influences on oyster beds and their functions and services.

reduced by bivalve grazing. In the San Francisco Estuary most of the turbidity is due to inorganic particles (Kimmerer 2004). No effect on turbidity was noted after the invasion of the "overbite" clam, *Corbula amurensis,* in 1987, despite its enormous abundance in soft sediments of the brackish northern estuary (Alpine and Cloern 1992). Since the greatest conceivable extent of restored and natural oyster beds is minuscule compared to the area suitable for clams, it is unlikely that oyster beds could exert a measurable control on turbidity except possibly in water immediately over or near dense oyster beds.

Native oysters colonize a mix of hard and soft substrate at China Camp State Park.

So far very few oysters have been found on soft substrates, although that could be partly due to inadequate sampling, owing to the lack of suitable technologies to carry out broad-scale surveys in the shallow subtidal zone. Oysters in Puget Sound are able to colonize on soft substrates (Betsy Peabody, 2007 West Coast Native Oyster Meeting), but in San Francisco Bay oysters probably cannot establish beds on soft substrate without larger particles for attachment due to the high resuspension rates of soft sediments (due to shallow water and wind waves). Since oysters are known to settle on existing shell, oyster beds could become established on shell deposits if the deposits are not too mobile.

The time scale for dispersal of oyster larvae (~2 weeks) is shorter than estimates of residence time in the estuary, which are up to 60 days for the northern estuary in summer and much longer for the south bay (Walters et al. 1985). This implies that a large proportion of the larvae would settle within the estuary. However, within-bay currents are large enough to disperse particles among the major basins in a few days, implying that the propagules generally should disperse broadly within the estuary before settling. Apart from larval supply, several factors may limit the development and maintenance of oyster beds. Juvenile oysters are particularly vulnerable to poor environmental conditions and predation, so variation in mortality of juveniles presumably has a big effect on subsequent abundance. Food limitation is very likely given the low chlorophyll concentrations in the northern estuary (and formerly in the south;

Cloern et al. 2007). Food limitation generally results in low growth rate, which extends the time to maturity, decreasing survival of oysters to maturity. In locations with low larval supply from other beds, local larval settlement may be limited by the density of adult oysters in the bed.

Threats to Native Oysters

The principal threats to native oysters seem to be high rates of sedimentation and extended periods of low salinity. Competition for space may be more important in the South Bay where hard substrate is limited and in the subtidal zone where fouling organisms such as sponges, tunicates, and hydroids are abundant. Intertidal substrate examined during surveys was around 40% clear of oysters, indicating that lack of attachment space may not limit abundance of intertidal oysters (Appendix 7-1). Other limiting factors include potential contaminant effects, especially for intertidal beds that are vulnerable to oil spills, and predation by fish, birds (for example, diving ducks), and possibly crabs. Oyster drills and small predatory snails present a low to moderate source of mortality to young oysters particularly in the South Bay. Diseases and parasites do not present a major threat, although this could change if population density increases and changes in water temperatures occur due to climate change. Heat stress in warm intertidal areas and overgrowth by algae may reduce oyster survival in local areas.

A recent bay-wide survey in 2006–07 (Appendix 7-1) found large areas of empty oyster shells in good condition, suggesting recent death. The high flows of 2006 may have reduced salinity for a long enough time in San Pablo Bay and possibly the South Bay to kill the oysters there. Daily mean salinity at the Romberg Tiburon Center monitoring site went as low as 5 ppm in spring of 2006, and X2 (distance up the estuary to where tidally-averaged bottom salinity is 2 ppm, Jassby et al. 1995) went below 45 km for several days, and was below 55 km for 3 months. This was the second longest duration of low salinity in the record since 1955 (Figure 7-4). Salinity in intertidal areas is subject to the large-scale salinity distribution in the estuary but can also be affected by local

Below: Native oyster.
Bottom left: Native oysters settled on rock.
Bottom right: Native oyster larvae ready to disperse into the water column.

