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Abstract

Before 1980, little scientific information was available to set water quality standards for the protection of the fish and invertebrates of San Francisco and San Pablo bays. In 1979, the Interagency Ecological Program (IEP) designed a plan to collect biological and physical data from South San Francisco Bay to the west delta. The State Water Resources Control Board (SWCRB) approved this plan and the Bay-Delta Division of the California Department of Fish and Game (CDFG), operating as part of the IEP, set the plan in action. The objective of the study was to determine the effects of freshwater outflow from the delta on the abundance and distribution of marine and estuarine fishes, shrimps, and crabs and use this knowledge to understand the volume and timing of freshwater outflow that is necessary for their well-being. In 1984, the U.S. Geological Survey started a hydrodynamic study of currents and salinity fluxes in the estuary(Smith and others 1995). The hydrodynamic data will eventually be useful in understanding the distribution and movements of fish and invertebrates.

This report presents data collected by the study on the abundance and distribution of selected organisms from 1980 to 1995 (shrimp and crab data extend to 1996). It is restricted mainly to presentation and description of the data. More detailed analyses will appear in subsequent reports and papers, although some have already been done for SWRCB Water Rights Hearings (CDFG 1987, 1992).

Report on the 1980–1995 Fish, Shrimp, and Crab Sampling in the San Francisco Estuary, California

by

Randall Baxter, Kathryn Hieb, Suzanne DeLeón, Kevin Fleming and James Orsi

Edited by

James Orsi

California Department of Fish and Game
4001 N. Wilson Way
Stockton, California 95205

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The Interagency Ecological Program for the Sacramento–San Joaquin Estuary

A Cooperative Program of the

California Department of Water Resources
State Water Resources Control Board
US Bureau of Reclamation
US Army Corps of Engineers
California Department of Fish and Game
US Fish and Wildlife Service
US Geological Survey
US Environmental Protection Agency

National Marine Fisheries Service

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Introduction

James Orsi

The San Francisco Estuary is the largest estuary on the west coast of North America. Located somewhat more than halfway up the California coast from the Mexican border, it is the natural exit point of 40% of California's freshwater outflow. This water is a prized commodity in California, sought after by farmers for food production, municipalities for people and industries, and environmentalists for the rich, but in some cases threatened, fish and invertebrate resources of the estuary. To capture the water for human needs, dams, aqueducts, canals, and pumping plants have been constructed to pump water out of the estuary and transport it to the San Francisco Bay area, the San Joaquin Valley, and southern California.

These human alterations affect the life of the estuary by reducing the freshwater flow that creates the estuary. Freshwater flowing seaward, mixing with ocean water, creates habitats that attract coastal fish to spawn, while providing low salinity habitat for the rearing of their young. Other fish, such as salmon, detect the scents of their home rivers in the freshwater outflow and enter the estuary on their spawning migrations. Still other fish and many open water and bottom crustaceans and shellfish reside in the brackish water regions all their lives.

California's 2 largest rivers, the Sacramento and the San Joaquin, merge to form the estuary (Figure 1). They drain part of the Sierra Nevada and Cascade mountains and form a large and convoluted delta in the Central Valley. The delta consists of about 1,100 km of river channels and sloughs that cover an area of about 3,000 km^2 and drain into Suisun Bay on the edge of the low mountains of the Coast Range. A 100-m deep ship channel runs along the south side of Suisun Bay. To its north are extensive shoals. West of Suisun Bay the deep trough of Carquinez Strait breaches the Coast Range and connects Suisun Bay with the much larger San Pablo Bay. Most of San Pablo Bay is a broad shoal, only the ship channel on its southeastern side provides deep water. San Francisco Bay is the last of the bays and empties into the Pacific Ocean through the Golden Gate. Its small northern quarter is termed Central Bay. Although small, it is the deepest of the bays with shoals confined mainly to its eastern side. The long southeast leg of San Francisco Bay is called South Bay. It has a central channel that narrows southwards and broad shoals on either side of the channel.

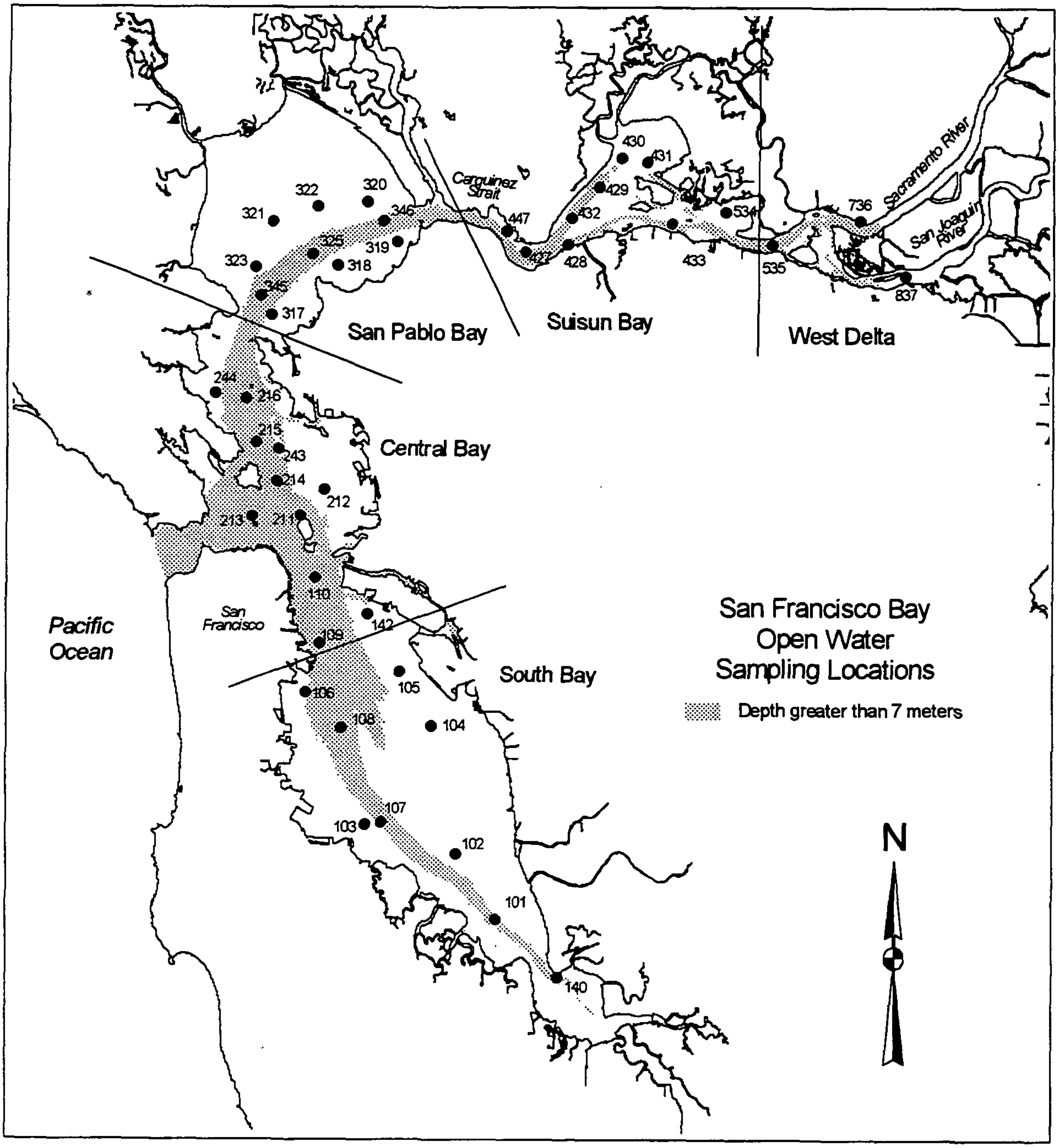

Figure 1 Map of the San Francisco Estuary showing the 7 m depth contour

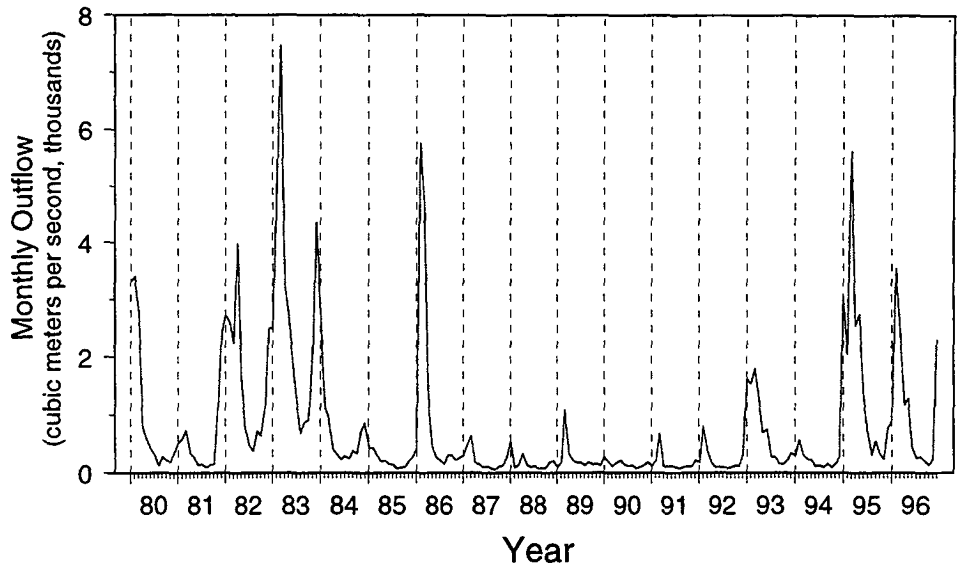

Figure 2 Mean monthly delta outflow in cubic meters per second at Chipps Island from 1980 to 1996

The climate is Mediterranean; most precipitation falls in winter and spring as rain throughout the Central Valley and as snow in the Sierra Nevada and Cascades. The freshwater outflow pattern is seasonal; highest outflow occurs in winter and spring. In summer, inflow to the Sacramento–San Joaquin Delta is controlled mainly by water released from Shasta Reservoir on the Sacramento River and Oroville Reservoir on the Feather River. A portion of this inflow is diverted to the San Joaquin Valley and southern California by the state and federal export pumping plants in the south delta. A smaller diversion in Suisun Bay diverts water into the Contra Costa Canal. Additionally, numerous small diversions on the delta islands remove water for local farming operations. The volume of water flowing seaward from Suisun Bay varies greatly both annually and seasonally due to variations in precipitation and export pumping (Figure 2).

