Assessing the Relationship between the Ichthyofauna and Oyster Mariculture in a Shallow Coastal Embayment, Drakes Estero, Point Reyes National Seashore

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ABSTRACT

Bivalve mariculture has the potential to affect the biological, physical, and chemical characteristics of the marine environment (Thia Eng et al. 1989, Ulanowicz and Tuttle 1992, Kaiser et al. 1998, Mazzouni et al. 1998, Mirto et al. 2000, La Rosa et al. 2002). While many studies have examined changes to these components, few have focused on the potential effects of mariculture on aquatic vertebrates. This study was designed to assess whether oyster mariculture affected ichthyofaunal species abundance, species richness, species composition, and species diversity in Drakes Estero, a shallow coastal embayment situated within Point Reyes National Seashore in northern California. I sampled the fish community seasonally from December 2002 to January 2004 to compare the fish assemblage in Schooner Bay, an arm of Drakes Estero that has supported oyster culture for seventy years, to that of Estero de Limantour, a geographically isolated reference arm without oyster culture. I found no statistically significant differences in fish abundance or species richness among the sampling locations, which indicated that the oyster farm had not exerted a noticeable effect on the ichthyofauna of Drakes Estero. Species diversity and species richness were greatest at stations closest to the oyster racks, which indicated that the physical structure associated with the mariculture facility likely provided resources (e.g., feeding opportunities or refuge) to species of fish capable of taking advantage of artificial habitat. Additionally, four out of five Indices of Similarity showed that the fish assemblage adjacent to the racks was comprised of a group of species that diverged compositionally from the fish species captured in the reference site, which suggested that the racks favored structure-oriented and crevice dwelling fish capable of taking advantage of increased habitat complexity. Because no previously published studies have examined the Drakes Estero fish community, this study also provided baseline information about fish composition, distribution, and diversity in this California marine embayment.

Key Words: *oyster mariculture, coastal embayment, Drakes Estero, ichthyofauna, habitat complexity, Estero de Limantour*

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INTRODUCTION

History and Background Information

Sir Francis Drake purportedly took safe harbor in what is now known as Drakes Estero, a shallow coastal embayment situated within Point Reyes National Seashore (PRNS) on the northern California coast (Figure 1). Drakes Estero is a dynamic environment with inflowing tributaries, a broad tidal exchange, intense solar radiation, and prevalent winter rains, all of which can rapidly change its prevailing physical and chemical characteristics. Although the exact location of Drake's landing is controversial (Hanna 1976), were it inside the sand spit that separates Drakes Bay from Drakes Estero, the bibulous crew would likely have benefited from the aquatic resources that are still plentiful in this treasured coastal ecosystem.

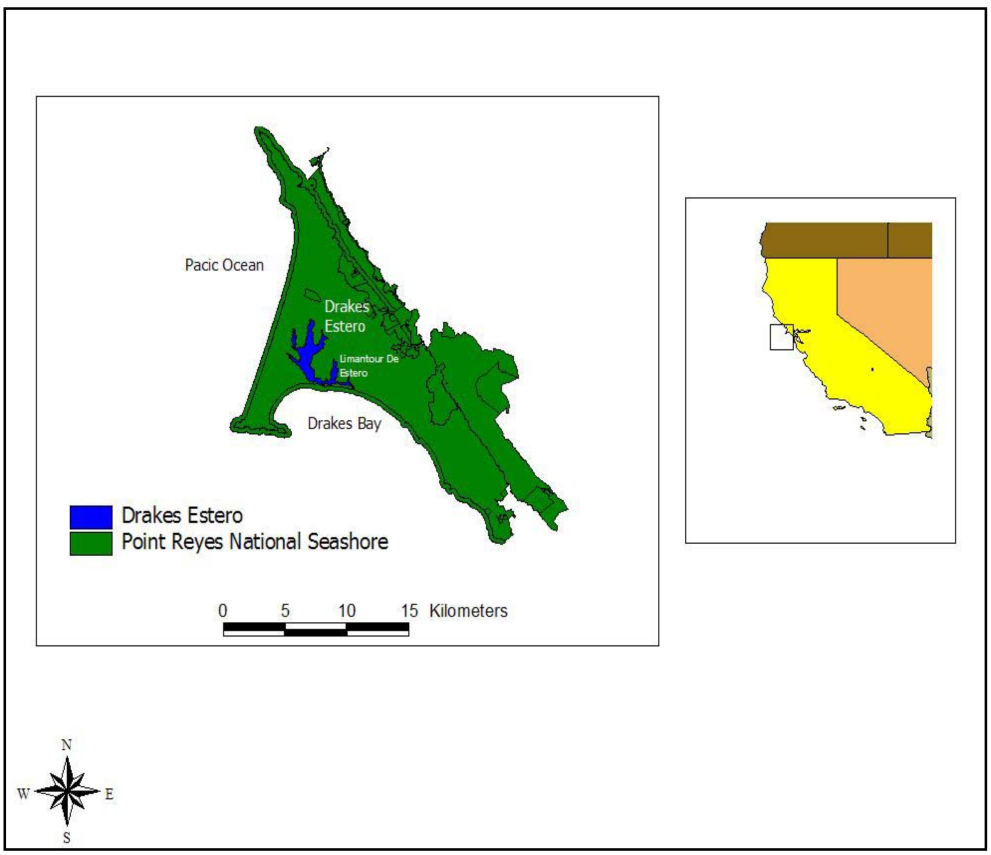

Figure 1. Location of the Drakes Estero Ichthyofauna - Oyster Mariculture study, Point Reyes National Seashore.

Today two organizations, the National Park Service (NPS) and Johnson's Oyster Company (JOC), value the estero for the ecologic and socioeconomic resources that it provides. Since the inception of PRNS in 1962, the parks resource management staff has been responsible for the maintenance of the estero's ecological function. JOC, a family owned and operated oyster farm, has cultured Pacific oysters (*Crassostrea gigas*) in Drakes Estero since 1954 and is dependent on the estero to provide their livelihood. As part of an ecosystem-wide project undertaken by the University of California, Davis, this study was conducted to determine whether the abundance, diversity, composition, and richness of the Drakes Estero ichthyofauna had been affected by the presence of oyster mariculture.

Ecological Value

The NPS and the California Department of Fish and Game (CDFG) consider Drakes Estero to be one of the most ecologically pristine coastal ecosystems in California (Elliott-Fisk and Allen 2003). Parts of the estero lie within the Phillip Burton Wilderness Area, a 26,000-acre preserve established in 1976 through the federal Wilderness Act. The estero is shallow and nutrient-rich, and aquatic productivity is likely high at all tiers of the trophic structure. Numerous species of shorebirds, bat rays (*Myliobatis californica*), and leopard sharks (*Triakis semifasciata*) are routinely visible, and the estero is marked by the presence of one of the largest colonies of northern elephant seals (*Mirounga angustirostrison*) on the California mainland (Dawn Adams, NPS Biologist, *pers. comm.*).

In 2003, the U.S. Fish and Wildlife Service (USFWS) identified eighteen aquatic species of concern or species with legal protective status that may occur in the Drakes

Bay quadrangle, which includes Drakes Estero (Table 1). Although federal agencies have yet to compile a complete species list for Drakes Estero, this USFWS inventory acknowledges that the estero may provide essential habitat for federally protected species. Federally listed California brown pelican (*Pelecanus occidentalis californicus*) and central California coast steelhead (*Oncorhynchus mykiss*) have been observed in Drakes Estero.

Table 1. Protected species or species of concern that may occur in Drakes Estero, Point Reyes National Seashore (adapted from 2003 USFWS Drakes Bay Quadrangle inventory list).

Scientific Name	Common Name
Arctocephalus townsendii	Guadaloupe fur seal
Eumetopias jubatus	stellar sea lion
Brachyramphus marmoratus	marbled murrelet
Charadrius alexandrinus nivosus	western snowy plover
Haliaeetus leucocephalus	bald eagle
Pelecanus occidentalis californicus	California brown pelican
Sterna antillarum	California least tern
Caretta caretta	loggerhead turtle
Chelonia mydas	green turtle
Dermochelys coriacea	leatherback turtle
Lepidochelys olivacea	olive ridley sea turtle
Rana aurora draytonii	red-legged frog
Eucyclogobius newberryi	tidewater goby
Oncorhynchus kisutch	coho salmon
Oncorhynchus mykiss	steelhead trout
Oncorhynchus tshawytscha	Chinook salmon
Haliotes sorenseni	white abalone
Lampetra tridentata	Pacific sea lamprey

For fish, coastal aquatic ecosystems can be of critical importance as nursery habitat, migratory routes, breeding sites, and as refuge areas (Yoklavich et al. 1991, Costa et al. 1994, Potter and Hyndes 1999, Mann 2000). Because they are nutrient-rich and biologically productive, these systems tend to support large populations of fish (Rozas and Minello 1997, Mann 2000). However, few species are permanent residents because the constantly shifting physico-chemical conditions increase the physiological requirements for survival (Mann 2000, Moyle and Cech 2000, Elliott and Hemingway 2002).