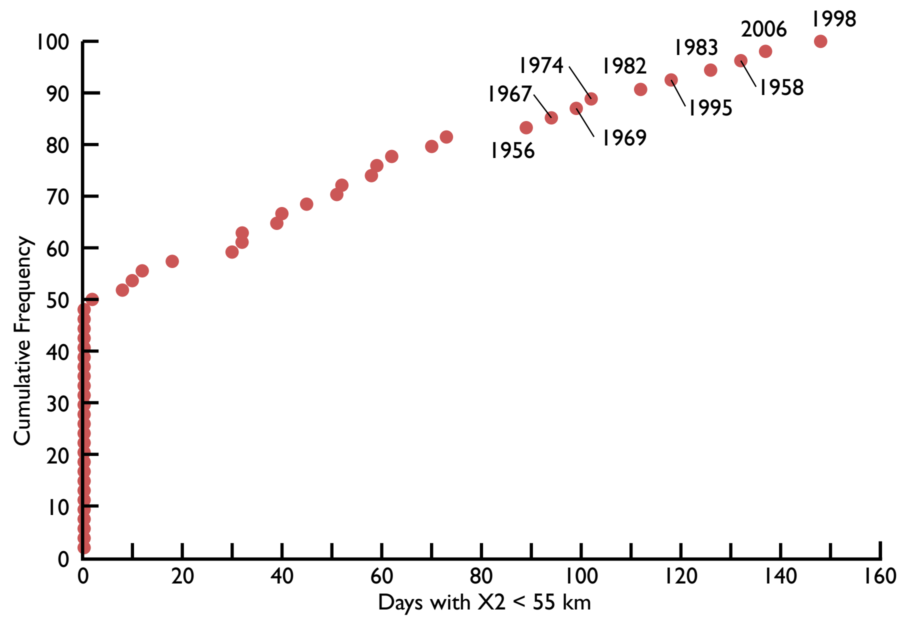


Figure 7-4: Low-salinity events in San Francisco Bay. The graph shows the frequency distribution of days with salinity less than 2 (near the landward limit of salinity penetration) < 55 km, approximately at the Benicia Bridge. The mean return time for a low-salinity event is the inverse of the frequency of events of at least that duration. For example, about 10% of the years have had low-salinity events at least as long as that in 1982 (112 days), so such an event can be expected roughly once in 10 years. Prediction of the frequencies of oyster die-offs would be more precise given estimates of the salinity-time envelope for survival of oysters. Data from Jassby et al. 1995 updated using the Interagency Ecological Program's Dayflow data (http://www.iep.ca.gov/dayflow/index.html).

runoff and discharge from wastewater treatment plants. This influence would be difficult to predict, and local runoff can be poorly correlated with flows through the delta. A San Rafael oyster restoration site lost around 99% of settled oysters after spring 2006, but the population recovered quickly (R. Abbott, Environ, 2009, pers. comm.).

Anthropogenic threats may include water pollution, boating, shipping, and dredging (Figure 7-5). If these activities occur near oyster beds they can directly disrupt beds or resuspend sediments that inundate beds. Ocean acidification is considered a growing threat to calcareous organisms in the ocean, and may become important particularly in the Central Bay with its strong oceanic influence. However, pH in much of the estuary may be controlled more by local processes (e.g., carbon dioxide input from sewage treatment plants and productivity cycles, Fuller 2010) than by any large-scale oceanic influence.

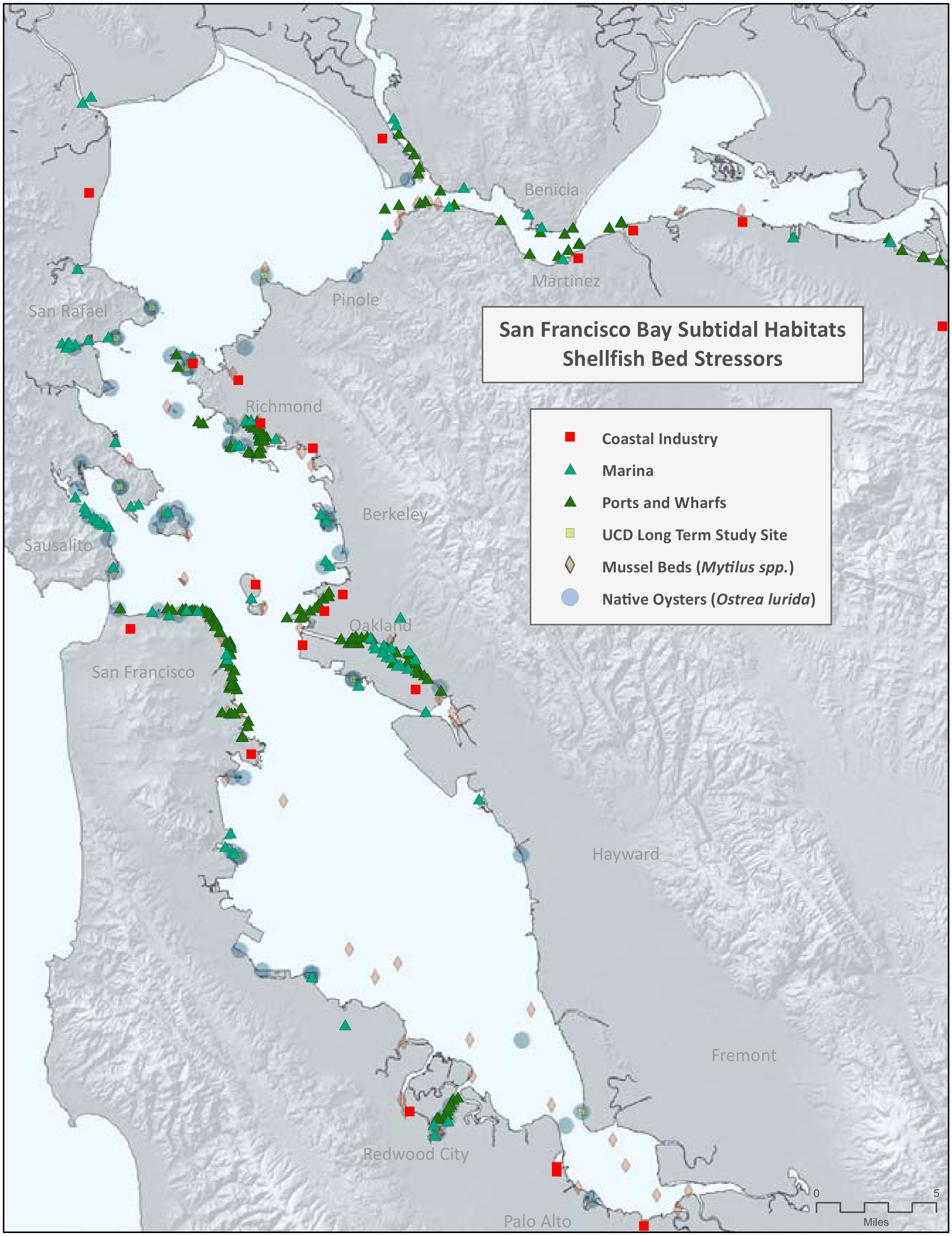


Figure 7-5: Locations of Shellfish Habitat Stressors in San Francisco Bay.