Ocean conditions affect the estuary. The California Current system dominates California's nearshore ocean environment. Off northern and central California, surface waters are driven south by northeasterly winds in spring and summer and, as a result of Ekman transport of surface water, cold, nutrient-rich water is upwelled to the surface and transported offshore. This creates one of the most productive ocean regions in the world. Off central California, upwelling is strongest in June and July, when winds are strongest. When winds and upwelling subside in August or September, sea surface temperature increases to an annual maximum in October. With the advent of winter storms and southerly winds in November or December, the nearshore surface current becomes northerly. This current is called the Davidson Current and is associated with downwelling and onshore Ekman transport of surface water.

Ocean temperature is a major factor determining the distribution of fish and invertebrates along the coast and consequently, the marine fauna of the estuary. There are major faunal breaks at Point Conception (subtropical fauna to the south) and Cape Blanco (cold water fauna to the north). The coast in between, including the San Francisco Estuary, is a transitional zone containing species from both faunas (Parrish and others 1981). In addition to the longitudinal temperature gradient and seasonal variation due to upwelling, there are large interannual temperature differences during El Niño events.

Before 1980, little scientific information was available to set water quality standards for the protection of the fish and invertebrates of San Francisco and San Pablo bays. In 1979, the Interagency Ecological Program (IEP) designed a plan to collect biological and physical data from South San Francisco Bay to the west delta. The State Water Resources Control Board (SWCRB) approved this plan and the Bay-Delta Division of the California Department of Fish and Game (CDFG), operating as part of the IEP, set the plan in action. The objective of the study was to determine the effects of freshwater outflow from the delta on the abundance and distribution of marine and estuarine fishes, shrimps, and crabs and use this knowledge to understand the volume and timing of freshwater outflow that is necessary for their well-being. In 1984, the U.S. Geological Survey started a hydrodynamic study of currents and salinity fluxes in the estuary (Smith and others 1995). The hydrodynamic data will eventually be useful in understanding the distribution and movements of fish and invertebrates.

This report presents data collected by the study on the abundance and distribution of selected organisms from 1980 to 1995 (shrimp and crab data extend to 1996). It is restricted mainly to presentation and description of the data. More detailed analyses will appear in subsequent reports and papers, although some have already been done for SWRCB Water Rights Hearings (CDFG 1987, 1992).

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Methods

Sampling Surveys, Frequency, and Station Location

Three types of sampling surveys were conducted: open water, beach seine, and ringnet (Table 1). The open water survey began in February 1980. We collected samples monthly from 35 stations from South Bay to the Sacramento River at Sherman Island and the San Joaquin River at Antioch (Figure 1). Seven stations were added in 1988, 4 in 1990, and 6 in 1994. Data from the additional stations were only used for some channel-shoal comparisons.

The beach seine survey started in August 1980 at 27 shore stations located primarily in San Francisco and San Pablo bays but also with stations in the delta at Antioch and Sherman Island (Figure 2). To reduce expenditures, the beach seine survey ended in January 1987.

Table 1 Months sampled by year and gear type from 1980 to 1996

Year	*Midwater and Otter Trawls*	*Plankton Net*	*Beach Seine*	*Ringnet*
1980	February-December	February-December	August-December	
1981	January-December	January-December	January-December	
1982	January-December	January-December	January-December	May-December
1983	January-December	January-December	January-December	January-December
1984	January-December	January-December	January-December	January-December
1985	January-December	January-December	January-December	January-December
1986	January-December	January-December	January-December	January-December
1987	January-December	January-December	January	January-December
1988	January-December	January-December		January-December
1989	January-August	January-July		January-December
1990	February-October			July-December
1991	February-October			July-December
1992	February-October			July-December
1993	February-October			July-December
1994	February-October[a]			
1995	January-December[b]			
1996	January-December[c]			

[a] Midwater trawl sampled only February to April.
[b] Midwater trawl sampled April to December, except August; otter trawl did not sample in August.
[c] Midwater trawl sampled April to December.