Socioeconomic Value

Since 1934, six companies have held CDFG mariculture leases in Drakes Estero that allowed them to farm Pacific oysters (Figure 2). JOC, the second largest oyster farm in California, has held two state mariculture lease allotments since 1954, which entitle the company to farm oysters in approximately 648 hectares (1,600 acres) (California Department of Health 1991). In 1972, the federal government purchased the five-acre

Figure 2. The oyster racks of Johnson's Oyster Company, Drakes Estero, Point Reyes National Seashore (photo courtesy of David Press).

parcel of land and shoreline dwellings located at the northern end of the estero from JOC. Since then, the oyster company has leased the facilities from NPS, and has the option to do so until 2012, assuming they uphold their lease conditions (Marin County Community Development Agency 1998). Because it is a Point Reyes National Seashore objective to preserve aspects of cultural significance, park staff has attempted to include oyster farming in its General Management Plan (National Park Service 1980).

The protected and undeveloped lands of the Drakes Estero watershed provide a water quality that is optimal for the culture of oysters (California Department of Health Services 1991). State, federal, and county agencies monitor the shellfish harvest to ensure JOC complies with the appropriate health standards for the production of shellfish. Because approximately 2,000 cattle graze in the watershed (Mark

Homringhausen, NPS Range Specialist, *pers. comm.*), JOC is required to conduct a monthly fecal coliform self-monitoring program; a three day harvest restriction goes into effect if rainfall events produce more than 19 millimeters in a twenty-four hour period (California Department of Health Services 1996).

Oyster Harvest Technique

JOC uses a hanging-line technique to grow oysters in the subtidal portion of Schooner Bay. There are two advantages to this technique: oysters are kept elevated above the substrate, thereby reducing the incidence of benthic predation, and oysters are submerged throughout the entire tidal cycle, which enhances their growth rate. (Matthieson 2001). Because the water temperature in Drakes Estero is too cold for Pacific oysters to successfully reproduce (Fred Conte, University of California, *pers. comm.*), JOC imports larval spat from international oyster stocking companies. Juveniles are incubated on shore for several weeks until they have settled onto old adult oyster shells (cultch), which are then spaced evenly on inverted U-shaped wire hangers (strings). Strings are draped over wooden racks in the nutrient-rich waters of Drakes Estero for approximately eighteen months. Harvested oysters are brought by flat-bottomed barge to a small processing plant at the head of Schooner Bay (Figure 3). At peak production, JOC processes up to 80,000 bivalves per day, which workers sort,

Figure 3. Wooden racks and oyster harvest technique, Johnson's Oyster Company, Drakes Estero, Point Reyes National Seashore.

shuck, clean, and sell on premises by the pint, quart, or on the half-shell. Johnson's oysters are available in local Marin County and San Francisco Bay area restaurants (Mark Johnson, Johnson's Oyster Company, *pers. comm.*). At the time of this writing, JOC employed approximately fifteen workers, although the farm has employed sixty people for harvest and culture purposes (Ben Johnson, Johnson's Oyster Company, *pers. comm.*).

In 2003, there were eighty-five oyster racks in the estero, most of which were located in Schooner Bay, Home Bay, and Drakes Bay proper; thirty-eight racks (45%) were either fully or partially active (Figure 4). The wooden racks are three meters wide, and vary in length from fifty to one hundred-fifty meters. Additionally, a small number of oysters are grown in floating or hanging mesh bags attached to racks or suspended in the water column.

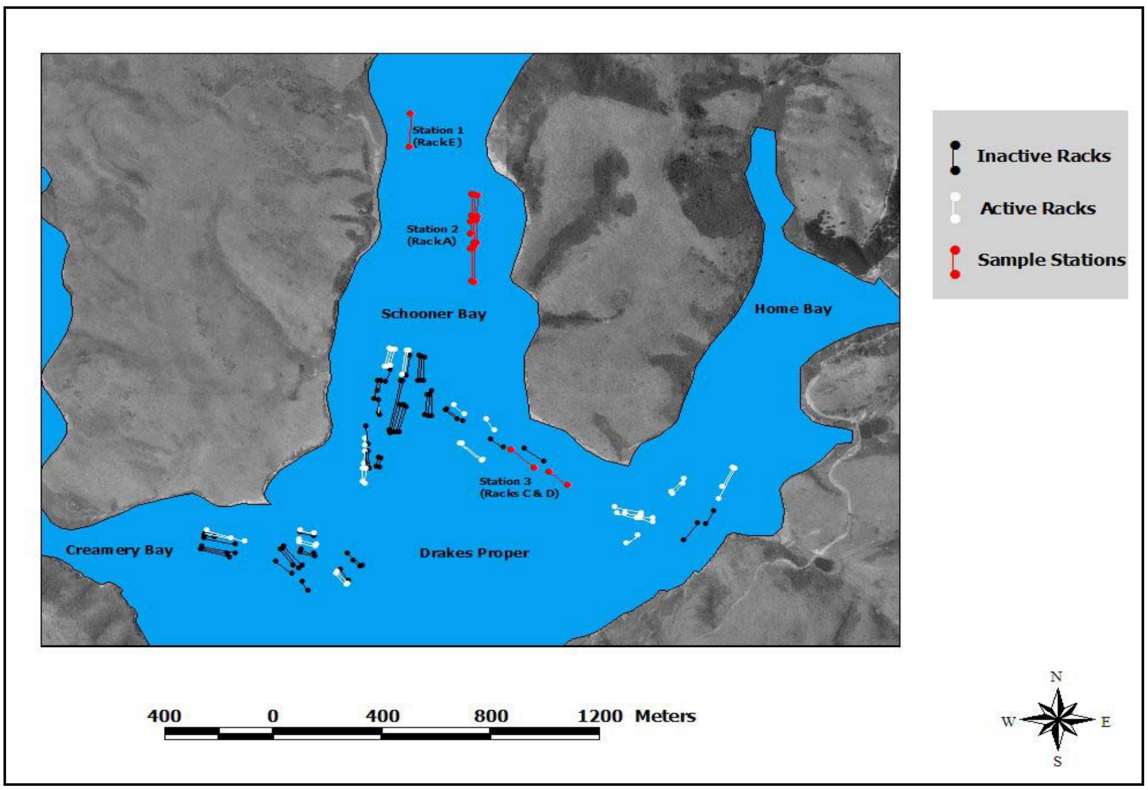

Figure 4. Location of the oyster racks and fish sampling stations in Drakes Estero, Point Reyes National Seashore.

The Seafood Industry and Aquaculture

Seafood accounts for nearly sixteen percent of total worldwide dietary protein, and in some African nations, it may constitute fifty percent of total dietary intake (Welcomme 1996, FAO 2002). Although there is considerable variation on a regional scale, the Food and Agricultural Organization of the United Nations (FAO) estimates seafood consumption reached a peak of approximately one hundred million tonnes in 2001, with an additional thirty million tonnes used for non-consumptive purposes (FAO 2002). Since 1990, the demand for fish products has increased nearly thirty-three percent and researchers predict annual fish consumption will increase to one hundred sixty million tonnes in the near future (Costa–Pierce 2002, FAO 2002). The socioeconomic implications are great: with increased demand for fish and fish derived goods, fish harvest jobs have increased to nearly thirty-five million, up from twelve million in 1970, and in 2002, worldwide trade of fish products reached a peak of $55 billion U.S. dollars (FAO 2002). The ecological implications are also great: the increased demand for fish products has likely affected worldwide fish stocks in an adverse manner. FAO reports that of marine stocks for which there is quality data, fifteen to eighteen percent are overexploited, forty-seven to fifty percent are fully exploited, nine to ten percent are depleted or recovering from depletion, and twenty-five to twenty-seven percent are under exploited (FAO 2002).

The Culture of Aquaculture

The continued demand for fish products, the decline of wild fish stocks, and the relative ease and economic potential of culture methods have contributed to a recent boom in the aquacultural sector of the world economy (Welcomme 1996, Costa-Pierce

2002, FAO 2002). Since African and Chinese cultures began actively cultivating aquatic species for consumption nearly 4,000 years ago, an evolution of technologies has led to large-scale fish and shellfish production operations, as well as a significant increase in the number and diversity of species cultured (Stickney 1994, Costa-Pierce 2002). Today, aquaculturists propagate nearly two hundred and twenty species for market or for subsistence, with an annual harvest approaching thirty-seven million tonnes (FAO 2002). This accounts for twenty-seven percent of annual fish production by weight, an increase of twenty-three percent in the last thirty years (Muir 1996). Although, the Chinese produce seventy percent of worldwide aquacultural products, the industry is growing consistently in other regions of the globe as well. In the United States, aquaculture is the leading agricultural economic sector, with production increases as much as sixteen percent since 1996 (http:\\www.nmfs.noaa.gov).

The rapid growth of the aquacultural industry does not come without repercussion. Aquacultural practices can cause a suite of ecological problems, including loss of aquatic habitat, overharvest of wild fish for feed, eutrophication, the unregulated use of antibiotics and fertilizers, competition with native fauna, and the genetic dilution of wild fish (Thia Eng et al. 1989, Fernandes et al. 2001, Costa-Pierce 2002). The link between aquaculture and detrimental environmental conditions has resulted in intensified scrutiny from government agencies and scientific organizations that are concerned with the potential for adverse consequences (Kaiser et al. 1998, Fernandes et al. 2001, Costa-Pierce 2002). However, if not the practitioners themselves, at the very least the scientific community and managing agencies are aware of the need for the development of environmentally responsible husbandry practices, and are actively pursuing management practices that aim to "green up of the blue revolution" (see

Costa-Pierce 2000, Costa-Pierce 2002).

