DISTRIBUTION AND LIMITING FACTORS OF *OSTREA CONCHAPHILA* IN SAN FRANCISCO BAY

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Biology: Marine Biology

by

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CERTIFICATION OF APPROVAL

I certify that I have read *Distribution and limiting factors of Ostrea conchaphila in San Francisco Bay* by Holly Elizabeth Harris, and that in my opinion this work meets the criteria for approving a thesis submitted in partial fulfillment of the requirements for the degree: Master of Arts in Biology: Marine Biology at San Francisco State University

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DISTRIBUTION AND LIMITING FACTORS OF *OSTREA CONCHAPHILA* IN SAN FRANCISCO BAY

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The native oyster, *Ostrea conchaphila,* in San Francisco Bay has undergone a decline in density in the past 155 years due to a number of limiting factors. In 2001 – 2003, I looked for oysters in the subtidal, intertidal and on marina docks. I based my ecological hypothesis for the oyster distribution on the identified limiting factors of salinity, predation, and substrate. The subtidal study yielded live oysters on only one site, the rocky substrate of Point Pinole. A relative distribution study was conducted in the intertidal. A more quantitative transect study was done comparing intertidal oysters with nearby subtidal attached dock oysters. The significantly higher densities of oysters found on the docks may be because the oysters are affected by the choking silt on the bottom of the bay. The higher density on the docks may also be because of lowered predation by the benthic bound oyster drill
U. cinerea.

I certify that the Abstract is a correct representation of the content of this thesis.

____________________________________ _______________________
(Chair, Thesis Committee) (Date)

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure Page

INTRODUCTION

The Native Oyster, *Ostrea conchaphila* Carpenter, 1857

Classification

Ostrea conchaphila has been called *Ostrea lurida* in past literature. Both species names were coined by Carpenter: the first, *O. conchaphila* in 1857 and the second *O. lurida* in 1864. *O. conchaphila's* type locality was Mazatlan, Mexico and *O. lurida's* type locality was Shoalwater (now Willapa) Bay. The early malacologists later estimated the respective species ranges as Alaska to Baja for *Ostrea lurida* and Baja to Panama for *Ostrea conchaphila*. The extremes of these ranges have never been confirmed and are doubtful. Further research is yet to be done to make sure that *Ostrea conchaphila* is one species from Alaska to Mazatlan. This would entail examination of material from Mazatlan. *Ostrea lurida* was found to be synonymous with *Ostreola conchaphila* by Harry (1985). The *Ostreola* and *Ostrea* genera were not found to be sufficiently different to warrant separate names. (P. Baker personal communication).

This species is within the phylum Mollusca, the class Pelecypoda (Bivalvia), the subclass Pteriomorphia, the order Ostreoida, the superfamily Ostreacea, and the family Ostreidae. Common names included native oyster, California oyster, and Yaquina oyster. The preferred common name is Olympia oyster (Baker 1995).

Identification

O. conchaphila is a small oyster compared to the larger, more marketable Pacific oyster from Japan, *Crassostrea gigas*, or the Atlantic and Gulf coast oyster, *Crassostrea virginica.* Adult *O. conchaphila* vary from over 6 cm in shell length at Vancouver Island to 5 cm in the southwest Puget Sound, WA, to even smaller lengths in San Francisco Bay (Figure 1). Shells of *O. conchaphila* are thin and not chalky like the *Crassostrea* species. The muscle scar is not much darker than the rest of the interior of the valve (Kozloff 1974). The valves are thin, irregular in shape, usually circular or elongate, and sometimes scalloped at the edges. The surface of both valves is flat, but may conform to the contours of the substrate. The outside of the shell may vary in color from dark grey to purplish-black, but brown and yellow striped forms have also been seen in San Francisco Bay (personal observation). The inside of the shell is shiny white or olive brown. There is only one adductor muscle present. Native oyster shells differ from the Atlantic oyster in that it never has black adductor muscle scars and from the giant Pacific oyster in its small size and thin flat shells (Fitch 1953).

Range

The fossil record shows that *O. conchaphila* is a fairly abundant Pleistocene fossil along most of its present range (Filice 1958, Atwater et al.

1981, Miller and Morrison 1988), and is sometimes the dominant fossil. The present latitudinal extremes of *O. conchaphila* are unclear. The northernmost limit may be near Sitka in southeast Alaska and the southernmost limit may be in Cabo San Lucas, Baja California Sur, Mexico (Fitch 1953). *O. conchaphila* is the native oyster historically found throughout San Francisco Bay (Bonnot 1935). These oysters have been in the Bay since the Pleistocene epoch (Atwater et al. 1981). *O. conchaphila* was at times an important food of the Ohlone, a Native American tribe of the San Francisco Bay region (Morris et al. 1980). Nelson (1909) mapped 425 mounds around San Francisco Bay. Some Ohlone shell mounds contain thick layers of *O. conchaphila* shell, Table 1 (Gifford 1916).

Packard's 1918 study of molluscan fauna in the San Francisco Bay found 17 different spots where there were live oysters. They were as far north as the Southampton Shoal and Point Isabel. He also found them on the eastern shore of Angel Island and Sausalito. In the Central Bay, he found them on the southern end of Yerba Buena Island and the western side of Alameda. They were also found south of Hunter's Point, off of Coyote Point, in several spots where the San Mateo Bridge now lies, off of Steinberger Slough and in a couple of spots south of where the Dumbarton Bridge now lies.

Habitat

O. conchaphila is moderately euryhaline and it has had an 80% survival at 15 practical salinity units (psu) (parts per thousand, ppt, is synonymous with psu), salinity for 49 days (Gibson 1974). Coe (1932) found them in full seawater in La Jolla Bay in California. Their northern limit is apparently set by temperature as *O. conchaphila* cannot withstand freezing (Davis 1955, as sited in Baker 1995) and also needs water of at least 12.5°C to reproduce (Hopkins 1937, as cited in Baker 1995). *O. conchaphila* has been found in a shipping channel in Coos Bay, Oregon at a depth of over 10m. Its shallowest depth can be found at least 2m above mean low water in the intertidal (Baker 1999). Miller and Morrison (1988) found fossils of oysters associated with eel grass beds at the mouth of the Mad River in Humboldt County in Northern California. They termed this oyster reef habitat an oyster garden. This oyster and eel grass mélange may have synergistic effects. The oysters filter the water, making the water more transparent for sunlight to reach the eel grass. Eel grass in turn stabilizes the sediment, so that oysters aren’t smothered in silt.

Life History

O. conchaphila is a brooding protandrous hermaphrodite with gonads forming at about 8 weeks after settlement. Spermatogonia are mature at 5 months, and the oogonia are mature at 6 months (Baker 1995). Spawning begins in southern California when the water temperature reaches 16°C for at least 7 months (Coe 1931). The observations and experiments of Santos et al. (1992) show that moving northward (to southwest Puget Sound) the spawning starts at lower temperatures (12.5-13°C) and does not last as long (6 months). Their experiments showed that the higher the temperature (up to 21°C), the faster gametogenesis occurred and the higher the productivity. The 12°C group peaked the latest at 8 weeks and the 21°C group peaked the earliest at 2 to 3.5 weeks. The 18°C group produced fewer larvae than the 21°C group, but ended up brooding more oysters. This was a result of the 21°C group's lower condition index or energy reserves. The 12°C group's condition index did not change despite spawning. Two spawning peaks per year are common (Hopkins 1937, as cited in Baker 1995).

Mature eggs have been reported to be 90 µm (Elsey 1935) to 100-110 µm (Loosanoff and Davis 1963, as sited in Baker 1995) in diameter. The eggs are kept within the branchial chamber (space between the gills) of the female, where they are fertilized (Nosho 1989). Larvae are brooded by the female for about 10-12 days (Coe 1931). This larval mass becomes whitish and this stage is called the "white sick" stage. The larvae gradually darken forming two more named stages, "grey sick" and eventually "black sick." The size of the brood is 200 –

300,000 (Hopkins 1936). When the high tide water reaches 13°C in the late spring the larvae can be released (Nosho 1989). The larvae are released by a gradual process, or “swarming” at about 180-185 µm in diameter (Stafford 1915, as cited in Baker 1995). Photos of larvae can be found in Loosanoff et al. (1966).

The larvae can spend from 3 to 8 weeks in the plankton, and settle at about 300 µm in diameter (Baker 1995). Settling planktonic larvae seem to prefer the undersides of objects (Hopkins 1935), although Bonnot (1937) found that they would settle on upper or lower surfaces of cement-covered plywood strips stacked several high with a narrow space in between, where it was dark. Hopkins (1935) demonstrated that the preferential settling wasn’t due to a negatively phototrophic reaction. The preference for settlement on undersides of objects had to do with the larvae’s swimming position. Hori (as sited by Hopkins 1935) observed that the larvae swam with their velum upward. The velum is a flattened, ciliated swimming organ and must support the weight of the body and the larval valves. This position also points the foot upward which then usually attaches to the undersurface of an object (Hopkins 1935). *O. conchaphila* larvae settle readily on concrete (Bonnot 1937), but apparently will not settle heavily on brush, as do the larvae of *Crassostrea* species (Stevens 1928, as cited by Baker 1995).

The growth rate of juveniles has not been studied (Baker 1995), which makes it difficult to make a growth rate curve. *O. conchaphila* grows to near maximum size in about 4 years and then grows relatively little after that (Baker 1995). Baker has found fossil shells of individuals in Coos Bay, Oregon, with 10 or more major hinge annuli, which may correspond to age in years.

At Tiburon Audubon Center pallets of shell bags were put out in late May of 2004. In September, 4 months later, the largest oyster we measured was 38mm. If the oyster recruited as soon as the oysters were in place then they grew at a minimum average rate of 9.5mm/month. This was for the largest oyster, but it may have settled on the shells some time after they were first put in the water (M. McGowan, unpublished data).

Coe and Allen (1937) conducted a study placing cement and wood blocks into the water at La Jolla, California. Oysters landed on the blocks in the months of May through October. The oysters grew 2 mm a week in the warmer months. The largest oysters found on their 4-week blocks measured 9 mm in length and on the 8-week blocks they were 16 mm. At the age of 16 weeks the length sometimes exceeded 35 mm. Sexual maturity slows the growth rate, but the shell can sometimes grow to be more than 50 mm in length when the animal is only 30 weeks old.

Human Utilization

O. conchaphila is generally not used for consumption because of its small size. However, there is a gourmet market for this oyster and it is still commercially grown in Puget Sound. The preference is for *C. gigas* as it takes 80-140 shucked, raw *C. gigas,* as compared to 1600-2000 shucked, raw *O. conchaphila,* to fill a gallon bucket. The native oyster still has a high price at $250 per gallon of shucked meat in 1988. This price still doesn’t compensate for the labor involved (Baker 1995). Native oyster beds have still been protected from non-native oyster bed culture (Orcutt 1958). The numerous shellmounds surrounding the Bay show that the Native Americans made extensive use of *O. conchaphila* (Nelson 1909).