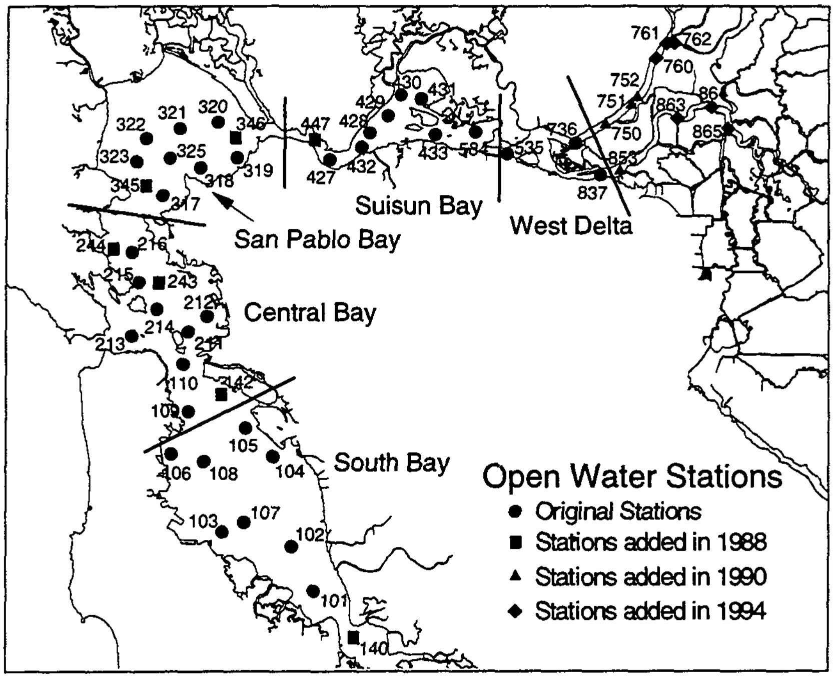

Figure 1 Map of open water stations

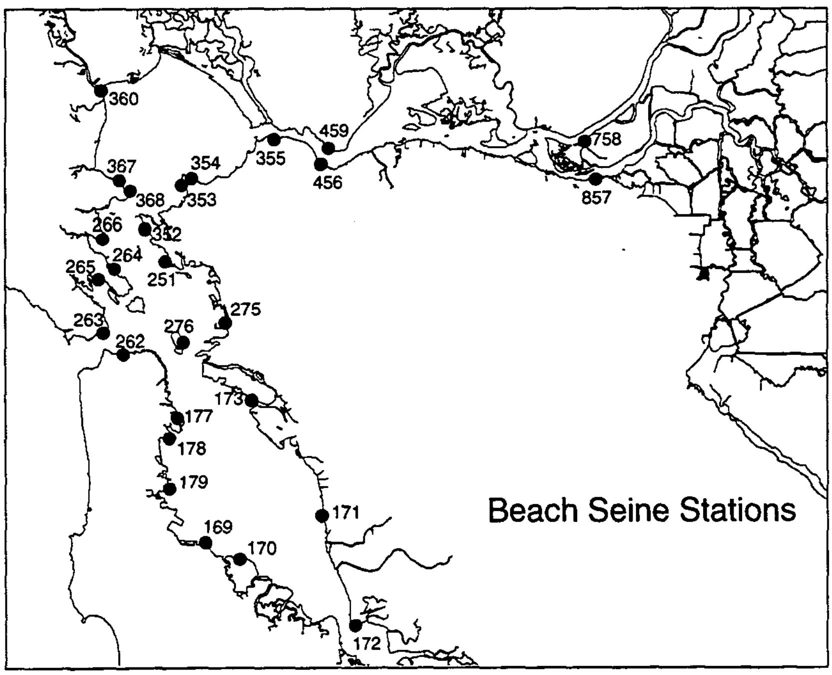

Figure 2 Map of beach seine stations

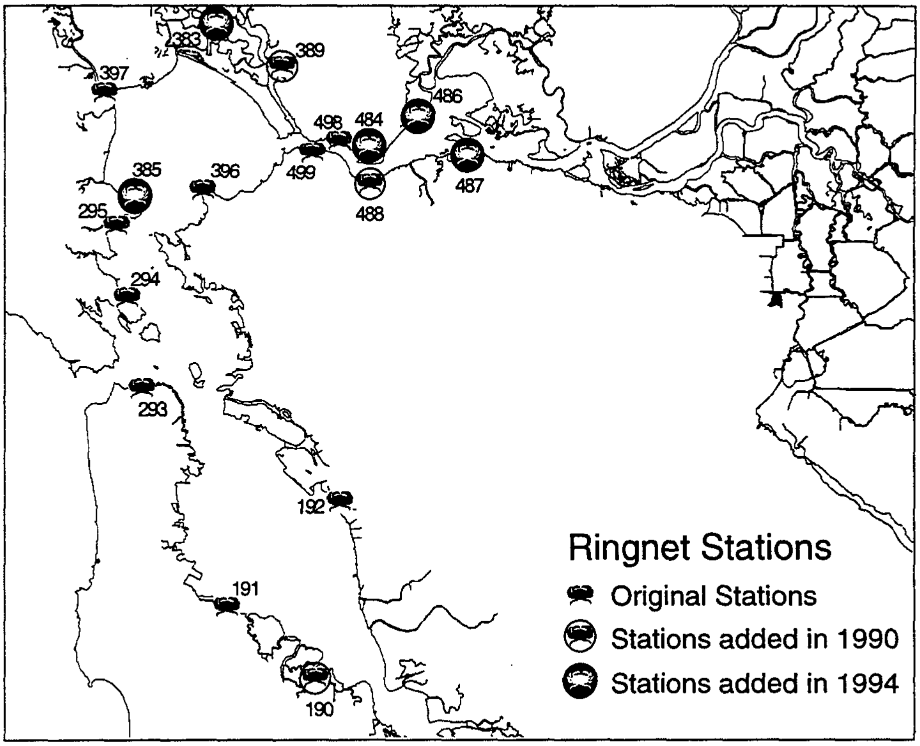

Figure 3 Map of ringnet stations

In May 1982, a monthly ringnet survey for crabs began at 9 stations in San Francisco and San Pablo bays and in Carquinez Strait (Figure 3). In 1990, sampling frequency was restricted to July to December and 3 new stations were added. In 1994, 5 stations were added and stations 190, 191, 192, and 293 were dropped.

Sampling Gear and Techniques

Open water stations were sampled with midwater and otter trawls and a plankton net. The otter trawl had a 4.9-m headrope, a 2.5-cm stretch mesh body, and a 1.3-cm stretch mesh codend. A 5:1 scope (ratio of cable out to water depth) was used to keep the otter trawl on the bottom. It was towed on the bottom and against the current for 5 minutes, and then retrieved. The distance towed was measured in nautical miles using Loran-C, starting from when the net reached the bottom and ending when retrieval began. Prior to May 1981, when the Loran was first used, and later for any tow on which the Loran malfunctioned, distance towed was estimated as the mean distance towed at that station. The area swept by the trawl was calculated as the product of the door spread and the distance towed (converted to meters from nautical miles), assuming a 70% door spread of 3.4 m.

The midwater trawl mouth measured 3.7 m^2. The mesh graduated in 9 sections from 20.3 cm stretch mesh at the mouth to 1.3 cm at the codend. A 5:1 scope was used when setting the midwater trawl. It was towed with the current for 12 min and retrieved obliquely. The volume filtered was calculated as the product of the net mouth area (10.7 m^2) and the distance traveled, as measured by a flowmeter suspended off the side of the boat.

The plankton net was made of 505 μm mesh, had a mouth area of 0.38 m^2, and was mounted on a steel sled with the net bottom 12 cm above the skids. A flowmeter positioned in the mouth of the net measured the flow of water through the net. The net was set to a 5:1 scope, towed for 5 min on bottom, and retrieved obliquely.

Shore sampling was conducted with a beach seine (15.2 m x 1.2 m) with 3-mm mesh. A bag (1.2 m x 1.2 m x 1.2 m) was sewn into the middle of the net. The headrope was marked at 0.5 m intervals so it could be used to measure the distance from shore at the start of a haul. The maximum depth of the set was measured using a scale marked at 0.1 m intervals on the net poles. The area sampled was calculated as the product of the distance from the shore (tow length) and the distance along the shore (tow width). Volume swept was calculated as half of the product of tow area and maximum depth. One, and when possible, 2 tows were made per station at flood tide.

Ringnets were 0.86 m in diameter and had 2.5-cm stretch mesh webbing. Four ringnets baited with fish heads were fished for 30 min at low slack tide.

In both otter and midwater trawl samples, fish and *Cancer* crabs were identified to species and all shrimp were separated from detritus and other invertebrates. Up to 50 randomly selected fish of each species were measured to the nearest millimeter fork length (FL) or total length (TL) for fish without forked tails and the rest were counted. For several fish species, individuals less than a specified length (minimum cutoff length) were not counted or measured because they were too small to be collected efficiently by the mesh size used. This procedure was first followed in 1984, but previous years' data were corrected before analyses were done. In 1989, in addition to total length, wing width was measured for bat rays. A wing width-total length relationship converted previous length measurements to wing widths. For all *Cancer* crabs, up to 30 randomly selected individuals of each species were sexed and carapace width (CW) was measured with calipers to the nearest millimeter. The rest were counted. *Cancer magister* were measured inside the 10th anterolateral teeth and all other species at the widest point of the carapace. *Cancer magister* >29 mm CW were sexed as were crabs >19 mm CW of other species.

Up to 0.94 L of sorted shrimp from each otter trawl sample were fixed in 10% formalin and processed in the laboratory. Any unidentified fish or crabs were fixed or frozen for later identification.

Larger fish and crabs collected in the beach seine were identified, counted and measured in the field as for otter and midwater trawl samples, but no minimum lengths were used. Fish and crabs not identified in the field and up to 0.94 L of shrimp were fixed in 10% formalin and returned to the laboratory for identification or processing. If necessary, subsamples of fish were taken.

If more than 0.94 L of small fish or shrimp was collected, the total volume was measured for each species of fish or all shrimp before further processing. For fish, a subsample of 0.24 L to 0.94 L, depending on the size of the fish, was randomly taken from the total volume. From the subsample, 50 fish were selected at random and measured as before and the rest were counted to determine the number per unit volume. Total catch was calculated as the product of number per unit volume and total volume.

For shrimp, a 0.94 L subsample was fixed as before, total and subsample volumes were recorded, and the sample was returned to the laboratory for further processing. In the laboratory, up to 100 randomly selected non-ovigerous shrimp of each species were sexed and measured (total length, including rostrum), and a maximum of 50 randomly selected ovigerous shrimp of each species were categorized by egg developmental stage and measured.

Specific conductance and temperature were measured at each station on all surveys. For open water stations during 1980 and for all beach seine stations, only surface measurements were made. A surface water sample was taken with a bucket, temperature was immediately measured to the nearest 0.1 °C, and the sample returned to the laboratory for conductance measurements with a conductance meter. From 1981 through February 1990, conductance and temperature were measured at 1 m depth intervals for stations where depth was <7 m and at 2 m intervals for deeper stations, using a Hydrolab Digital 4021 or Martex 10 Water Quality Monitor. After February 1990, a Seabird Electronics 19 Seacat Profiler was used to record specific conductance, temperature, and depth every 0.5 s during deployment to the bottom and retrieval. The data were averaged to derive a value for every meter of depth in 1990 and every half meter from 1991 to 1996. All conductance data were converted to salinity at 25 °C using the equation:

$$S^{0}/_{00} = -100\ln\left(\frac{1 - C_{25}}{178.5}\right)$$, where C_{25} is specific conductance in milliSiemens/cm at 25 °C.

For ringnet stations, a Van Dorn sampler was used to collect a bottom water sample. Temperature was immediately measured to the nearest 0.1 °C and the sample returned to the laboratory to measure conductance with a conductance meter.

Data Analysis

Data for 32 fish species, 6 shrimp species, and 4 crab species are included in the report. Depending on species, data from 1 or more gear types are presented. For each species, size frequency data were summed by month into 2 to 50 mm intervals, depending on maximum size, and examined to determine if age–0 individuals could be reliably separated from older year classes (age 1+) by size. For species with distinguishable age–0 individuals, monthly cutoff lengths were established between the size of the largest age 0 and the smallest age 1+. These cutoff sizes were then applied to all size data to determine the age–0 fraction of the catch. In cases where no visual separation of age–0 fish or crabs was possible, either no separation was made or other criteria were used, such as length at maturity or length at age 1 from the literature, and applied to all months. Shrimp were separated into juveniles and adults based on average size at sexual maturity from the literature and unpublished CDFG data. All analyses (abundance, distribution, salinity, and temperature) were done for each age category when a distinction could be made and when there was a sufficient number of organisms collected in the age class.

