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The native oyster recruitment study in Central and South San Francisco Bay 2006-07

Sumudu Welaratna
San Jose State University

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THE NATIVE OYSTER RECRUITMENT STUDY IN CENTRAL AND SOUTH SAN
FRANCISCO BAY 2006-07

A Thesis

Presented to

The Faculty of the Department of Environmental Studies

San Jose State University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

by

Sumudu Welaratna

December 2008

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APPROVED FOR THE DEPARTMENT OF ENVIRONMENTAL STUDIES

Dr. Lynne Trulio, Professor, Department of Environmental Studies

Dr. Will Russell, Assistant Professor, Department of Environmental Studies

Rena Obernolte, MACTEC Engineering and Consulting Incorporated

APPROVED FOR THE UNIVERSITY

11/25/08

ABSTRACT

NATIVE OYSTER RECRUITMENT STUDY IN CENTRAL AND SOUTH SAN FRANCISCO BAY 2006-07

By Sumudu Welaratna

The Olympia oyster, *Ostrea conchaphila*, once abundant in West Coast estuaries of North America, is now uncommon in the San Francisco Bay, especially the South Bay. This study evaluated native oyster recruitment, at three sites each, in the South and Central Bay, using three experimental substrates: oyster shell strings, PVC recruitment tiles, and oyster shell bags. Oyster numbers and data on other settling organisms were recorded bi-monthly from October 2006 to October 2007. Oyster settlement was seasonal, major spatfall occurring between June 2007 and October 2007. Compared to the Central Bay, the South Bay was more productive for oyster settlement and had higher abundance of other hard shelled organisms. Of the three substrates, shell bags, which offered more surface area, were most productive. This research suggests *Ostrea conchaphila* restoration efforts in the South Bay may be successful, but more information is needed on conditions promoting long-term oyster survival and reproduction.

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The Native Oyster Recruitment Study in Central and South San Francisco Bay 2006-07

The range of the Olympia oyster, *Ostrea conchaphila*, extends along the west coast of North America from Alaska to Baja California (Kirby, 2004), and is the only oyster native to western North America (Figure 1). Over the past 200 years, this species has experienced serious population collapses throughout its range. Despite the need for research, *O. conchaphila* has not been the focus of study by modern scientists, resulting in information gaps regarding their basic biology, current status, and current and historic distributions. *O. conchaphila*, once plentiful in San Francisco Bay, were thought to grow in large reefs and probably had a large impact upon the ecology of the Bay. However, poor fishing practices, pollution, the introduction of invasive non-native species, and the massive losses of the wetlands of the Bay have greatly reduced their numbers (Cohen, 2005; Friedman, Brown, Ewing, Griffin, & Cherr, 2005; Kirby, 2004; SBSPRP, 2007).

Figure 1. Range of the Olympia Oyster.

In order to plan restoration activities for this species, it is imperative that habitat managers have as much information as possible regarding distribution of existing populations. Oyster restoration programs typically rely on natural populations for recruitment of spat, either through natural recruitment or through the use of natural populations to “seed” cultch and move newly settled spat into new locations (Obernolte, 2007). It seems clear that the Olympia oyster was historically a dominant species in San Francisco Bay ecology. Efforts to restore the ecological functioning of this bay cannot be complete without attempts to recover oyster populations. This research focused on current distributions and description of reproduction dynamics to help direct restoration efforts in San Francisco Bay by sampling oyster recruitment at multiple sites over the course of one year. The findings from this study are intended to identify potentially successful restoration sites and further describe seasonal recruitment rates. The results will be useful to restoration managers working in San Francisco Bay and all along the west coast within the range of the Olympia oyster, to either focus on or include oyster restoration as a component of project goals.

Background

Oceans and Oysters

People have long been under the impression that oceans were so vast that humans could not affect them with pollution inputs or by overharvesting organisms for food. The oceans seemed to be a world unto themselves, mysterious and plentiful (Craig, 2002). However, there is abundant evidence that humans are having significant detrimental impacts on the oceans, as fisheries all over the world are collapsing or exhibiting signs of stress (Halpern et al., 2008; Craig, 2002). The term “fishery” is a complex term, defined by the National Oceanic and Atmospheric Administration (NOAA) as including some or all of the following: “people involved, species or type of fish, area of water or seabed, method of fishing, class of boats, and purpose of the activities; any species of ocean organisms that humans harvest for food including fish, mollusks, and crustaceans” (NOAA, 2006). Halpern et al. (2008) studied 17 types of human impacts to the oceans of the earth, including organic pollution, damage from industrial fishing techniques, and intensive traditional fishing methods along coral reefs, and found that about 40% of ocean areas are strongly affected. Chan et al. (2008) studied the continental shelf area near the coast of Oregon and found that extreme anoxic conditions in the northern California Current system caused the deaths of benthic invertebrates in 2006. These types of massive eutrophication events are thought to be human caused, due to urban and agricultural runoff along the highly populated west coast (Chan et al., 2008). Halpern et al. (2008) categorized only four percent of ocean areas as being in pristine condition.

Oysters are found throughout most of the world in estuarine environments where freshwater from land enters the ocean. Estuaries support extremely high levels of biodiversity and productivity (Craig, 2002; Kirby, 2004). However, these environments are now negatively impacted throughout the world. Since industrialization, humans have made unprecedented landscape changes that have introduced massive quantities of sediment and nutrients into these habitats. In addition to terrestrial actions, humans have over-harvested oysters, directly destroyed ocean and estuarine habitat through large scale dredging, filling, and construction, introduced non-native invasive species, introduced pollutants, and altered water chemistry (Craig, 2002; Kirby, 2004).

Ecological Functions of Oysters

Oysters are recognized as a keystone or foundation species, meaning they have significant impacts on other species in their environment (Kimbrow & Grosholz, 2006). Beyond serving as a direct source of food for other species, the effect of oysters includes filtering water, suppressing organic matter and phytoplankton, nutrient dynamics, sediment and bank stabilization, and habitat support and breeding grounds for other species (Coen & Luckenbach, 2000; Craig, 2002; Kirby, 2004; Piazza, Banks & La Peyre, 2005).

Ostrea conchaphila are bivalves, which are invertebrates with two highly calcified shells which surround a soft body (Figure 2). Relatives include mussels, clams, and scallops. Shell widths are typically 35 – 40 mm in mature oysters, the maximum reported size of Olympia oysters is 75 mm (Couch, 1989).

Figure 2. Olympia Oysters, Photo: M. Phipps, Gallery of Marine Invertebrates of the Puget Sound; http://www.nwmarinelife.com/images/O_lurida.jpg.

Bivalves are filter feeders, effectively cleaning water by filtering organic matter, including phytoplankton, organic carbon, sediments, pollutants, and microorganisms, from water. One major contributing factor to the decrease in the health of the earth's oceans is eutrophication, a phenomenon in which high levels of nutrients such as phosphate and nitrogen are input into nutrient limited systems, resulting in very high productivity of plant growth and causing algal blooms (Craig, 2002; Kirby, 2004; Rosenberg, 1985). When the algae die, the decomposition of their material consumes the available oxygen in the water, resulting in low dissolved oxygen conditions, such as hypoxia, or even complete lack of dissolved oxygen, anoxia. These conditions are often temporary, but marine organisms may become ill or die when deprived of oxygen for even a short time. Eutrophication has long been an observable problem in freshwater systems and in semi-enclosed ocean environments such as bays and estuaries, and is now an increasing problem in the open ocean as well (Chan et al., 2008; Rosenberg, 1985).

By consuming plankton, oysters reduce the primary productivity of algae in the water column, thereby reducing the magnitude of local eutrophication, and therefore local hypoxic and anoxic conditions.

Another extremely important ecosystem function provided by oysters is the conversion of nutrients in the water column into a form that is consumed by benthic diatoms and other benthic organisms (Coen & Luckenbach, 2000; Ruesink et al., 2005; Sculati, 2004; Tolley, Volety, & Savarese, 2005). This increases the primary productivity in the benthic diatoms, providing more usable nutrients for the entire local foodchain. The bulk of what oysters filter from water is assimilated into the oysters themselves, who serve as an important food source for many marine species (Anderson & Connell, 1999; Tolley et al., 2005). What is not assimilated into the oyster is incorporated into larger particles which drop to the bottom and consumed by other benthic organisms (Tolley et al., 2005). Removal of particulates from the water column also reduces turbidity and increases light penetration through the water column, which is beneficial for aquatic vegetation including eelgrass, and other seagrasses which have been recognized as providing important habitat for many marine species (Coen & Luckenbach, 2000; Ruesink, 2005; Tolley et al., 2005). This clarity provides healthier habitats for aquatic organisms including fish, vegetation, and benthic organisms (Tolley et al., 2005).

The magnitude of the water filtration function provided by oysters can be very large. Unfortunately, so little is known about the current and historic San Francisco Bay oyster populations that no data are available on the estimated impacts of filtration

services to the Bay. However, peak historic populations of Atlantic oysters (*Crassostrea virginica*) in Chesapeake Bay on the east coast of the United States are estimated to have had the capacity to filter the entire volume of water in that bay once every three days, while the current population is thought to require almost year to do the same (Coen & Luckenbach, 2000; Craig, 2002).

As oysters decline, estuarine habitats have experienced a shift from calcium-rich rocky oyster reefs to soft mud (Piazza et al., 2005; Sculati, 2004). The rocky reefs are desirable both for the habitat they provide for countless species, and for the shoreline protection they provide to reduce erosion, and the impact of catastrophic storms (Piazza, 2005). To restore rocky structures, scientists in Louisiana and North Carolina are experimenting with introduced oyster reefs, composed of piles of shucked oyster shell, to provide shoreline protection in areas experiencing shoreline erosion and retreat. The reefs themselves are a hard substrate less susceptible to erosion. When oysters settle they produce calcium carbonate, which can act as a cementing agent within soft sediments to create more structure (Piazza, 2005).

As a keystone species, oysters have an essential role in providing habitat for an extensive array of marine life. The hard surfaces of oyster shells and the spaces between the shells provide places where a host of small animals can live (Coen & Luckenbach, 2000; Ruesink et al., 2005). When oysters form dense communities called beds or reefs, the surface area available to other sessile and mobile organisms is increased many times as compared to a similar sized flat substrate. In addition, the habitat of hard substrate provided by oyster shells supports a different array of organisms compared to muddy soft

substrate. Such species include smaller invertebrates such as mussels, barnacles, and anemones, along with larger invertebrates and vertebrates including crabs and small fish, and other organisms (Ruesink, 2005; personal observations, December 14, 2006). For example, fish egg clusters, gobies, and crabs (species unknown) are found in bags of oyster shells that have been set out at sites in San Francisco Bay for just two months (personal observation, February 26, 2007). In turn, numerous fish, bird and mammal species prey upon the organisms supported by oyster reefs (Anderson & Connell, 1999; Coen & Luckenbach, 2000; Tolley et al., 2005).

Many fish species also take advantage of the structural security provided by oyster reefs to lay eggs and use the reefs as nesting sites (Coen & Luckenbach, 2000; Grabowski, Hughes, Kimbro, & Dolan, 2005; Harding, 2003; Peterson, Grabowski, & Powers, 2003; Tolley et al., 2005). Fish are a crucial part of the marine ecosystem and an important economic commodity. Research conducted on the east and south coasts of the United States compared both the abundance of fish and fish health between habitats with an oyster reef substrate and soft sediment substrate, and found higher fish success associated with oyster reef substrate (Harding, 2003; Peterson, 2003). Peterson, Grabowski, and Powers (2003) conducted their study on the southeast coast of the United States to quantitatively evaluate the production of large fish and large mobile crustaceans on oyster reefs and sedimentary bottoms, with the purpose of estimating the degree to which oyster reef restoration could increase large fish and crustacean abundances. They tested whether large reef-associated fish and mobile crustacean production were limited by available oyster reef habitat. They found that 10 m² of restored oyster reef can yield

an additional 2.6 kg yr⁻¹ production of large fish and mobile crustaceans for the lifetime of that reef, which is important justification for the benefits of oyster reef restoration efforts (Peterson et al., 2003). Harding and Mann (2001) conducted a study in the Piankatank River in Virginia to assess the relationship between the abundance of transient fish species and oyster reef habitat. They found that as habitat complexity increased from the sandy shores to the oyster reefs, transient fish size and abundance increased. These associations between fish success and oysters further strengthen the argument that protecting oyster populations is of significance for insuring worldwide fisheries health. Similar work remains to be conducted on the west coast on the United States.