At right: Mobile oyster larvae swimming in the water column.
Far right: Native oysters settled on Pacific oyster shell.

Rationale for Establishing Goals for Shellfish Beds

Shellfish beds are an intertidal to subtidal habitat created by the interaction of living organisms with particular physical conditions in the estuary. Several functions of shellfish and specifically oyster beds discussed above could be considered helpful in moving the estuary toward a more natural, less uniform state with local heterogeneity benefiting some species. In regards to restoration, it remains to be seen whether it is possible to establish persistent oyster beds over a large enough area to have substantial ecological impacts. However, small-scale restoration projects have reported increases in species use such as herring depositing roe on the structures and birds feeding on them (R. Abbott, 2009, pers comm.). It may be prudent to continue to research methods to establish oyster beds, while also further investigating their ecosystem functions. It is also not clear to what extent the functions of restored oyster beds are due to the oysters or to the structures put in place to allow oysters to settle.

Below: Size difference between small native oysters and large Pacific oyster shell, used as a substrate for oyster restoration.
Bottom: Monitoring plate with newly settled oysters, tunicates, and barnacles.

Applying the approach outlined in Chapter 2, it is clear that the restricted extent of oyster beds may be limiting their support of valued ecosystem services. Furthermore, restoration has been demonstrated and is therefore feasible (Appendix 7-1), although questions remain about the anticipated trajectory of restoration and associated response of ecosystem functions and services. Therefore, restoration is warranted for oyster beds, but should be done within an experimental framework (see Adaptive, Phased Approach below and discussion of adaptive management in Chapter 2).

Ongoing restoration work near San Rafael has succeeded in obtaining population growth and good recruitment in at least some years. The oysters grow well, reach reproductive capacity early, are free of disease and parasites, and have low losses to predation (R. Abbott and C. Zabin, 2009, pers. comm.). Providing a substrate with highly complex surface areas (bagged clean Pacific oyster shells) results in high rates of settlement and abundant oysters, compared to less complex substrates such as riprap. Required maintenance appears to be minimal (R. Abbott, 2009, pers. comm.).

If restoration (including enhancement or creation) of oyster habitat should proceed, many aspects of the process will require investigation and refinement. Restoration projects should move towards larger-scaled pilot projects, but the focus should be on the value of knowledge gained as well as the value of the restoration projects themselves. Experimental restoration will help to answer broader-scale questions about the likely outcomes of restoration. Regardless of the extent of future restoration, oyster beds remain potentially valuable resources. The success of restoration, protection, and management depends on adequate understanding of how these beds develop, how they are maintained, and what threats they face.

The beds formed by mussels do not appear to be a priority for restoration in San Francisco Bay, because the beds are small, little is known of their ecological importance, and the mussels are abundant on the open coast and in other estuaries. There may be interest in researching the interaction and hybridization of *Mytilus galloprovincialis* with the native *M. trossulus*, but managing them would be difficult since these species and their hybrids are not easily distinguished.

Goals for shellfish bed habitat focus on protecting existing native oyster beds, creating and enhancing additional beds, and improving our understanding of ecosystem services, factors influencing the beds, and restoration methods, in order to improve our ability to protect and restore this habitat. The principal restoration goal, pending a satisfactory determination of its benefit, is to restore large areas of habitat suitable for native oysters. The 50-year maximum restoration targets are based on the acreage of shoreline areas out to a depth of 2m where native oysters have been documented, and correlate with recent monitoring data regarding distribution. Native oysters would not be restored throughout these target areas, but at a subset of locations within these larger

Biologists install bagged Pacific oyster shell reefs at the Marin Rod and Gun Club restoration site in San Rafael.

Mounds of Pacific oyster shells and eelgrass "seed buoys" (see stakes in the background) were used to restore oysters and eelgrass at the Marin Rod and Gun Club.

areas. The long-term acreage targets were developed with the assumption that without restoration efforts native oyster abundance will remain relatively stable. Should native oyster acreage increase considerably independent of restoration efforts, that increase should count towards the overall acreage target.

An Adaptive, Phased Approach to Oyster Restoration

An adaptive approach to restoration, conducted in phases from small scale to large (Appendix 7-1), would have two key advantages. First, the effort can begin at small enough scales to be tractable and to allow for the learning necessary to expand the scale of restoration projects in subsequent phases. Second, within a program of adaptive management, pursuing restoration in phases can ensure that information is gathered to answer the fundamental questions about the roles of oyster beds (i.e., questions under Science Goal 1, below) and the responses of oyster beds to environment (Science Goal 2), as well as questions related to restoration itself (Science Goal 3). That is, at each phase, investigations into the roles and responses of oyster beds and the relationship of these to the scale of the restoration will be embedded in any significant restoration project.