The Growth of Bivalve Culture

Mollusk culture has also grown rapidly as an economic sector in the past few decades, accounting for nearly eleven million harvested tonnes of meat in 2000, approximately four times the production of the 1970s (FAO 2002). A significant component of this sector's growth has been the husbandry of bivalves, specifically clams, oysters, and mussels. Culture operations include both penned onshore facilities and coastal offshore facilities. Although generally considered more benign than fish farming, the potential exists, especially in areas of intensive culture, for bivalve farming to adversely affect the aquatic environment (Dahlback and Gunnarson 1981, Kautsky and Evans 1987, Gilbert et al. 1997, Kaiser et al. 1998, Sorokin et al. 1999, Mirto et al. 2000, Hayakawa et al. 2001, Smaal et al. 2001, La Rosa et al. 2002).

To feed, bivalves filter fine organic and inorganic particles from the water column. Material that is not biologically essential is released through the process of biodeposition. As a result, sedimentation rates can increase from three to eight times when influenced by biodepositional processes, and consequently may affect benthic community ecology, water quality, and nutrient budgets (Dahlback and Gunnarsson 1981, Dame 1996, Navarro and Thompson 1997). Haven and Morales (1966) reported that a one-acre oyster reef could produce 981 kg of biodeposits during a single week. Lund (1957, from Haven and Morales 1966) calculated a biodeposition rate of 7.58 metric tons over an eleven-day period for an acre of oysters. Studying blue mussel (*Mytilus edulis*) culture in Sweden, Mattsson and Linden (1983) presented evidence of decreasing oxygen availability, increased organic sediment composition, and increased microbial activity because of elevated sedimentation rates. Additionally, macrofaunal (>0.5 mm) invertebrate species diversity decreased and a complete succession of benthic macrofauna to a more tolerant species of polychaete occurred. Dahlback and Gunnarson (1981), also studying blue mussel reefs, noted sedimentation rates up to 1,000 g C m^2 / year, changes in organic sediment concentration, and the build up of sulfide.

Alternatively, other studies support the idea that biological productivity may be bolstered by the biodepositional processes of bivalves. While studying horse mussels (*Modiolus modiolus*) in New Foundland, Navarro and Thompson (1997) concluded that the organic material contained within biodeposits provided a source of energy rich matter for benthic deposit feeders, supporting the idea that bivalve filter feeders may affect trophic structure positively. In a study of the Ria De Arosa in Spain, Tenore and Gonzalez (1975) collected over one hundred species of epifaunal organisms from the lines used to hang mussels in the water, and showed that raft culture of mussels provided habitat for fish and increased biological productivity through the enhancement of the detrital food web. In a subsequent study of the Ria De Arosa, Chesney and Iglesias (1979) observed a greater diversity and biomass of demersal fishes, more epifaunal invertebrates, and an increase decapod biomass in areas associated with mussel raft culture as compared to non-raft areas. In freshwater systems, although generally considered detrimental to aquatic systems, non-native zebra mussel (*Dreissena polymorpha*) invasions have influenced fish communities by restructuring hard substrates, altering macroinvertebrate communities, and by affecting water column characteristics (Richardson and Bartsch 1996, Thayer et al. 1997, Mayer et al. 2001).

Study Approach and Intent of Project

As part of a collaborative effort between the National Park Service and the University of California, Davis, this project was designed to provide a science-based evaluation of the ichthyological response to bivalve mariculture in Drakes Estero. The use of fish communities to test the integrity of aquatic ecosystems and to assess the effects of human–induced ecological change is widely accepted as a viable methodology in the fishery profession (Karr 1981, Stephens et al. 1988, Whitfield and Elliott 2002). This approach has several advantages, including the ease of capture and identification, the relatively long life span of fish (as compared to other indicator species), and the ease of communicating results to the public (for a complete review see Karr 1981, Whitfield and Elliott 2002). For coastal waters, researchers have developed estuarine biotic indices that incorporate fish community dynamics to evaluate the effects of anthropogenic activity on aquatic resources (Deegan et al. 1997, Hughes et al. 2002). Since no previously documented studies exist regarding the Drakes Estero ichthyofauna, this report also provided baseline biological information about fish community dynamics.

Because studies have shown that bivalve mariculture can affect the biological, physical, and chemical characteristics of an aquatic ecosystem, I hypothesized that adjacent to the Drakes Estero oyster racks: (a) fish species diversity would be reduced, (b) fish abundance would be reduced, (c) fish species richness would be decreased, and (d) a few tolerant species would dominate the fish community. Alternatively, since the presence of bivalve filter feeders may bolster productivity and provide aquatic habitat abundance, richness, and diversity of fishes may have increased.

Methods

Study Area

Drakes Estero (UTM coordinates: N 4209350, E 10S 505750; NAD 27 – mouth of estero) formed when rising sea levels intruded inland during post-Wisconsinan glacial retreat, inundating the former river valleys of the Point Reyes peninsula (Galloway 1977). The 930-hectare estuary is composed of five finger-like bays, four of which aggregate in the shallow main water body of Drakes Estero proper (Figure 5). Estero de Limantour, considered an independent body of water or the fifth arm of Drakes Estero, accounts for an additional 313-hectares (Shufford et al. 1989). Water depth is generally less than two meters, although along the interior edge of the sand spit that separates the estero from Drakes Bay, a maximum depth of eight meters occurs (Anima 1990). Daily water temperature can fluctuate from twelve to twenty degrees Celsius, as cooler ocean water intrudes, warms, and recedes. Average annual rainfall resulting from this Mediterranean-like climate pattern ranges from six hundred and ten to six hundred and sixty-six millimeters with the majority of precipitation coming during winter months (Galloway 1977). Salinities are generally greater than thirty-two parts per thousand (ppt) throughout the year, although winter rains dilute the concentration of dissolved solids to less than twenty-four ppt.

Figure 5. Aerial view of Drakes Estero and the migratory sand spit that separates the embayment from Drakes Bay. Sir Francis Drake's purported landing is inside the spit © 2002-2003 Kenneth Adelman.

The estero is mesotidal with semidiurnal tides that range between approximately 0.6-meters below and 2.13-meters above mean sea level. A high width to depth ratio combined with a large exchange volume results in a well-mixed water body with no stratification. The retreating tides expose mud and sand flats that provide ample habitat and feeding opportunities for marine birds and mammals. Aquatic macrophytes, primarily eelgrass (*Zostera marina*) beds, were the predominant form of subtidal and intertidal biological material in Drakes Estero. These beds provide an extensive array of habitat for aquatic biota, and are likely important breeding grounds and refuge areas for juvenile fish. Small zones of giant kelp (*Macrocystis pyrifera*) and big-leaf algae (*Ulva spp.*) were present in the estero, as were bands of salt marsh plants in the middle and high intertidal zones.

The surficial geology of the estero is dominated by the diatomaceous and silaceous sediments of the Purisima Formation (formerly Drakes Bay Formation). These uplifted mud and siltstones layers were deposited during the Pliocene epoch (5.3 mya to 1.8 mya), and are underlain by the Monterey Formation, which consists primarily of sandstone (D. Elliott-Fisk, University of California, *pers. comm.*). The Monterey sandstones form the estero's white-cliffs (see title page), which may have attracted Sir Francis Drake to the area in the 16th Century (Galloway 1977).

Sampling of the Ichthyofauna

I sampled the fish community both adjacent to (Schooner Adjacent) and at a distance of approximately seventy-five meters (Schooner Away) from three randomly selected oyster racks in the subtidal portion of Schooner Bay. For comparison, three randomly selected sites were sampled in Estero de Limantour; a marine reserve located approximately three nautical miles away from the oyster farm. Sampling was conducted from December 2002 until January 2004. All sampling took place during the day at high or slack tide and lasted for three to five days (Table 2). A 4.3-meter aluminum Klamath skiff with a Mercury 10 HP engine was used for all fish sampling efforts. The shallow draw of the skiff allowed access to most areas of the estero during high or slack tides. Average water depth at the time of sampling was between one and two meters. Due to inclement weather and mechanical difficulties with the sampling boat, I was not able to complete the surveys in December 2002 and April 2003; that portion of the data was used to report on species presence and absence only. Since the majority of oyster racks were located in eelgrass beds, all sampling was conducted primarily within the heavily vegetated portions of the estero. Surveys were conducted seasonally to gather additional information about the temporal use of Drakes Estero by marine fishes.

Table 2. Sample dates for the Drakes Estero Ichthyofauna – Oyster Mariculture study, Point Reyes National Seashore.

Sample Number	Sample Period
1*	December 3 - December 4, 2002
2*	April 3 - April 4, 2003
3	June 28 - July 2, 2003
4	July 24 - July 28, 2003
5	August 25 - September 6, 2003
6	October 4 - October 6, 2003
7	October 17 - October 19, 2003
8	November 12 - November 15, 2003
9	January 10 - January 12, 2004

* sample not used for analysis

At each station, I took three replicate otter-trawl samples that lasted from three to five minutes each depending on the dimensions of the oyster rack. When adjacent to an oyster rack, I navigated the boat and trawl as close to the structure as possible without endangering the net, a distance of approximately one to two meters, depending on the prevailing wind and tidal direction. Trawl direction was alternated to coincide with both incoming and outgoing tides. Because water depth was generally less than two meters, the trawl effectively captured benthic and pelagic fish simultaneously. In October, trawling was ineffective because of increased eelgrass density; therefore, a thirty-meter boat seine was used instead.