Currently, oyster reefs are not protected by law, but the link between oyster reefs and fish habitat could result in protection under the Magnuson-Stevens Fishery Conservation and Management Act of 1996. The Act was first established in 1976 to better manage the fisheries of the United States. In 1996, the Act was amended to institute the concept of “Essential Fish Habitat,” which is defined as

“aquatic areas and their associated physical, chemical, and biological properties that are used by fish and may include aquatic areas historically used by fish where appropriate; substrate includes sediment, hard bottom, structures underlying the waters, and associated biological communities; necessary means the habitat required to support a sustainable fishery and the managed species’ contribution to a healthy

ecosystem; and spawning, breeding, feeding, or growth to maturity covers a species' full life cycle" (NOAA, 2007).

With the definition of Essential Fish Habitat came the regulatory means to protect these habitats by governmental management agencies as a way to preserve fish. Although the association between oyster reefs and fish is being explored, more supporting information is required to officially classify oyster reefs as Essential Fish Habitat (Harding & Mann, 2001). Such a designation would mean that the Magnuson-Stevens Fishery Conservation and Management Act would provide regulation to protect existing oyster populations and help justify new oyster reef restoration and creation.

Historical Oyster Populations in San Francisco Bay

Ostrea conchaphila were once quite prolific in the San Francisco Bay. It was not until the mid-1850s when European settlers began commercially exploiting the oyster populations, that people significantly impacted their numbers (Friedman et al., 2005; Sculati, 2004). Early European settlers harvested Olympia Oysters for food, and their destructive dredging and trawling methods resulted in a dramatic decline in populations (Booker, 2006). Additionally, much of the shallow subtidal areas of San Francisco Bay have transformed from former rocky bivalve reefs to soft and muddy shorelines (Sculati, 2004). This is due to several factors including the introduction of very heavy siltation resulting from the extensive mining in the upper watershed of the Bay caused by extensive mining during the gold rush in the mid 1850s, the widespread timber harvesting in the early 1900s in the upper watershed of the Bay, and the ongoing erosion from heavy agricultural use and urban development within the watershed of the Bay. Other causes

for this shift in bay substrate include the destruction of existing oyster reefs from both poor fishing practices and the mining of oyster shell for use in cement mix and animal feed and the development of the Bay shoreline for urban uses (Booker, 2006; Sculati, 2004). By the late 19th century, people were harvesting farmed oysters rather than natural populations. Atlantic oysters, *Crassostrea virginica*, were shipped across the country and cultivated as the preferred species for consumption (Booker, 2006; Ruesink et al., 2005). However, intense pollution of the Bay resulted in the collapse of this commercial fishery in the early twentieth century (Booker, 2006).

Impacts of Non-Native Species

The earliest known non-native to be collected from the San Francisco Bay was the Atlantic Ocean barnacle found in 1853 (Cohen, 2005). By 2005, the numbers of exotic organisms overshadowed the native organisms. In many habitats within the Bay, including the muddy bottom and the salt marshes in the southern part of the Bay, “exotic species account for over half to nearly all of the species, individuals, and biomass” (Cohen, 2005). These introductions have dramatically reduced all native species populations, and altered natural habitats. Coupled with extensive changes due to development, such as siltation and pollution, the Bay is no longer comparable to what it was prior to the early 1800s. Many of the invasive species include invertebrate settling organisms such as sponges, tunicates and exotic bivalves, all of which are direct competitors for space with *Ostrea conchaphila*. These organisms also have the potential to overgrow and smother native oysters. It is difficult to understand and anticipate the ways in which non-native species alter the Bay ecosystem, and the role they play in the

limiting populations of Olympia oysters. This is a complicating factor in research projects in the Bay, requiring attention be devoted to non-native settling organisms and predators in any oyster study.

Non-native oyster species, which were brought in for food production, also have the potential to exclude native oysters from existing suitable habitat. Currently, the Pacific oyster, *Crassostrea gigas*, native to the pacific coast of Korea, Japan, and China, is commercially farmed in Tomales Bay, California, approximately 30 miles north of San Francisco Bay. Invasion by introduced oyster species can often be slow and subtle, as shown by a 30 year lag from the time Pacific oysters were introduced to the coast of South Africa to the time modest populations began to be observed in estuarine habitats (Robinson, Griffiths, Tonin, Bloomer, & Hare, 2005). Pacific oysters were also able to take hold in the Wadden Sea near the north coast of Germany, where they settled on native mussel beds, which are the only hard substrate to be found in the area (Diederich, 2005). In this case, the Pacific oysters grew aggressively enough to overgrow the mussel beds in some areas. Diederich's (2005) study found that several factors influenced the success of *C. gigas* in this natural ecosystem, including tidal height, the existence of a naturally occurring algae, and overgrowth by barnacles although only in cases where the oysters had settled on top of mussels. While her work also showed that mussels can co-exist with oysters, this research does not answer the question of whether the *C. gigas* might eventually exclude natives (Diederich, 2005). The complexity of the habitat effects and intra-species effects as well as the relatively slow movement for invasion illustrate how little is known the impacts of non-natives on *Ostrea conchaphila*.

Although the introduced oysters have not rapidly invaded their new environments, they do bring with them another problem: the potential to transmit disease causing organisms (Ruesink, 2005). Oysters are susceptible to disease, and oyster populations throughout the world have suffered mortality due to diseases and parasites (Encomio, Stickler, Allen Jr., & Chu, 2005). Friedman et al. (2005) studied the existence of various diseases and parasites within the micro-populations of oysters throughout the San Francisco Bay. They found parasites and disease infections on oysters at several locations within the Bay, while others were free of any infections (Friedman et al., 2005). This information is intensely valuable to restorationists who want to relocate oysters that, though native, may still transmit diseases and parasites (Friedman et al., 2005). There is no obvious indication that the presence of disease and parasites has an observable impact on San Francisco Bay Oyster populations (Obernolte, personal communication, March 13, 2008), but more study is needed. There is also the possibility that oysters may transmit diseases to fish, as Starliper (2005) found in a study on the transmission of pathogens between mussels and brook trout. Starliper (2005) found that by quarantining the mussels to allow the diseases to leave the organism, they were no longer a danger to the trout.

Research on Existing Oyster Populations and Recruitment

Challenges of Oyster Restoration

Although it is known that oysters and oyster reefs provide significant fish habitat and ecological functions, there is insufficient knowledge of oyster biology and functioning of oyster reefs in general (Coen & Luckenbach, 2000; Piazza et al., 2005;

Ruesink et al., 2005). According to Kirby (2004), this lack of knowledge can be attributed “to ‘shifting-baseline syndrome’ where no scientist alive today has ever seen an undisturbed, fully functioning oyster reef,” (Kirby, 2004, p. 13096) and this is a serious limitation for restorationists who are identifying restoration goals and associated success criteria for projects. In their 2007 report on the Subtidal Habitats in San Francisco Bay, The National Oceanic and Atmospheric Administration National Marine Fisheries Service (NOAA NMFS) described native oyster beds as “undoubtedly the most poorly understood of any San Francisco Bay habitat type... to date no live subtidal Olympia oyster beds have been found throughout the Bay” (NOAA, 2007).

Studying oysters involves considering many complex factors. Hydrodynamics, salinity, flow rates and temperature gradients are all potentially critical to the success and survival of oysters. It is very difficult to isolate these factors and understand them in natural settings. However acknowledging that these factors may play important roles in oyster health and survival as well as the health and survival of most marine species will aid restorationists to set restoration goals.

Methods for Surveying and Describing Oyster Populations

Due to the lack of data and the difficulty of obtaining it, many innovative methods must be used in studying this marine organism. Kirby (2004), from the University of California at San Diego, researched the history of oyster populations in 28 estuaries in eastern North America (*Crassostrea virginica*), western North America (*Ostrea conchaphila*) and eastern Australia (*Saccostrea glomerata*). In order to piece together the story of oysters in these areas, he first compiled anecdotal data but found there was not

enough direct data to create a comprehensive understanding of historical populations. Therefore, he assigned proxies, that are defined as “measurable descriptors that ‘stand in’ for desired but unobservable phenomena” (Kirby, 2004, p. 13098). He used four proxies including government actions taken in 1658 and 1679 to limit oyster harvesting, the oyster harvest weights as recorded in the 1600s and 1700s, and dating the earliest evidence of bottom dredging used in each estuary (Kirby, 2004). He showed that fishery collapse began in estuaries closest to urban centers, and more remote estuaries experiences collapses later, as those were fished for oysters as well. This estimation of collapse gives restorationists more information regarding how long the species have been severely impacted, and more information regarding restoration goals for population sizes.

In order to determine current populations, oyster researchers employ many different methods. Trulio and Obernolte (2001) surveyed a 19 hectare artificial lake, named the Sailing Lake in Mountain View, California, to collect data on the benthic community. They took two to three grab samples along eight transects at depths of one to four meters. Grab samples were strained with a one centimeter sieve, and the average density of bivalves per meter² was calculated and multiplied by the area of the lake between the depths of one and four meters to estimate the total lake population (Trulio & Obernolte, 2001). This was a relatively thorough population estimate, and was possible due to the small size of the lake and relatively dense oyster population. It would be hard to use this method for a sparsely populated, large area such as San Francisco Bay.

In 2005, Obernolte, Trulio, Mulvey and Abbott surveyed the Shoreline Sailing Lake for potential oyster predators and competitors. This was accomplished by divers making

observations and taking manual grab samples. The samples were again strained with a smaller one millimeter sieve. The oysters collected during this sampling were sent to the California Department of Fish and Game's Shellfish Health Laboratory at the Bodega Marine Laboratory, Bodega Bay, California, to test for presence of parasites or lesions. No oyster drills, parasites or disease agents were found outside of common polychaete worm parasites (Oberholte et al., 2005). Again, these methods are appropriate for relatively small, dense populations.

Kennedy and Roberts (1999) conducted a survey of the natural existing population of *Ostrea edulis*, the oyster native to the Strangford Lough in northeast Ireland. They surveyed transects in intertidal zones at spring low tides and subtidal zones with the help of scuba divers using inventive methods to secure the transect lines and quadrats. Percent coverage was estimated when collecting the data using quadrats. They then calculated the total available suitable substrate and the actual total population (Kennedy & Roberts, 1999).

Kater, van Kessel, and Baars (2006) created survey methods to estimate the distribution of local edible cockles, *Cerastoderma edule*, in the Eastern Scheldt region in the Netherlands. Cockles are a bivalve with a habitat distribution similar to oysters, and there are similar challenges to describing their population. Kater et al. (2006) surveyed the intertidal area by setting up 500 survey stations at which they collected physical samples and took biomass measurements for 11 years. These data were coupled with environmental parameters, including current velocities and salinity gradients, and

incorporated into a computer model to create a habitat map for this organism in this area (Kater et al., 2006).

Ford, Cummings, and Powell (2006), representing three different marine research institutes in the northeastern United States, undertook the task of estimating mortality in natural oyster populations in Delaware Bay. To estimate historical populations, dredge records were assigned as proxies. To determine current population mortality, they used the box-count method where dead individuals are those in which the valves are still articulated, in a effort to avoid re-counting dead individuals more than once. To gather current natural population data, they employed dredging to sample the numbers of live and dead oysters in given areas (Ford et al., 2006). These studies show surveying existing populations of benthic marine creatures is difficult, expensive, and at best provides estimates rather than specific counts.