Catch per unit effort (CPUE) calculations varied by gear type (Table 2). Monthly abundance indices for each species of fish, shrimp, or crab were calculated as the mean CPUE of all stations in a geographical region (for example, Suisun Bay) multiplied by the region's volume weighting factor (Table 3) (calculated by mean depth × area) and summed for all 5 regions in the case of the midwater trawl and plankton net, or by the region's areal weighting factor in the case of the otter trawl:

$$\text{Monthly Abundance Index} = \sum_{\text{REGION}=1}^{5} (\bar{X}_{\text{CPUE}} \times \text{Region Weighting Factor})$$

Annual abundance indices for species caught with the otter and midwater trawls were calculated as the average of monthly indices over the period for which the life stage was most abundant. For beach seine and ringnet surveys, no area or volume factors were calculated for the regions, so annual abundance indices were the average CPUE over a specified period of months.

Table 2 Catch per unit effort (CPUE) calculations for the otter trawl, midwater trawl, plankton net, beach seine, and ringnet

Otter Trawl

For fishes: CPUE = (number caught/tow area) × 10,000
where tow area = distance towed in meters × 3.42 m (door spread)

For shrimps and crabs: CPUE = number caught/5 min tow

Midwater Trawl

CPUE = (number caught/tow volume) × 10,000
where tow volume = number of flowmeter revolutions × 0.0269 m/revolution × 10.7 m^2 (net mouth area)

Plankton Net

CPUE = (number caught/tow volume) × 1,000
where tow volume = number of flowmeter revolutions × 0.0269 m/revolution × 0.38 m^2 (net mouth area)

Beach Seine

For demersal species: CPUE = (number caught /tow area) × 10,000
where tow volume = tow width (m) × tow length (m)

For pelagic species: CPUE = (number caught/tow volume) × 10,000
where tow volume = tow width (m) × tow length (m) × 0.5 maximum depth (m)
If more than 1 tow was made per station, CPUE was the average CPUE for both tows

Ringnet

CPUE = total number of crabs/set
where a set = 4 baited ringnets fished for 30 minutes at 1 station

Table 3 Weighting factors by region and gear type

		Weighting Factors	
Location	*Region Number*	*Midwater Trawl, Plankton Net (Volume 10^8 m^3)*	*Otter Trawl (Area 10^8 m^2)*
South Bay	1	1505.38	250.15
Central Bay	2	2865.13	216.34
San Pablo Bay	3	861.40	153.54
Suisun Bay	4	471.64	55.29
West Delta	5	253.68	28.01

Seasonal abundance was calculated as an average monthly abundance index for the years 1981 to 1988 (years when all 12 months were sampled) or as the monthly abundance from a single year that was considered a representative of all years. Annual distribution was calculated as the average CPUE for each region over the specified index period. Seasonal distribution was calculated as the average CPUE for each area by month (January to December) for the years in which samples were collected in all months: 1981 to 1988 for otter and midwater trawls; 1981 to 1986 for the beach seine; and 1983 to 1989 for the ringnet. Alternately, a single year or group of representative years was used for calculation of seasonal distribution. The methods sections of each chapter describe when this was done.

The Venice salinity classification was used to characterize salinity. This system defines salinities of 0.0‰ to 0.5‰ as limnetic, 0.5‰ to 5.0 ‰ as oligohaline, 5‰ to 18‰ as mesohaline, 18‰ to 30‰ as polyhaline, and >30‰ as euhaline.

Salinity and Temperature

James Orsi

Salinity

The estuary is a series of mixing bowls receiving inputs of freshwater primarily from the Sacramento and San Joaquin rivers and inputs of marine water through the Golden Gate. River outflow (at Chipps Island in Suisun Bay) was highest in winter and spring and varied greatly from year to year (see Figure 2 in the Introduction chapter). The early years of the study were classified as "wet" water years (California Department of Water Resources classification), but after 1986 an extended drought lasted until 1993. Of the 17 years sampled, 9 were classified as "dry" or "critically dry," 7 as wet, and 1 was "above normal" (Table 1).

Salinity was highest in South and Central bays, frequently exceeding 30‰ both on surface and at bottom (Figures 1 and 2). San Pablo Bay was much fresher—even bottom salinities never exceeded 29‰ and during exceptionally high freshwater flows in 1982, 1983, and 1986, dropped below 2‰ at all depths (Figure 3). In Suisun Bay, salinities <10‰ were common except during the drought of 1987–1992, and salinities >15‰ were rare at any depth (Figure 4). The west delta was usually fresh (<0.5‰) prior to 1987, but was rarely so during the 7-year drought (Figure 5). The highest west delta salinity was about 8‰ in 1989. High freshwater outflow reduced salinity but increased salinity stratification from Suisun Bay seaward.

Table 4 Classification of water year type from 1980 to 1996

Year	*Classification*
1980	Wet
1981	Dry
1982	Wet
1983	Wet
1984	Wet
1985	Dry
1986	Wet
1987	Critically Dry
1988	Critically Dry
1989	Dry
1990	Critically Dry
1991	Critically Dry
1992	Critically Dry
1993	Above Normal
1994	Critically Dry
1995	Wet
1996	Wet

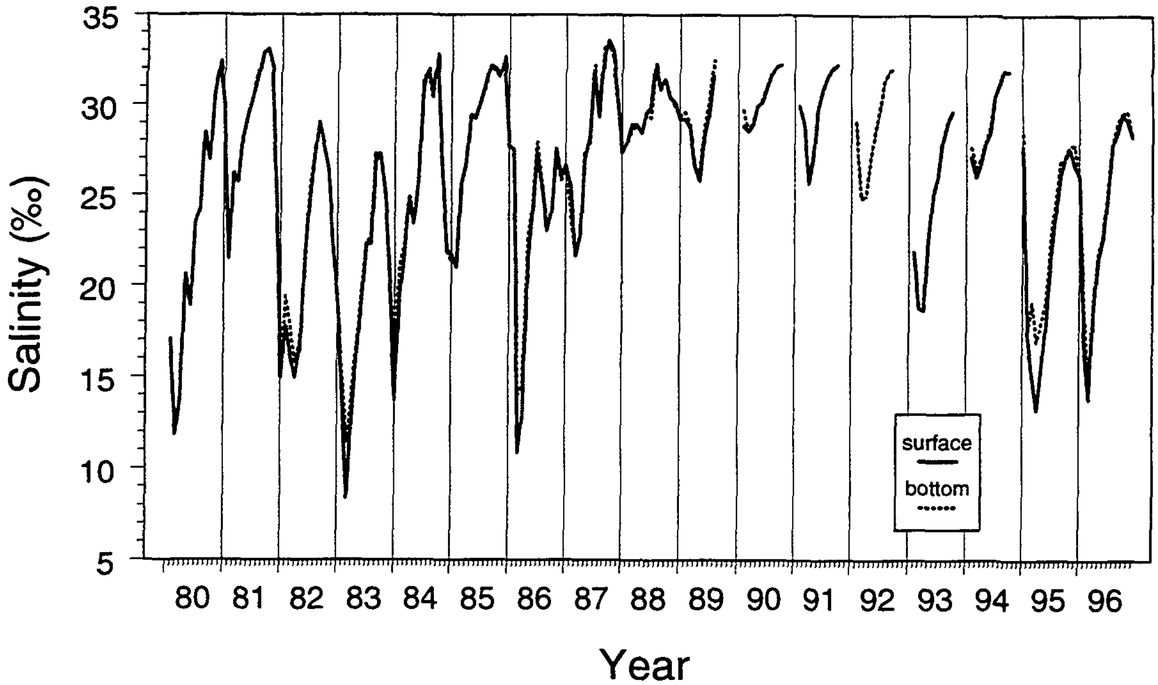

Figure 1 Monthly surface and bottom salinity in South San Francisco Bay from 1980 to 1996

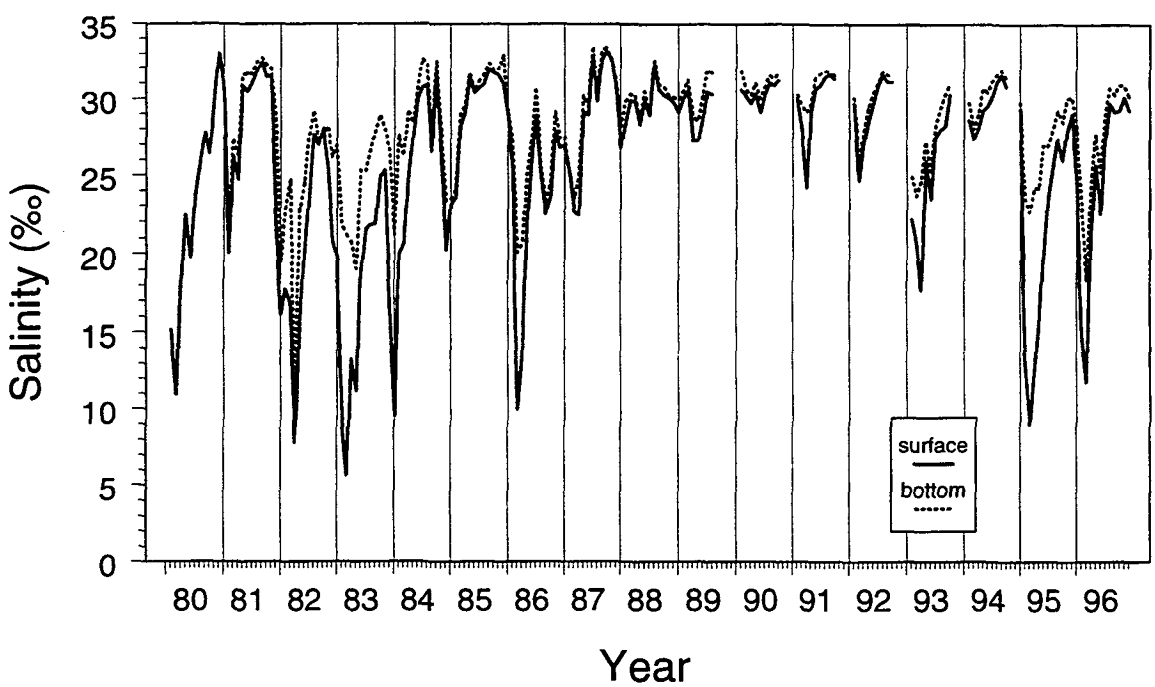

Figure 2 Monthly surface and bottom salinity in Central San Francisco Bay from 1980 to 1996