A 1.8-meter X 60-meter monofilament experimental gill net with eight panels (1.27-cm to 10.16-cm) was fished repeatedly at all sites for 0.5 to 1.5 hours, depending on the initial catch rate of the first set. The high density of fish, sharks, and rays in the estero mandated short gill sets to reduce the likelihood of incidental mortality. Three sets were made per site per sampling episode. Adjacent to the racks, the gill net was attached directly to the wooden supports. At sites away from the racks, the gill net was set parallel to the rack orientation at a distance of approximately seventy-five meters. In Estero de Limantour, where water depth allowed, the gill net was set as close to the trawl sites as possible.

To catch small benthic and crevice dwelling fish, I set four to six minnow traps at each sampling station for eighteen to twenty-four hours. All traps were attached to fluorescent buoys to allow for relocation and retrieval. Adjacent to the oyster racks, minnow traps were attached directly to the wooden supports. Away from the racks and in Estero de Limantour, traps were set approximately 10 meters apart. I used several baits to experiment with fishing effectiveness including stink bait, cat food, squid, herring, and anchovies.

Rectangular collapsible mesh fish traps were used experimentally, but because they were often damaged by benthic decapods, this method was discarded. Hoop nets and fyke nets were also used on an experimental basis, but were not particularly successful; both of these methods were discarded.

Miller and Lea's *Guide to the Coastal Marine Fishes of California* (1972) was used for all fish identifications made in the field. Fish not identified in the field were collected and brought to the Wildlife, Fish, and Conservation Biology Department lab at the University of California, Davis, for identification. Total length for all individual fish and biomass per species were recorded unless there were delays associated with measurements that increased the likelihood of fish mortality. Recorded fish length was used as an indication of lifestage to assess the nursery function of the estero.

Analysis of Data

To test for significant differences in fish abundance and species richness between Estero de Limantour and the two Schooner Bay locations, I used a two-way analysis of variance (ANOVA) with log-transformed data, as recommended by statistical consultants from the University of California, Davis (Dr. Mitchell Watnik, Statistician, University of California, Davis, *pers. comm.*).

Comparing Ecological Guilds

To determine if the oyster farm affected fish community structure at the guild level, a basic comparison of ecologically similar species was implemented. This classification was based on recognizable feeding habits and the likely distribution of fish within the water column. Fish were placed into the following five ecological guilds: schooling planktivores, benthic-oriented feeders, structure (reef) feeders, crevice dwelling fish, and eelgrass dependent (inconspicuous). Because of their generalist nature and broad tolerance to different environments, three-spined sticklebacks were excluded from this analysis because they did not fit into a distinct class (Moyle 2002).

Indices of Similarity and Ecological Characteristics

To compare the similarity of the fish community composition at the three sample areas, I calculated seven measures of ecological structure. From Krebs (1999), one interprets these as follows:

- Species Richness – raw count of species;
- Shannon-Weiner Function of Diversity – a predictive measure used to determine the species of the next individual collected (the higher the value, the more diverse the community);
- Renkonen Percent Similarity Index – ranges from 0 (no similarity) to 100 (identical);
- Average Euclidian Distance Index – sum of the hypotenuse length of plotted species abundances (the higher the value, the greater the compositional difference);
- Bray-Curtis Index of Similarity – values range from 0 (similar) to 1 (dissimilar);
- Canberra Index of Similarity – standardized Bray-Curtis (1/# of species in common), values range from 0 (similar) to 1 (dissimilar);
- Morista Index – values range from 0 (dissimilar) to 1 (similar), recommended as best overall similarity index for ecological use (Krebs 1999).

Physical and Chemical Measurements

The following samples were collected periodically to gather information about water quality: clarity, total suspended solids (TSS), ammonia, nitrate, dissolved oxygen, salinity, and temperature. Ammonia, nitrate, and TSS samples were taken at a depth of thirty centimeters with a bottle-mounted pole sampler and brought to the DANR Analytical Lab at the University of California, Davis, for processing. Clarity was measured in the field with a Secchi disc; salinity, temperature, and dissolved oxygen were measured in the field with a YSI 85 meter. Results from the physico-chemical and nutrient samples are presented in Appendix B and Appendix C.

RESULTS

Abundance and Species Composition

I caught 3,128 fish, which represented twenty families and thirty-five species (Appendix A). The surfperches (Embiotocidae) were the predominant family, represented by eight species, followed by the sculpins (Cottidae) with four species. All other families consisted of two or fewer species. Because of sampling difficulties encountered during the December 2002 and April 2003 sampling efforts, only the data from the seven sampling periods from June 2003 through January 2004 were used for the statistical tests and descriptive accounts of the fish communities; this data incorporated 2,816 fish and twenty-nine species. Of this total, forty-four percent of the fish were captured in Estero de Limantour, thirty percent away from the racks, and twenty-six percent adjacent to the racks (Figure 6).

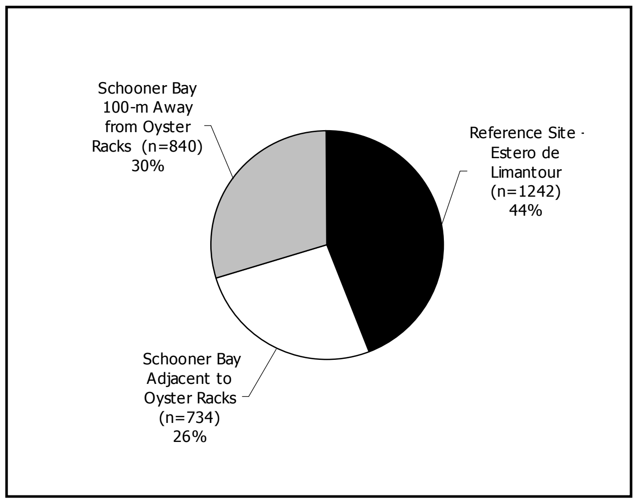

Figure 6. Percentage of the total catch from the three sampling locations in Drakes Estero, Point Reyes National Seashore.

Five species, topsmelt (*Atherinopsis affinis*), three-spined stickleback (*Gasterosteus aculeatus*), staghorn sculpin (*Leptocottus armatus)*, bay pipefish (*Sygnathus leptorhynchus*), and kelp surfperch (*Brachyistius frenatus)* dominated the fish assemblage and accounted for eighty-nine percent of the total catch (Table 3). It is likely that these five species are permanent residents of Drakes Estero, as they were collected during all sampling episodes. Six species were intermediate in abundance, represented by greater than ten but fewer than one hundred individuals. The remaining eighteen species were captured in lower frequencies with total catch per species consisting of ten individuals or fewer. In comparing Estero de Limantour and Schooner Adjacent, the relative abundance and rank order of the five predominant species was nearly reversed, while a more equitable pattern of abundance for these five species was noted at Schooner Away (Table 3). This trend reemphasizes a possible shift in the fish assemblage to a group of species capable of taking advantage of the rack structure in the water.

Table 3. Relative abundance of the fish species captured during the Drakes Estero Ichthyofauna – Oyster Mariculture study, Point Reyes National Seashore, December 2002 - January 2004.

Scientific Name	Common Name	Estero de Limantour	Schooner Adjacent	Schooner Away	Grand Total	Relative % of Total
Atherinopsis affinis *	topsmelt	487	83	306	876	31.11%
Gasterosteus aculeatus *	three-spined stickleback	317	54	80	451	16.02%
Leptocottus armatus *	staghorn sculpin	226	97	108	431	15.31%
Sygnathus leptorhynchus *	bay pipefish	102	180	132	414	14.70%
Brachyistius frenatus *	kelp surfperch	41	195	105	341	12.11%
Cymatogaster aggregata	shiner surfperch	14	39	41	94	3.34%
Triakis semifasciata	leopard shark	15	31	25	71	2.52%
Citharichthys stigmaeus	speckled sanddab	1	20	10	31	1.10%
Atherinopsis californiensis	jacksmelt	8	5	12	25	0.89%
Gibbonsia metzi	striped kelpfish	8	3	3	14	0.50%
Embiotoca jacksoni	black surfperch	7	3	3	13	0.46%
Micrometrus minimus	dwarf surfperch	3	5	0	8	0.28%
Aulorhynchus flavidus	tubesnout	1	1	6	8	0.28%
Clinocottus analis	wooly sculpin	0	6	1	7	0.25%
Sebastes sp.	unid. rockfish	0	3	2	5	0.18%
Hyperprosopon argenteum	walleye surfperch	2	2	0	4	0.14%
Pholis ornata	saddleback gunnel	2	2	0	4	0.14%
Platichthys stellatus	starry flounder	2	0	1	3	0.11%
Lepidogobius lepidus	bay goby	0	0	3	3	0.11%
Damalichthys vacca	pile surfperch	2	0	0	2	0.07%
Isopsetta isolepis	butter sole	2	0	0	2	0.07%
Microgadus proximus	Pacific tomcod	0	2	0	2	0.07%
Clupea harengus	Pacific herring	1	0	0	1	0.04%
Hypsopsetta guttulata	diamond turbot	1	0	0	1	0.04%
Cebidichthys violaceus	monkey-faced eel	0	1	0	1	0.04%
Hemilepidotus spinosus	brown Irish Lord	0	0	1	1	0.04%
Hypomesus pretiosus	surf smelt	0	1	0	1	0.04%
Porichthys notatus	plainfin midshipman	0	1	0	1	0.04%
Scorpaenichthys marmoratus	cabezon	0	0	1	1	0.04%
Total Number of Individuals		1,242	734	840	2,816	-
Percent of Total		44.11	26.07	29.83	-	100.00%
Species Diversity		1.63	2.05	1.91	-	-
Species Richness		20	21	18	29	-

* Likely permanent residents

The Shannon-Weiner Function of Diversity Index indicated that the fish community associated with the oyster racks was the most diverse. Species richness was similar among all three sites, ranging from eighteen in Schooner Away to twenty-one in Schooner Adjacent (Table 3). However, since the number of fish captured was unequal among the three locations, a standardized data set would likely have shown that the difference in species richness was more pronounced (i.e., if the samples drawn from Schooner Adjacent and Schooner Away were equal to the total catch from Estero de Limantour (n=1242), species richness would likely have been higher in the two Schooner Bay samples).