Oyster shells found on the bottom of the Bay were used for poultry feed (Aplin 1967). There are extensive deposits of shell in the shallow water of the western part of the Bay. Shell bars extending into the Bay were also formed. Schooners carried away loads of shell for the formation of garden walks and other purposes to which oyster shells were adapted (Townsend 1893 as reported by Skinner 1962). The South Bay is one of the few places in the world where cement is made from shells and perhaps the only place in the world where mud and shell exist in almost exactly the right proportions for cement making (Gilliam 1957 as reported by Skinner 1962). This deposit of shell has supported a cement industry since 1933. There were enough shells in 1957 to harvest 500,000 cubic yards a year until 2007 (Gilliam 1957 as cited by Wooster 1968).

Limiting Factors

Limiting factor theory

In order to live in a given area organisms in general need to have essential materials for growth and reproduction. If the amounts of these necessities, such as oxygen, fall below the minimum, the organism disappears. This law of the minimum is used for limiting factors of chemicals like oxygen that are necessary for the physiology of marine organisms.

Likewise there are certain factors that have maxima for organisms. This is explained by the law of tolerance (Odum 1971). A marine organism may have a maximum and minimum temperature of water that it can tolerate. The period of reproduction for oysters is regulated by a minimum water temperature.

The depth of oyster shell found in Bay cores and shell mounds shows the oyster was at one time very plentiful (Table 1). Since the Gold Rush, the oysters have been in decline (Barrett 1963). Introduction of the Virginia oyster for commercial cultivation brought in the predatory Atlantic oyster drill, *Urosalpinx cinerea* (Stearns 1894). By the early 20th century, bayside urban pollution and siltation from the foothills of the Sierra Nevada goldfields almost totally depleted the oysters in San Francisco Bay (Nelson 1909 and Wooster 1968).

The *O. conchaphila* populations living in San Francisco Bay now are not limited by oxygen, food or temperature. San Francisco Bay is probably productive enough and definitely sufficiently well-mixed to provide food and oxygen for the oyster. The temperature of the water also reaches a requisite temperature for spawning for many months in each year. Other factors may be limiting the population of oysters.

Potential limiting factors for native oysters

Pollutants

Pollutants are a limiting factor. Some can be benign in small amounts. The Bay however, is full of a large variety of pollutants, some in great concentrations. Barrett stated in 1963 that oyster beds in San Francisco Bay would have to be abandoned when new nearby sewage outfalls would be built. As of 1979, all shellfish harvesting for human consumption in San Francisco Bay, including for *Ostrea conchaphila*, was prohibited because of bacterial contamination, but not because of heavy metals (Baker 1995). Bradford and Luoma (1980) did find high heavy metal amounts in shellfish in San Francisco Bay as compared to Tomales Bay. Tomales Bay is a small embayment found a few kilometers north of San Francisco and receives only small and insignificant discharges of urban runoff. Although Bradford and Luoma did not look at the concentrations in tissues of *O. conchaphila*, they did look at other species, such as bivalves: bent-nosed clam (*Macoma nasuta)*, Japanese little-necked clam (*Venerupis philippinarum)*, and the Eastern mud snail (*Nassarius obsoletus)*. For all species, zinc was found to be high in concentrations above the alert limits of 178 mg/kg dry weight. In *N. obsoletus,* cadmium and copper concentrations were also above alert limits of 3.0 and 148 mg/kg dry weight respectively. In conclusion, Bradford and Luoma's 1980 study found high concentrations of silver, lead, and mercury in the Bay. Copper wasn't found in great concentrations compared to other bays, but was found to be highly bioavailable to organisms. Lead levels in the eastern softshell clam, *Mya arenaria,* were found to be higher than in pristine environments, but lower than the alert limits. Mercury has been identified in only a few species, despite mercury's availability from natural local cinnabar deposits and the historic mining of mercury in the watershed.

Clark et al. (1974) did a study testing outboard motor effluent on *O. conchaphila* and the mussel, *Mytilus edulis.* They found that this pollutant had a greater effect on *M. edulis* than on *O. conchaphila*. In 2001, a native oyster was found attached to an outboard motor at the Romberg Tiburon Center (personal communication: Jay Tustin). These oysters were exposed to hydrocarbons and antifouling paint. Patrick Baker (1999) also found oysters growing on discarded lead-acid batteries.

Diseases

Compared to other oyster species, *O. conchaphila* is relatively disease free, but experience virus-like lesions and several proliferative diseases that have been reported at low incidence (Baker 1995). *O. conchaphila* has been known to be a host for Togaviridae; virus-like particles bud through the plasma membrane of oyster cells. But infected cells and virions (or virus particles) were rare and only seen in one animal (Farley 1978).

Microorganisms are known to invade oysters. Microcell disease or an infection by *Microcytos mackini* was found in *O. conchaphila* in Oregon. This recently described microorganism infects the vesicular connective tissue of the oyster, such as that of the mantle or gonads. The infection was enzootic to Yaquina Bay, Oregon (Farley et al. 1988). A possibly pathogenic flagellate, *Hexamita* sp., has been reported to occur in Washington and Oregon (Weitcamp et al. 1969). This flagellate has eight long flagella in its trophozoite stage, six at one end and two at the other. Ideal conditions for *Hexamita* sp. are low temperature, overcrowding, and recirculation of water in basins such as those in which commercial oysters are sometimes kept. *Hexamita* occurs in the blood-cells of the oyster and also as cysts, packing the blood vessels and penetrating the tissues. Bacteria subsequently invade, causing degeneration and inflammation (Yonge 1960).

Neoplasias in oysters associated with the paralytic shellfish poison, PSP, produced by the dinoflagellate, *Alexandrium catenella,* have been reported in Yaquina Bay. These have led to mortalities of native oysters (Landsberg 1996).

A Parasite and Epibionts

Parasitism is another limiting factor in the distribution of oysters. The parasitic copepod, *Mytilicola orientalis,* has been well-documented (Odlaug 1946, Cheng 1967, Bernard 1969, Weitcamp et al. 1969, Bradley and Siebert Jr. 1978, Carlton 1979). Odlaug (1946) purported that the oyster has a lower condition factor when parasitized by *M. orientalis*. But Bernard (1969) contends that this parasite has not been found to have an economic significance on oyster culture in British Columbia. Bradley and Siebert (1978) showed that *O. conchaphila* was parasitized by *M. orientalis* in San Francisco Bay, but to a lesser extent than *Mytilus edulis*.

Smothering epibionts may also cause oyster mortality. An unknown species of bryozoan and the tube-dwelling amphipod *Corophium spinicorne* were major sources of *O. conchaphila* juvenile mortality in Yaquina Bay, OR (Dimick et al. 1941 as reported by Baker 1995). Other epibionts include three barnacles, *Balanus glandula, Chthamalus dalli ,* intertidally, and *Balanus crenatus* subtidally. The following sponges also inhabit the oyster: the boring sponge, *Cliona celata,* and Crumb-of-Bread sponge, *Halichondria* sp., in areas of higher salinity. Various bryozoans and the polychaete, *Polydora* sp.*,* are also epibionts of the native oyster. The colonial tunicates, *Botryllus* sp. and *Botrylloides* sp., have been known to completely cover *O. conchaphila*. The epibiont slipper limpet, *Crepidula fornicata* came from the Atlantic, but has been found not to be a competitor with *O. conchaphila* (McKernan et al. 1949 as cited by Baker 1995).

Salinity

In San Francisco Bay, actually a stratified estuary, the freshwater comes from two river sources that flow into the delta, which then drains into the Bay. The seawater flows into the deepest part of the Bay from the Pacific Ocean at the Golden Gate between the northern end of the San Francisco Peninsula and the southern end of the Marin Headlands. The Sacramento/San Joaquin River system of the Central Valley drains 40% of the surface area of the state and 90% of San Francisco Bay's freshwater inflow comes from this system into the North Bay (Nichols et al. 1986).

O. conchaphila's optimal salinity range is 20-30 psu (practical salinity units) (Baker 1995). As a stratified estuary, San Francisco Bay experiences salinity changes throughout the year. Salinity below 10 psu for weeks at a time can be deadly for the oyster. Gibson (1974) found native oysters to be tolerant of reduced salinity during the winter. From his study in Oregon during the years of 1966-1972, he also found that low salinity stress caused over half of the mortalities each winter. The salinity was below 10 psu for more than 3 weeks. The mortalities ranged from 9.6-28.2%.

The salinity is optimum for the oyster in most parts of the Bay for most of the year. Only in the upper reaches of the Bay near the mouth of the delta does the salinity drop to levels too fresh for the oyster to withstand. During El Niño years when the freshwater flows are higher, the salinity may become too low for too long a period of time for the oysters. These events are infrequent and are not a threat to the population of oysters as a whole in San Francisco Bay.

An example of the limiting factor of salinity was shown in Coos Bay, Oregon. For unknown reasons, the native oyster became locally extinct from that bay prior to European settlement (Dall 1897 as cited by Baker et al 1999). Recently, navigational dredging in Coos Bay deepened the main channel, permitting higher salinity oceanic water to intrude. This dredging activity created a euryhaline habitat suitable to *O. conchaphila*. The increased depth also increased water retention during tidal fluctuation, which could reduce flushing pressure on the estuarine larvae of *O. conchaphila* (Baker et al. 1999).

Predation

The oyster's benthic intertidal predators in the San Francisco Bay are the native predatory snail, *Acanthina spirata,* and the introduced Atlantic oyster drill, *Urosalpinx cinerea*. *U. cinerea* was brought in with Atlantic oyster, *C. virginica,* spat by train (Carlton 1992). The indigenous *Cancer productus* or red crab, and the introduced European green crab, *Carcinus maenus*, can eat the oyster in its juvenile state. Waterfowl such as scaups and scoters also feed on Olympia oysters (Couch and Hassler 1989). These include the white-winged scoter, *Melanitta fusca*, the black scoter, *Melanitta nigra*, and the greater scaup, *Aythya marila* (Baker 1995). The oyster catcher, *Haematopus bachmani,* seems aptly named as an oyster predator, but references that list it as an actual predator of the oyster are almost nonexistant. It seems to prey on limpets (Ricketts et al. 1985). Elasmobranchs such as bat rays, (*Myliobatus californica)*, and leopard sharks, (*Triakis semifasciata),* are predators of the oyster (Wicksten 1978).

Humans, of course, are also predators on the oyster, but not so much in San Francisco Bay where pollution has thwarted shellfish gathering in general. Overfishing of oysters did occur in Willapa Bay, Washington where the native oysters were shipped to San Francisco for the gold rush as early as 1851. This unrestricted fishing led to the oyster's depletion, from which it hasn't recovered (Hertlein 1959).