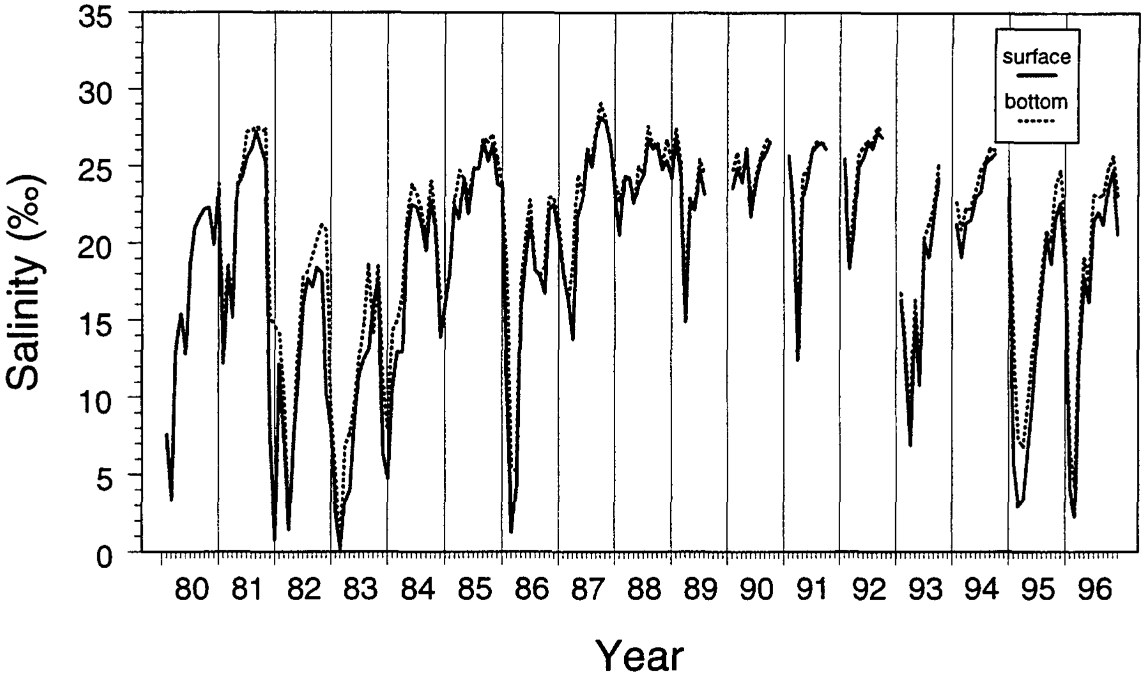

Figure 3 Monthly surface and bottom salinity in San Pablo Bay from 1980 to 1996

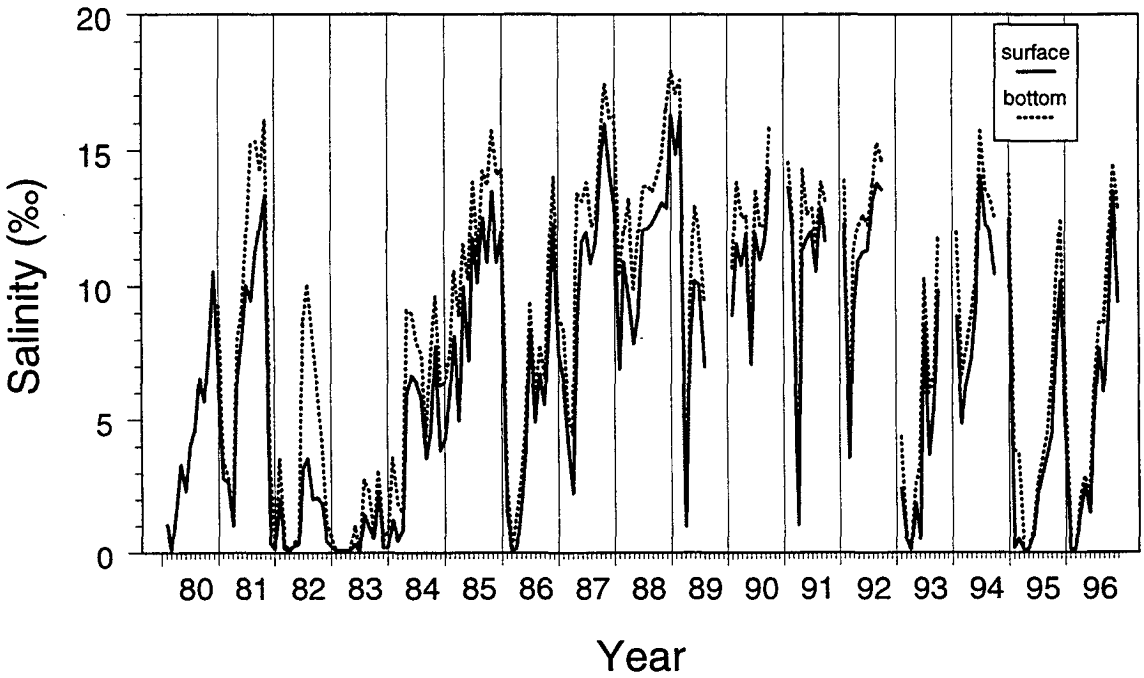

Figure 4 Monthly surface and bottom salinity in Suisun Bay from 1980 to 1996

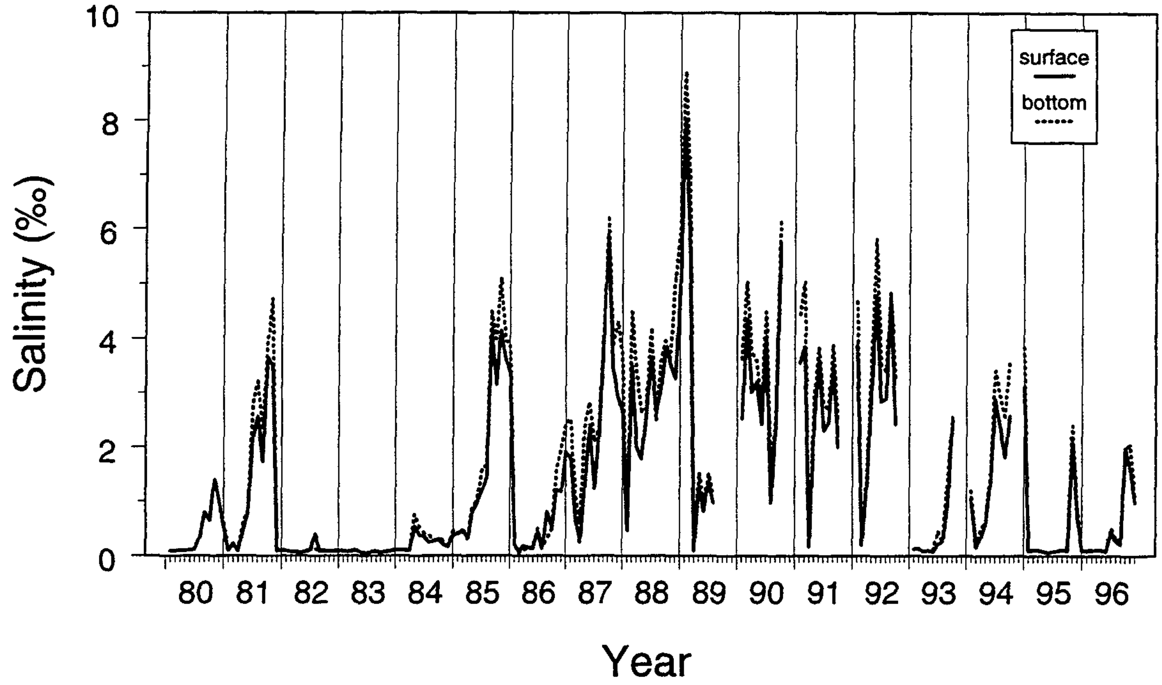

Figure 5 Monthly surface and bottom salinity in the west delta from 1980 to 1996

Temperature

Temperature was influenced by the moderating effect of the ocean, which kept summer temperatures down in areas where intrusion of oceanic water was high. The temperature range was greatest in the west delta (Figure 6), which had both the highest and lowest temperatures, always >20 °C in summer and as low as 7 to 8 °C in winter. Suisun Bay temperatures were similar to those of the west delta except that summer temperatures were not quite as high (Figure 7). San Pablo Bay had a narrower temperature range than Suisun Bay and the west delta (Figure 8). Summer temperatures there were rarely >20 °C. Central Bay had the narrowest temperature range (Figure 9). Only in 1983, an El Niño year, did temperature there exceed 20 °C and only rarely were temperatures <10 °C. But Central Bay showed more temperature stratification than any other region. South Bay was warmer in summer and cooler in winter than Central Bay, often >20 °C, and more often <10 °C in winter (Figure 10). Little or no temperature stratification occurred in South Bay.