As shown in Figure 7, the evenness of the catch was similar, although fish in Estero de Limantour were distributed in a slightly more homogeneous fashion since four species dominated the catch. The distribution of fishes captured in the two Schooner Bay sites was slightly more heterogeneous; these sites were dominated by five to seven species. Twelve species were common to all three sampled areas, six species were captured in two of the three sampled areas, and eleven species were found exclusively in one sampling area.

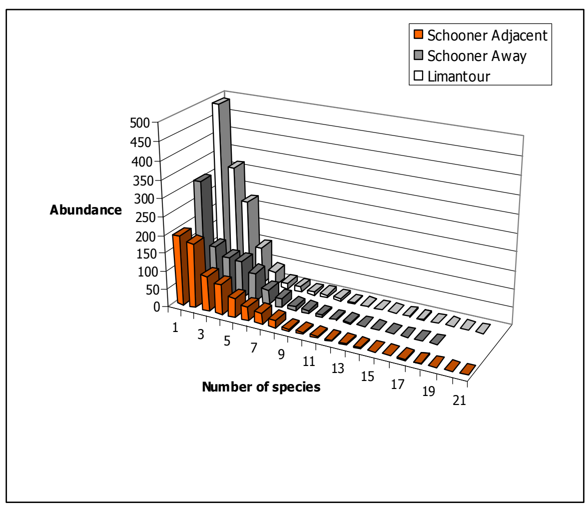

Figure 7. Heterogeneity and evenness of species captured in Drakes Estero, Point Reyes National Seashore.

Analysis of Variance

Calculated ANOVA values indicated that there were no significant differences in the abundance of fish over time (F=0.55, p=0.01) or among sites (F=0.23, p=0.01) between Schooner Adjacent, Schooner Away, and Estero de Limantour. There were also no significant differences in the number of species captured (F=1.07, p=0.01) or number of species among sites (F=0.16, p=0.01) during this study (Table 4).

Table 4. Two-way analysis of variance for abundance of fish and number of species, Drakes Estero Ichthyofauna – Oyster Mariculture study, Point Reyes National Seashore, December 2002 – January 2004.

ANOVA results for tests of significance for abundance of fish captured (p=0.01)						
Source of Variation	**Sum Squares**	**Degrees of Freedom**	**Variance**	**Calculated F-values**		**p**
SS between	2.27	20	0.11	variable A (date) =	0.55	**0.01***
SS variable A (date)	0.82	6	0.14	variable B (site) =	0.23	**0.01***
SS variable B (site)	0.11	2	0.06	interaction =	0.45	**0.01***
SS interaction	1.33	12	0.11			
SS within	9.22	37	0.25			
ANOVA results for tests of significance for number of species captured (p=0.01)						
Source of Variation	**Sum Squares**	**Degrees of Freedom**	**Variance**	**Calculated F-values**		**p**
SS between	0.926	20	0.04	variable A (date) =	1.07	**0.01***
SS variable A (date)	0.351	6	0.05	variable B (site) =	0.16	**0.01***
SS variable B (site)	0.017	2	0.009	interaction =	0.85	**0.01***
SS interaction	0.557	12	0.04			
SS within	2.026	37	0.05			

***significant at the p=0.01 level.**

Similarity of the Fish Communities

Four of the five similarity tests (Renkonen Percent Similarity, Euclidian Distance, Bray-Curtis Index, Morista Index) indicated that the fish communities in Schooner Adjacent and in Estero de Limantour were the most compositionally divergent (Table 5). Specifically, the Renkonen Percent Similarity index showed the fish communities in Schooner Adjacent and the Estero de Limantour reference site were the least similar (47%), while the reference site fish community and the Schooner Away fish were the most similar (74%). Average Euclidian distance was highest when comparing Estero de Limantour to Schooner Adjacent (98.29), indicating that the greatest difference in fish composition existed between these two sites. Two of the three calculated similarity coefficients, the Bray-Curtis and the Morista Index, indicated a similar trend: of the three communities examined, the Schooner Adjacent fish assemblage was composed of species that showed the greatest divergence from what was observed in Estero de Limantour. The Morista Index is reportedly the most appropriate for use in ecological analysis (Krebs 1999), and showed that the most pronounced difference in fish assemblages occurred between Estero de Limantour and Schooner Adjacent. In contrast, the Canberra Index indicated that all three communities were compositionally similar.

Table 5. Similarity of fish communities from the three locations sampled in Drakes Estero, Point Reyes National Seashore, December 2002 – January 2004.

Index Used	Sites Compared		
	Limantour v. Schooner Away	Schooner Away v. Schooner Adj.	Limantour v. Schooner Adj.
Renkonen Percent Similarity [1]	74.30	70.67	47.91
Average Euclidian Distance [2]	61.28	45.95	98.29
Bray-Curtis Index of Similarity [3]	0.34	0.29	0.57
Canberra Index of Similarity [4]	0.64	0.55	0.59
Morista Index of Similarity [5]	0.91	0.93	0.44

1 – ranges from 0 (no similarity) to 100 (identical)
2 – sum of the hypotenuse length of plotted species abundances, the higher the value, the greater the difference
3 – values range from 0 (similar) to 1 (dissimilar);
4 – standardized Bray-Curtis (1/# of species in common), values range from 0 (similar) to 1 (dissimilar)
5 – values range from 0 (dissimilar) to 1 (similar), recommended as best overall similarity index for ecological use (Krebs 1999).

Ecological Guilds

The number of species per guild was not greatly altered by the presence of the oyster racks, but changes in fish abundance within each guild were observed (Table 6). Fewer pelagic planktivorous and more structure feeding fish (e.g., Embiotocidae) were found associated with the racks. Although more species of the Embiotocidae family were captured in Estero de Limantour, kelp surfperch (*B. frenatus*) and shiner surfperch (*C. aggregata*) were found in higher densities in Schooner Adjacent. Nearly twice as many benthic fish were captured in Estero de Limantour, although ninety-one percent were staghorn sculpin (*L. armatus*). Of the predominant benthic feeding species, speckled sanddab (*C. stigmaeus*), wooly sculpin (*C. analis*), and leopard sharks (*T. semifasciata*) were captured more frequently in Schooner Adjacent. The frequency of crevice dwelling

Table 6. Number of fish per ecological guild captured during the Drakes Estero Ichthyofauna – Oyster Mariculture study, Point Reyes National Seashore, December 2002 - January 2004.

Schooling Plantivores	**Common Name**	**Estero de Limantour**	**Schooner Adjacent**	**Schooner Away**
Atherinopsis affinis	topsmelt	487	83	306
Atherinopsis californiensis	jacksmelt	8	5	12
Clupea harengus	Pacific herring	1	0	0
Total		**496**	**88**	**318**
Structure Feeders	**Common Name**	**Estero de Limantour**	**Schooner Adjacent**	**Schooner Away**
Brachyistius frenatus	kelp surfperch	41	195	105
Cymatogaster aggregata	shiner surfperch	14	39	41
Embiotoca jacksoni	black surfperch	7	3	3
Damalichthys vacca	pile surfperch	2	0	0
Hyperprosopon argenteum	walleye surfperch	2	2	0
Micrometrus minimus	dwarf surfperch	3	5	0
Total		**69**	**244**	**149**
Benthic–Oriented	**Common Name**	**Estero de Limantour**	**Schooner Adjacent**	**Schooner Away**
Leptocottus armatus	staghorn sculpin	226	97	108
Triakis semifasciata	leopard shark	15	31	25
Citharichthys stigmaeus	speckled sanddab	1	20	10
Lepidogobius lepidus	bay goby	0	0	3
Clinocottus analis	wooly sculpin	0	6	1
Hemilepidotus spinosus	brown Irish Lord	0	0	1
Platichthys stellatus	starry flounder	2	0	1
Scorpaenichthys marmoratus	cabezon	0	0	1
Isopsetta isolepis	butter sole	2	0	0
Porichthys notatus	plainfin midshipman	0	1	0
Hypsopsetta guttulata	diamond turbot	1	0	0
Microgadus proximus	Pacific tomcod	0	2	0
Total		**247**	**157**	**150**
Crevice Dwellers	**Common Name**	**Estero de Limantour**	**Schooner Adjacent**	**Schooner Away**
Gibbonsia metzi	striped kelpfish	8	3	3
Cebidichthys violaceus	monkey-faced eel	0	1	0
Pholis ornata	saddleback gunnel	2	2	0
Total		**10**	**6**	**3**
Eelgrass-Dependent	**Common Name**	**Estero de Limantour**	**Schooner Adjacent**	**Schooner Away**
Sygnathus leptorhynchus	bay pipefish	102	180	132
Aulorhynchus flavidus	tubesnout	1	1	6
Total		**103**	**181**	**138**

species was highest in Estero de Limantour; however, the chosen sample gear was not successful in capturing many individuals (Table 6). Anecdotally, numerous crevice-dwelling fish [e.g., monkey-faced eels (*C. violaceus*), striped kelpfish (*G. metzi*)] were observed on the flat-bottomed barges used to harvest oysters, suggesting that these species use the oyster shell matrix as habitat. Similar numbers of eelgrass dependent fish were observed in all sites.