Methods to Study Oyster Recruitment

Researchers studying oyster recruitment have also used many different methods. Kimbro and Grosholz (2006) recently completed a study of the effects of disturbance on Olympia oyster community richness in Tomales Bay located on the coast of California approximately 50 miles north of San Francisco Bay. In order to study the effects of disturbance, they randomly marked 0.15 x 0.15 meter quadrats along 50 meter transects along the naturally existing shoreline, which consists of a rocky intertidal zone. Within the quadrats, levels of disturbance were assigned. To simulate the disturbance of waves and overturning of rocks, primary sessile species were removed with a hammer and chisel at varying percents of reduced cover from 100% to 0%. Recolonization of the naturally

existing and disturbed substrate by both sessile and mobile species was studied to determine community richness, evenness and diversity. They found that quadrats with more oysters were associated with higher intertidal species diversity than quadrats with fewer oysters (Kimbrow & Grosholz, 2006). Clearing existing substrate and measuring recruitment rates could provide different results than measuring recruitment on newly introduced substrates.

Hixon and Brostoff (1996) compared effects of succession and fish grazing on Hawaiian coral reef algae. Although they were not studying oysters, they employed methods that are useful for oyster recruitment research. Specifically, they used primary settling tiles as are often used for studying benthic marine organisms, and in order to reduce introduced bias from the tile material, three types of tiles were used: naturally occurring coral material with contours and irregular shapes; square flat tiles cut of coral rock all of the same size; and PVC settling tiles all of the same size. By employing these methods in situations where the fish herbivory could be controlled, Hixon and Brostoff (1996) were able to compare the herbivory intensity in difficult to sample ecosystems and found that herbivory had a large effect on the composition and biomass of algal assemblages on coral reefs. The use of multiple types of settling materials is of interest to oyster researchers as there appears to be preferential settlement that is not completely understood.

Saucedo, Bervera-Leon, Monteforte, Southgate, and Monsalvo-Spencer (2005) experimented with the influence of recruitment material and color on recruitment rates of hatchery reared pearl oysters, *Pinctada mazatlanica*. They used an “envelope” type

recruitment collector, consisting of an outer bag and inner substrate made of the same materials. Bags were made in different color combinations, and with different materials and placed at different depths within settlement tanks. There were significant findings regarding preference for a depth of 60-90 cm in the water column, preference for collector materials, with fishing net being most the most preferable material and, surprisingly, for collector color, where the red/green collector received highest recruitment levels (Saucedo et al., 2005). These findings confirm that there is preferential settlement between recruitment collectors due to material type. Therefore the materials used to measure recruitment must be chosen with care.

Restoration Efforts in San Francisco Bay

Current Oyster Populations in San Francisco Bay

Efforts to restore *Ostrea conchaphila* in the San Francisco Bay are relatively recent. Naturally occurring populations were almost extirpated, but they do still exist throughout their range in limited numbers, although not in the form of reefs or beds (Friedman et al., 2005). Natural populations exist in pockets throughout the Bay, growing on rocks, cement and other hard substrates along the shoreline (Figure 3). A survey by Harris (2004) also concluded that *Ostrea conchaphila* is mainly limited to rip rap in docks and marinas.

Figure 3. Typical Rip Rap Shoreline Along the Western Shore of San Francisco Bay,
Photo: J. Stalker, Save the Bay, 2006.

The 2007 NOAA NMFS report describing subtidal habitats and associated taxa was produced as part of the San Francisco Bay Subtidal Habitat Goals project, “a collaborative effort to establish a comprehensive and long-term management vision for research, restoration and management of the subtidal habitats of the San Francisco Bay” (NOAA, 2007). The Project is an interagency partnership between the San Francisco Bay Conservation and Development Commission (BCDC), the California Coastal Conservancy, National Oceanic and Atmospheric Administration, and the San Francisco Estuary Project (BCDC, 2007). The purpose of this project was to provide common understanding of the subtidal habitats and to have common goals and direction for research and restoration based on good information (BCDC, 2007; NOAA, 2007). A map in the NOAA NMFS report showed oyster presence documented only as far south as Redwood City.

The exception is one naturally occurring subtidal population of *O. conchaphila* thriving in a man-made lake in Mountain View, the Sailing Lake. Built in the 1980s adjacent to a closed landfill, the Sailing Lake is a 50 acre lake in Mountain View's Shoreline Park. The water for the lake is pumped in from the adjacent Charleston Slough and flows out the other side into Permanente Creek. Both the slough and the creek are intertidal at those points, with full Bay interaction. More abundant bivalves found in the San Francisco Bay, based on biomass, are the Japanese littleneck clam (*Venerupis philippinarum*), the green mussel (*Musculista senhousia*), the Baltic Clam (*Macoma balthica*) the eastern soft-shell clam (*Mya arenaria*), and the amethyst gem clam (*Gemma gemma*) (Trulio & Obernolte, 2001). Not one of these species is native to the west coast of North America, much less to San Francisco Bay. In Shoreline Lake, the species with the greatest number of individuals were the Olympia oyster (*Ostrea conchaphila*), eastern soft-shell clam, the bay mussel (*Mytilus trossulus*), and Japanese littleneck clam (Trulio & Obernolte, 2001). Of these, the Olympia oyster and Bay mussel are native to the Bay. Not only was the makeup of the bivalve distribution quite different in the lake from the Bay, it was also dominated by *Ostrea conchaphila*, the native oyster which seemed to be struggling in the Bay proper. Further study of the oyster bed and water quality at Shoreline Lake would be useful for understanding why this particular population is thriving (Trulio & Obernolte, 2001). Factors that may contribute to the presence of this population are hard substrate on lake sides, clear water, constant water velocities, and spat retention.

Restoration Potential for the San Francisco Bay

Because Olympia oysters are still present in the San Francisco Bay, new populations can potentially be established by providing attractive substrate for them to settle on. Existing native oysters release spat into the waters which can then attach to a hard surface and grow into adult organisms. A female oyster can release up to 250,000 fertile spat each mating cycle (Sculati, 2004) (Figure 4). The species name *conchaphila* means “shell loving” and *Ostrea conchaphila* spat readily attach to and thrive on oyster shells. They are also able to colonize rocks, cement, and other hard surfaces. In the Bay, scientists and restoration groups have put out clean oyster shell, the preferred substrate for *Ostrea conchaphila*, and found juvenile oysters within months (Oberholte, 2007).

Figure 4. *Ostrea conchaphila* Veligers from an Individual Olympia Oyster from San Francisco Bay, Photo: J. Moore, California Department of Fish and Game, 2007.

The current strategy for restoration in the San Francisco Bay is to provide more substrate; this is the same strategy that is employed in Chesapeake Bay on the East Coast of the United States, where oyster restoration efforts have been underway for decades. Adding more oyster shell substrate, thereby creating more habitat for *Ostrea conchaphila*, is a difficult and expensive undertaking. There is also some debate as to whether this is indeed the best method and if other native or less permanent substrates should be considered. And there is additional debate as to whether oysters are in fact

substrate limited or if other environmental factors such as salinity, flow rates or interaction with competitors are limiting their reproduction and survival. More research is needed to understand the dynamics of the existing populations of Olympia oysters to ensure that future restoration efforts are as targeted and successful as possible.

The San Francisco Bay Native Oyster Working Group

In the last five years, the interest in *Ostrea conchaphila* within the San Francisco Bay has steadily grown. This is in large part due to support and funding given by the National Oceanic and Atmospheric Administration (NOAA) towards research and restoration efforts of the Olympia oyster. Research on this species began a bit earlier in the more northern reaches of its range, especially in and around the Puget Sound in Washington State where the Olympia oyster has relatively large naturally occurring populations. NOAA funded the first ever West Coast Native Oyster Conference for three days in the fall of 2006. The location was at the Marin Rod and Gun Club, in San Rafael, which is home to oyster research projects run by MACTEC Engineering and Consulting Inc. Bringing together researchers from Oregon and Washington states and prominent Atlantic oyster researchers from the East Coast was enlightening and motivational for the researchers in the San Francisco Bay Area. During the conference, some myths that Olympia oyster researchers in California had were dispelled, including the ability of oysters to live on relatively soft substrates. Although the mud in the North Bay of Case Inlet in Washington is composed of larger soil particles, unlike the very soft fine clay sediments around the San Francisco Bay, it was a surprise to California researchers when

those from Washington presented information on a large naturally occurring Olympia oyster population living on mudflats.

The greatest impact of the first West Coast Native Oyster Conference was that it inspired the creation of the San Francisco Bay Native Oyster Working Group. This is an informal collaborative partnership between groups doing oyster restoration and monitoring in San Francisco Bay, including the California Coastal Conservancy, Kleinfelder, MACTEC Engineering and Consulting Inc., the Natural Heritage Institute, the NOAA Restoration Center, San Jose State University, Save The Bay, the Smithsonian Environmental Research Center, the Richardson Bay Audubon Center, the University of California at Davis, and others. In 2007, the working group took on the tasks of developing shared protocols for survey methods and to focus on highest priority information including viability of substrates for restoration, timing of settlement, intensity of competition from other settlers, and settlement rates at two distinct depths. By having shared protocols researchers can easily pool data for a more comprehensive picture of San Francisco Bay with regards to the Olympia oyster.

Current San Francisco Bay Restoration and Oyster Recruitment Projects

This research is especially relevant now, as there are a number of very large estuarine restoration projects under way in the San Francisco Bay. The largest and most high profile of these is the South Bay Salt Pond Restoration Project. Since the early 1800s, an estimated 85% of the historic tidal marshes in the San Francisco Bay and Bay Delta Estuary were lost to development for urban and agricultural use and salt production. South of the San Mateo Bridge, most of the San Francisco Bay is ringed by

commercial salt ponds, which had their beginnings in the mid-1800s (SBSPRP, 2006). In 2003, The United States Fish and Wildlife Service and the California Department of Fish and Game acquired 15,100 acres of these former salt ponds located at the south end of the San Francisco Bay with the intention of restoring a large portion of them back their historic habitat of tidal wetlands (Figure 5). This is the largest wetland restoration effort on the west coast of the United States (SBSPRP, 2006). The project's goals are to "[1] restore and enhance a mix of wetland habitats, [2] provide for flood management, and [3] provide public access and recreation opportunities" (SBSPRP, 2006). Oyster restoration has the potential to play an integral role in the first of these goals and to a lesser degree in the second two. The restoration of a functioning wetland is not completely understood, and this lack of knowledge about what makes a fully functioning wetland makes it difficult to set restoration goals (Zedler, 1996). Similarly, insufficient knowledge of the role oysters play within the larger ecosystem also makes setting specific goals for restoration of oysters difficult (Coen & Luckenbach, 2000; Ruesink et al., 2005). The South Bay Salt Pond Restoration Project has coordinated teams of researchers to conduct extensive detailed analyses of existing conditions, including bathymetric surveys of the area, water and sediment sampling, hydrodynamic information, mapping of existing infrastructure, and existing wildlife use of salt ponds and adjacent habitats. The Native Oyster Recruitment Study in Central and South San Francisco Bay 2006-07 Project was established in part to provide information to incorporate into this extensive body of knowledge being compiled by the SBSPRP to benefit the Salt Pond Project restoration

managers if they seek to incorporate oyster population protection and enhancement goals within the larger salt pond restoration project.

Figure 5. South Bay Salt Pond Restoration Project Map.

The University of California at Davis is currently conducting a two year project in the San Francisco Bay called Documenting the Status of Native Oysters in San Francisco Bay, California. The primary goal of their project is to “provide critically needed information for native oyster restoration groups regarding how to prioritize sites for restoration efforts” (Grosholz, 2006, p. 2). This includes “information about where and why to expect high recruitment, growth and survival and which predators and competitors [particularly the invasive predator, the Atlantic oyster drill (*Urosalpinx*

cinerea)] are most likely to limit growth and survival will be key to the success of these efforts” (Grosholz, 2006, p. 2). UC Davis surveyed at 12 sites during their project (Figure 6).