Although there are many predators of *O. conchaphila* as stated above, my study focused on the benthic Atlantic oyster drill *Urosalpinx cinerea*. The shell of *Urosalpinx* has strong axial ribs as well as finer spiral ridges (Kozloff 1973). The introduction of *U. cinerea* to San Francisco Bay came with Atlantic oyster spat in 1890 and later years (Carlton 1992). Although the larvae of *U. cinerea* are crawl-away (non-planktonic), the snail was still able to spread throughout the Bay. The large range of the oyster drill in San Francisco Bay is attributed to the wide-ranging oyster beds found in the Bay at the turn of the century (Bonnot 1935). The drills have been known to over-winter in the mud, which could make them harder to find at that time of year (Haydock 1964). This seems to be contradicted by Wicksten (1978) who found drill egg masses at all seasons of the year at Coyote Point.

U. cinerea preys on both oyster larvae and adults. Haydock (1964) suggested that young drills might be more voracious than the adults because the mortality rate may be as high as 58% for spat. In Boundary Bay, British Columbia, the mortality rate of juvenile *O. conchaphila* to *U. cinerea* was 10-20%

(Elsey 1933). *U. cinerea* has had a significant negative effect on the oyster populations in Tomales Bay (Haydock 1964).

U. cinerea is also a formidable predator in that it can regenerate its radula even upon amputation (Carriker et al. 1972). The radula, along with a chemical secretion produced in an accessory boring organ (ABO) in the foot, forms a boring instrument of great precision (Yonge 1960). This ABO's viscous secretion may be acidic at times (pH can be 3.8) and contains the enzyme carbonic anhydrase. This secretion softens both calcareous and protein components of the shell. The ABO may take up to a few minutes or an hour to soften the shell (Morris et al. 1980). *U. cinerea* was so abundant in Tomales Bay that any attempt to culture *O. conchaphila* was stopped (Bonnot 1938).

U. cinerea has an advantage over the oyster in that it can move and escape siltation. The drill's behavior demonstrates this. They move away from gravitational pull (negative geotaxis) and towards light (positive phototaxis) and so tend to leave the bottom and escape danger from suffocation by the silt. Once the drills are on shore, their pattern of behavior changes. There they display negative phototaxis and move away from the light to the shade of the rocks to escape desiccation (Carriker 1927 as sited in Yonge 1960).

Substrate

O. conchaphila larvae attach to hard substrates. This leads to their species name of “conchaphila”, or shell-loving. The hard substrate for attachment can be of very small size (Fasten 1931). The largest aggregations usually occur in low intertidal or shallow subtidal mud areas of estuaries. Populations are also found on rocky reefs, pilings, and floating piers (Baker 1995). The oyster has even been found attached to iron (MacGinitie 1935). In San Francisco Bay the oyster was found attached to shopping carts and car batteries (J. Thompson and R. Mooi, personal communication). The firm substrate should also be in an area where there are no scouring currents (Nosho 1989). *O. conchaphila* has formed large reefs or beds in San Francisco Bay since the Pleistocene (Wooster 1968).

Another requirement for the substrate of *O. conchaphila* is that the substrate cannot be smothered by silt. This is due to *O. conchaphila’s* intolerance for turbid water (Barrett 1963). Dredging has been found to kill oysters by stirring up silt (Wooster 1968). Oysters are unable to feed while getting rid of silt as they expel silt by snapping their shells (Elsey 1935). *O. conchaphila* protects its young from a silted habitat by brooding them (Hopkins 1936). The blue mud shrimp, *Upogebia pugettensis*, and the bay ghost shrimp, *Callianassa californiensis*, are native to San Francisco Bay, and are predisposed to stirring up the sediment by resuspending it, which could possibly choke the oysters (Stevens 1929). Shrimp cannot live where there are eel grass beds or oyster shell on top of the benthos (Feldman et al. 2000). In contrast, these habitats are ideal for the oyster.

Substrate that is floating, like a floating dock, has many advantages for habitat for the oyster. Oysters are kept above the silty bottom. Some crawling predators, such as *U. cinerea,* cannot reach the oysters. Even in the larval stage, *U. cinerea* are crawling (non-swimming) and wouldn't float up to the dock. The parasite, *M. orientalis,* also would be hindered from reaching the oysters on a floating dock. *M. orientalis* has a short larval stage and does not travel far. Oysters that were raised above the substrate were not infected with *M. orientalis* (Bernard 1969).

The Bay has varied substrata of mud, rock, and shell. The soft sediments of San Francisco Bay are not indigenous to its original formation, but came from hydraulic mining in the foothills in the years 1853 to 1884. These 11 years of mining were so destructive to farm fields, let alone the original substrate of the Bay, that an early environmental law was passed banning the practice. The oyster beds in the Bay were damaged by sediments as thick as 0.25 - 1 m. These new shallows altered tidal circulation patterns, made mudflats, expanded marshland across original mudflats, and reduced the water volume of the Bay

(Nichols et al. 1986). Oysters were easily suffocated by silt (Barrett 1963), brought down from the goldfields. Bradford and Luoma reported in 1980 that the reason for the decline of the oyster-rearing industry in the Bay after 1905 probably was physical. That is, the oysters were probably buried in silt. Siltation and filling for development, occurring at the turn of the last century, changed the Bay so that wind and tidal resuspension became more intense. Stability of the sediments on the shoals was decreased, causing the oysters to be buried. Nichols and Thompson (1985) have documented that entire communities can be buried in this flocculant sediment.

Previous Study

In 1999 I conducted a brief distribution survey of *O. conchaphila* in San Francisco Bay. I was unable to find oysters in Redwood City in Westpoint Slough and Steinberger Slough, at the West San Mateo Bridge, Coyote Point, and Oyster Point in the South Bay. I did find them in Strawberry Point and Tiburon in Marin County in the North Bay. After finding them at Strawberry Point I counted the number of oysters and mussels in 0.1 m^2 plots. On average, I found the mussels outnumbered the oysters by a ratio of 16 to 1. This difference in abundance didn’t seem to be because of substrate competition as I found oysters attached to the mussels.

Restoration Work

Recent interest has been stirred in restoring oysters to San Francisco Bay. Why the oysters have not made a comeback on their own needs to be investigated. This thesis is a step toward this investigation. The advantages of increased water quality and restoration of native habitat (oyster reefs and eel grass beds) makes restoring the oysters an attractive prospect. Live oysters also provide habitat for epibionts, such as mussels, macroalgae, and sponges, and for the native Dungeness crab that use them as a refuge (Feldman et al. 2000). In the summer of 2001, oyster shell necklaces were made by Save the Bay volunteers by punching holes in Pacific oyster shells and knotting them together on ropes. These necklaces were placed throughout the Bay and provided abundant recruitment of oyster larvae onto hard substrate (Latta 2002). In the end over 100 oysters became attached to the shells on the necklaces. Even the sparse population of adults near the necklaces on the bottom of the Bay or on nearby pilings was enough to provide recruitment of larvae. The next step for restoration was to provide whole shell pyramids on the bottom of the Bay. These pyramids were placed in Richardson’s Bay during the spring of 2004. By the fall, recruitment to the pyramids had been seen. Another way of restoration is by planting spat or larval oysters in sections of the Bay. The spat need to be free from parasites and predators, in order for this to be effective. Raising larvae in hatcheries would help attain this goal (Carriker 1992). Truly successful restoration must overcome whatever limiting factor is operating at present.

Cook et al. (2000) has drawn up a plan to rebuild stocks of Olympia oysters in Washington State. The tribal oyster fisheries of Washington were so precious that there was at least one tribal war fought over the rights to harvest Olympia oysters (Swan 1857 as cited by Cook et al. 2000). Genetic integrity of the oysters would be kept by using brood stock for seed production from the same geographic area where seeding would take place. The minimum number of brood stock necessary would be established and kept in order to maintain genetic variability and stock identity (Cook et al. 2000).

Statement of Purpose

This study seeks to understand the impact of three limiting factors on the oyster in San Francisco Bay in order to aid in further restoration efforts of the oyster.

Hypotheses

From my review of the possible effects of limiting factors on *O. conchaphila*, I based my ecological hypotheses for the oyster distribution on the limiting factors of salinity, predation, and substrate.

My null hypothesis is as follows:

H_0: There will be no significant relationship between oyster density and the three limiting factors of salinity, predation, and substrate.

My three alternating hypotheses with these factors are first, that the oyster's density will be greater in a salinity of 20-30 psu, second, the number of oysters will be inversely related to the density of predators, and third, the oyster's density will also be higher on rocky substrates in comparison to other substrates.

After gathering data on benthic substrate, predation, and salinity, I added another type of substrate to the study. These were the floating docks. My hypothesis was that the docks would have a higher density of oysters than the nearby shoreline. Benthic predators will be unable to reach the oysters on these floating substrates. There is also greater larval retention amidst these docks that are often in enclosed areas within a marina.

METHODS

Subtidal Sampling:

The research area was San Francisco Bay, California, 37.8° N, 122.4° W. San Francisco Bay is a geologically recent estuary. The San Francisco Bay system is actually two different types of estuaries, the North and the South Bay. The North Bay's freshwater flow comes in from the delta from the large watershed in the surrounding Central Valley. The North Bay is a partially mixed estuary because of the vertical differences in salinity (Smith *et al*. 1985). The South Bay is a shallow lagoon type estuary characterized by extensive shoals bordering a deep 10-15m wide longitudinal tidal channel (Powell *et al.* 1989).

I looked for the oysters using a Wildco biological oyster dredge (50-cm mouth, 2cm mesh) (Figure 2). I also measured salinity, depth, size, and number of oysters for each tow. Dredges were 2 minutes long and towed at minimal speed. Oysters were counted and recorded as either adults (>20 mm in shell height, for *O. conchaphila*) or juveniles (Baker 1995). I recorded dead specimens with both shells attached by the ligament as recently dead. I noted presence or absence of some suspected *O. conchaphila* predators, including crabs, (*Cancer* spp.) and the predatory snail, *Urosalpinx cinerea*, at the sites. I measured salinity using a conductivity, temperature, and depth meter (CTD).

I first sampled in the North Bay in deep channels of suitable salinity near Southampton Shoal, (Table 2). Then I sampled channels in Richardson Bay. Oysters were historically cultivated here and Strawberry Point contains them in the intertidal. I then looked in the South Bay where there are extensive shell banks. My final cruise was in San Pablo Bay, where there was suitable substrate for the oysters (Figure 3).