Nursery Function and Seasonal Abundance of Fish

Juvenile fish were captured in the estero throughout this study, which indicated that the estero fulfills a substantial nursery habitat function (Table 7). Additional studies will be needed to determine which of these species spawn in the estero and which move into the estero during a post-spawning migration. By comparing the maximum known species length to the minimum species length captured, fish were classified as young-of-year, juvenile, subadult, or adult. Young-of-year fish were identified in forty percent of the species captured, which indicated that reproduction of these species likely occurs within the estero. However, only two species were observed in an obvious reproductive state: three-spined stickleback (*G. aculeatus*) and bay pipefish (*S. leptorhynchus*).

The seasonal abundance of fish captured in the estero was relatively steady except during the August – September survey when the maximum number of fish was captured (Figure 8). This peak in abundance was largely due to several large gill net hauls of schooling topsmelt (*A. affinis*). The number of species captured per sampling episode ranged from a minimum of nine in October to a maximum of sixteen in November (Figure 8). Species composition also varied seasonally as different species entered the estuary at different times of the year. The nine most dominant fish were captured in the estero during all sampling events indicating that at least one life stage may be present in the estero at any point during any given year. These nine species did exhibit a seasonal pattern with regard to the use of the system (Figure 9).

Table 7. Life stages and Size Ranges of the fish captured during the Drakes Estero Ichthyofauna - Oyster Mariculture study, Point Reyes National Seashore.

Scientific Name	Common Name	Size Range Captured (mm)	Maximum length for Adult Fish (mm)*	Life Stage
Amphistichus argenteus	barred surfperch	282 - 313	425	A, SA
Atherinopsis affinis	topsmelt	47 - 245	360	J, SA, YOY
Atherinopsis californiensis	jacksmelt	305 - 425	438	A, SA
Aulorhynchus flavidus	tubesnout	125 - 169	175	A, SA
Brachyistius frenatus	kelp surfperch	30 - 155	324	J, SA, YOY
Cebidichthys violaceus	monkey-faced eel	93	750	J
Citharichthys stigmaeus	speckled sanddab	40 - 125	168	J, SA, YOY
Clinocottus analis	wooly sculpin	51 - 99	150	J, SA, YOY
Clupea harengus	Pacific herring	85	450	J
Cymatogaster aggregata	shiner surfperch	45 - 138	175	J, SA, YOY
Damalichthys vacca	pile surfperch	316 - 342	435	A, SA
Embiotoca jacksoni	black surfperch	85 - 382	384	J, A
Engraulis mordax	northern anchovy	58	175-225	YOY
Gasterosteus aculeatus	three-spined stickleback	25 - 86	100	J, SA, A, YOY
Gibbonsia metzi	striped kelpfish	39 - 120	231	J, SA, YOY
Hemilepidotus spinosus	brown Irish Lord	155	250	SA
Hyperprosopon argenteum	walleye surfperch	71 - 170	300	J, SA
Hypsopsetta guttulata	diamond turbot	49 - 180	450	J, SA, YOY
Isopsetta isolepis	butter sole	50 - 69	544	J, YOY
Lepidogobius lepidus	bay goby	84 - 104	100	A, SA
Leptocottus armatus	staghorn sculpin	34 - 195	300	J, SA, YOY
Microgadus proximus	Pacific tomcod	85 - 110	300	J, SA
Micrometrus minimus	dwarf surfperch	52 - 123	156	J, SA, YOY
Ophiodon elongatus	lingcod	100	1125	J
Hypomesus pretiosus	surf smelt	168	300	SA
Phanerodon atripes	white surfperch	75	310	J
Pholis ornata	saddleback gunnel	98 - 158	300	SA
Platichthys stellatus	starry flounder	130 - 204	900	J
Porichthys notatus	plainfin midshipman	149	375	SA
Scorpaenichthys marmoratus	cabezon	180	975	J, SA
Sebastes sp.	unid. rockfish	70 - 86	-	-
Sygnathus leptorhynchus	bay pipefish	05 - 317	325	J, SA, A, YOY

* data from Guide to the Coastal Marine Fishes of California, Miller and Lea (1972)
A = adult
SA = sub-adult
J = juvenile
YOY = young-of-year

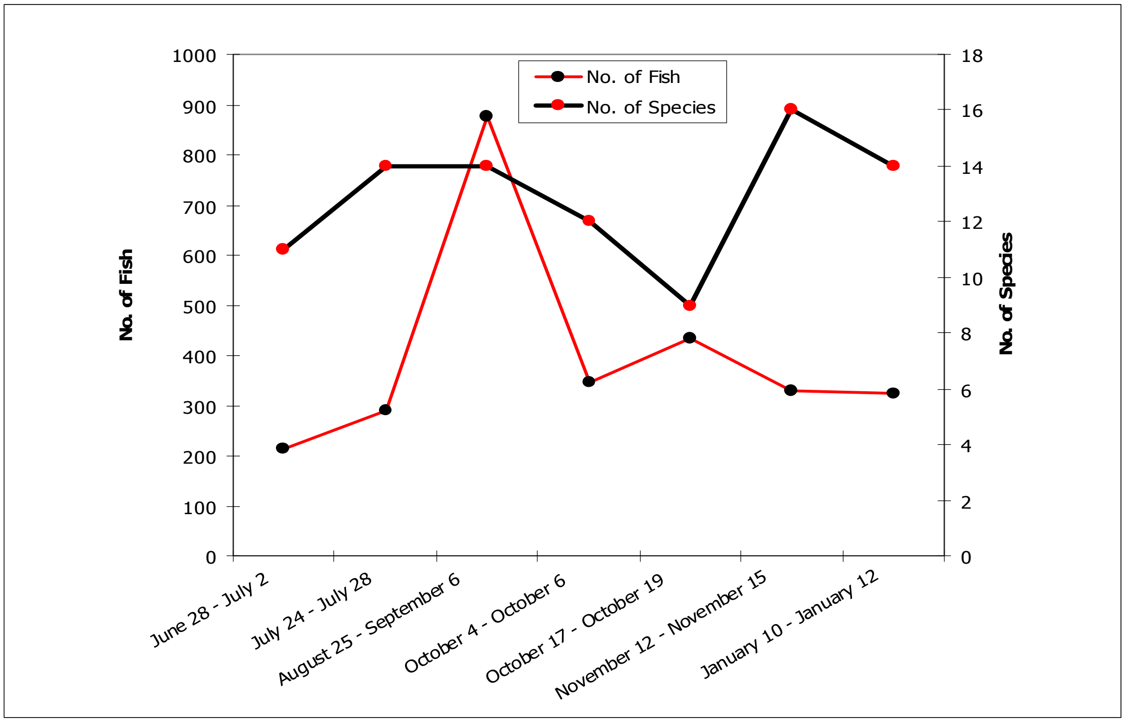

Figure 8. Seasonal abundance of fish captured in Drakes Estero, Point Reyes National Seashore.

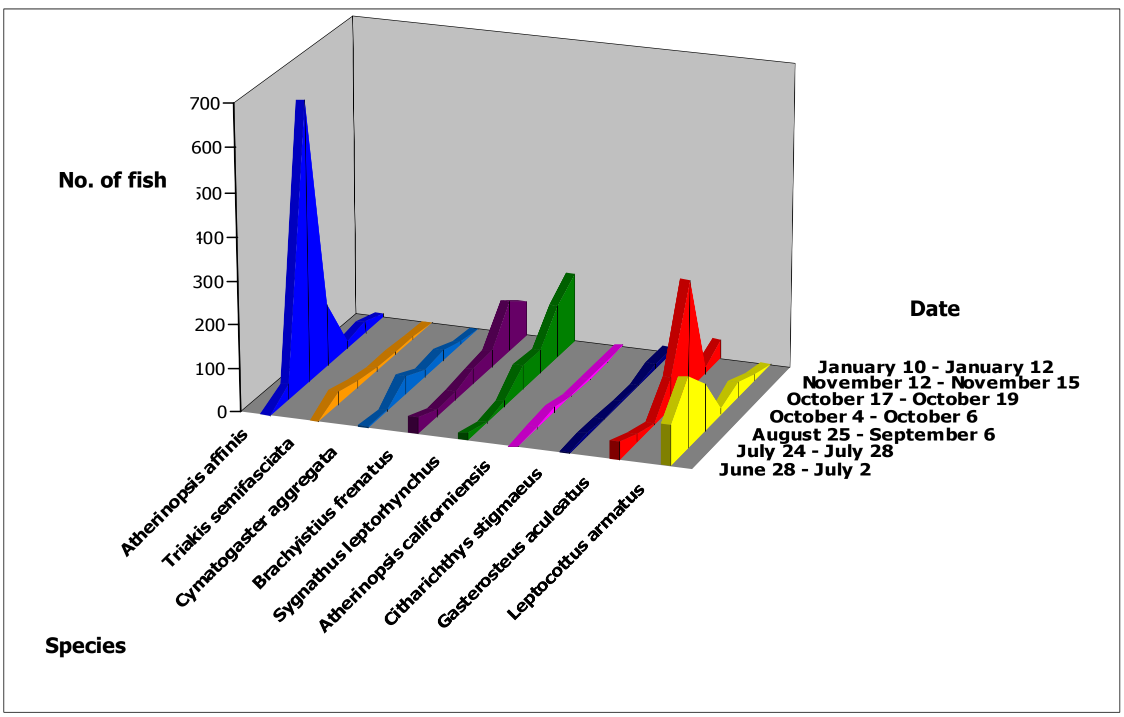

Figure 9. Seasonal abundance of the nine most common species captured in Drakes Estero, Point Reyes National Seashore.