Since 2005, a private consulting firm, MACTEC Engineering and Consulting Inc., has been implementing grant funded oyster research and restoration efforts in San Rafael and Redwood City. They began by setting out various configurations of Pacific oyster shells in mesh bags in subtidal areas in San Rafael and Redwood City to record oyster settlement data (Figure 6). They have also experimented with transplanting Pacific oyster shell that is "seeded" with Olympia oyster spat from known populations to enhance nearby restoration efforts. In 2007 they installed small artificial reef configurations in San Rafael to begin to understand the realities of hydrodynamics and especially the intense sedimentation issues within San Francisco Bay with regards to oyster restoration efforts.

The Richardson Bay Audubon Center and Sanctuary also began looking at oyster settlement in 2006 (Figure 6). They have conducted eelgrass habitat research and restoration, and have located their oyster settlement research in these areas in order to see if there are effects by eelgrass beds on oyster recruitment. They have partnered with the West Coast Native Oyster Working Group (Richardson Bay Audubon Center and Sanctuary, 2007).

And finally this study, The Native Oyster Recruitment Study in Central and South San Francisco Bay 2006-07, is a joint effort of Save the Bay staff and myself. We partnered to study six sites in the Central and South San Francisco Bay (Figure 6).

Methods were designed by a working group of staff from Save the Bay, scientists from San Jose State University, the Smithsonian Environmental Research Center, UC Davis, NOAA, and private consultants.

Figure 6. Map of all Native Oyster Projects in San Francisco Bay 2006-07.

Native Oyster Recruitment Study in Central and South San Francisco Bay 2006-07

Research Objectives

This study was a collaborative effort to research population dynamics and restoration opportunities for *Ostrea conchaphila* in San Francisco Bay and included collecting data from six different sites. Three sites were located in the South Bay, in the area of the South Bay Salt Pond Restoration Project. The other three sites were located further north in the Central Bay. The sites were selected to assess recruitment rates in parts of the Bay

that differ in terms of hydrology and water quality. This range of sites was chosen to identify potentially successful future restoration locations. Data were collected bi-monthly and quarterly and three to four different recruitment substrates were used to collect data on oyster spat recruitment at each site. The recruitment rates were measured bi-monthly in order to capture the timing of spatfall and assess how oyster recruitment interplays with recruitment by other species. This information is expected to help managers in their efforts to maximize oyster restoration in a habitat that is full of other organisms competing for settlement space. This study addressed the following research questions:

1. Where are oysters found, using site surveys and recruitment surveys, in Central and South Francisco Bay?
2. How do oyster spat recruitment rates vary throughout the year?
3. How does oyster spat recruitment differ between the Central and South Bay?
4. How do oyster spat recruitment rates differ between different substrates including oyster shell strings, PVC recruitment tiles, the bricks to which tiles are attached, and oyster shell bags?
5. How do the variety and number of other species present on different substrates vary between the Central and South Bay sites and over time?

Methods

Study Area

This study focused on oysters found in San Francisco Bay, located on the west coast of California, in the middle of their range from north to south. The San Francisco

Bay drains approximately 40% of California's land area. The Sacramento, San Joaquin and Guadalupe Rivers and numerous smaller rivers and creeks drain into this Bay and out into the Pacific Ocean. The Bay is surrounded by heavily populated and developed areas supporting over seven million people, including the cities of San Francisco, Oakland, and San Jose.

Site Selection

Sites were selected based on these criteria:

1. Three sites were located in Central San Francisco Bay and three in South San Francisco Bay. NOAA defines the south central and northern parts of the Bay by using the bridges as delineators. The area south of the Bay Bridge is the Southern Bay, between the Bay Bridge and San Rafael Bridge is the Central Bay, and above the San Rafael Bridge is the North Bay (NOAA, 2007). For this project sites south of the Dumbarton Bridge are considered in the South Bay, and for simplicity the other three sites are considered Central Bay, although Oyster Point Marina site is a little south of the Bay Bridge and the San Rafael Canal site is a little north of the San Rafael Bridge.
2. Naturally occurring *Ostrea conchaphila* populations were confirmed at or within the vicinity of each site to ensure probable sources for recruitment. Choosing sites with confirmed natural populations was a challenge, and exceptions were made for this criterion. Exceptions included all three south bay sites, where no existing naturally occurring oyster populations could be observed along the nearby shorelines. However populations occurring to the

north and south within five miles were considered evidence of existing oyster populations that could provide recruitment to our introduced substrates.

3. Sites included a dock, bridge, or other structure that extends into the water to provide a structure to suspend experimental substrates from
4. Sites were owned or managed by persons or agencies that would permit access, allow project installation for a one-year period, and allow monthly monitoring activities.

Figure 7. Locations of Study Sites for The Native Oyster Recruitment Study in Central and South San Francisco Bay 2006-07.

Selected Sites

Specific details on each site are as follows:

- 1) San Rafael Canal, San Rafael (lat: 37° 58' 11" N, long: 122° 29' 59" W). The San Rafael Canal is located on the west side of the Central Bay just north of the San Rafael Bridge. Initial surveys did not show naturally occurring oysters, however, good recruitment was observed by MACTEC Engineering and Consulting Inc. at the Marin Rod and Gun Club approximately 2.1 miles (3.38 kilometers) south of project site. In late 2007, naturally occurring oysters were found on rip rap surrounding the marina. Experimental substrates were hung roughly 0.3 meters below the surface from a floating dock behind a residential complex.
- 2) Berkeley Marina, Berkeley (lat: 37° 51' 60" N, long: 122° 18' 58" W). The Berkeley Marina is located on the east side of central San Francisco Bay, north of the Bay Bridge and south of the San Rafael Bridge, and is privately owned. Naturally occurring oysters were found in relatively low densities on rip rap surrounding the marina. Experimental substrates were hung roughly 0.3 meters below the surface from a floating dock in the middle of the marina.
- 3) Oyster Point Marina, South SF (lat: 37° 39' 49" N, long: 122° 22' 41" W). This site is located on the west side of South San Francisco Bay just north of the San Francisco Airport, and is privately owned. Naturally occurring oysters were found on rip rap surrounding the marina. Experimental substrates were hung roughly 0.3 meters below the surface from a floating dock adjacent to the harbor master's office.

4) Ravenswood Pier, East Palo Alto, (lat: 37° 30'10" N, long: 122° 7' 21" W). The Ravenswood Fishing Pier is the west end of the former Dumbarton Bridge. The pier was closed when the new bridge was built in the 1980s and is managed by California Department of Transportation. It extends from the edge of the city of East Palo Alto approximately 0.39 miles (0.63 kilometers) into the Bay just next to the new bridge. The shoreline in this area is a very large, shallow mudflat extending almost the length of the pier before dropping off into a deeper channel near the center of the Bay. While there were no known oysters in this area, naturally occurring oyster populations were confirmed approximately five miles (8.05 kilometers) north in Redwood City. The Sailing Lake in Mountain View is approximately four a half miles (7.24 kilometers) to the south. After this project began, surveys conducted by UC Davis found oysters at the east end of the Dumbarton Bridge. Experimental substrates were hung from the pier at the point where the mudflat began to drop off in depth towards the channel, just above the mudflat.

5) Palo Alto Baylands, Palo Alto (lat: 37° 27'28" N, long: 122° 6' 4" W). Palo Alto Baylands is a 2100 acre nature preserve located on the west side of South San Francisco Bay, managed by the City of Palo Alto. It includes natural and impacted areas such as the wetlands preserve, the adjacent Palo Alto Municipal Golf Course, the Palo Alto Airport, the Baylands Athletic Center, the Palo Alto Regional Water Control Plant, and the landfills of the Palo Alto Recycling Center. There were no known oysters in this area. However, there was anecdotal evidence that Olympia oysters were found at the mouth of San Francisquito Creek one mile (1.6 kilometers) to the north. The Sailing

Lake in Mountain View is approximately one and a half miles (2.41 kilometers) to the south. Experimental substrates were hung from a floating dock approximately 0.2 meter below the surface.

6) Permanente Creek, Mountain View (lat: 37° 25' 55" N, long: 122° 5' 12" W).

Permanente Creek, drains down from the foothills and out into San Francisco Bay through the city of Mountain View on the west side of South San Francisco Bay. It runs adjacent to the Sailing Lake in Shoreline Park, managed by the City of Mountain View, which is home to the densest known population of Olympia oysters in the San Francisco Bay Area, and the only know subtidal population (Trulio and Obernolte, 2001). The lake receives water pumped in from the Charleston Slough and the water exits into the Permanente Creek. Experimental substrates were hung from a pedestrian bridge over the creek approximately 60 meters downstream from the outfall from the lake, and approximately 1.41 miles (2.27 kilometers) from the Bay. At low tide the creek is approximately 5 to 10 centimeters deep. The substrates were hung just above the bottom of the creek at all times, and were submerged and exposed daily with the tide, with lower overall creek heights during the summer months. After installing the substrates to span the creek, this project posed a potential hazard to birds flying under the bridge. After one month, substrates were re-hung to span half the creek and the total number was reduced.

Project Permits

The project received a permit from the Institutional Animal Care and Use Committee (IACUC) at San Jose State University to work with a live organism. The Ravenswood Pier is under the jurisdiction of the California Department of Transportation

(CalTrans) and they granted access through an amendment to an encroachment permit held by the San Francisco Estuary Institute. For all other sites, less formal arrangements were made with the cities and private dock and marina owners to grant access.

Experimental Substrate Descriptions and Photos

Three substrates were chosen including Pacific Oyster shell strings, PVC Settling Plates, and Pacific Oyster Shell Bags. Experimental substrates were chosen according to the following criteria:

1. Methods have been used by researchers in the field for prior studies.
2. Equipment building labor requirements were feasible within project scope.
3. Materials cost was feasible within the project scope.
4. Experimental substrates would not introduce environmental hazards or pollutants.

Shell strings were made of Pacific oyster shells with holes bored strung along a rope at regular intervals (Figure 8). NOAA provided Pacific oyster shell from commercial oyster growers in Washington State, and insured it was not live by keeping it dry and clean. Shell strings were created by sorting out large shells (longest dimension no less than 10 centimeters) and drilling a hole through the middle, large enough to accommodate the one-quarter inch nylon rope used to create the strings. The shells were strung along the rope approximately six to eight centimeters apart, with the smooth surface of the shell facing up, and simple knots tied above and below each shell.

Figure 8. Sample Shell String, Photo: J. Stalker, Save the Bay, 2006.

PVC settling plates were plates of polyvinyl chloride, also known as PVC, which were attached to bricks to provide weight and hung PVC tile surface facing down (Figure 9). The PVC plates were dark gray, $\frac{1}{4}$ inch thick, and cut into 5 x 5 cm squares. Each tile was sanded to create a rough surface that hung face down. Tiles were drilled with one-quarter inch holes at each corner. They were attached to 5 x 5 x 3 cm bricks using 14 inch long plastic zip ties, were threaded through the holes in the PVC tile and then tied together around the brick. Nylon rope was tied to the zip ties to hang the tiles.

Figure 9. Sample PVC Settling Plate, Photo: J. Stalker, Save the Bay, 2006.

Oyster shell bags were small mesh bags filled with Pacific oyster shell to mimic a complex pile of shells (Figure 10). Shell bags were assembled by filling a bucket to a line drawn on the bucket to a volume of approximately three liters. The shell was then poured into plastic mesh bags it arrived in. The bags were closed by knotting the top and bottom. Nylon rope was tied around the bag just below the upper knot to hang the bags.

Figure 10. Sample Shell Bag, Photo: J. Stalker, Save the Bay, 2006.