The phased approach begins with selecting sites for experimental restoration projects, mainly to refine site selection and restoration methods. Results from this phase will be used to design the pilot phase, which will scale methods to larger areas and also begin to gather evidence on the likely outcomes of restoration. Depending on results from the pilot phase, restoration could then be attempted at larger sites, with each step contingent on the development of evidence in previous phases indicating a high value for restored oyster beds.

The knowledge developed during each phase will be critical for answering the key research questions enumerated below. These include determining the effectiveness of oyster restoration in providing valued ecosystem services, the environmental controls on oyster beds, and the methods that will maximize the success of the restoration. Of these questions, the most critical is the provision of ecosystem services, since this is the justification for attempting restoration beyond the experimental scale. Thus, understanding of the extent of ecosystem services provided by restored oyster beds should be improved substantially at each phase beginning with the pilot phase, before the process moves into the next phase. To continue restoration without this knowledge could risk wasting public money if the restoration proves ineffective, and could jeopardize support for these and other restoration activities.

Before restoration is undertaken, principles for site selection should be established. These could include local conditions (for example, depth profile, sediment type, waves and currents, salinity patterns, turbidity) and the environmental context (for example, proximity to hardened shorelines, ports or piers, proximity to source beds for larvae, convenience for access and monitoring), taking into account likely changes in these attributes with long-term trends such as sea level rise and increasing water clarity. Initial work has been completed (Appendix 2-2 and 7-1).

Restoration phases may overlap to some extent; for example, evaluation could begin as soon as a year or more of data were available from each project. To maximize knowledge gained from each project, basic monitoring (for example, abundance of oysters) should continue annually after the end of the project; thus each project should be funded for a long enough period to encompass the design, construction, operation and monitoring, reporting, and post-project monitoring. The decision to terminate this monitoring should be based on the knowledge foregone by termination as well as by the additional cost of ongoing monitoring. Monitoring of the large-scale restoration projects should continue indefinitely to allow for answers to be developed about the long-term trajectories and responses to environmental conditions.

NATIVE OYSTER MONITORING AND RESTORATION PILOT PROJECTS

- Holly Harris, San Francisco State University: 1999 monitoring study, 2004 Masters Thesis
- Save The Bay/ San Francisco State University: 2001–02 recruitment study
- Richardson Bay Audubon Center: 2004–2010 monitoring and recruitment studies
- Marin Rod and Gun Club, Robert Abbott, Rena Obernolte, et al: 2004–2010 restoration project
- Berkeley Marina, Robert Abbott, Rena Obernolte, et al: 2010 restoration project
- Outer Bair Island, Robert Abbott, Rena Obernolte, et al: 2004–2006 recruitment study
- Pt Pinole Pier area, Obernolte et al, The Watershed Project: 2006–2010 recruitment study
- Save The Bay/San Jose State University: 2006–2007 recruitment study
- UC Davis, Zabin, Grosholz et al: 2007–2010 monitoring and recruitment studies

Above left: Marin Conservation Corps members and community volunteers bag Pacific oyster shell for restoration. Above right: A Marin Rod and Gun Club member shows a Pacific oyster shell string, another method of monitoring oyster recruitment.

PHASES IN AN OYSTER RESTORATION EFFORT

PHASE I. EXPERIMENTAL RESTORATION

This phase will develop the experimental design for the restoration to answer key questions about sites and methods (science goals). The phases within this group should be followed in sequence but can be accomplished for different sites at different times.

Phase I-1: No prior knowledge of site

Conduct a basic site survey.

Phase I-2: Limited site knowledge

Condition: Mapping or surveys have been conducted.

- Assess suitability of the site for restoration.

Phase I-3: Experimental restoration

Condition: Phase 1-1 and 1-2 actions completed; area is unlikely to recruit naturally and is suitable.

- Determine experimental design to fit the site.
- Establish replicated small-scale test plots at various elevations, and other treatments.
- Evaluate outcomes: persistence, recruitment, abiotic conditions, use by other organisms.
- Report evaluates restoration potential and lessons learned.

Following this phase an evaluation takes place in which decisions are made about whether and to what extent to proceed into pilot restoration. This decision should be made largely on the basis of feasibility and conditions at individual sites.

PHASE II: PILOT RESTORATION

This phase will expand on the previous experimental phase to determine the suitability of alternative methods of restoration at a larger scale than the experimental scale. It will also begin to evaluate the larger implications of restoration for its value in increasing the provision of ecosystem services (science goals 1 and 2 below).

Condition: Phase I has been completed for candidate site, and site remains suitable.

- Design small pilot restoration project (0.5 acre or less) to test hypotheses developed or provisionally tested in Phase I.
- Design includes explicit measures to determine quantitatively the use of the restored site by organisms and other evidence about the likely benefits of restoration.
- Establish replicated moderate-scale test plots.
- In the second year of the program, begin to assess aspects of ecosystem function (e.g., spawning substrate and nursery and foraging habitat).
- Evaluate outcomes including those in Phase I, and aspects of ecosystem function.
- Report findings including evaluation of restoration potential, value, and lessons learned.