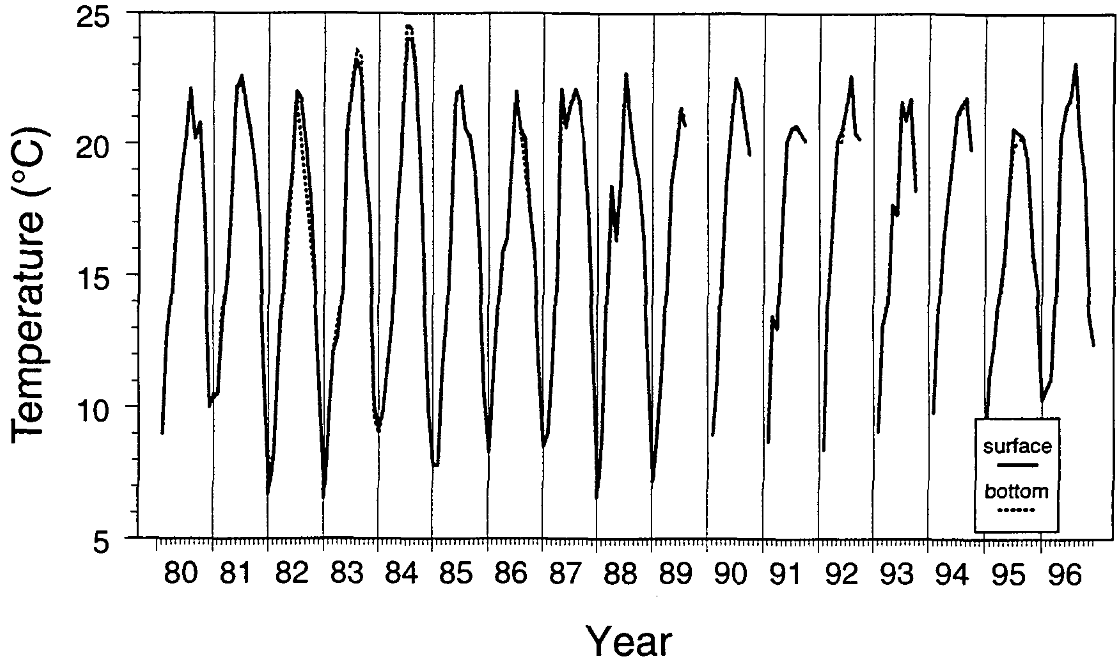

Figure 6 Monthly surface and bottom temperature in the west delta from 1980 to 1996

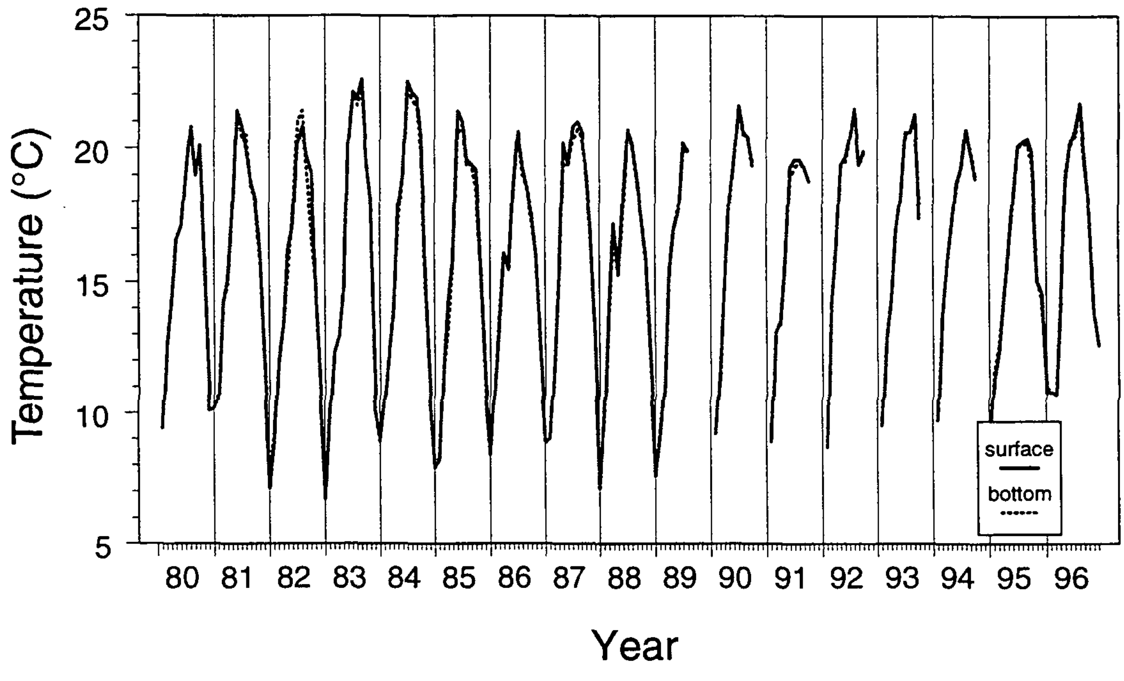

Figure 7 Monthly surface and bottom temperature in Suisun Bay from 1980 to 1996

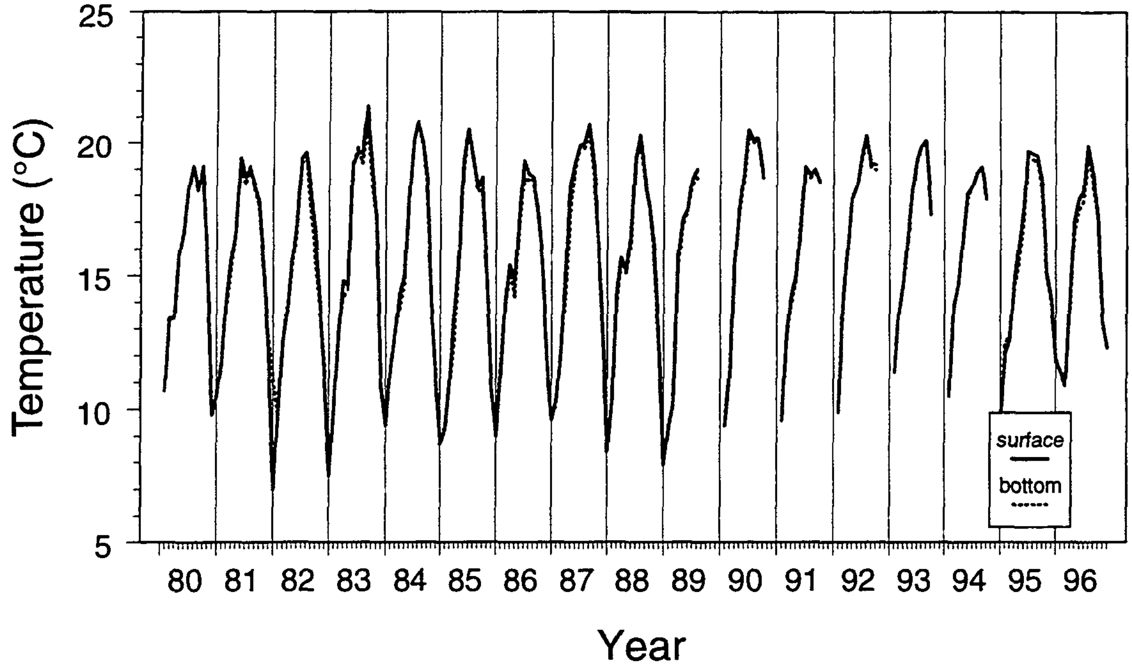

Figure 8 Monthly surface and bottom temperature in San Pablo Bay from 1980 to 1996