Intertidal Relative Distribution Sampling:

Intertidal sampling was conducted in San Francisco Bay along the shoreline. Ten sites were looked at in the North Bay, fifteen in the Central Bay and nine in the South Bay (Table 3). I first measured the distribution of oysters by relative density. The search time was recorded, while oysters were counted. Thus, this method measured density by catch per unit effort, CPUE, or oysters per minute. I used this method at first because of the relatively rare occurrence of oysters in some parts of the Bay. Substrate was qualitatively classified in eight different categories: rock on mud, rock on sandy mud, rock on clamshell mud, rock on sand, riprap on sand, riprap, rock on rock, and cement piles (Table 4). All sampling trips were undertaken at low tides. The sampling was stratified in that it was conducted as close to the waterline as possible. A subset of oysters was measured. Salinity samples were collected and predators and other organisms were noted. The predatory Atlantic oyster drill, *Urosalpinx cinerea,* was counted. Salinity was later measured with a YSI meter or a refractometer with +/- 2 psu accuracy. I also averaged salinities for a 30-year period using the United States Geological Survey (USGS) online database. Linear regressions were conducted on the data gathered from the limiting factors of salinity and number of the predator, *U. cinerea*. Spearman correlation coefficients were found for various limiting factors.

Marina and Nearby Intertidal Distribution Sampling

In 2003, oyster density was measured in 10 x 1 m transects (Table 7). It was necessary to get more quantifiable data than the relative density method, since the results for that method did not yield many statistical relationships. These shoreline samples were taken as close to the nearby dock samples as possible. I searched on the docks as they were relatively free from crawling predators such as *U. cinerea*. All of the above methods: salinity measurement, the counting of predators, substrate classification, and measurements of subsets of oysters, were used in this transect study. I looked under every rock that could be lifted with two hands within each intertidal transect next to the docks. The intertidal sites were chosen close to the docks that were sampled. Dock sampling was done at the water line and 10 cm below for 5 m at each transect. Dock sampling was stratified in that it was conducted above a suitable depth, so that the bottom of the dock wasn’t resting on the ground at low tide. Samples were also taken usually near or facing the nearby shoreline that was also sampled, if possible. A sign test was conducted upon the data collected from the marina and near shore intertidal study (Zar 1974). This enabled the densities of the marina and shore to be compared.

RESULTS

Subtidal Sampling:

Out of 16 dredges in 13 locations in the Bay, live oysters were found only at Point Pinole. We collected six adults and four juveniles during a 2 minute dredge tow (Figure 4). The depth at which samples were taken at Point Pinole is 3.4 meters. Salinity there was 23 psu and the temperature was 12˚ C. The salinity was between 23-32 psu at the other sites. Temperatures were between 12 and 17˚ C at the other sites. No other sites had any live oysters. The substrate at Point Pinole was different from all the other sites in that there was no mud or silt, just shell and cobble (Table 2). The 2 knot current around the Point was able to wash away the silt. Richardson Bay was typical of many of the other sites that had just mud or silt substrate (Figure 5).

On the first cruise to South Hampton Shoal, only mud tubes and a *Mya arenaria* shell were found. The second cruise in the North Bay also yielded just mud, clam shells, the snail, *Nassarius mendicus,* mud tubes, red algae, and eel grass. On the third and fourth cruises in the South Bay we found shells of *O. conchaphila*, but no live oysters (Figure 6). The shells were so old that bryozoans had grown on the shells in layers, sometimes an inch thick. The fifth and final cruise back up to the Northeast part of the Bay to Point Pinole yielded live *O. conchaphila* in the second haul on shell and rock substrate.

Intertidal Relative Distribution Sampling:

The relative density of *O. conchaphila* found at all the intertidal sites sampled is shown in Figure 7. These data are also presented by location on a map of San Francisco Bay (Figure 8). Field data on location, salinity, date of collection, substrate, and relative densities of oysters and the predatory snail *U. cinerea* are presented in Tables 3, 4, and 5. Table 6 shows correlation coefficients for variables in this study.

Oysters were found in high relative density (or between 10 – 30 oysters per minute) at four sites in the North and Central Bay: Point San Quentin; China Camp in Marin County; and Berkeley Marina, South (or Shoreline Nature Center); and Emeryville Yacht Harbor, south of the jetty in the East Bay (Figure 8). Oysters were found in medium density (or between 2-9 oysters per minute) at nine locations in the North and Central Bay. Oysters were found at low density (or 1.9 and below oysters per minute) at 15 locations around the Bay. No oysters were found at Greenwood Cove in Tiburon although there was a low number of 0.7 oysters per minute just 1 kilometer east at Blackie’s Pasture (Figure 8). Oysters were not found at the shoreline near Fort Point Road in San Francisco. This was the only location that had the substrate of riprap on sand. Surfers were taking advantage of the strong waves that also wash away any deposited silt, leaving only heavy sand. The riprap protects the road from washing out.

Across the Golden Gate, oysters were found in low numbers because of the shelter of the jetties from the Fort Baker Presidio Yacht Club and Coast Guard. In the South Bay, oysters were not found on the cement wall jetty of Oyster Point Marina, on the riprap of the Hayward Regional Shoreline, nor at the Palo Alto Baylands or along the nearby San Francisquito Creek. All of these places that lacked oysters are surrounded by fine mud and silt (Tables 3 & 4). The oysters tended to be more abundant in habitats that were judged to be lower in fine sediment concentration.

Oysters were more plentiful in the northern part of the Bay where the salinities were lower (Table 3). They were larger in the southern part of the Bay where salinities were higher. Salinities varied from 9.5 psu at Pinole Bayfront Park on December 17, 2002 to 32.4 psu at Candlestick Point on November 3, 2002. From averages of the USGS water quality databases for the past 30 years, the lowest average for locations sampled is at Pinole with an average of 15.9 psu and the highest is at the Golden Gate with an average of 29 psu (Table 5).

The predatory Atlantic oyster drill, *Urosalpinx cinerea,* was found at six sites. *U. cinerea* was more abundant in the South Bay. They were found in Blackie’s pasture in Tiburon, near the Fruitvale Bridge, in Oyster Bay in San Leandro, at Coyote Point Marina, at the west side of the San Mateo Bridge, and in front of the Marine Science Institute in Redwood City. All of these sites have had Atlantic oyster aquaculture for at least 10 years in the nineteenth century (Figure 3). *U. cinerea* was relatively more abundant where oysters were more plentiful and it probably had a negative impact on the average size of the oysters (Table 6).

Marina and Nearby Intertidal Distribution Sampling:

From January to May, 2003 oyster density was measured at several marinas and the adjacent rocky shoreline in the Bay. These data are presented in Tables 7 and 8 and Figures 9 and 10. Table 7 shows oyster density, average size, drill density, and substrate. Table 8 shows salinity at time of sample and average salinities from USGS data. Figure 9 shows oyster density on the docks and on the shore from north to south. Figure 10 shows oyster density on the docks and the marina on the San Francisco Bay map.

On the dock samples oysters were found at a high density (or above 30/m^2) at San Leandro Marina. Oysters were found at a medium density (or from 10-29/m^2) at Berkeley, Emeryville, and Redwood City Municipal docks. Oysters were found at a low density (or 9/m^2) and below at six other docks on the bay (Table 7). No oysters were found on the docks at Port Sonoma Marina and Clipper Yacht Harbor in Sausalito (Figure 9). At the Port Sonoma Marina, the salinity was 11 psu, which is below the optimal range for the oyster. The covering of the float at Sausalito was black rubber, which may be an unsuitable substrate for the oyster to attach. However, I did find oysters on the shoreline at the yacht harbor in Sausalito.

Near the docks, in the intertidal, oysters were found at a much lower density than on the docks. The highest density, at 8.3 oysters/m^2, was at the Shorebird Nature Center in Berkeley. The substrate here was unique, as it was rock and sand. The next highest density, at 6.4 oysters/m^2, was found nearby at the Emeryville shoreline south of the fishing pier in front of the docks. Oysters were found at a density of 2.3/m^2 at the shoreline in front of the docks in San Leandro. The substrate there was rock and mud, a substrate that is usually not conducive to high oyster densities. However, San Leandro had the highest densities at 126/m^2 found for the dock samples (Figure 9). Oysters were found in low densities, below 1/m^2 at Sausalito, San Francisco Marina, and Brisbane shorelines in front of the docks. No oysters were found on the shorelines at Coyote Point, the Redwood City marinas, and at Port Sonoma (Figure 9).

Salinities varied from 11 psu at Port Sonoma Marina on February 26, 2003 to 27.5 psu on January 30, 2003 at the San Francisco Marina. From averages of the USGS water quality databases for the past 30 years, the lowest average for locations sampled is at Port Sonoma with an average of 20.3 psu and the highest is at San Francisco Marina with an average of 29.2 psu (Table 8).

The Atlantic oyster drill, *Urosalpinx cinerea*, was absent from all dock transects taken. It was found in the three locations in the South Bay where no oysters were found and at Grand Marina in Alameda. All of these locations have had Atlantic oyster farming for at least 10 years somewhere between 1851 and 1910 (Barrett 1963). On the shorelines without *U. cinerea,* the mean oyster density was 2.3/m^2, while on the shorelines with drills the density was 0.325/m^2. On the shorelines with drills the combined mean size was also smaller (20 mm) vs. 29.3 mm where they were absent.

Dock and shoreline samples were tested using the sign test. In 12 pairs of dock-shoreline, native oysters were more abundant on the dock in 9 of the comparisons. This is statistically significant by a critical value of .025. The average density on the docks was 17.5/m^2 while the average density on the nearby shorelines was 1.65/m^2.

DISCUSSION

My ecological hypothesis for the oyster distribution was based on the identified limiting factors of salinity, substrate, and predation. My null hypothesis was that there would be no significant relationship between oyster density and these three limiting factors. My alternative hypothesis was that the oyster's density would be dependent on a salinity of 20-30 psu, rocky substrate, and a density of predators twice as low as the number of oysters. *O. conchaphila's* optimal salinity range is 20-30 psu (Baker 1995).

Subtidal Sampling

Despite 16 dredges in 13 locations in the Bay, only one live oyster was found subtidally at Point Pinole. This area has swift currents and a rocky bottom unlike the silt-covered benthos of most of the rest of the Bay. The results of the subtidal study showed that the live oysters were found in the only rocky area that was included in the study (Table 2). This subtidal distribution of oysters found was limited by the availability of hard substrate.

Intertidal Relative Distribution Sampling

This study didn't yield many statistical relationships, but it did yield some interesting results. No oysters were found in the South Bay near broad mud flats such as Hayward Regional Shoreline, San Francisquito Creek and Palo Alto

Baylands (Table 3). This may be because of increased outflow of low salinity sewage and/or lack of substrate. I first checked San Francisquito Creek as I was told of oysters attached to a shopping cart at the mouth of the creek (J. Thompson, personal communication). I checked slightly lower down on the creek near the Friendship Bridge between Palo Alto and East Palo Alto. There is a sewage outlet there, which may bring in too much fresh water to this area for the oyster.

Numerous oysters, greater or equal to 14 or more oysters per minute, were found in China Camp, Point San Quentin, Berkeley Marina, and Emeryville Yacht Harbor (Figure 8). I found the substrate in these locations to be very suitable for oysters, all on rock. They are also all found in the Central or North Bay. Berkeley Marina and Emeryville Yacht Harbor are both in enclosed coves which are conducive to larval retention.