Following this phase an evaluation takes place in which decisions are made about whether and to what extent to proceed into larger-scale restoration. The decision about whether to expand the scale of restoration should be based on an assessment that the restored oyster beds likely provide ecosystem services commensurate with the cost and effort involved in the restoration. This decision could be made provisionally on the basis of a few pilot projects, and re-evaluated as more pilot projects are completed. The decisions about where and how to restore should be based on lessons learned from individual sites about feasibility and conditions.

PHASE III. LARGER-SCALE RESTORATION PROJECT

This phase will expand on the pilot phase with the principal purpose being to evaluate the larger implications of restoration for its value in increasing the provision of ecosystem services (science goals 1 and 2 below). This phase will also determine how alternative methods of restoration scale up beyond the pilot scale.

Condition: Phase II has been completed for candidate site, and site remains suitable.

- Design intermediate-scale restoration project (~1 acre) to answer questions under science goals 1 and 2, and to further develop the art and science of oyster restoration.
- Design includes explicit measures to determine quantitatively the use of the restored site by organisms and other evidence about the likely benefits of restoration.
- Establish replicated larger-scale test plots.
- In the second year of the program, begin to assess aspects of ecosystem function (e.g., spawning substrate and nursery and foraging habitat).
- Evaluate the response of ecosystem functions and likely ecosystem services.
- Report findings including evaluation of restoration potential, value, and lessons learned.

If the value of the restoration as estimated in this phase continues to suggest further expansion, this phase may be repeated at different sites as pilot programs are completed, and the acreage target expanded at each site and the above process repeated. The decision about whether to expand the scale of restoration should be based on an assessment that the restored oyster beds likely provide ecosystem services commensurate with the cost and effort involved in the restoration. This decision would remain provisional with additional information coming in as pilot and then larger-scale projects are completed. The decisions about where and how to restore should be based on lessons learned from individual sites about feasibility and conditions.

At this scale a critical issue is the long-term viability of the restored oyster beds and their provision of ecosystem services.

Science Goals for Shellfish Beds

SHELLFISH BEDS SCIENCE GOAL 1

Understand the ecosystem services the shellfish beds support, and in what quantities, in their current state and after restoration.

Question A. What specific functions do shellfish beds support?

This question could be addressed in part by an examination of extant beds in different parts of the bay, supplemented by lessons learned during early restoration. These lessons may be transferable among sites if the influence of local conditions can be understood and quantified.

Question B. How much is attributable to the structure vs. the shellfish?

The basis for this question is discussed above.

Question C. How do the ecosystem services provided by restored oyster beds scale with the total area restored and its spatial configuration?

If oyster beds are being restored to support ecosystem services, enough beds must be restored to provide a substantial increase in these services. These services may scale linearly with the increase in bed area, or some other way (see discussion of restoration and ecosystem services in Chapter 3). The shape of this relationship presumably depends on feedbacks between the existing bed structure and both settlement success and mortality. This would be difficult to determine, particularly before restoration began. Assuming a linear response, though, it should be possible to calculate the extent or value of an ecosystem service of constructed oyster reefs, perhaps in terms of food, structural habitat for fishes and birds of concern, and shoreline protection per unit area or shoreline distance. This information could be used to project the value of the restored habitat, and this projection could be periodically updated with newly gathered data.

Native oysters are established on rock and soft substrates near Rat Rock in China Camp State Park.

A corollary of this question is how the degree of fragmentation of the habitat influences its function, i.e., whether a series of fragments performs the same function as a contiguous habitat of the same area.

Question D. What is the current extent of subtidal populations of oysters?

Intertidal oyster beds have been partially inventoried, but subtidal oyster beds are hard to see and most remote-sensing techniques are unsuited for use in shallow water. Knowing the extent of these beds is essential for answering the other questions about oyster beds, including their ecosystem-level effect and the large-scale impacts of restoration.

SHELLFISH BEDS SCIENCE GOAL 2

Understand the factors controlling the development and persistence of oyster and other shellfish beds.

Question A. How do individual beds respond to their local biotic and abiotic environment?

Dense beds of native oysters provide multiple habitat benefits, including establishing on available space and outcompeting non-native invasive species.

Salinity, temperature, wind and wave patterns, currents, sediment delivery, and predation or consumption may all play a role in the growth or shrinkage of oyster beds. However, these influences are understood only at the most basic level. The relationship between initial settlement of oyster larvae and hydrodynamic conditions, and between survival and both hydrodynamics and sediment supply, may determine population growth. However, predators can play an important role. Since oysters on a reef can be inventoried and examined, it should be possible to determine their population dynamics and mortality factors.

Question B. What limits the establishment of new beds, either under natural conditions or as restoration projects?

Oysters in the intertidal zone occupy less than half of the available space in regions where they occur. The extent of settlement may be related to larval supply, provided the available space is actually suitable for settlement. However, other unknown factors may be limiting the establishment of new beds.

Question C. How does estuarine circulation influence the movement of larvae and subsequent recruitment?