The treatments were of different sizes. A larger shell on a string was chosen to be a unit of substrate so that newly settled oysters could be counted as oysters per shell. The PVC plates were specifically designed to be comparable to the large shells in size. The bricks the PVC plates were attached to had roughly one and a half times more surface area than a large oyster shell. The shells in the shell bags were a bit smaller than the large shells used for the strings. By comparing the surface area of 20 shells from a shell bag to the surface area of 20 shells selected for shell strings, the surface area of all the shells in the bag averaged roughly three quarters the surface area of the shells on the strings (Table 1).

Table 1. *Conversions to Substrate Unit to Calculate Oyster Recruitment Densities*

Shell on string = 1 Shell Unit
PVC plate = 1 Shell unit
Brick = 1.5 Shell units
Shell in bag = .78 Shell units

Installation and Replacements of Recruitment Substrates

In total, each site was fitted with nine shell strings, nine PVC tiles, and three shell bags, hung in a random order. Of those, three shell strings, three PVC tiles and one shell bag were randomly chosen to be examined and replaced during each monitoring session. One string and one PVC tile were randomly chosen to be replaced and not monitored except in the case that another replacement substrate was lost. Five strings, five PVC tiles and one shell bag were randomly chosen to remain undisturbed throughout the year, and examined quarterly.

The data gained from removing and replacing substrates every two months was used to isolate the timing of recruitment to two-month windows and to observe the impact of other marine invertebrates that also competed for settlement space on the substrates during those two-month windows over the course of a year. The data gained from substrates left for the whole year was used to gain information regarding cumulative settlement for the year. Substrates left out for the year were monitored quarterly, with as little disturbance to the substrate as possible. For the final monitoring at the end of the year, these substrates were removed from the water and thoroughly examined for oysters.

From October 2006 to December 2006, the replacement substrates were removed, examined and replaced every month. However, in December 2006, the monthly substrates at Palo Alto Baylands had yielded no oysters, while thirteen oysters were found among the yearly substrates. This implied that one month might not be long enough to capture spatfall data. It could be that settled oysters were too small to observe, or that the substrates needed to be in the water some time before oysters would settle on them. Therefore the replacement timing was increased to two months, or bi-monthly, beginning in December 2006.

From October 2006 to December 2006, the replacement substrates included five shell strings, five PVC plates, and one shell bag. By December 2006, it was apparent that this was too difficult given time and staff constraints for equipment production. The numbers of the bi-monthly replacement substrates were reduced to three shell strings, three PVC plates, and one shell bag.

Table 2. *Replications of Experimental Substrates at Each Site*

Replacement Timing	Shell Strings	PVC Tiles	Shell Bags
Replaced Bi-Monthly	3	3	1
Left for 4 Months	0	0	1
Left for One Year	5	5	1

The installation at each site occurred in September 2006, to begin monitoring in October 2007, except for the Ravenswood Pier site, for which installation was conducted in December 2006 when permission to enter was granted. The installation was on existing structures at each site. At most sites, treatments were hung from pressure-treated two-by-four boards which were attached to the existing structures. Each two-by-four had U-shaped fencing nails attached approximately every 20 cm, and each site required two eight-foot boards. The substrates were tied to these fencing nails and hung down into the water. The substrates were hung at each site to have the PVC tile, the middle shell on each string, and the middle of each bag to be at approximately the same depth (Figure 11). The depth of substrates into the water was determined by the constraints at each site, between 30 and 100 cm below the surface of the water. The substrates were all hung shallowly enough so that none of them rested on the Bay floor but high enough so that at low tide the substrates remained just above the substrate. On the floating docks, the substrates move up and down in the water column with the tide. The substrates hung from the bridge and the pier did not move up and down in the water column with the tide.

Figure 11. Diagram of a Typical Installation.

The sites at Palo Alto Baylands, Oyster Point Marina, Berkeley Marina, and the San Rafael Canal all had floating docks, to which the two-by-four boards were attached with long wood screws. At the Permanente Creek site, a pedestrian bridge was used to hang the treatments. The two-by-four board was attached to the bridge and metal cables were threaded through holes drilled through the two by four and looped around the vertical beams along the bridge which support the side rails and secured with cable clamps. Due to the narrow width of the creek, the number of yearly treatments were reduced to three shell strings, three PVC plates, and one shell bag. At the Ravenswood site, the substrates were hung off a long fishing pier. They were hung from horizontal bars along the pier fence, with the ropes tied directly onto the bars. Due to equipment

constraints, the number of yearly treatments were reduced to three shell strings, three PVC plates, and one shell bag

Data Collection

To monitor bi-monthly substrates, each site was visited during the first week every other month for one year, beginning in September 2006 and ending in October 2007. During each site visit, temperature, salinity, and turbidity were recorded. Temperature was measured with a thermometer. Salinity was measured with a salinity test kit. Turbidity was measured using an eight inch diameter Secchi disk, with the visibility distance taken in meters. The bi-monthly treatments were removed one at a time, each carefully examined for presence of settled oyster spat. Other species that settled were removed to ensure finding all oysters. Newly settled spat was less than five mm and difficult to detect, therefore hand magnifying lenses with a 10X lens were used. The oyster spat on each removed treatment were counted and recorded. Other colonizing species that settled were also recorded to the highest level of taxonomic specificity possible, given that many marine invertebrates were difficult to identify. This was achieved through in-field identification with marine biologists, using the San Francisco Estuary Institute Guide to the Exotic Species of San Francisco Bay (Cohen, 2005), and more informal identification guides put together by Save the Bay Staff. The percent cover of other colonizing species was recorded as being in one of three categories: high (70-100% percent cover); medium (40-69% percent cover); and low (0-39% percent cover). Photos were taken of representative substrates removed during every monitoring trip. Once all the bi-monthly treatments were examined and removed, the new shell

strings and bag were installed. The monthly PVC tiles were scrubbed clean with wire brushes and sandpaper and then re-hung, and care was taken to ensure the zip ties were all in good shape. Any that looked weak or broken were replaced.

Once every three months, the yearly substrates were pulled up, examined, and then re-hung with as little disturbance to the substrates as possible to allow a careful visual survey for settled oysters. Both written and photographic documentation were used to record the abundance and types of other colonizing species. At the end of the project, these yearly substrates were removed and taken apart with care to document all oysters and all other colonizing species as specifically as possible.

Data Analysis

Research data were evaluated qualitatively and with statistics. To assess how oyster spat recruitment rates varied throughout the year, results were totaled for each bi-monthly interval for each site, and the data for the Central Bay and South Bay sites were aggregated. The means and standard errors were derived at a 95% confidence level and compared. These results were plotted on a graph by month to show fluctuations during the project year.

Differences in oyster spat recruitment between the Central and South Bay were determined by totaling the oysters settled at each site. The data for the Central Bay and South Bay sites were aggregated. The mean and standard error were derived at a 95% confidence level and compared.

Oyster spat recruitment rates were compared for oyster shell strings, PVC-recruitment tiles, and the oyster shell bags. A fourth substrate, the bricks to which the tiles were

attached, was included when yearly substrate recruitment rates were compared. The numbers were totaled for each substrate type and then converted to density of settled oysters per Pacific Oyster shell unit. These data were calculated for the last two months of bi-monthly collection and for the year-end collection. The means and standard errors were derived at a 95% confidence level. The mean densities of oysters settled per substrate type were compared.

All species that colonized recruitment substrates were identified to the most specific taxonomic level possible. These species were all listed in a table, marked if they were seen in the South Bay sites, the Central Bay sites or both, and additional abundance and seasonal abundance information was recorded.

Results

Oysters were found at four of the six study sites. In the Central Bay they were found at San Rafael Canal in San Rafael and Oyster Point Marina in South San Francisco. In the South Bay they were found at Ravenswood Pier in East Palo Alto and at Palo Alto Baylands in Palo Alto.

The average temperature in the Central Bay for the duration of the project was 15.9 °C (N=18, SE=0.96) with a high of 22°C and a low of 9°C. The average temperature for the South Bay sites was 16.25°C (N=20, SE=0.62) with a high of 23°C and a low of 11°C.

The average salinity for the Central Bay was 25.73 parts per million salt (ppm) (N=18, SE=1.42) with a high of 33 ppm and a low of 8 ppm, and for the South Bay it was 20 ppm (N=20, SE=1.12) with a high of 31 ppm and a low of 12 ppm.

The average turbidity in the Central Bay measured by Secchi disk depth was 1.18 meters (m) (N=18, SE=0.15) with a high of 2.25 m and a low of 0.5 m. The average turbidity in the South Bay sites was 0.34 m (N=17, SE=0.03), with a high of 0.6 m and a low of 0.1 m.

Thirty-five different taxa settling on experimental substrates are listed with information regarding their status as native to the San Francisco Bay, their presence at Central Bay sites, presence at South Bay sites, qualitative abundance levels (high (H), medium (M), and low (L)), and any observation of seasonality to their abundance (Table 3).

Table 3. *List of All Organisms Observed on Substrates at All Six Sites from October 2006 – October 2007*

	Taxa	Native	Where Found		Abundance		Seasonal Dominance	Comments
			South	Central	South	Central		
1	Olympia Oyster, <i>Ostrea Conchaphila</i>	Y	Y	Y	M	M	Late Summer Aug – Oct	Abundance varied at sites
2	Acorn Barnacle, <i>Balanus glandula</i>	Y	Y	Y	H	M	More dense settlement observed in winter/spring	
3	Striped Barnacle, <i>Balanus amphitrite</i>	N	Y	Y	L	L		
4	Bay Mussel, <i>Mytilus trossulus/galloprovincialis</i>	Y	Y	Y	H	L		High at Permanente Creek, far fewer at other sites
5	Green Mussel, <i>Musculista senhousia</i>	N	Y	?	L	n/a		Again, mostly at Permanente Creek
6	Asian Clam, <i>Corbula amurensis</i>	N	Y	*Y	L	L		
7	Eastern Soft Shelled Clam, <i>Mya arenaria</i>	N	*Y	?	L	n/a		Believe to have found this in Permanente Creek

8	Bay and Grass Shrimp, <i>Crangon franciscorum</i> , <i>Palaemonetes pugio</i>	Y	Y	Y	L	L		
9	Pacific Rock Crab, <i>Cancer antennarius</i>	Y	*Y	Y	L	L		
10	Eastern Mud Snail, <i>Ilyanassa obsoleta</i>	N	*Y	*Y	H	L	Egg capsules at Ravenswood in Aug - Oct	Lots on mudflats at Ravenswood - few at Permanente
11	Atlantic Oyster Drill, <i>Urosalpinx cinerea</i>	N	Y	N	M	n/a		At Ravenswood only
12	Bay Goby, <i>Lepidogobius lepidus</i>	Y	*Y	*Y	L	L		
13	Threespine Stickleback, <i>Gasterosteus aculeatus</i>	Y	*Y	*N	L	n/a		Found one at Palo Alto Baylands
14	Bay Pipefish, <i>Syngathus leptorhynchus</i>	N	*N	*Y	n/a	L		
15	Chain Sea Squirt, <i>Botrylloides sp.</i>	N	N	Y	n/a	H		Two distinct colors: orange and black
16	Star Sea Squirt, <i>Botryllus sp.</i>	N	N	Y	n/a	H		Two distinct colors: orange and black
17	Red Beard Sponge, <i>Clathria porifera</i>	N	N	Y	n/a	L		
18	Yellow Sponge, <i>Halichondria bowerbanki</i>	N	N	Y	n/a	L		
19	Striped Anenome, <i>Diadumene lineate</i>	N	Y	Y	L	L		
20	Clear Tunicate, <i>Ciona savignyi</i> , <i>Ciona intestinalis</i>	N	Y	Y	L	H	Lots all year in Central Bay, but more April - October	Very similar, difficult to distinguish, can confirm both existed at Oyster Point
	Solitary Sea Squirt, <i>Molgula manhattensis</i>	N	Y	Y	L	H	Lots all year in Central Bay, but more April - October	Similar to Cionas, but rounder and tougher
21	Sea Squirt, <i>Ascidia zara</i>	N	?*	Y*	n/a	M		Hard to distinguish, can confirm at Oyster Point
22	Club Sea Squirt, <i>Styela clava</i>	N	N	Y	n/a	M		Leather and long tunicate