There were significantly more drills in the South Bay than the North Bay. The correlation coefficient given in Table 6 for *U. cinerea* density with latitude is a significant finding. Given these data, as far as restoration efforts are concerned, perhaps the South Bay is not the best place to restore oysters.

Marina and Nearby Intertidal Distribution Sampling

The highest density of oysters found in the intertidal transect study was at the Shorebird Nature Center in Berkeley (Figure 9). The substrate here was different from the other sites as it was rock and sand.

The dock environment was better for the oysters in terms of density and size, but the actual cause cannot be determined absolutely from these data. On docks, oysters are suspended above the bottom, thereby escaping smothering by siltation. There may also be a slightly more retentive aspect to the docks as they are not as subject to the intertidal wave action as the shore and are protected from currents by jetties or sea walls. Constant immersion for feeding in this subtidal environment on the docks is another favorable factor.

On docks, oysters are also protected from predation by drills. Predation by *U. cinerea* also seems to be a factor on the shoreline, because within the group of shoreline areas where drills were present, the oysters were less abundant and smaller.

San Leandro Marina's docks had the highest density of oysters. This marina is adjacent to Oyster Bay. It is also almost completely enclosed with dikes and jetties leading to an extremely retentive environment for recruitment of larvae. Oysters were not found at Clipper Yacht Harbor dock in Sausalito. This dock is made of black rubber, unlike the docks at other marinas, which are made of cement or styrofoam.

Conclusions

The subtidal distribution of oysters was limited by the availability of hard substrate. The intertidal distribution of oysters was also primarily limited by availability of suitable, hard, substrate. Enclosed bays and coves that would provide better retention of larvae had higher relative abundance of oysters than open shores in the intertidal. Locations with high oyster abundance had low or zero occurrence of non-native oyster drills. Marina docks were favorable habitat for the oyster because they provided hard substrate, they were suspended above the silty bottom, they provided for continuous feeding because they moved up and down with the tides, and they had very low or no non-native predatory drills, which are found on the bottom of the bay. Salinity and temperature were not found to be limiting to the oyster because much of the bay is within the known ranges of tolerance of the oyster.

The historical shell mound data show that oysters have thrived in the Bay in the past. The oyster is viable in San Francisco Bay as long as there is enough hard substrate that is silt-free in a relatively quiet environment for the larvae to attach to. The oyster's higher density on docks definitely supports this hypothesis. Drills were found to be predominantly in the South Bay. This gives the North Bay an advantage for oyster restoration.

Oyster recruitment would probably be successful in the South Bay, if it was upon floating structures. This is shown by the number of oysters found on the San Leandro dock. Even structures suspended off the bottom like the oyster shell necklaces did well for recruitment in the Alameda Estuary at Fruitvale Bridge at the mouth of Sausal Creek. At that location in the South Bay, over 100 larval oysters were recruited in 2001.

Further Study

There was no significant difference in the abundance of oysters in sites with 20-30 psu and lower. Perhaps a comparison of oyster distribution inside San Francisco Bay to the outside of the Golden Gate along the Pacific Coast or into Suisun Bay would yield significant results in this limiting factor. Outside of the Golden Gate the salinity is generally at full sea water or 35 psu. Suisun Bay has a lower average salinity than that found west of the Carquinez Strait.

No statistical relationship was found between the different types of intertidal substrate and oyster density. This may have been because of lack of discrete quantifiable data. A study of transects among the different substrates throughout the Bay may yield a significant result between types of substrates and varying densities of oysters.

The significant result with the higher density of oysters on the dock rather than the shore could lead to more experiments by laying out substrate in larval retentive areas such as the enclosed areas containing the marina docks. Floating docks are usually protected by some kind of man-made cove structures enclosing the docks, protecting them from wave action and currents that could sweep out larvae.

Studies on the rates of siltation or differences in oyster density in different current areas could lead to more understanding of the oyster population's limitations. A study on the rate of actual larval retention would take more time, but would lead to meaningful results.

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Table 1: *Ostrea conchaphila* shell found in these 18 shellmounds around San Francisco Bay

(Bickel 1978, Davis and Treganza 1959, Gifford 1916, Greengo 1951, Loud 1924, McGeein and Mueller 1955, Schenk 1926, Uhle 1907, Wallace and Lathrop 1975)

Location	**Mound name**	**Age: B.P.: Before Present**	**Depth [ft]**	**Depth of *Ostrea lurida* in mound**	**Amount in mound**	**Reference**
Benicia	Carquinez				< 0.001%	Gifford, 1916
El Sobrante	C Co-151		5		0.03%	Greengo, 1951
San Rafael			10	thin: up to 4 feet (1-3%) only then absent	>.001% and <1%	Gifford, 1916
Greenbrae			14	sporadic throughout (9% at bottom, 6% at top, no shell at some depths)	1%	Gifford, 1916
Richmond	Ellis Landing, C Co 295		20	up to 18 feet, then there are *Macoma* shells	>.001% and <1%	Gifford, 1916; Greengo, 1951
Richmond	Stege mounds, C Co299		3			Loud, 1924
Richmond	Stege mounds, C Co297		6 ?			Loud, 1924
Richmond	Stege mounds, C Co298		7			Loud, 1924
Richmond	Stege mounds, C Co300		9			Loud, 1924
Strawberry Point	Mrn 20		5	thinly throughout (oyster shell also found placed an inch thick on top of a skull)	2-3% of total shell	McGeein and Mueller, 1955
Berkeley	West Berkeley, Ala 307	3860 +/ - 350	17	throughout (heavier towards bottom: 57% at 13' and 10% at top	35%	Gifford, 1916; Greengo, 1951; Wallace and Lathrop, 1975; Bickel, 1978
Sausalito					>.001% and <1%	Gifford, 1916
Emeryville, (IKEA)	Cone A and B	2310 +/-220	19.5	throughout (heavier at bottom (64%), thin in middle (1%), thicker again at top (12%)	8%	Uhle, 1907; Gifford, 1916; Schenk, 1926; Bickel, 1978
San Francisco					>.001% and <1%	Gifford, 1916
San Mateo Point					22%	Gifford, 1916
San Mateo			14	throughout (14 feet - 50%; 8 feet -46%; 6 feet - 59%; 3 feet -38%)	31%	Gifford, 1916
Alvarado	Ala-328	2330 +/- 90	13		38.1%, 82.7% of shell species	Davis and Treganza, 1959; Bickel, 1978
Mountain View	Castro		5	throughout (heavier at bottom (33%), thin in middle (9%), thicker again at top (29%)	3%	Gifford, 1916

Table 2. San Francisco bay subtidal physical and biological samples from five cruises on the RV Questary, Fall 2001.

Sample	Date	Location	Secchi (m)	Depth (m)	Substrate	Salinity	Temp. in C
1	10/4/2001	Southampton Shoal	2	9.8	mud	31.5	16.5
2	10/4/2001	Southampton Shoal	2	6.6	mud	32	16.2
3	10/26/2001	Paradise Cay	4	12.6	mud	31.4	15.4
4	10/26/2001	Strawberry Point #1	2.5	2.8	mud	31.5	15.3
5	10/26/2001	Strawberry Point #2	too shallow	2.9	mud	32.4	15.6
6	11/9/2001	San Lorenzo Creek	0.75	2.5	mud & shell	31.2	15.2
7	11/9/2001	N.San Mateo Bridge	0.75	4.5	mud & shell	31.6	16.2
8	11/9/2001	Coyote Point	2.5	2.5	mud & shell	31.7	15.4
9	11/9/2001	Oyster Point	2.5	6.8	mud	31.6	16.6
10	11/9/2001	Southampton Shoal	1.5	15.6	mud & sand	31.8	14.4
11	11/30/2001	Coyote Hills Slough	0.5	4.1	mud & shell	30.6	13.4
12	11/30/2001	Redwood Creek	0.5	4	mud	30.2	13.7
13	11/30/2001	San Leandro Bay	0.6	3.9	mud & shell	29.6	12.5
14	12/3/2001	China Camp	0.3	3.2	none seen	23.3	11.7
15	12/3/2001	Pinole Point	0.4	3.4	shell & rock	22.5	11.6
16	12/3/2001	Lone Tree Point	0.5	4.5	mud	22.8	12.6

Sample	# Oysters	Other organisms
1	0	jellyfish caught in dredge
2	0	mud tube worms
3	0	*Nassarius mendicus* , (snail), *Venerupis philippinarum, Macoma nasuta,* (clams: shells only) worm (Maldanidae?) tubes
4	0	*Macoma nasuta* , red algae, eel grass
5	0	*M.nasuta, V.philippinarum,* red algae, eel grass
6	0	oyster shells, clam shell, mud tubes, bryozoans
7	0	oyster shells, *Styela* sp.(tunicate), barnacles, limpet, *Urosalpinx cinerea* (snail), clam shell
8	0	oyster shells, polychaete worms, limpet, clam shell, red beard sponge, *Codium* , (Dead man's fingers algae), red algae
9	0	*Styela* sp., orange colonial tunicate, *Ciona* sp., crabs (spider shape), mussels, red algae
10	0	none
11	0	oyster shells, *Hemigrapsus oreganensis* (mud crab), worm, limpets, bryozoans
12	0	mud tubes for worms
13	0	oyster shells, *Styela* sp.,*Ciona sp.* , sea pork tunicate, clam shells, bryozoans, red algae
14	0	Clay tubes of worms?, clam shells, *Ulva*
15	10	*Ostrea conchaphila* , *Cancer magister* (Dungeness crab), *Eriocheir sinensis* (mitten crab), anemones (solitary orange), barnacles, clams, clam shells, hydroids
16	0	tunicates, clam shells, clay tubes of worms?

Table 3: Field data of relative intertidal oyster density taken from February 2002 to January 2003, 34 sites total. Size was averaged from a subset of oysters found.