Once beds have been established, the potential exists for them to send larvae to other areas of the estuary and to establish remote daughter beds. This potential depends on duration of the larval stage and the very specific details of circulation both at the scale of the beds themselves and at a broader scale. Large restoration sites may contribute to settlement and even establishment of beds in remote locations provided the substrate is available and the local and regional currents are favorable. At the scale of individual beds, the rate of settlement is likely affected by local conditions and the behavior of late larval stages as well as the rate of supply of larvae.

Question D. What is the degree of connectivity among beds?

The previous question can be turned around: how do population and genetic structure vary among beds, and what can that tell us about the connectivity among beds? This is a particularly important component for understanding the larger-scale issues raised under Science Goal 1. Note that genetic structure and ecologically relevant population structure are likely to be different and operate at different scales, and require different tools for investigation. Research to date indicates some genetic structure among oyster beds (Jim Moore, 2008, CDFG, pers. comm.).

Question E. What influences survival of newly settled oysters?

Juvenile oysters are more vulnerable than adults to predation and other causes of mortality, and therefore variation in juvenile mortality can have a big effect on subsequent abundance.

Question F. What is the extent of mortality in oyster beds due to exogenous factors and how fast do the beds recover?

Low salinity caused die-backs on restored oyster beds in 2006, although the oyster populations on these beds rebounded quickly. Other potential hazards to oyster beds include oil spills, contaminant inputs, and physical disturbance.

SHELLFISH BEDS SCIENCE GOAL 3

Develop the most effective ways of restoring and protecting oyster beds.

Question A. How do physical structures, materials, spacing, and orientation of restored beds interact with the local environment to influence settlement and survival?

Local conditions including salinity, currents, and the supply rate of food, sediment, and larvae are likely to influence settlement and survival. Design and construction of oyster beds may influence settlement and survival differently depending on these local conditions. Therefore lessons from one site may not be entirely transferable to another.

Question B. What is the influence of predation, parasitism, disease, and algal overgrowth on the success of restoration?

Parasitism and disease have not yet been identified as significant factors in the dynamics of oyster populations in the estuary. This could change with increasing population density, and effects are likely to be sporadic and therefore difficult to detect and assess. Consumption by predators is both a source

Below left: Volunteers make Reef Balls™, artificial reef structures composed of native bay sediments (mud and sand), historic dredged oyster shell, and a small amount of Portland cement.
Below right: Volunteers retrieve shell bags from constructed reefs to monitor them onshore.

Volunteers monitor individual Pacific oyster shells covered in newly settled native oysters.

of mortality and a means by which the beds support ecosystem processes, so some amount of consumption is consistent with "success." Algal overgrowth has been identified in some beds.

Question C. How can beds be designed and built so as to make them self-sustaining and minimize the need for ongoing intervention?

Oysters must be dense enough on the beds to allow for reproduction. The minimum density probably depends on the physical layout and local currents. Ongoing restoration efforts indicate that oyster beds need to be cleaned of sediment periodically but require no other maintenance. Minimizing human intervention would reduce the cost of restoration and increase the likelihood of long-term persistence of the beds. This of course does not eliminate the need for periodic monitoring.

Question D. How do oyster beds and eelgrass beds interact, and how do they interact with other habitats?

Since some of the functions of eelgrass and oyster beds are similar, there may be advantages to establishing them in close proximity. Also, restoration should take into account potential negative effects on other habitats or services.

Question E. What are the best methods and timing for oyster restoration that minimize settlement of invasive species?

Question F. How do wind waves, wakes, water intakes, and turbidity affect oyster beds?

Wave action can affect beds directly or indirectly through increases in turbidity and suspended sediment. The degree and spatial extent of disruption to oyster beds by vessel wakes and turbidity and suspended sediment from wakes or dredging should be investigated to determine if protective actions are needed. Industrial intakes of water might entrain an excessive proportion of larvae if the intakes are located close to large oyster beds or restoration sites.

Question G. How do constructed oyster beds influence local water motion and sediment deposition?

Potential positive and negative effects of the beds as structure must be considered in designing and building oyster beds. These may affect the long-term success of the beds as well as conditions in the surrounding areas.

Protection Goals for Shellfish Beds

SHELLFISH BEDS PROTECTION GOAL 1

Protect San Francisco Bay native shellfish habitats (particularly native oyster *Ostrea lurida*) through no net loss of existing habitat.

Native oysters colonized on rocky substrate or possibly on artificial substrate such as a discarded tire.

- Shellfish Beds Protection Objective 1-1: Provide public access and recreational opportunities that minimize impacts to existing intertidal native shellfish habitat in the bay.

  Shellfish Beds Protection Action 1-1-1: Develop community stewardship of native shellfish beds through placement of educational materials and signs that educate the public about the importance of shellfish bed habitat. Place educational signs at high-density intertidal sites and at restaurants serving oysters, and work with agencies to include shellfish information in Water Trail, Bay Trail, and Department of Boating and Waterway educational materials.

- Shellfish Beds Protection Objective 1-2: Support preservation of existing intertidal and subtidal native shellfish habitat by locating new or reconstructed structures and shoreline infrastructure, or new dredging projects, away from high density native shellfish beds.

  Shellfish Beds Protection Action 1-2-1: When new construction or operation of shoreline infrastructure occurs close to shellfish habitat, conduct preconstruction surveys of native shellfish to determine if significant populations (high densities, large adults, multiple age classes) are present.