23	"Branching" Hyrdoids/Nidarian, <i>unknown genus/sp.</i>	N	Y	Y	L	M		With medusas at Ravenswood in Aug
24	"Bushy" or "Branching" bryozoan, <i>Bugula sp.</i>	N	Y	Y	H	M	Lots at PA Baylands in the summer months April - July	
25	Colonial Sea Squirt, <i>Didemnum sp.</i>	N	?	Y	n/a	M		
26	Encrusting Bryozoan, <i>Watersipora sp.</i>	N	Y	Y	L	L	Found more at Ravenswood in late summer	
28	Encrusting Bryozoan, <i>Cryptosula sp. or</i> <i>Schizoporella sp.</i>	N	Y	Y	M	L	Found more at Ravenswood in late summer	Difficult to distinguish, both can be expected in SF Bay
29	Green "Sheetlike" Seaweed, <i>Ulva sp.</i>	?	Y	Y	L	L		Found attached closer to surface of water
30	Green "Stringy" Seaweed, <i>Enteromorpha</i> <i>muscooides</i>	?	Y	Y	L	L		
31	Nudibranch <i>Genus</i> <i>and species unknown</i>	?	Y	Y	L	L	Found at Ravenswood from early to late summer	
32	Polychaete Worms, <i>Genus and species</i> <i>unknown</i>	?	Y	Y	L	M		
33	Tube/Soft Worms, <i>Genus and species</i> <i>unknown</i>	?	Y	Y	M	M		
34	Isopods, <i>Idotea sp.</i>	?	Y	Y	H	M	Lots all year at PA Baylands, higher in winter months	
35	Amphipods, <i>Genus</i> <i>and species unknown</i>	?	Y	Y	H	L	Lots all year at PA Baylands, higher in winter months	
*Relatively certain, but identification difficult								

Bi-monthly recruitment collectors were set out at all six sites from October 2006 to October 2007. The first oyster spat found on any monthly recruitment collector was recorded at Oyster Point Marina in June, 2007. In August, 2007, 172 oysters were found on bi-monthly substrates at Palo Alto Baylands, 62 at San Rafael Canal, and five at Oyster Point. In October of 2007 there were fewer than half as many oysters on bi-

monthly substrates at Palo Alto Baylands and San Rafael Canal, however 33 oysters were found on bi-monthly substrates at Ravenswood, the first recruitment at this site. Two sites, Permanente Creek and Berkeley Marina had no recruitment for the duration of the project (Table 4). The mean number of oysters found per month in the Central and South Bays (three sites aggregated) in August 2007 was 22 (N=3, SE=19.5) in the Central Bay, and 57 (N=3, SE=57) in the South Bay. In October 2007 the Central Bay had mean of 11 oysters (N=3, SE=6.6), and the South Bay had a mean of 25 (N=3, SE=12.7) (Figure 16). These data show settlement in the South Bay was over double that of the Central Bay in both August and October of 2007.

Table 4. *Total Number of Oysters found on all Bi-Monthly Substrates at all Sites from October 2006 – October 2007*

	Permanente Creek	Palo Alto Baylands	Ravenswood Pier	Oyster Point Marina	Berkeley Marina	San Rafael Canal
Oct-06	0	0	0	0	0	0
Nov-06	0	0	0	0	0	0
Dec-06	0	0	0	0	0	0
Feb-07	0	0	0	0	0	0
Apr-07	0	0	0	0	0	0
Jun-07	0	0	0	1	0	0
Aug-07	0	172	0	5	0	61
Oct-07	0	42	33	10	0	23

Figure 12. Mean Number of Oysters found on Bi-Monthly Substrates per Site at Central and South San Francisco Bay from October 2006 – October 2007, (means and SEs).

The yearly treatments showed the same late summer/fall spatfall pattern. The same individuals were likely to be re-counted during quarterly monitoring. In December 2006, 13 oysters were found at Palo Alto Baylands. In June 2007 one oyster was found at the Oyster Point site. Substrates were removed and studied to thoroughly count oysters in October 2007. Palo Alto Baylands yearly substrates had the highest recruitment numbers with 304 oysters, Ravenswood Pier and San Rafael Canal had similar amounts with 176 and 130 respectively, and Oyster Point had 44. Two sites, Permanente Creek and Berkeley Marina had no recruitment (Table 5). The number of oysters found per month at each of the three sites in the Central and South Bays were aggregated by monitoring visit (Figure 17). The mean number of oysters found on yearly substrates at the three Central Bay sites in October 2007 was 58 ($N=3$, $SE=38.17$), and 160 ($N=3$, $SE=88.12$) in the South Bay. While these differences could not be tested for significance, the South Bay had more than double the number of oysters as the Central Bay sites.

Table 5. *Total Number of Oysters found on all Yearly Substrates Per Sites from October 2006 – October 2007*

	Permanente Creek	Palo Alto Baylands	Ravenswood Pier	Oyster Point Marina	Berkeley Marina	San Rafael Canal
Dec-06	0	13	0	0	0	0
Mar-07	0	7	0	0	0	0
Jun-07	0	3	0	1	0	0
Oct-07	0	304	176	44	0	130

Figure 13. Mean Number of Oysters found on Yearly Substrates at Central and South San Francisco Bay sites from October 2006 – October 2007, (means and SEs).

The total of all oysters found on all bi-monthly substrates over the entire last year at the South Bay sites versus the Central Bay sites were compared (Figure 18). The mean number of oysters found at the three Central Bay sites was 33.3 (N=24, SE=25.75). For the South Bay sites the mean number of oysters found was 82.3 (N=24, SE=66.52). The South Bay substrates had almost two and a half times more oysters than the Central Bay.

Figure 14. Comparison of Mean Number of Oysters found on All Bi-Monthly Substrates per Site in Central and South San Francisco Bay between October 2006 and October 2007, (means and SEs).

The total number of all oysters found on all yearly substrates during 2007 at the South Bay sites versus the Central Bay sites were compared (Figure 19). The mean number of oysters found on yearly substrates at the three Central Bay sites was 58.33 ($N=12$, $SE=38.11$), and 167.66 ($N=12$, $SE=94.48$) at the South Bay sites. The South Bay substrates had more than two and a half times more oysters than the Central Bay substrates.

Figure 15. Comparison of Mean Number of Oysters found on All Yearly Substrates per Site in Central and South San Francisco Bay between October 2006 and October 2007, (means and SEs).

The three substrates used for the bi-monthly sampling were compared (Figure 20). The number of oysters found on bi-monthly substrates during the recruitment months of August and October 2007 were totaled for each substrate type and then converted to densities to compare substrates of varying surface areas. The density was calculated as number of Olympia oysters settled per Pacific oyster shell (Table 1). The mean densities of oysters per shell for the three bi-monthly substrates were 0.32 (N=36, SE=0.21) for shell strings, 0.10 (N=34, SE=0.08) for PVC settling plates, and 0.30 (N=12, SE=0.14) for shell bags. Per unit area, shell strings and shell bags were quite comparable, while PVC plates were generally lower.

Figure 16. Oyster Recruitment Density by Bi-Monthly Substrate Type for August 2007 - October 2007, (means and SEs).

The three substrates used for the yearly sampling were compared, along with an additional substrate, the brick the PVC plates were attached to (Figure 21). The total numbers of oysters found over the year on yearly substrates were totaled for each substrate type and converted to densities to compare substrates of varying surface areas (Table 1). The mean densities of oysters per shell for the four yearly substrates were 1.91 (N=23, SE=1.07) for shell strings, 1.06 (N=18, SE=0.55) for PVC settling plates, 2.39 (N=18, SE=0.92) for bricks, and 0.97 (N=6, SE=0.50) for shell bags. Bricks and Shell Strings appear to have more potential for higher oyster recruitment density over the course of a year than PVC plates or shell bags.

Figure 17. Oyster Recruitment Density by Yearly Substrate Type for October 2007, (means and SEs).

The four substrates used for the yearly sampling were also compared by showing the mean number of oysters attached per substrate type (Figure 22), to look at the mean number of oysters that can be collected regardless of surface area. The total oysters settled on each substrate was added, and then all substrates from all sites were grouped by substrate type. The mean number of oysters per substrate type unit for the four yearly substrates were 10.98 (N=23, SE = 6.75) for shell strings, 1.06 (N=18, SE = 0.55) for PVC settling plates, 2.39 (N=18, SE = 0.92) for bricks, and 41.67 (N=6, SE = 20.68) for shell bags. It was possible to show a significant difference between some of the substrate types with a paired two sample t-test ($\alpha = 0.05$). The mean number of oysters on yearly plates and bricks differed significantly ($p = 0.03$). The other substrates had such highly ranging values between them that the p-values were over 0.05, but the p-value was nearly

significant in the case of the PVC plate versus the shell bag ($p=0.051$), and in the case of the brick versus the shell bag ($p=0.052$).

Figure 18. Mean Number Oysters Settled per Yearly Substrate Type for October 2007, (means and SEs).

Discussion

Oysters in the Central and South San Francisco Bay

This study found natural oyster recruitment at two of the three South Bay sites, at Palo Alto Baylands and Ravenswood Pier. Prior to this study, no naturally occurring oysters have been observed in these areas in recent times, and no naturally occurring oysters were found during initial surveys. In addition, oyster recruitment rates between the Central and South Bay sites showed major differences. For three measures of oyster recruitment, South Bay numbers were more than two and a half times that of Central Bay numbers. For example, the mean number of oysters found during the recruitment season (August and October 2007) on all bi-monthly collectors in the Central Bay was 33.3

oysters per site, while the mean for the South Bay was 82.3 oysters per site, 249% higher than the Central Bay mean. Further study with more sites is needed to statistically quantify differences between parts of the Bay.

Researchers believe that the lack of suitable substrate may have serious negative impacts on oyster population numbers (Coen & Luckenbach, 2000; Kirby, 2004; Piazza et al., 2005). Oyster restoration often involves creation of desirable substrate, which naturally occurring spat settle on to populate (Coen & Luckenbach, 2000; Lenihan, 1999). At times these substrates may be seeded with larvae from lab settings, commercial fishery stocks, or from known naturally existing populations (Piazza et al., 2005; Obernolte et al., 2007). The introduction of non-seeded substrate into the Central and South Bay in this study resulted in settlement at four sites, two of which were in the South Bay where no naturally occurring oysters or substrate occurred. These findings suggest that these areas may be substrate limited.

The areas surveyed for naturally occurring oysters in the South Bay had little to no naturally occurring hard intertidal substrate, but rather thick layers of very fine sediments. The Central Bay surveys showed heavy rip-rap lined shores and some naturally occurring rocky shorelines. These rocky areas often had naturally occurring oysters in rather low densities. However, the rocky shorelines also had empty space on them, suggesting that factors other than just lack of substrate may limit oysters in the rocky intertidal zone of the Central Bay. More research is needed to understand the significance that factors such as elevation, salinity fluctuation, temperature fluctuation, flow velocity, sedimentation rate, and predation have on oyster abundance (Coen &

Luckenbach, 2000; Lenihan, 1999; Lenihan, Peterson, & Allen, 1996). We did find available substrate was very limited in the South Bay indicating that adding more hard substrate in the intertidal zone could boost numbers of oysters significantly. Whether in the long term oysters have similar low densities in the South Bay as in the Central Bay will require study.

The abundance of oysters found in this study does suggest that the South Bay in particular is an excellent place to locate oyster restoration projects. The recruitment success implies that any introduced substrate will receive native oyster settlement. There is much to be learned by observing oyster survival in this region over time.