Location	**Date**	**Substrate**	**Density oysters/min**	**Average Size (mm)**	**Density *U. cinerea* /min**	**Salinity**	**Latitude**	**Other**
Pinole Bayfront Park	17-Dec-02	2	1.04	22	0	9.5	38.0135	
Point Pinole	30-Apr-02	4	1.6	23.5	0	26.4	38.012817	
China Camp	25-Mar-02	2	14	19	0	18.6	38.000767	
Mc Nears	25-Mar-02	2	4	32	0	21.7	37.992583	
Point San Pedro (S)	25-Mar-02	2	3	18	0		37.984267	water unreachable
San Rafael Creek	25-Mar-02	6	5		0		37.966533	oysters unreachable
Point San Quentin	29-May-02	6	17	25	0	23.2	37.943467	
Point Molate	30-Apr-02	4	2	50	0	26.4	37.946183	
Point Isabel	23-Jul-02	4	0.7	46	0	30.7	37.896783	
Fleming Point (S)	23-Jul-02	4	0.7	43	0	30.6	37.885867	
Blackie's Pasture	25-Jun-02	2	0.7	44	1.6		37.891667	water unreachable
Audobon Sanctuary	25-Jun-02	2	0.7	45	0		37.89365	water unreachable
Greenwood Cove	25-Jun-02	1	0		0		37.896083	water unreachable
Strawberry Point, Tib.	9-Jul-02	3	2	51	0	30.6	37.877117	
Sausalito (Caruso's)	9-Jul-02	8	5	46	0	31.2	37.870117	
Berkeley Marina (S)	14-May-02	4	15	51	0		37.865017	water unreachable
Emery Point (N)	14-May-02	7	4	47	0	26.7	37.8595	
Point Emery	14-May-02	7	4	47	0	26.1	37.84555	
Emeryville Yacht Harbor	26-Mar-02	7	25	40	0	24.4	37.841933	
Emeryville Rip-rap	26-Mar-02	6	0.08	35	0		37.838833	
Ft Baker Presidio Y.C.	02-Jan-03	7	0.57	37	0	28	37.8318	
Ft Baker Coast Guard	02-Jan-03	6	1	26	0	28	37.8314	
Fort Point Road, S.F.	02-Jan-03	5	0		0		37.8089	
Mission Creek, S.F.	8-Mar-02	6	0.2	33	0	27.8	37.774483	
Fruitvale Bridge, Oak.	24-Jun-02	7	0.1	32	0.7	29.2	37.768883	
Oyster Bay, San Leandro	24-Jun-02	6	2	27	22		37.7	water unreachable
Oyster Point, S.S.F.	27-Mar-02	2	0.3	39	0	26.7	37.661333	
Oyster Point cement wall	27-Mar-02	8	0		0	26.7	37.661333	
Coyote Point, San Mateo	28-May-02	3	0.2	42	0.4	26	37.589217	
Hayward Reg. Shoreline	24-Feb-02	6	0		0		37.625183	water unreachable
San Mateo Bridge West	8-Jul-02	3	0.02	42	17	30.7	37.590483	
Marine Science Institute	28-May-02	6	0.1	38	0.3	24	37.512717	
San Francisquito Creek	28-Apr-02	6	0		0		37.461033	raccoon prints in mud
Palo Alto Baylands	28-Apr-02	1	0		0	21.1	37.458583	

Table 4: Substrate classification

Substrate Classification	Substrate
1	Rock on mud
2	Rock on sandy mud
3	Rock on clam shell mud
4	Rock on sand
5	Rip-rap on sand
6	Rip-rap
7	Rock on rock
8	Cement piles

Table 5: Relative oyster density data with salinity averages. Average sizes taken from a subset of oysters found.

Location	**latitude**	**longitude**	**USGS Station #**	**Average Salinity**	**Salinity**	**Density oysters/min**	**Average size (mm)**
Pinole Bayfront Park	38.0135	122.2955	12	15.88	9.5	1.04	22
Point Pinole	38.01282	21.901	12	15.88	26.4	1.6	23.5
China Camp	38.00077	27.629	14	19.95	18.6	14	19
Mc Nears	37.99258	27.075	15	21.03	21.7	4	32
Point San Pedro (S)	37.98427	26.908	16	22.97	*	3	18
San Rafael Creek	37.96653	30.401	16	22.97	#	5	^
Point San Quentin	37.94347	28.697	16	22.97	23.2	17	25
Point Molate	37.94618	25.321	16	22.97	26.4	2	50
Point Isabel	37.89678	19.498	17	24.49	30.7	0.7	46
Fleming Point (S)	37.88587	19.006	17	24.49	30.6	0.7	43
Blackie's Pasture	37.89167	29.11	17	24.49	*	0.7	44
Audubon Sanctuary	37.89365	29.054	17	24.49	*	0.7	45
Greenwood Cove	37.89608	30.122	17	24.49	*	0	
Strawberry Point	37.87712	29.848	17	24.49	30.6	2	51
Sausalito (Caruso's)	37.87012	29.881	18	27.01	31.2	5	46
Shorebird Nature Center	37.86502	18.59	20	26.32	*	15	51
Emery Point (N)	37.8595	18.327	20	26.32	26.7	4	47
Point Emery	37.84555	18.143	20	26.32	26.1	4	47
Emeryville Yacht Harbor	37.84193	18.78	20	26.32	24.4	25	40
Emeryville Rip-rap	37.83883	18.914	20	26.32	*	0.08	35
Ft Baker Presidio Y.C.	37.8318	122.4729	19	29.15	28	0.57	37
Ft Baker Coast Guard	37.8314	122.475	19	29.15	28	1	26
Fort Point Road, S.F.	37.8089	122.4714	19	29.15	#	0	
Mission Creek	37.77448	23.571	21	25.32	27.8	0.2	33
Fruitvale Bridge, Oakland	37.76888	13.79	22	25.28	29.2	0.1	32
Oyster Bay, San Leandro	37.7	11.543	23	25.29	*	2	27
Candlestick Point	37.7084	122.373	24	25.22	32.4	2.2	22
Oyster Point	37.66133	39.68	25	24.76	26.7	0.3	39
Oyster Point cement wall	37.66133	39.68	25	24.76	26.7	0	
Coyote Point	37.58922	35.353	27	24.85	26	0.2	42
Hayward Reg. Shoreline	37.62518	37.511	28	24.43	*	0	
San Mateo Bridge West	37.59048	35.429	28	24.43	30.7	0.02	42
Marine Science Institute	37.51272	30.763	30	24.4	24	0.1	38
San Francisquito Creek	37.46103	27.662	31	23.79	#	0	
Palo Alto Baylands	37.45858	27.515	32	23.2	21.1	0	

* Salinity was not taken as the water had receded with the tide too far off shore from the expansive mud and/or sand flats in these locations.

Salinity was not taken as I failed to attain a water sample.

^ Oysters were difficult to measure as they were all under large riprap rocks.

Table 6: Table of correlation coefficients for relative distribution intertidal study

Variable	Correlation Coefficient
Average size vs. substrate classification	0.169
Salinity and density	-0.362
Salinity and size	0.512
Density and latitude	0.63
Size and latitude	-0.167
Density with *U. cinerea*	-0.206
Size with *U. cinerea*	-0.048
U. cinerea density with latitude	-0.543
Correlations looking at the 6 locations where *U. cinerea* was present	
Size	-0.174
Density	0.319

Table 7: Oyster dock density and shoreline transect data taken from January to May in 2003. Size was averaged from a subset of oysters found.

Location of marina	Date	Latitude	Covering of styrofoam float	Oysters/m^2	Average size(mm)	Drills/m^2	USGS Station #	Average Salinity	Salinity
Port Sonoma Marina	26-Feb	38.1151	none	0		0	13	20.31	11
Clipper Yacht Harbor	26-Feb	37.8728	black rubber	0		0	18	27.01	26.4
Berkeley Marina K Dock	15-Jan	37.86502	none	18	49	0	20	26.32	19
Emeryville Marina dock E	28-Feb	37.841	none	10	41	0	20	26.32	24.2
San Francisco Marina Dock N	30-Jan	37.8057	none	6	53	0	19	29.15	27.5
Grand Marina, Alameda	7-May	37.77	cement	6	20	0	21	25.29	26
Ballena Bay Yacht Club, Alameda	7-May	37.76	cement	4	35	0	22	25.41	28
San Leandro Marina A Dock	17-Jan	37.7	none	126	34	0	23	25.29	22.4
Brisbane Marina Slip 1	31-Jan	37.6744	cement	4	12	0	25	24.6	22.9
Coyote Point Marina	16-Jan	37.58922	none	6	56	0	27	24.85	22.3
Redwood City Municipal Dock	25-Feb	37.5023	cement	24	46	0	30	24.4	16.7
Pete's Harbor, Redwood City	25-Feb	37.4998	fiberglass	6	36	0	30	24.4	14
Location of shoreline			**Substrate**						
Port Sonoma public access	26-Feb	38.1151	rock on mud	0		0	13	20.31	11
Sausalito: N. of CYH gangway	26-Feb	37.8728	rock on mud	0.2	31	0	18	27.01	26.4
Shorebird Nature Center	15-Jan	37.86502	rock on sand	8.3	30	0	20	26.32	19
Emeryville south of fishing pier	28-Feb	37.841	rock on mud	6.4	36	0	20	26.32	24.2
S. F. Marina East of office	30-Jan	37.8057	rip-rap	0.5	37	0	19	29.15	27.5
Grand Marina, Alameda	7-May	37.77	rock on mud and shell	1.3	20	0.4	21	25.29	26
Ballena Bay Yacht Club, Alameda	7-May	37.76	rock on mud	0.1	15	0	22	25.41	28
San Leandro (in front of) A Dock	17-Jan	37.7	rock on mud	2.3	32	0	23	25.29	22.4
Brisbane: in front of docks	31-Jan	37.6744	rock on mud and shell	0.7	24.2	0	25	24.6	22.9
Coyote Point Marina (in front of)	16-Jan	37.58922	rock on mud and shell	0		1.6	27	24.85	22.3
Redwood City Marina	25-Feb	37.5023	rock on mud and shell	0		0.3	30	24.4	16.7
Pete's Harbor, Redwood City	25-Feb	37.4998	rock on mud and shell	0		1.1	30	24.4	14

Table 8: Salinity data for oyster dock and intertidal density. Average salinity attained from USGS water quality databases. Average sizes taken from a subset of oysters found.