Native oysters and seaweeds attach themselves to monitoring stakes as part of a project by San Francisco State University researchers on the North Richmond Shoreline.

Shellfish Beds Protection Action 1-2-2: Promote partnerships with cities and counties to ensure that all proposed water intakes (for example, from once-through cooling and desalination facilities) minimize impacts to native shellfish beds by locating structures away from existing native shellfish beds and promoting use of technologies that avoid high levels of larval entrainment (for example, subsurface intakes near large shellfish beds).

SHELLFISH BEDS PROTECTION GOAL 2

Protect areas in San Francisco Bay with potential for future shellfish expansion, restoration, or creation.

- Shellfish Beds Protection Objective 2-1: Purchase subtidal property from willing sellers or create conservation easements for shellfish protection or restoration (including enhancement or creation). (Potential sources of funding may include the National Fish and Wildlife Foundation, The Nature Conservancy, State Coastal Conservancy, Audubon, NOAA Coastal Estuarine Land Conservation Program, land trusts, etc.).

- Shellfish Beds Protection Objective 2-2: If new projects are located in intertidal or subtidal areas, scale and orient them in ways that maintain or improve physical conditions (bathymetry, currents, etc.) needed to support shellfish survival and growth in areas identified in this report for future native shellfish habitat enhancement or creation projects.

Restoration Goals for Shellfish Beds

SHELLFISH BEDS RESTORATION GOAL 1

Increase native oyster populations in San Francisco Bay within 8,000 acres of potential suitable subtidal area over a 50-year time frame through a phased approach conducted within a framework of adaptive management.

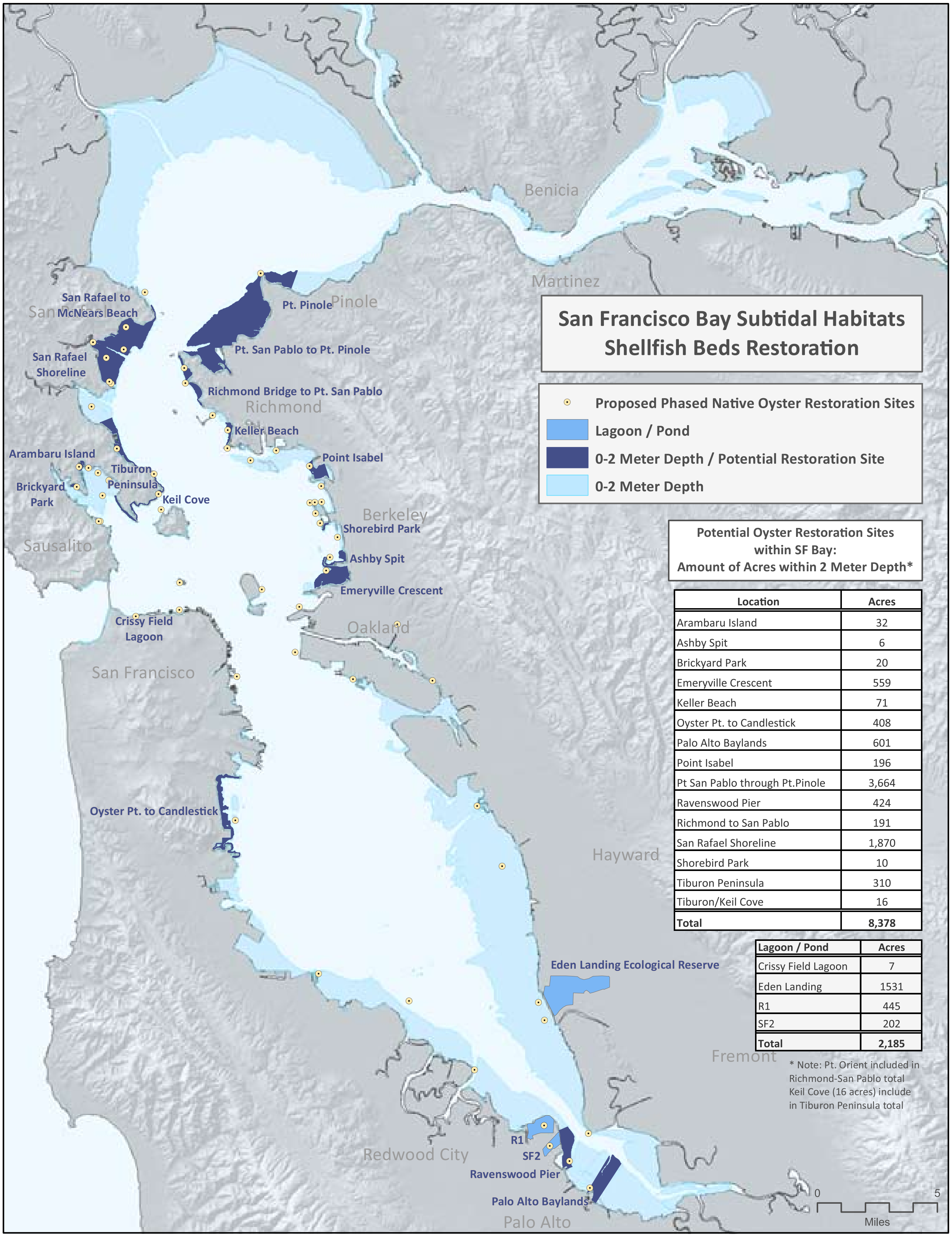
- Shellfish Beds Restoration Objective 1-1: Implement a program of adaptive management with phased restoration. Periodic reviews will determine whether the knowledge is adequate to support proceeding to the next phase. Provisionally the targets would be to increase native oyster populations within 10 acres of subtidal area within 5 years, within 400 acres of subtidal area within 10 years, and within 8,000 acres of subtidal area within a 50-year time frame (Figure 7-6).
- See list of priority native oyster restoration sites below, and more detail in the Native Oyster Restoration Table in Appendix 7-1 for site-specific phased actions.