Environmental Factors

Sites in the South and Central Bay were chosen for comparison because the two areas are very different hydrologically and morphologically. The Central Bay has clearer water, deeper water, less mudflat and more hard shoreline than the South Bay. The occurrence of naturally occurring oysters on rocky intertidal shores in the Central Bay also set it apart from the South Bay. The environmental conditions that were measured were temperature, salinity and turbidity, with a snapshot sample of each variable during every monitoring session. Flow rates, which also play an important role in oyster recruitment, growth, and survival were not measured (Lenihan et al., 1996). Temperature and salinity were very similar between the South and Central Bay sites. However, turbidity was quite different between the two regions. The average turbidity measured by Secchi disk depth throughout the year at the Central Bay sites was 1.18 m, while the average Secchi disk depth at the South Bay sites was only 0.34 m. Lenihan conducted a

study in 1999 looking at the effects of multiple environmental factors, including both sedimentation and flow rate, on the growth and survival of the Eastern oyster, *Crassostrea virginica*, on built reefs. Sedimentation, the settling of suspended particles, is different than turbidity, which is a measure of lack of water clarity due to suspended particles. Lenihan found sedimentation reduced oyster survival due to burial. However, flow rate was positively correlated with oyster growth rates, and the higher growth rates were at taller parts of the reefs which were less susceptible to dissolved oxygen fluctuations and burial from sedimentation. In an earlier laboratory study, Lenihan et al. (1996) also found that oyster growth rates are positively linked to increased flow rates, although they were careful to point out that flow rates above a certain level will likely inhibit feeding ability. Turbidity is most likely linked to higher numbers of oysters in the South Bay by affecting the assemblage of other settling invertebrates. Whether or not the flow rates at the sites surveyed in the South Bay were higher than flow rates at sites surveyed in the Central Bay requires further study.

Other Species

The South Bay had a higher abundance of hard shelled bivalves, gastropods and crustaceans than the Central Bay. The species in these groups that showed the greatest differences in abundance favoring the South Bay were the Acorn Barnacle, *Balanus glandula*; the Bay Mussel, *Mytilus trossulus/galloprovincialis*; and the Eastern Mud Snail, *Ilyanassa obsoleta*. Other species that were more abundant in the South Bay included "Bushy" or "Branching" bryozoans, *Bugula sp.*; Encrusting

Bryozoans, *Cryptosula sp. or Schizoporella sp.*; Isopods, *Idotea sp.*; and Amphipods, *Genus and species unknown*. All of these species also have hard outer surfaces.

The Central Bay had a higher abundance of soft bodied invertebrates, especially tunicates of varying species. These included the Clear Tunicate, *Ciona savignyi* or *Ciona Intestinalis*; the Solitary Sea Squirt, *Molgula manhattensis*; and "Branching" Hyrdoids/Nidarian, *unknown genus/sp.* The Central Bay also had a higher diversity of sea squirts and sponges. Species that could be identified with confidence, found at Central Bay sites but not South Bay sites, included the Chain Sea Squirt, *Botrylloides sp.*; the Star Sea Squirt, *Botryllus sp.*; the Red Beard Sponge, *Clathria porifera*; the Yellow Sponge, *Halichondria bowerbanki*; and the Club Sea Squirt, *Styela clava*. All of the species that were found in both areas but were more abundant in the Central Bay, and all those species observed exclusively in the Central Bay are soft bodied organisms.

The South Bay may be a prime location for oyster restoration efforts due to the potential for lower competition for space with the soft bodied organisms which may not be as tolerant to high turbidity. Long term studies and laboratory research are needed to answer this question with more certainty.

Seasonality of Recruitment

By observing oyster recruitment data for both bi-monthly and yearly substrates throughout the Bay over the course of a year, this study found that spatfall was seasonal. The first recruitment was observed in June of 2007. And then much higher numbers were found at all four productive sites in August and October of 2007. The thirteen oysters that were found at Palo Alto Baylands in December 2006 had set sometime after

September 2006 when the substrates were hung, and are not counted as part of the main spatfall event. They were likely settlers from the prior year's spatfall season.

This seasonality is probably due to environmental factors, especially temperature. In Willapa Bay, Washington state, Olympia oysters release spat at water temperatures of 13 to 16 degrees Celsius, and may have one or two spawning cycles during the summer (Couch and Hassler, 1989). The spatfall timing found in this project, was consistent with the timing for spatfall found in Willapa and that found in San Francisco Bay by the UC Davis project, the MACTEC Engineering and Consulting Inc. projects and the Richardson Bay Audubon Center and Sanctuary project during 2007 (Oberholte, personal communication, November, 2007).

Substrate Comparison

This project evaluated different substrates for recruitment rates and found all experimental collectors, bricks, PVC plates, shell strings, and shell bags had very similar densities, measured in units of Olympia oysters settled per Pacific oyster shell, ranging from 0.98 for the bricks, 1.0 for the PVC plates, 1.9 for the shell strings, and 2.3 for the shell bags. This similarity in recruitment between different materials is consistent with field observations of oysters growing on a variety of existing hard surfaces including rip-rap, cement, rebar and on barnacles and mussels. Saucedo et al. (2005) did find preferential recruitment by Pearl oyster, *Pinctada mazatlanica*, to collectors of varying textures and colors; however, these studies were performed to collect information to refine hatchery techniques. Cook, Shaffer, Dumbauld and Kauffman (2000) who worked on a plan to rebuild Olympia oyster populations in Washington State identifies water

quality problems and over-harvesting as the major factors causing its near demise in their region. In San Francisco Bay there is the added problem of the highly changed ecosystem due to incredibly high levels of siltation and introduced invasive marine species. Although Olympia oysters may have preferences for various materials, finding the similar settlement densities over these four substrates may mean that differences in the type of material may not matter so much as the amount of surface area available and the existence of cracks and crevices that may provide protection.

Oysters settled per substrate type, without taking into account that differences in surface area were highest for the shell bags, with a mean of 46.67 oysters per shell bag collector. The other collectors averaged 10.98 oysters per shell string, 2.38 oysters per brick, and 1.05 oysters per PVC plate. Shell bags offer more recruitment potential than any other single substrate. Future researchers may decide to include this method to check for presence or absence of oysters in an area, as it is the most likely method to show higher recruitment numbers for the relatively low equipment construction and monitoring effort. This also implies that providing a large, complex surface area for settlement may be more important than the specific substrate type for the goal of promoting oyster settlement.

Management Recommendations

A goal of this study was to help direct future research and restoration activities by looking for effective restoration sites and methods. There are several major questions that can still be answered before large scale oyster reef restoration takes place in San Francisco Bay. These include

- 1) What are the specific limiting factors for oyster settlement on natural substrate, and do these limiting factors differ in different areas?
- 2) What is the best substrate type and shape to use for permanent restoration structures?
- 3) How do natural and restored oyster populations fluctuate over the years?
- 4) How do restored and natural oyster populations interact with other settling species?
- 5) What temperatures, salinity levels, water flows, and turbidity levels can oysters tolerate? At what levels do they thrive?
- 6) What role does turbidity play in oyster survival rates either through preference for turbidity or through reduced competition in turbid environments?

To answer these questions, longer studies are needed. Studying oyster reproduction and survival five years or longer will provide much more information to correlate various factors with Olympia oyster success. Understanding the factors that influence reproduction and survival will help restoration managers design more targeted restoration projects with a higher likelihood of success. Further research should be conducted at a mesocosm scale. Experiments that are large scale enough to account for the influence of factors, such as water flow rates and interactions with other species, could provide extremely valuable information as to the most desirable locations and configurations for any proposed large-scale restoration programs. Ideally, mesocosm studies could be replicated in more than one part of the bay to also study other factors,

especially turbidity. These studies should include only types of substrate that are suitable for potential long term restoration materials.

Future Studies

One of the major goals of this project was to provide information to the South Bay Salt Pond Restoration Project managers regarding native oyster populations in the vicinity of their project. The ponds offer an interesting potential for targeting oyster restoration. A portion of the salt ponds will remain managed ponds to maintain shorebird populations. Oyster reefs provide important habitat for many species, and the density of oysters at the Sailing Lake in Mountain View is a good reference site for any potential restoration of oysters within managed salt ponds. The controlled water circulation and the prolonged residence time of water in the managed ponds could be beneficial to oyster populations as it seems to have been in Sailing Lake. The Ravenswood Pier Site is just north of SBSRP Pond SF2. Pond SF2 and Pond A16, located further south in Alviso, will be restored to include constructed islands with water levels managed to remain 6-10 inches deep to create optimal habitat for wading shorebirds. Next to each constructed island there will be a deeper ditch where the sediment will be removed to build the islands. These borrow ditches provide an excellent opportunity for constructing artificial oyster reefs to support Olympia oysters and other associated species. The ponds will have water exchange with the bay and, in the case of Pond SF2, be located just a few hundred yards from the Ravenswood Pier Project, a confirmed area for natural oyster recruitment. The constant shallow subtidal environment should be very similar to the environment in which the oysters thrive at Sailing Lake. It may be possible to

additionally test the effectiveness of different reef substrates in establishing oyster populations within these ponds. If the oyster project could be included without compromising existing restoration goals, then it would be extremely valuable to have both oyster studies and bird studies in the same ponds to take advantage of cooperative data collection and monitoring efforts and to pool data for more comprehensive analyses.

In other parts of the bay, oyster research continues to be refined. The San Francisco Bay Native Oyster Working Group has produced the draft San Francisco Bay Native Oyster Survey Protocol. The protocol outlines consistent survey methods, which will be at least in part employed by all groups researching oysters in the San Francisco Bay. Pooling these data will reduce the noise that site location, environmental factors, and researchers themselves can introduce into the information that is collected.

The following groups will employ the Native Oyster Survey Protocol within their existing research projects. UC Davis is continuing its survey of central and north bay sites. Researchers from Davis will also begin culturing Olympia oysters collected from San Francisco Bay in a lab setting to further study their basic biology, especially to understand their tolerance for salinity fluctuations. The Richardson Bay Audubon Center and Sanctuary is continuing to sample oyster recruitment in relation to native eelgrass beds. MACTEC Engineering and Consulting, Inc., are continuing to work in San Rafael. Private consultants, including some from MACTEC, may be installing a larger mesocosm level study to better understand salmonid use of oyster-shell habitat. This is an exciting project not only due to the larger scale, but also as it may strengthen the link between

oyster habitat and fish survival which could help to define Olympia oyster habitat as Essential Fish Habitat under the Magnusen-Stevens Fishery Act.

Although Olympia oyster numbers are low in the San Francisco Bay, they are by no means gone. They have survived massive changes in the bay ecosystem with no active intervention by humans. A modest restoration goal is simply to increase oyster numbers, which will increase the important habitat they provide for so many other species and increase the ecosystem services they provide in the highly impacted San Francisco Bay. Over time perhaps this species can be restored to high enough numbers to play the keystone role they once did.

References

- Anderson, M. J. and Connell, S. D. (1999). Predation by Fish on Intertidal Oysters. *Marine Ecology Progress Series*, 187, 203-211.
- Booker, M. M. (2006). Oyster Growers and Oyster Pirates in San Francisco Bay. *Pacific Historical Review*, 75(1), 63.
- Chan F., J. A. Barth, J. Lubchenco, A. Kirincich, H. Weeks, W. T. Peterson, B. A. Menge. (2008). Emergence of Anoxia in the California Current Large Marine Ecosystem. *Science*, 319(5865), 920.
- Coen, L. D., M. W. Luckenbach. (2000). Developing Success Criteria and Goals for Evaluating Oyster Reef Restoration: Ecological Function or Resource Exploitation. *Ecological Engineering*, 15, 323-343.
- Cohen, Andrew N. (2005) *Guide to the Exotic Species of San Francisco Bay*. Retrieved January 15, 2007, from San Francisco Estuary Institute Web site: <http://www.exoticguide.org>
- Couch, D., T. J. Hassler. (1989). Species profiles: life histories and environmental requirements of coastal fishes and invertebrates (Pacific Northwest)--Olympia oyster. *U.S. Fish Wildlife Service Biol. Rep.*, 82(11.124), U.S. Army Corps of Engineers, TR EL-82-4, 8.
- Cook, A.E., J. A. Shaffer, B. R. Dumbauld, B. E. Kauffman. (2000). A plan for rebuilding stocks of Olympia oysters in Washington State. *Journal of Shellfish Science*, 19(1), 409-412.
- Craig, R. K. (2002). Taking the Long View of Ocean Ecosystems: Historical Science, Marine Restoration, and the Oceans Act of 2000. *Ecology Law Quarterly*, 29, 649-705.
- Diederich, S. (2005). Differential recruitment of introduced Pacific oysters and native mussels at the North Sea coast: coexistence possible? *Journal of Sea Research*, 53(4), 269-281.
- Encomio, V. G., S. M. Stickler, S. K. Allen Jr., F. L. Chu. (2005). Performance of "Natural Dermo-Resistant" Oyster Stocks – Survival, Disease, Growth, Condition and Energy Reserves. *Journal of Shellfish Research*, 24(1), 143-155.
- Farrell, Joe. (2006). Plastic Pollution in the Marine Environment: Boaters can Help Control a Growing Problem. *University of Delaware Sea Grant Marine Advisory*

Service Note, University of Delaware College of Marine and Earth Studies and the Sea Grant College Program.