Location of marina	**Latitude**	**oysters/m2**	**Average size (mm)**	**USGS Station #**	**Average salinity**	**Salinity**
Port Sonoma Marina	38.1151	0		13	20.31	11
Clipper Yacht Harbor	37.8728	0		18	27.01	26.4
Berkeley Marina K Dock	37.86502	18	49	20	26.32	19
Emeryville Marina dock E	37.841	10	41	20	26.32	24.2
San Francisco Marina Dock N	37.8057	6	53	19	29.15	27.5
Grand Marina, Alameda	37.77	6	20	21	25.29	
Ballena Bay Yacht Club, Alameda	37.76	4	35	22	25.41	
San Leandro Marina A Dock	37.7	126	34	23	25.29	22.4
Brisbane Marina Slip 1	37.6744	4	12	25	24.6	22.9
Coyote Point Marina	37.58922	6	56	27	24.85	22.3
Redwood City Municipal Dock	37.5023	24	46	30	24.4	16.7
Pete's Harbor, Redwood City	37.4998	6	36	30	24.4	14
Location of shoreline						
Port Sonoma public access	38.1151	0		13	20.31	11
Sausalito: N. of CYH gangway	37.8728	0.2	31	18	27.01	26.4
Shorebird Nature Center	37.86502	8.3	30	20	26.32	19
Emeryville south of fishing pier	37.841	6.4	36	20	26.32	24.2
S. F. Marina East of office	37.8057	0.5	37	19	29.15	27.5
Grand Marina, Alameda	37.77	2	1.3	21	25.29	
Ballena Bay Yacht Club, Alameda	37.76	6	0.1	22	25.41	
San Leandro (in front of) A Dock	37.7	2.3	32	23	25.29	22.4
Brisbane: in front of docks	37.6744	0.7	24.2	25	24.6	22.9
Coyote Point Marina (in front of)	37.58922	0		27	24.85	22.3
Redwood City Marina	37.5023	0		30	24.4	16.7
Pete's Harbor, Redwood City	37.4998	0		30	24.4	14

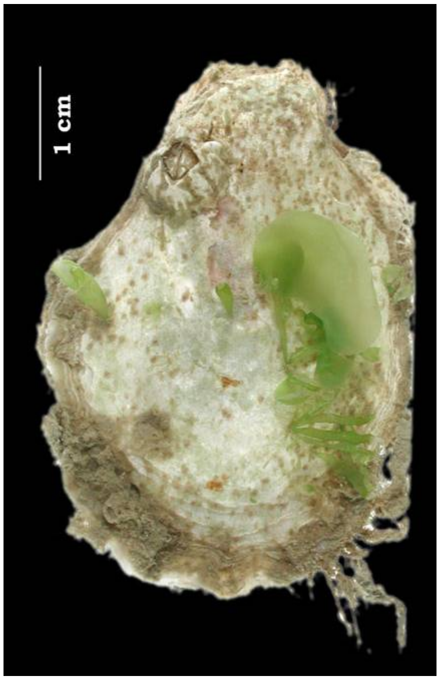


Figure 1. *Ostrea conchaphila*, photo from California Academy of Sciences SFBay:2K study. Epibionts shown are green algae and a barnacle.

Figure 2. Wildco biological oyster dredge, (50-cm mouth, 2cm mesh) on the stern of the RV Questuary, October 4th, 2001. Cable is hooked up to hydraulic winch. Dredge used for subtidal sampling study.

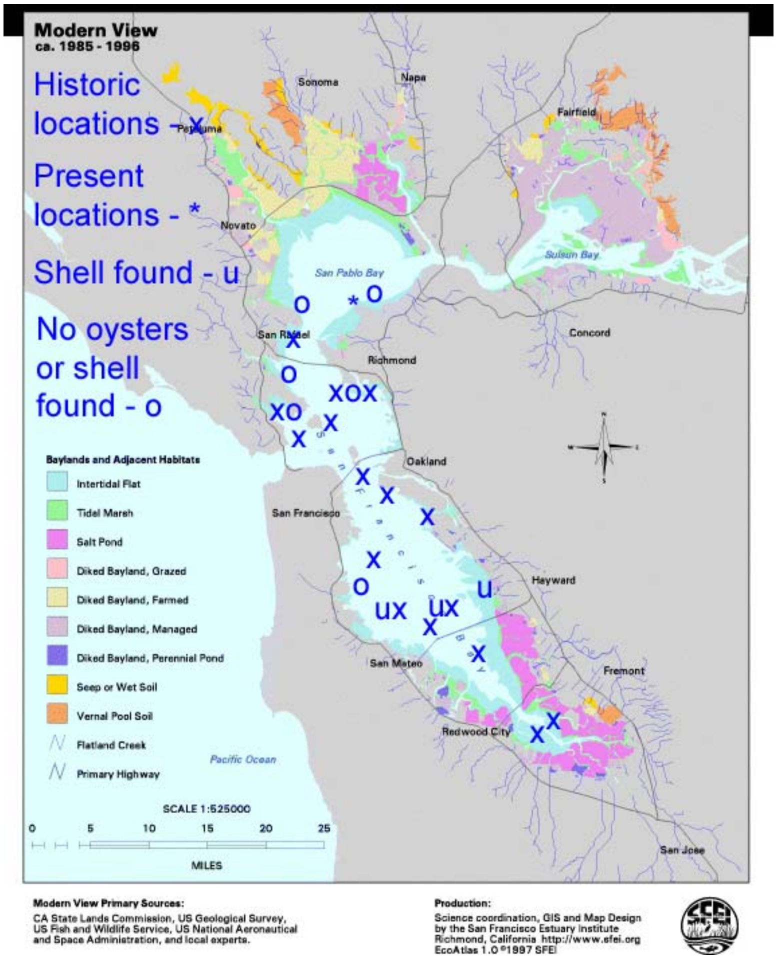


Figure 3. Map showing historic and recent subtidal distribution of native oysters in San Francisco Bay.

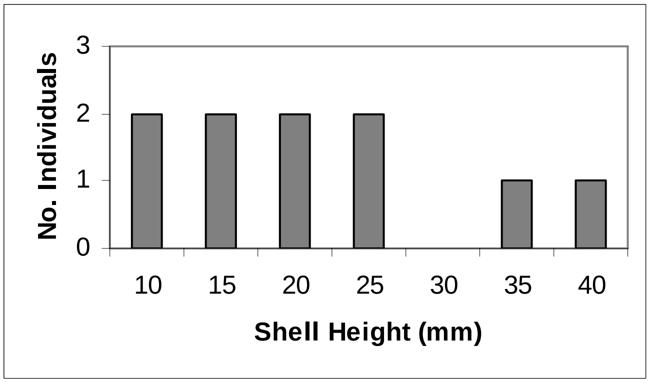
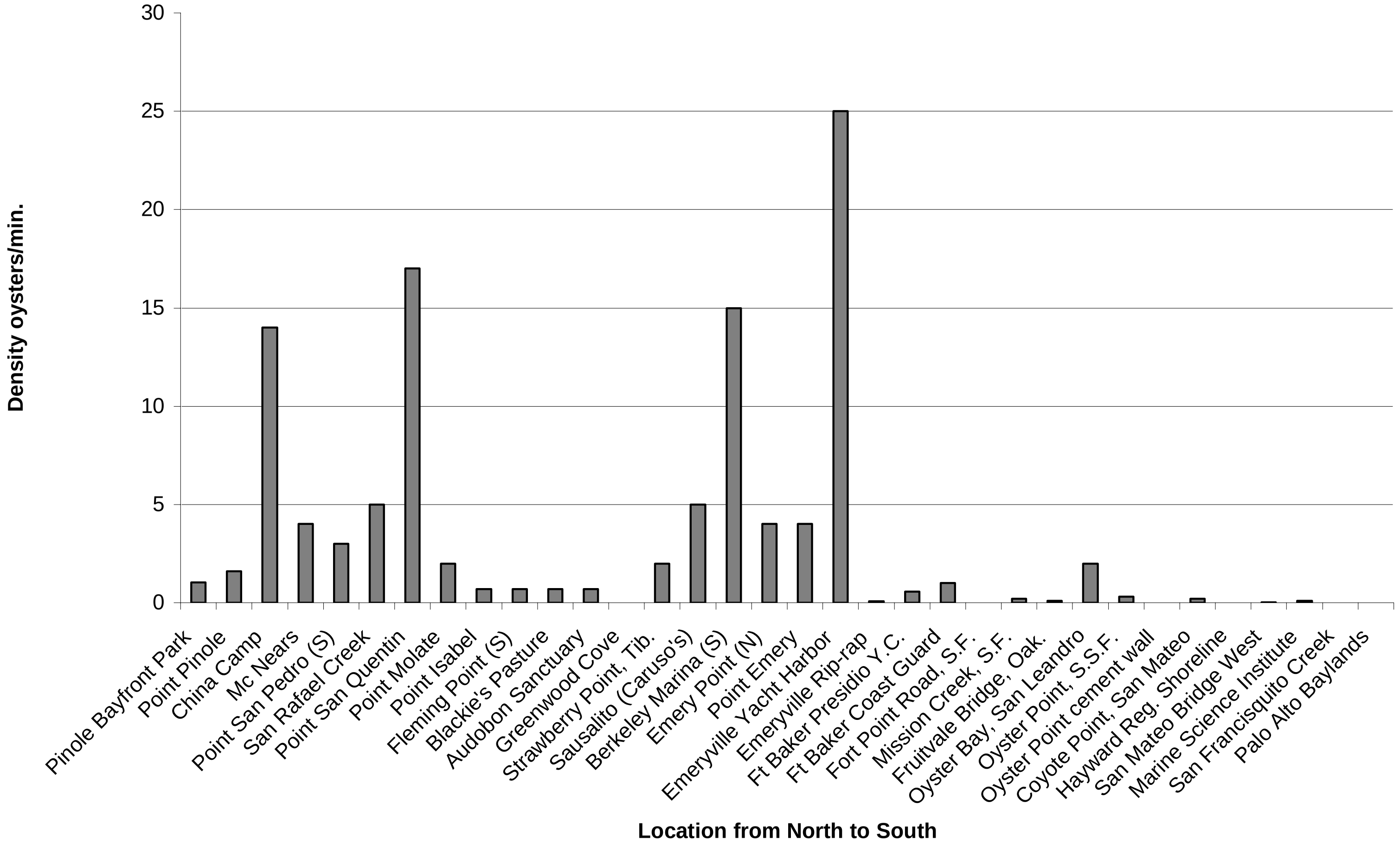


Figure 4. Size frequency distribution of *Ostrea conchaphila* at Point Pinole on December 3, 2001
from a subtidal dredged sample.

Figure 5. Dredge full of mud, red algae, and worm casings from Richardson Bay tow, October 26th, 2001.

Figure 6. Tripp McCandlish straining out mud from the shell from the San Lorenzo Creek tow, November 9th, 2001.