RECOMMENDATIONS FOR RESTORING OYSTER BEDS

In areas with potential for restoration, UC Davis researchers estimate total potential acreage at preferred sites as 8,000 acres, the area defined by the shoreline segment out to 2m depth, which is about 9% of the total intertidal and subtidal habitat from the shoreline to a 2m depth. The site recommendations below are based largely on the recommendations from previous monitoring and restoration projects, two West Coast Native Oyster workshops, and the San Francisco Bay Native Oyster Working Group, and from participants in a workshop on shellfish restoration held in Tiburon, California in December 2008.

Priority native oyster restoration sites:

Earl F. Dunphy Park, Sausalito
Brickyard Park, Strawberry
Angel Island
Richardson Bay
Arambaru Island, Richardson Bay
San Rafael Shoreline from Marin Rod & Gun Club to south of McNears Beach area
Marin Islands National Wildlife Refuge
Richmond Bridge north to Point Pinole
Point Isabel Regional Shoreline
Albany Beach
Berkeley Shorebird Park
Ashby Spit to Emeryville Crescent
North Cesar Chavez Park, Berkeley
Lake Merritt, Oakland
Oakland Middle Harbor
Area adjacent to San Leandro Marina and nearby shoreline
Eden Landing Ecological Reserve, Hayward
Ravenswood Pier
South Bay Salt Ponds and adjacent offshore subtidal areas
Palo Alto Baylands Nature Preserve
West Point Harbor, Redwood City
Bair Island National Wildlife Refuge, Redwood City
Coyote Point, San Mateo
Oyster Point to area adjacent to Sierra Point Marina, South San Francisco



Potential Oyster Restoration Sites within SF Bay: Amount of Acres within 2 Meter Depth*

Location	Acres
Arambaru Island	32
Ashby Spit	6
Brickyard Park	20
Emeryville Crescent	559
Keller Beach	71
Oyster Pt. to Candlestick	408
Palo Alto Baylands	601
Point Isabel	196
Pt San Pablo through Pt.Pinole	3,664
Ravenswood Pier	424
Richmond to San Pablo	191
San Rafael Shoreline	1,870
Shorebird Park	10
Tiburon Peninsula	310
Tiburon/Keil Cove	16
Total	**8,378**

Lagoon / Pond	Acres
Crissy Field Lagoon	7
Eden Landing	1531
R1	445
SF2	202
Total	**2,185**

* Note: Pt. Orient included in Richmond-San Pablo total
Keil Cove (16 acres) include in Tiburon Peninsula total

Figure 7-6: Locations of recommended sites for phased native oyster restoration in San Francisco Bay.

Shellfish Beds Restoration Action 1-1-1: Establish a standing objective review panel to evaluate results and make recommendations on stepping through phases of restoration.

Shellfish Beds Restoration Action 1-1-2: Develop an integrated program of research, pilot projects, and eventually full-scale projects following the adaptive management framework (Chapter 2, Figure 2-3, see Phased Approach above), with the intent of simultaneously increasing the area of shellfish beds and learning about their contributions to ecosystem services. Specific attention should be paid to assessing the quantitative ecosystem response to restoration, and the resulting increases in ecosystem services to be expected.

Shellfish Beds Restoration Action 1-1-3: Develop a programmatic environmental review and permitting process to facilitate subtidal restoration projects, including native oyster restoration projects, to achieve multiple habitat and shoreline protection objectives.

- Shellfish Beds Restoration Objective 1-2: Incorporate native oyster restoration into other regional restoration and shoreline protection projects and initiatives.

Shellfish Beds Restoration Action 1-2-1: Initiate pilot subtidal integration projects, including living shorelines and living breakwaters, to demonstrate effectiveness and collaboration. When appropriate, construct living shorelines, including reef balls™ and other techniques, from native, biodegradable materials, maintenance dredging material that can be beneficially reused, or native rock.

Shellfish Beds Restoration Action 1-2-2: Support public–private partnerships to restore native oysters. Work with regional organizations and agencies to identify partners and projects that could incorporate native oyster restoration and monitoring into existing or planned projects. Groups include the San Francisco Bay Joint Venture, California Department of Fish and Game, Jerico Products, Inc., the Wildlife Conservation Board, and others.

Shellfish Beds Restoration Action 1-2-3: Incorporate San Francisco Bay oyster restoration goals into national strategies such as The Nature Conservancy Shellfish at Risk Program and the National Fish and Wildlife Foundation's Keystone Species Initiatives.