- Ford, S. E., M. J. Cummings, E. N. Powell. (2006). Estimating Mortality in Natural Assemblages of Oysters. *Estuaries and Coasts*, 29(3), 361-374.
- Friedman, C. S., H. M. Brown, T. W. Ewing, F. J. Griffin, G. N. Cherr. (2005). Pilot Study of the Olympia Oyster *Ostrea conchaphila* in the San Francisco Bay estuary: Description and Distribution of Diseases. *Diseases of Aquatic Organisms*, 65, 1-8.
- Grabowski, J. H., A. Randall Hughes, D. L. Kimbro, M. A. Dolan. (2005). How Habitat Setting Influences Restored Oyster Reef Communities. *Ecology*, 86(7), 1926-1935.
- Grosholz, E. D. (2006). Documenting the Status of Native Oysters in San Francisco Bay, CA. Project Recipient Agreement and Scope of Work.
- Halpern B. S., S. Walbridge, K. A. Selkoe, C. V. Kappel, F. Micheli, C. D'Agrosa, J. F. Bruno, K. S. Casey, C. Ebert, H. E. Fox, R. Fujita, D. Heinemann, H. S. Lenihan, E. M. P. Madin, M. T. Perry, E. R. Selig, M. Spalding, R. Steneck, R. Watson. (2008). A Global Map of Human Impact on Marine Ecosystems. *Science*, 319(5865), 948-952.
- Harding, J.M., R. Mann. (2001). Oyster Reefs as Fish Habitat: Opportunistic Use of Restored Reefs by Transient Fishes. *Journal of Shellfish Research*, 20(3), 951-959.
- Harris, H. (2004). Distribution and limiting factors of *Ostrea conchaphila* in San Francisco Bay. Masters thesis. San Francisco State University.
- Hixon M.A., W. N. Brostoff. (1996). Succession and herbivory: Effects of differential fish grazing on Hawaiian coral-reef algae. *Ecological Monographs*, 66(1), 67-90.
- Kater, B. J., AJMG van Kessel, JJMD Baars. (2006) Distribution of Cockles *Cerastoderma edule* in the Eastern Scheldt: Habitat Mapping with Abiotic Variables. *Marine Ecology Progress Series*, 318, 221-227.
- Kennedy, R. J., D. Roberts. (1999). A Survey of the Current Status of the Flat Oyster *Ostrea edulis* in Strangford Lough, Northern Ireland, with a View to the Restoration of its Oyster Beds. *Biology and Environment: Proceedings of the Royal Irish Academy*, 99B(2), 79-88.
- Kimbro, D. L., E. D. Grosholz. (2006). Disturbance Influences Oyster Community Richness and Evenness, but not Diversity. *Ecology*, 87(9), 2378-2388.

- Kirby, M. X. (2004). Fishing down the coast: Historical expansion and collapse of oyster fisheries along continental margins. *Proceedings of the National Academy of Sciences of the United States of America (PNAS)*, 101(35), 13096-13099.
- Lenihan, H. S. (1999). Physical-Biological Coupling on Oyster Reefs: How Habitat Structure Influences Individual Performance. *Ecological Monographs*, 69(3), 251-275.
- Lenihan, H. S., C. H. Peterson, J. M. Allen. (1996). Does Flow Speed Also Have a Direct Effect on Growth of Active Suspension-Feeders: An Experimental Test on Oysters. *Limnology and Oceanography*, 41(6), 1359-1366.
- National Oceanic and Atmospheric Administration (NOAA) National Marine Fisheries Service. (2007). Report on the Subtidal Habitats and Associated Biological Taxa in San Francisco Bay. Santa Rosa, CA Office.
- National Oceanic and Atmospheric Administration (NOAA) National Marine Fisheries Service. (2006). NOAA Fisheries Glossary: NOAA Technical Memorandum NMFS-F/SPO-69, Revised. Silver Springs, MD Office.
- Oberholte, R. (1999). Using Inbenthic Species to Assess the Ecological Status of Restored Salt Marshes. San Jose, CA: San Jose State University, pp. 1-67.
- Oberholte, R., L. Trulio, B. Mulvey, R. Abbott. (2007). Use of a Unique Olympia Oyster Population for Species Restoration in San Francisco Bay. *The Journal of Shellfish Research*, Draft version, accepted for future publication.
- Peterson, C. H., J. H. Grabowski, S. P. Powers. (2003). Estimated Enhancement of Fish Production Resulting from Restoring Oyster Reef Habitat: Quantitative Valuation. *Marine Ecology Progress Series*, 264, 251-266.
- Piazza, B. P., P. D. Banks, M. K. La Peyre. (2005). The Potential for Created Oyster Shell Reefs as a Sustainable Shoreline Protection Strategy in Louisiana. *Restoration Ecology*, 13(3), 499-506.
- Richardson Bay Audubon Center and Sanctuary. (2007). *Richardson Bay Conservation Projects*. Retrieved January 14, 2007 from http://www.tiburonaudubon.org/conserve_bay.html#oyster
- Robinson, T. B., C. L. Griffiths, A. Tonin, P. Bloomer, M. P. Hare. (2005). Naturalized Populations of Oysters: *Crassostrea gigas* Along the South African Coast: Distribution, Abundance and Population Structure. *Journal of Shellfish Research*, 24(2), 443-450.

- Rosenberg, R. (1985). Eutrophication – The Future Marine Coastal Nuisance? *Marine Pollution Bulletin*, 16(6), 227-231.
- Ruesink, J. L., Lenihan, H. S., Trimble, A. C., Heiman, K. W., Micheli, F., Byers, J. E., Kay, M. C. (2005). Introduction of Non-Native Oysters: Ecosystem Effects and Restoration Implications. *Annu. Rev. Ecol. Evol. Syst.*, 36, 643-689.
- South Bay Salt Ponds Restoration Project. (2007). *Project Description*. Retrieved January 14, 2007, from http://www.southbayrestoration.org/Project_Description.html
- San Francisco Bay Conservation and Development Commission. (2007). *About the Bay and BCDC*. Retrieved January 14, 2007, from <http://www.bcdc.ca.gov/index.php?cat=19>
- Saucedo, P. E., H. Bervera-Leon, M. Monteforte, P. C. Southgate, P. Monsalvo-Spencer. (2005). Factors Influencing Recruitment of Hatchery Reared Pearl Oyster Spat. *Journal of Shellfisheries Research*, 24(1), 215-220.
- Sculati, C. (2004). The Bay's Native Oysters: Still Hanging On. *Bay Nature*, October-December, 34-38.
- Smithsonian Environmental Research Center. (2007). *Marine Invasions Research Lab Fouling Communities Invasions*. Retrieved January 17, 2007, from http://www.serc.si.edu/labs/marine_invasions/biogeography/surveys.jsp
- Starliper, C. E. (2005). Quarantine of *Aeromonas salmonicida* – Harboring Ebonyshell Mussels (*Fusconaia ebena*) Prevents Transmission of the Pathogen to Brook Trout (*Salvelinus fontinalis*). *Journal of Shellfish Research*, 24(2), 573-578.
- Trulio, L., R. Obernolte. (2001). The Distribution of Bivalves and Their Contribution to Water Filtering at Shoreline Sailing Lake, City of Mountain View, CA. Report Prepared for Hydroikos and Associates.
- Tolley, S. G., A. K. Volety, M. Savarese. (2005). Influence of Salinity on the Habitat Use of Oyster Reefs in Three Southwest Florida Estuaries. *Journal of Shellfish Research*, 24(1), 127-137.
- Zedler, Joy. (1996). Tidal Wetland Restoration: A Scientific Perspective and Southern California Focus. In California Sea Grant College System Publication (pp. 1-18) No. T-038, La Jolla.

Reproductions of Required Permits

**San Jose State University
Institutional Animal Care and Use Committee**

LETTER OF OFFICIAL PROTOCOL REVIEW

Date: June 16, 2006

Dear Dr. Trullo,

The animal care and use portion of your research proposal indicated below was reviewed by the Institutional Animal Care and Use Committee (IACUC). The status of your proposal is as follows:

Principal Investigator(s): Lynne Trullo, Sumudu Welaratna

Protocol #: 2006-G

Title: Design methods for survey and data analysis of *Ostrea conchaphilla* recruitment rates in San Francisco Bay.

The application was approved without modification by the IACUC

Approval date: August 1, 2006 * Expiration Date: August 1, 2008

The IACUC must be informed in writing of any proposed changes to the approved protocol outline and approval must be granted in writing by the IACUC before any change is instituted. If you wish to continue the approved outline beyond the expiration date, it is required that you request an approval period extension for IACUC consideration in July 2008.

The protocol number (#2006-G) may only be used by the principal investigator and participants included on the approved application form. The protocol number will be required on grant and contract proposals to fund the project. To maintain valid protocol approval, route a copy of all renewed permits, requests for permit extensions, correspondence with the P.I. and government agencies and related business to the UAC office at extended zip 0100 to be included in your animal use file.

If you have any questions, feel free to contact me at extension 4-4929.

Larry Young, RVT, L&Tg
IACUC Coordinator

Cc: UAC Office

ENCROACHMENT PERMIT RIDER
TR-0122

Collected by	Permit No. (Original)
	0406-6SV1350
Rider Fee Paid	Dist/Co/Rta/PM
\$164.00	04-Ala-92-2.4/14.4
Date	Rider Number
October 10, 2006	0406-6RW1713

TO: ☐ SAN FRANCISCO ESTUARY INSTITUTE
7770 Pardee Lane, 2nd Floor
Oakland, CA 94621-1424

Attn: Andrew Cohen
☐ Phone: (510) 746-7367

☐ , PERMITTEE

We are hereby amending the above numbered encroachment permit as follows:

Date of completion extended to: December 31, 2007

Reference your project to: Remove by hand the non-native oysters (threat to the restoration of native oysters) wherever they are found on underwater bridge structure supports and other substrate area on Highways 04-SM/Ala-84, Post Mile 29.2/0.8, and 04-SM/Ala 92, Post Mile 14.4/2.4, at the Dumbarton Bridge # 35-38 and San Mateo Bridge # 35-54, respectively, in San Mateo and Alameda Counties.

Permission is granted to include hanging 20-30 oyster settling substrates from the closed fishing pier at Ravenswood, and monitor oyster settlement and growth.

Except as amended, all other terms and provisions of the original permit shall remain in effect.

APB
CC: MMc, BSalar, NF,AA,FF,
DTM-B.Loo, J.Richardson,
Toll Bridges - J. Newman,
Mtce.-A. Compancy, W. Cooper,
CHP-Hayward, Redwood City, Nimitz Fway.

APPROVED:

BLIAN SARTIPL, District Director

BY:

Michael D. Condie
MICHAEL D. CONDIE, District Permit Engineer