Figure 7: Relative density of oysters by location



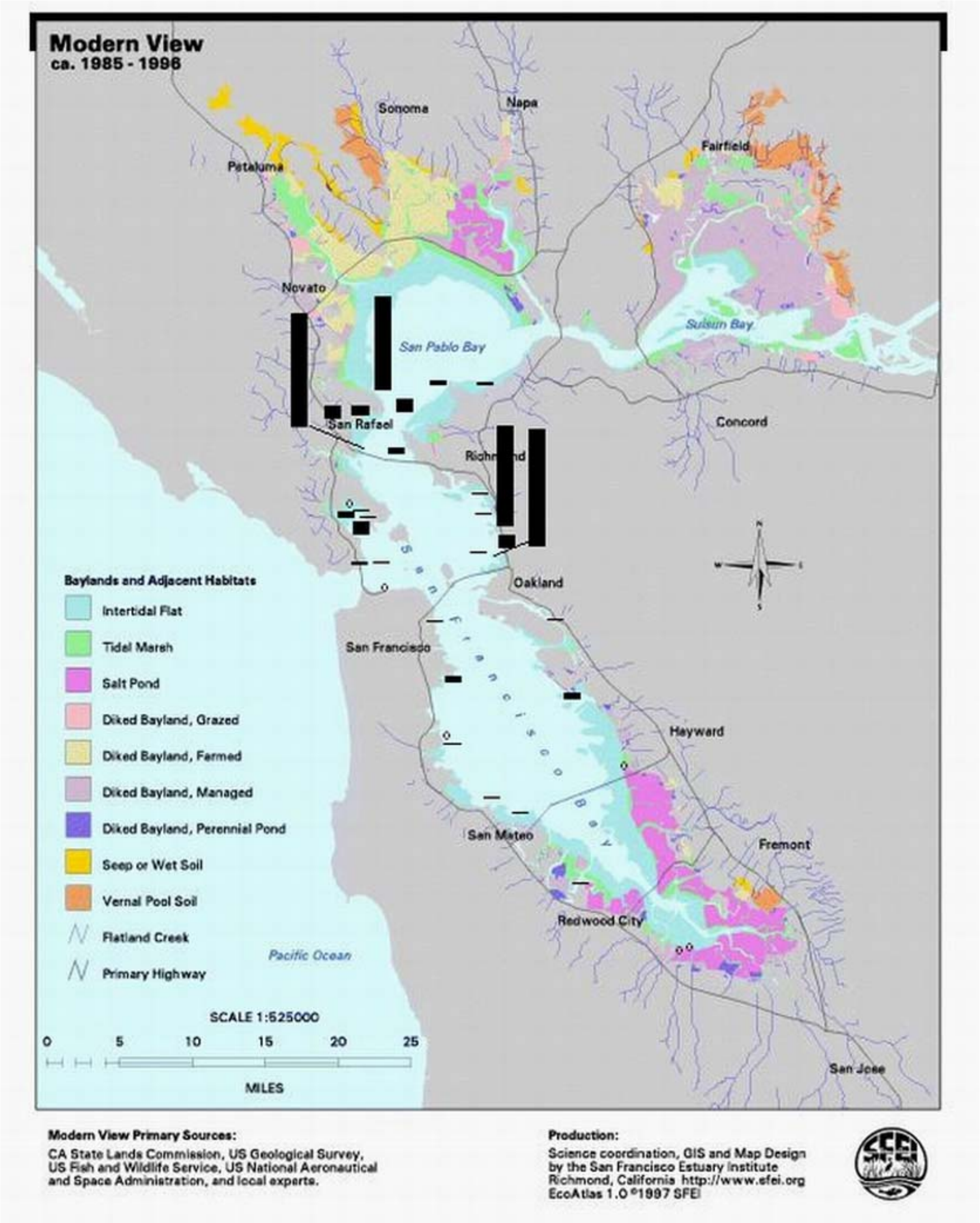


Figure 8: San Francisco Bay histogram map showing relative density of oysters in the intertidal. Zeros indicate no oysters found. This data is overlaid on the SFEI map of present day wetlands habitat types and taken from the Wetlands Goals Project (1999)

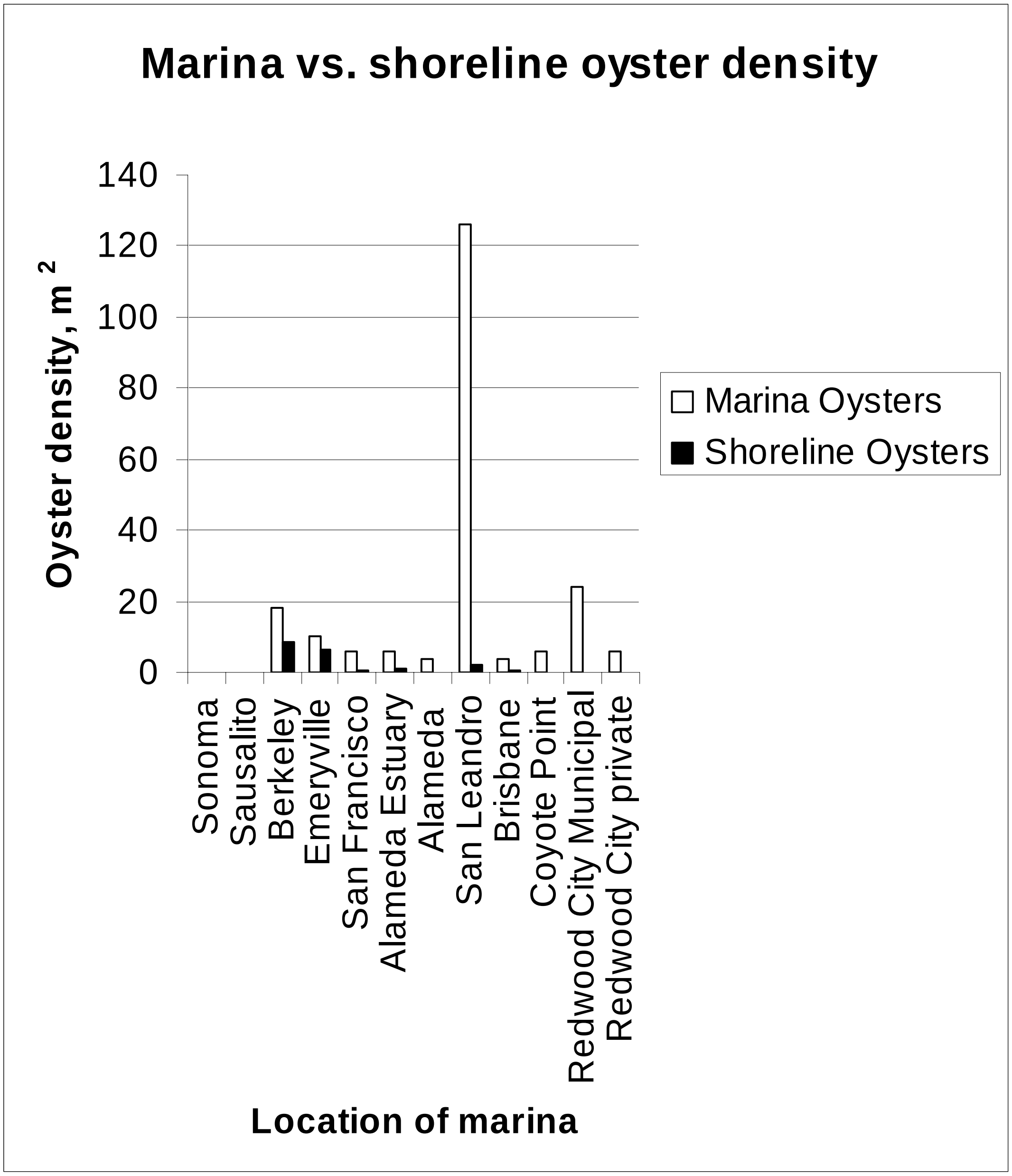


Figure 9: Marina vs. shoreline oyster density for transects in the subtidal, dock and intertidal, on the shore.

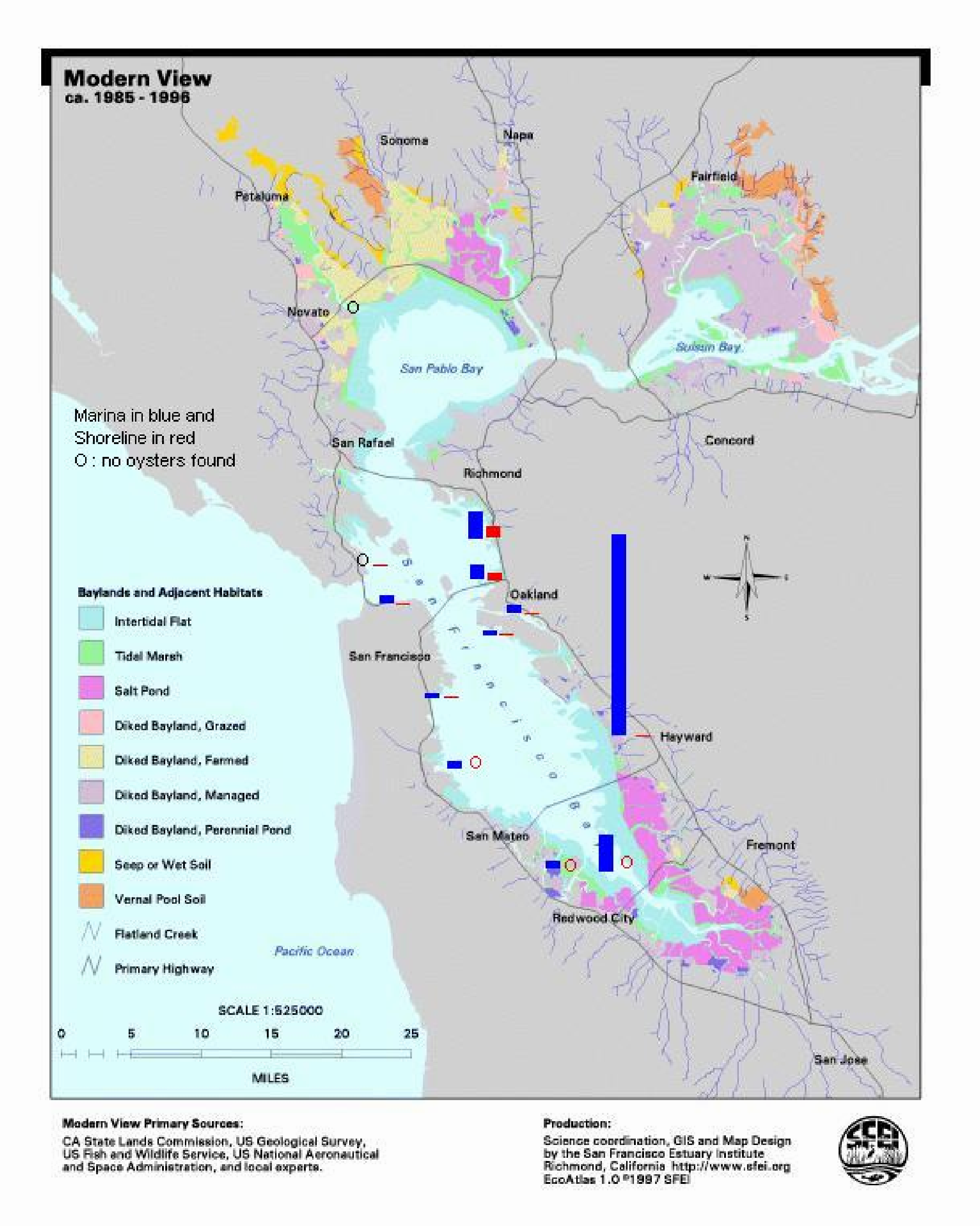


Figure 10: Marina vs. shoreline oyster density for transects in the subtidal, on floating docks, and in the intertidal, on the shore. Marina densities are blue bars. Shoreline densities are red bars. Zero indicates no oysters found. This data is overlaid on the SFEI map of present day wetlands habitat types and taken from Wetlands Goals Project (1999).