DISCUSSION

The Fish Community and Habitat Complexity

This preliminary investigation into the relationship between oyster mariculture and the Drakes Estero ichthyofauna suggested that the fish community had not been adversely affected by the presence of the Johnson's Oyster Company. Analysis of variance tests showed no significant difference in species abundance or species richness at Schooner Adjacent, Schooner Away, or Estero de Limantour. Because species richness and species diversity were greatest in the samples taken adjacent to the oyster racks, it is likely that the physical structure associated with the oyster mariculture facility has enhanced habitat complexity, thereby providing additional resources (e.g., cover and feeding opportunities) for fish. These results support the ecological theory of spatial heterogeneity, which postulates that a direct correlation exists between increased habitat complexity and species diversity (Heck and Wetstone 1977).

The results of this study indicate that a localized shift in species composition, distribution, and population dynamics of certain fish species has occurred. Alterations to the relative percentage of species captured both within and amongst ecological guilds indicate that the resource base (i.e., prey items, shelter) may have shifted to favor several structure-oriented feeders [e.g., kelp surfperch (*B. frenatus*)]. Four of the five indices used to assess the similarity of the fish assemblages showed the greatest compositional divergence was between Estero de Limantour and Schooner Adjacent. This suggested that the use of the artificial habitat derived from mariculture facilities attracted opportunistic fish species to the racks if they provide resources not otherwise available, or supplemented preexisting conditions.

Coen et al. (1999) classified oyster reefs as Essential Fish Habitat (EFH), defined by the National Marine Fisheries Service as "those waters and substrate necessary for spawning, breeding, feeding, or growth to maturity" (http://www.nmfs.noaa.gov). The authors summarized the benefits of healthy bivalve populations as "having the ability to affect population, community, landscape, and basin wide ecosystem processes, primarily through water filtration and the creation of reef structure that can be used as physical habitat by other marine organisms." In Drakes Estero, the wooden support structures, oyster cultch, and developing oysters may mimic the role of natural oyster beds by providing physical habitat, feeding opportunities, and cover for fish and invertebrates. For structure-oriented suction feeding fish, crevice-dwelling fish, and benthic fish, the racks and oyster shell matrix of the mariculture facility provides cover for fish, a prey source for sharks and rays, and a substrate for the development of invertebrates (Figure 10). The placement of artificial structures (e.g., tires, automobiles, shipwrecks) into aquatic systems is a well-used fisheries management strategy employed to bolster fish stocks and increase habitat complexity (Ambrose and Anderson 1990, Ulanowicz and Tuttle 1992, Harding and Mann 1999, Tugend et al. 2002). Although there is debate as to whether artificial structures increase fishery production, there is little doubt that artificial habitat does attract, and is used by fish for the provision of resources (Lindberg 1997).

Figure 10. Oyster shell matrix at Johnson's Oyster Farm, Drakes Estero, Point Reyes National Seashore.

Eelgrass Beds

A major concern in coastal environments is the loss of eelgrass beds that results from encroaching development (Hughes and Deegan 2002). Eelgrass beds add to the complexity of the coastal marine environment and provide a diversity of feeding opportunities for fish and invertebrates (Orth and Heck 1980, Costa et al. 1994). The interaction between bivalve mariculture and eelgrass is an important topic for mangers of the estuarine and coastal environment because bivalve culture can adversely affect eelgrass by inhibiting its spatial distribution and attenuating solar radiation (Conte and Moore 2004). Studies have shown that adjusting the way in which bivalves are cultured can be critical to alleviating the effects of bivalve mariculture on eelgrass beds. Researchers from the South Slough National Estuarine Research Reserve in Oregon have shown that culture methods that elevate oysters off the seafloor enhance the opportunity for eelgrass beds to redevelop in areas where they have been previously disturbed, which in turn benefits aquatic biota (http://www.oregonstatelands.us/news/news_ssnerr.htm). Their study also indicated that increasing the spacing between hanging lines allowed eelgrass to grow directly under oyster racks. Further studies are required to determine whether bivalve mariculture affects water quality in a manner that affects eelgrass survivability. Alternatively, Peterson and Heck (1999) suggest that because biodeposits from bivalves are high in nitrogen and phosphorus, organic enrichment from biodeposition can enhance growth of aquatic macrophytes, specifically kelp and eelgrass.

Eelgrass beds are prevalent throughout the Drakes Estero ecosystem. A qualitative look at the distribution of eelgrass beds in Schooner Bay indicated that its productivity was not affected substatnially by oyster mariculture; however, eelgrass growth is restricted directly beneath the oyster racks due to light attenuation. Adjusting the spacing between oyster lines would likely restore productivity under the racks, and could allow oysters and eelgrass to be grown in concert. Further analysis of the spatial distribution and shoot density of eelgrass in Drakes Estero is suggested.

Nursery Function and Seasonal Fish Use of Drakes Estero

The calm nutrient-rich waters of Drakes Estero provide ample nursery and rearing habitat for marine fishes. This protected environment likely provides numerous feeding, spawning, and predator avoidance opportunities not otherwise available in Drakes Bay or the Pacific Ocean. Juvenile stages of all fish species captured in this study were found in the estero, including juveniles of several commercially important species and sport fish [e.g., Pacific herring (*C. harengus*), Northern anchovy (*E. mordax*), lingcod (*O. elongatus*). Based on the size range of the fish captured in the estero, it is estimated that thirteen species spawn in the estero. However, only three-spined stickleback (*G. aculeatus*) and bay pipefish (*S. leptorhynchus*) were observed in a reproductive state; leopard sharks (*T. semifasciata*) are known to spawn in the estero as well (Sarah Allen, NPS Chief Scientist, *pers. comm.*). Because sport and commercially important species made up such a small percentage of the total catch, additional studies are recommended to assess the population dynamics and life history of these species in Drakes Estero.

Because coastal marine environments can provide refuge from harsh oceanic conditions, seasonal use by fishes is common in Drakes Estero. However, because the coastal aquatic environment can be physiologically demanding, few species are permanent residents; opportunistic fishes most likely come into the estero to take advantage of the resource surplus. The nine most common species did show seasonality in their use of the estero; however, the peak in their abundance is also likely related to spawning events and recruitment of fish.

Hydrology and Water Quality

The hydrologic conditions of a receiving basin, including water circulation patterns, precipitation, and tidal exchange rates, play an important role in determining the fate of materials that have been deposited in a marine environment (Hayakawa et al. 2001). Although numerous studies have shown that large-scale aquaculture facilities can adversely affect the aquatic environment (Dahlback and Gunnarson 1981, Kautsky and Evans 1987, Hayakawa et al. 2001), the relatively small scale of the Johnson's Oyster Company combined with the hydrologic conditions in Drakes Estero likely dissipate the accumulation of biodeposits that in other studies have been shown to affect benthic ecology and water quality. In Drakes Estero, the tidal prism is high and a large volume of water drains twice daily. The anecdotal look at aquatic physico-chemical conditions undertaken in this study indicated that no major deteriorations in water quality existed adjacent to the oyster racks (see Appendices B and C). A more intensive study of water quality, nutrient budgets, and sedimentation rates is advised.

Management Practices

Although this study did not find evidence supporting the idea that oyster mariculture adversely affected the fish fauna in Drakes Estero, several management directives could be implemented that may enhance the overall ecological structure and productivity of the system. Historically, Olympia oysters (*Ostreola conchaphila*), the native oyster of the Pacific coast, were found from Baja, California to Alaska (Cook et al. 2000). This bivalve was important in the Pacific Northwest for Native Americans, and was an important commodity for settlers in the early-twentieth century (Cook et al. 2000). Baker (1995) reported these oysters to have been common in Drakes Estero, although it is unknown if a remnant population still exists. In Washington State, recent fishery plans have explored reestablishment of native oyster stocks for commercial use as a means to restore ecological communities (Chew 1999, Cook et al. 2000). Breitburg et al. (2000) indicated that both sustainable commercial harvest and the provision of ecological services (e.g., filtration, nutrient enrichment, habitat) were attainable within a comprehensive management plan for the restoration and harvest of native Olympia oyster populations. In California, researchers from the University of California, Davis, are examining the utility of remnant and re-introduced populations of native oysters in Tomales Bay (in close proximity to Drakes Estero) as a foundation species, important for the redevelopment of the historical ecological conditions that likely existed in the bay (Grosholz 2003).

Although individuals are relatively small, the culture of the Olympia oyster would likely provide additional habitat for aquatic species in Drakes Estero and provide a marketable product for JOC. Unlike Pacific oysters, which cannot reproduce reliably in the cold waters of Drakes Estero (Fred Conte, University of California, Davis, *pers. comm*.), Olympia oysters would reproduce naturally, creating more consolidated reef habitat for fish and invertebrates. A successful management plan would need to be implemented that used the best possible harvest practices, allowing culling to take place in a manner that would leave a sufficient portion of the structure for the associated aquatic biota to develop and sustain itself.