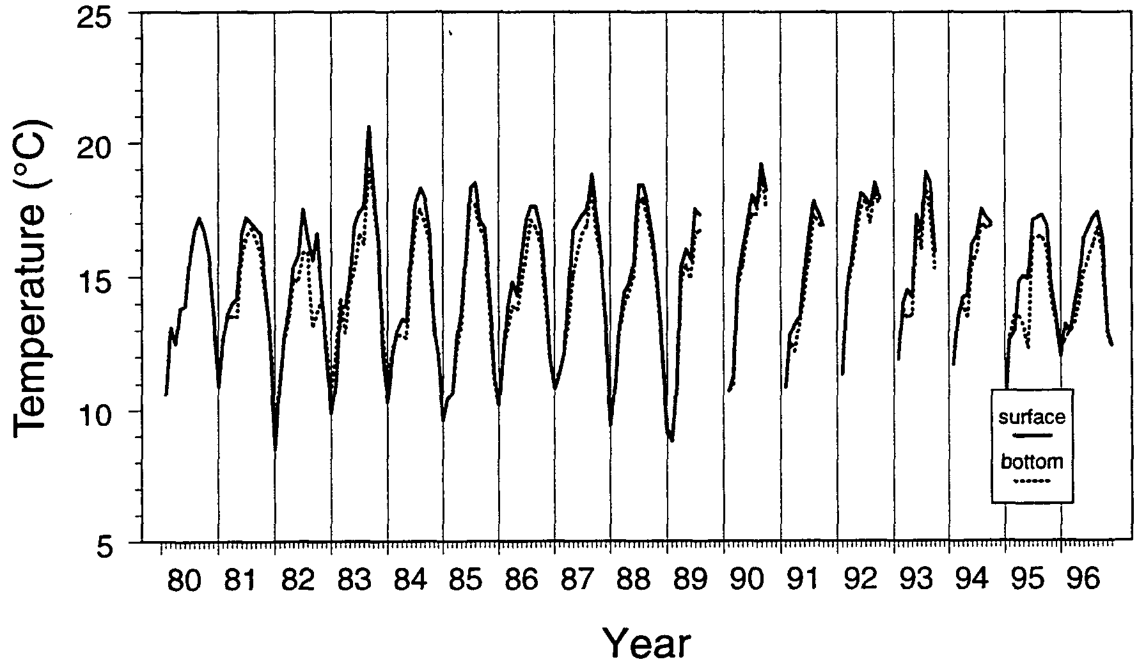

Figure 9 Monthly surface and bottom temperature in Central San Francisco Bay from 1980 to 1996

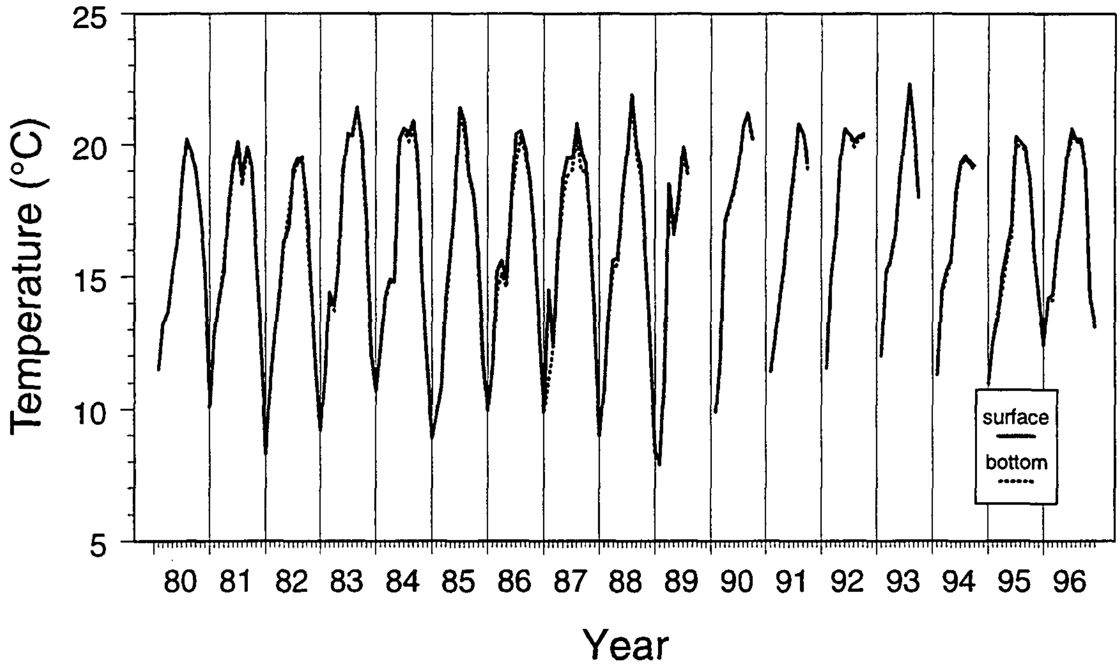

Figure 10 Monthly surface and bottom temperature in South San Francisco Bay from 1980 to 1996

A temperature record exists for the ocean at the Farallon Islands, 42 km west of the Golden Gate (Figure 11). Surface temperatures there ranged from 10 to 16.4 °C from 1980 to 1996. During the sampling period, temperatures tended to be warmer than the 72–year (1925–1996) mean. Warmer than average temperatures occurred during 1982–1983, 1986–1987, 1992–1993, and in 1995.

The Farallon Islands temperature record showed that the ocean was considerably colder than Central Bay except in December, January, and February (Figure 12). Average January temperatures were almost 2 °C warmer at the Farallon Islands than in Central Bay. In summer, however, Central Bay temperatures averaged as much as 4.5 °C higher than at the Farallons. Ocean temperature declined slightly in spring, whereas Central Bay temperature climbed sharply.

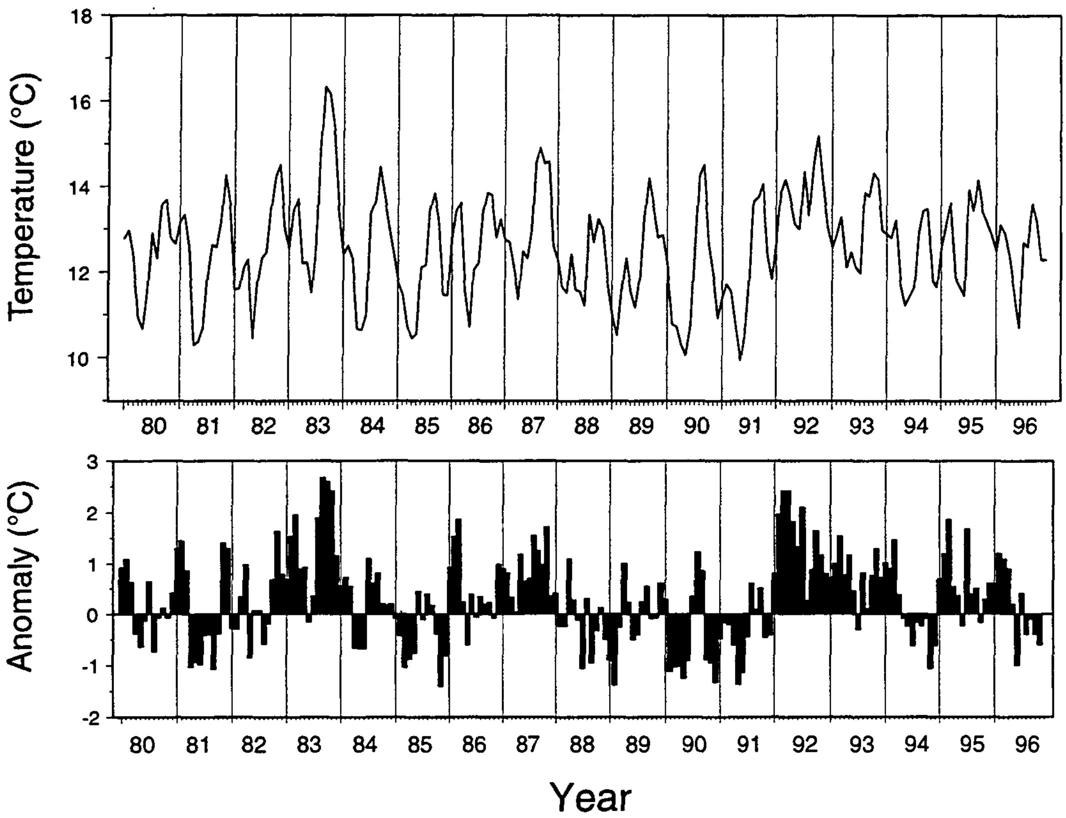

Figure 11 Mean monthly surface temperatures at the Farallon Islands from 1980 to 1996 (upper graph) and deviations from the 1925 to 1995 mean (lower graph)

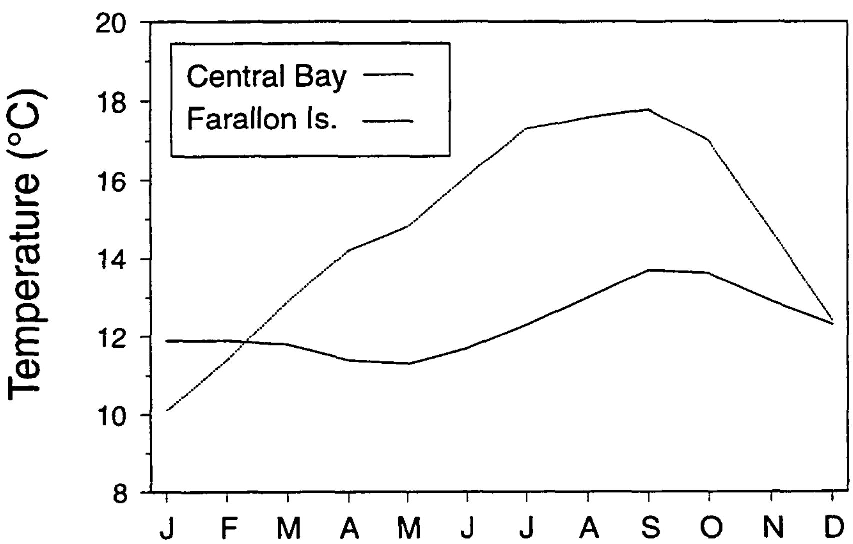

Figure 12 Average monthly surface temperatures (°C), at the Farallon Islands (1925 to 1996) and in Central San Francisco Bay (1980 to 1996)

Cancer Crabs

Kathryn Hieb

Introduction

Cancer crabs were the most common genus of brachyuran crabs collected by the San Francisco Bay Study's monitoring program from 1980 to 1996. Six species were collected in the otter trawl, 4 in the beach seine, and 5 in the ringnets (Table 1). Four of these species are the focus of this chapter: *Cancer magister*, the Dungeness crab; *C. productus*, the red rock crab; *C. antennarius*, the brown rock crab; and *C. gracilis*, the slender crab. The 2 other species, *C. anthonyi*, the yellow crab, and *C. jordani*, the hairy rock crab, are briefly reviewed.