Economically, the native species is likely to fetch a higher return: a gallon of Olympia oyster meat can sell for six times as much as the Pacific oyster (Chew 1999). JOC, or a future permitee, may be able to establish a market niche for California native oysters that would allow them to fetch a higher per oyster return to compensate for the difference in culture technique, oyster growth patterns, and any infrastructure development that would be needed to transition to native oyster culture. An integrated management plan administered by the NPS could provide habitat for fish and wildlife, maintain important ecological services, and sustain oyster farming in Drakes Estero.

Costa-Pierce (2002) termed the evolution of aquaculture towards a more sustainable system of practices as the "greening-up of the blue revolution." Although Johnson's Oyster Farm was not observed to have adversely affected the fish community, a cooperative effort between NPS and JOC is recommended to ensure that future management actions maintain a viable oyster fishery and conserve the valuable ecological structure in this unique and pristine California marine environment. The continued production of oysters will likely continue to bolster the condition of the fish community in the estero by enhancing habitat complexity and feeding opportunities. A transition to native Olympia oyster culture could serve the needs of both organizations, as they continue to work cooperatively to establish a management plan that sustains JOC, while allowing for the continued protection of the diverse aquatic biota in Sir Francis Drake's estero.

APPENDICES

Appendix A. List of all species captured during the Drakes Estero Ichthyofauna – Oyster Mariculture study, Drakes Estero, Point Reyes National Seashore.

Species #	Scientific Name	Common Name	Number Captured	Percent of Total
1	*Atherinopsis affinis*	topsmelt	977	31.23%
2	*Sygnathus leptorhynchus*	bay pipefish	519	16.59%
3	*Gasterosteus aculeatus*	three-spined stickleback	472	15.09%
4	*Leptocottus armatus*	staghorn sculpin	435	13.91%
5	*Brachyistius frenatus*	kelp surfperch	375	11.99%
6	*Cymatogaster aggregata*	shiner surfperch	96	3.07%
7	*Triakis semifasciata*	leopard shark	81	2.59%
8	*Citharichthys stigmaeus*	speckled sanddab	49	1.57%
9	*Atherinopsis californiensis*	jacksmelt	27	0.86%
10	*Gibbonsia metzi*	striped kelpfish	16	0.51%
11	*Embiotoca jacksoni*	black surfperch	14	0.45%
12	*Aulorhynchus flavidus*	tubesnout	8	0.26%
13	*Micrometrus minimus*	dwarf surfperch	8	0.26%
14	*Clinocottus analis*	wooly sculpin	7	0.22%
15	*Hyperprosopon argenteum*	walleye surfperch	7	0.22%
16	*Sebastes sp.*	unid. rockfish	5	0.16%
17	*Pholis ornata*	saddleback gunnel	4	0.13%
18	*Isopsetta isolepis*	butter sole	3	0.10%
19	*Lepidogobius lepidus*	bay goby	3	0.10%
20	*Platichthys stellatus*	starry flounder	3	0.10%
21	*Amphistichus argenteus* *	barred surfperch	2	0.06%
22	*Damalichthys vacca*	pile surfperch	2	0.06%
23	*Hypsopsetta guttulata*	diamond turbot	2	0.06%
24	*Microgadus proximus*	Pacific tomcod	2	0.06%
25	*Cebidichthys violaceus*	monkey-faced eel	1	0.03%
26	*Clupea harengus*	Pacific herring	1	0.03%
27	*Engraulis mordax* *	northern anchovy	1	0.03%
28	*Hemilepidotus spinosus*	brown Irish Lord	1	0.03%
29	*Hypomesus pretiosus*	surf smelt	1	0.03%
30	*Mustelus californicus* *	brown smoothhound	1	0.03%
31	*Myliobatis californica* *	bat ray	1	0.03%
32	*Ophiodon elongatus* *	lingcod	1	0.03%
33	*Phanerodon atripes* *	white surfperch	1	0.03%
34	*Porichthys notatus*	plainfin midshipman	1	0.03%
35	*Scorpaenichthys marmoratus*	cabezon	1	0.03%
Grand Total			3128	100.00%

* not included in statistical analysis

Appendix B. Environmental characteristics measured in Estero de Limantour and Schooner Bay during the Drakes Estero Ichthyofauna – Oyster Mariculture study, Drakes Estero, Point Reyes National Seashore, 2002 - 2004.

Date	Location	Depth (m)	Salinity (ppt)	Temp (C)	Clarity (m)	DO (mg/l)	DO (%)
12/4/02	Limantour	2.10	32.7	13.3	2.10	7.33	85.0
12/4/02	Limantour	1.67	32.7	12.5	1.67	6.35	74.6
4/14/03	Limantour	1.55	32.2	13.5	1.55	7.79	89.4
4/14/03	Limantour	0.65	32.5	13.9	0.65	9.01	106.2
4/14/03	Limantour	1.50	32.0	14.7	1.50	7.23	86.5
4/14/03	Limantour	1.10	32.7	12.8	1.10	8.94	103.4
7/1/03	Limantour	0.97	32.6	19.5	0.61	13.27	176.0
7/1/03	Limantour	1.73	32.3	15.0	1.28	10.43	125.3
7/27/03	Limantour	2.00	33.0	18.7	2.00	9.50	124.5
10/17/03	Limantour	2.07	33.7	11.7	2.07	7.80	88.0
10/17/03	Limantour	1.46	33.9	13.5	1.46	9.71	115.3
10/17/03	Limantour	2.59	33.9	12.7	2.59	8.16	96.5
11/14/03	Limantour	*	32.5	12.2	*	6.82	77.8
11/14/03	Limantour	2.10	32.7	12.5	2.01	7.68	88.5
11/14/03	Limantour	1.34	32.4	12.5	1.34	8.02	92.4
1/12/04	Limantour	1.44	29.8	12.0	1.44	8.45	93.2
1/12/04	Limantour	1.30	28.7	12.1	1.30	8.47	94.4
	Mean	**1.60**	**32.37**	**13.71**	**1.54**	**8.53**	**101.00**
12/3/02	Adjacent	2.30	32.8	12.0	2.30	9.50	*
4/11/03	Adjacent	2.10	34.0	15.7	1.75	8.44	104.0
4/14/03	Adjacent	*	32.8	13.2	*	7.36	86.4
4/14/03	Adjacent	1.45	32.7	14.3	1.45	8.44	100.8
6/28/03	Adjacent	1.60	32.3	18.9	1.07	10.75	140.5
7/24/03	Adjacent	1.60	34.6	19.4	6.70	6.70	89.5
7/25/03	Adjacent	1.65	34.3	20.6	1.65	10.31	140.0
10/18/03	Adjacent	1.25	33.9	13.4	1.25	8.07	95.5
11/12/03	Adjacent	1.92	31.6	12.8	1.92	7.88	91.1
11/12/03	Adjacent	1.86	31.8	12.8	1.86	8.51	98.3
11/12/03	Adjacent	2.01	31.7	12.3	1.71	7.43	84.7
1/10/04	Adjacent	1.98	28.9	12.2	1.14	7.71	86.2
1/10/04	Adjacent	1.52	29.3	13.1	0.83	8.67	98.2
	Mean	**1.68**	**32.00**	**14.18**	**1.83**	**8.43**	**99.76**
4/11/03	Away	1.05	33.5	18.1	1.05	11.08	143.0
4/14/03	Away	1.45	32.4	12.5	1.45	7.33	84.4
6/29/03	Away	1.58	32.8	20.6	0.97	8.75	117.5
7/24/03	Away	1.50	31.5	15.7	1.50	11.31	139.0
10/18/03	Away	1.58	34.2	15.4	1.58	7.84	96.0
10/18/03	Away	1.83	33.8	14.6	1.83	9.80	118.3
11/12/03	Away	1.52	31.6	12.8	1.52	7.98	92.0
11/12/03	Away	1.55	31.8	12.8	1.55	8.90	102.8
11/12/03	Away	2.07	31.4	12.5	1.46	7.31	82.5
1/10/04	Away	2.38	27.9	12.4	0.91	8.66	93.8
1/10/04	Away	1.88	23.5	12.3	0.45	8.74	92.0
	Mean	**1.73**	**31.16**	**13.95**	**1.39**	**8.61**	**101.15**

* not recorded

Appendix C. Water column variables measured during the Drakes Estero Ichthyofauna – Oyster Mariculture study, Point Reyes National Seashore, December 2002 – January 2004.

Date	Location	Ammonia (NH4-N)	Nitrate (NO3-N)	Total Suspended Solids
April	Limantour	0.13	0.050	112.00
April	Limantour	0.11	0.170	84.00
April	Limantour	0.12	0.050	86.00
April	Limantour	0.16	0.050	110.00
July	Limantour	0.18	0.050	62.00
July	Limantour	0.21	0.050	56.00
July	Limantour	0.21	0.050	94.00
	Mean	***0.16***	***0.07***	***86.29***
April	Schooner Adjacent	0.13	0.060	104.00
April	Schooner Adjacent	0.14	0.080	98.00
April	Schooner Adjacent	0.12	0.050	108.00
July	Schooner Adjacent	0.20	0.050	96.00
July	Schooner Adjacent	0.14	0.050	94.00
July	Schooner Adjacent	0.38	0.050	72.00
	Mean	***0.19***	***0.06***	***95.33***
April	Schooner Away	0.12	0.050	112.00
April	Schooner Away	0.12	0.050	82.00
April	Schooner Away	0.21	0.050	116.00
July	Schooner Away	0.25	0.050	58.00
July	Schooner Away	0.21	0.050	72.00
July	Schooner Away	0.12	0.050	70.00
	Mean	***0.17***	***0.05***	***85.00***

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