Table 1 *Cancer* spp. catch by species and gear type at all stations and surveys from 1980 to 1996

Species	*Otter trawl*	*Beach seine*	*Ringnet*	*Total*
Cancer magister	4962	357	4580	9899
Cancer gracilis	3390	1	403	3794
Cancer productus	640	2	2704	3346
Cancer antennarius	1498	3	576	2077
Cancer anthonyi	42	0	4	46
Cancer jordani	2	0	0	2

Cancer magister supports a substantial commercial fishery and a smaller sport fishery in central California coastal waters. This is a male-only fishery, with a minimum size of 153 mm (6 inches) carapace width (CW) for the commercial fishery and 147 mm (5.75 inches) CW for the sport fishery. It is currently illegal to keep *C. magister* of any size caught in the San Francisco Estuary. The central California commercial fishery is discussed in more detail in the *C. magister* section.

Cancer productus and *C. antennarius*, along with *C.anthonyi* in southern California, collectively constitute the commercial rock crab fishery in California. Usually, only the claws are taken, although a limited market for live crabs has developed in recent years. There is a small sport fishery for rock crabs in San Francisco Bay. They are commonly caught using baited nets and traps from piers and jetties in Central Bay, northern South Bay, and lower San Pablo Bay. The minimum commercial size for rock crabs is 108 mm (4.25 inches) CW and the recreational minimum size is 102 mm (4 inches) CW, with a bag limit of 35 crabs per day.

Pacific coast *Cancer* species share many life history traits. Mating, which is between a soft shell female and hard shell male, occurs from spring to fall, depending on the species. Peak larval hatching is in winter or spring; all species have 6 planktonic larval stages (5 zoeal and 1 megalopal). Most juveniles settle in spring or summer and pass through 10 to 12 instars before maturity. Males grow faster than females, mature at a larger size, and reach a larger maximum size. The maximum number of instars is 12 or 13, but maximum age and size varies by species and location. Although *Cancer* crabs are demersal, substrate preference varies by species, ranging from sand to complex rocky reefs. All *Cancer* crabs are omnivores, but the ability to eat hard-shelled organisms, such as mussels and barnacles, varies with claw morphology, which differs by species.

Methods

Methods common to all species are presented here and species-specific methods are presented in the individual species' sections that follow. Larval data were used only for seasonal abundance and a general description of distribution; zoeal data were available from 1980 to 1985 and megalopal data from 1980 to 1988. Only data from 1982 to 1993 for the original 9 stations were used for the ringnet abundance indices; although this survey changed substantially in 1994, the 1994 data were used in the size frequency and salinity-temperature analyses. Age–0 crabs were separated from age–1+ crabs by visual inspection of the monthly size frequency data and for some species, size-at-age information from the literature. Both the otter trawl and ringnet data were used for the sex ratio by size class, annual and seasonal abundance, and salinity and temperature analyses. Generally the otter trawl data were used for the annual and seasonal distributional analyses and the ringnet data were used for very general descriptions of distribution. All sizes are carapace width.

Cancer magister

Cancer magister, the Dungeness crab, ranges from Point Conception to the Aleutian Islands (Schmitt 1921, MacKay 1942, Dahlstrom and Wild 1983). It prefers sandy bottoms and has been collected from the intertidal to 230 m, but it is not abundant in waters >90 m. Male *C. magister* mature at about 116 mm and reach a reported maximum size of 210 mm and females mature at about 100 mm and reach a reported maximum size of 182 mm (Cleaver 1949, Butler 1960, Orensanz and Gallucci 1988). Both sexes probably live no more than 8 years (Butler 1961). Estuaries are important nursery areas for *C. magister* throughout much of its range (Tasto 1983, Emmett and Durkin 1985, Gunderson and others 1990).

Cancer magister supports a large commercial fishery from northern California to British Columbia. The San Francisco area fishery, which occurs exclusively along the coast outside of the San Francisco Estuary, historically made a major contribution to California landings. Landings from the San Francisco area reached a peak of almost 9 million pounds during the 1956–1957 season but declined to under 2 million pounds each season since 1961–1962 except for 1987–1988 and 1994–1995, when landings were 3.1 and 2.9 million pounds, respectively (Figure 1).

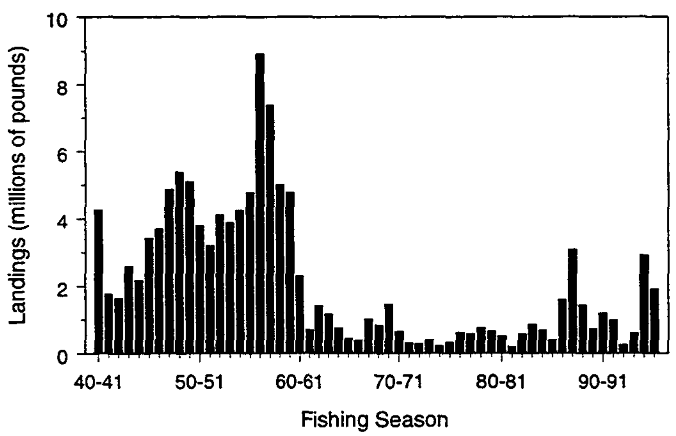

Figure 1 Commercial landings (millions of pounds) of *C. magister* from the San Francisco area (Princeton to Bodega Bay) by fishing season from 1940 to 1996

Mating occurs from March through May in the ocean and peak hatching occurs from late December to mid-January in the Gulf of the Farallones. *Cancer magister* larvae pass through the 6 planktonic stages over 105 to 125 days and are often carried far from the coast by currents after several larval stages. Possibly aided by currents, megalopae (the last larval stage) return to the nearshore coastal area and newly settled crabs immigrate to central San Francisco Bay from March to June (Reilly 1983a). Early instar crabs are most common in the channels north of the Golden Gate the first 2 to 3 months after immigration. By September, age–0 crabs are widely distributed in San Pablo and lower Suisun bays (Tasto 1983). In April and May age–1 crabs begin to consolidate near or in the channels and emigrate to the ocean, and by September most have emigrated.

A tagging study demonstrated that *C. magister* rearing in the San Francisco Estuary grew at about twice the rate of ocean-reared crabs and had an average size of approximately 100 mm 1 year after hatching (Collier 1983). Increased food availability, particularly crustaceans, and warmer estuarine temperatures may be responsible for this rapid growth (Tasto 1983). Estuary-reared crabs are probably recruited to the fishery 3 years after hatching, whereas ocean-reared crabs enter the fishery 4 to 5 years after hatching. Estimates of the number of juvenile crabs in the estuary, as a percentage of the total number of juveniles in the estuary and Gulf, ranged from 38% to 82% from 1975 to 1978 (Tasto 1983).

Cancer magister is both an important predator and prey in nearshore coastal and estuarine habitats (Pauley and others 1989). It is an omnivore and diet varies with size. In Grays Harbor, Washington, smaller crabs (<60 mm commonly preyed on small bivalves, medium sized crabs (60 to 100 mm) consumed more crustaceans (primarily *Crangon*) and small fish, and larger crabs consumed more small fish than bivalves and crustaceans (Stevens and others 1982). A variety of fish, including brown smoothhound, big skate, white sturgeon, green sturgeon, pile perch, Pacific staghorn sculpin, white croaker, and starry flounder, prey on *C. magister* in the estuary (McKechnie and Fenner 1971, Reilly 1983b). Pacific staghorn sculpin are the major predator of age–0 *C. magister* in Grays Harbor (Fernandez and others 1993).

Methods

Age–0 *C. magister* were separated from age–1+ crabs based on sizes from the literature (Collier 1983) and visual inspection of the monthly size frequency data (Table 2, Figures 2 and 3). Although age–0 *C. magister* did not enter the estuary until April or May, they were assigned January as a birth month because this is when peak hatching occurs in the Gulf of the Farallones. All sizes reported are carapace width (CW).

Table 2 Sizes used to separate age–0 from age–1+ C. magister

Month	*Size (mm)*
April	20
May	35
June	55
July	70
August	80
September	90
October	105
November	115
December	125

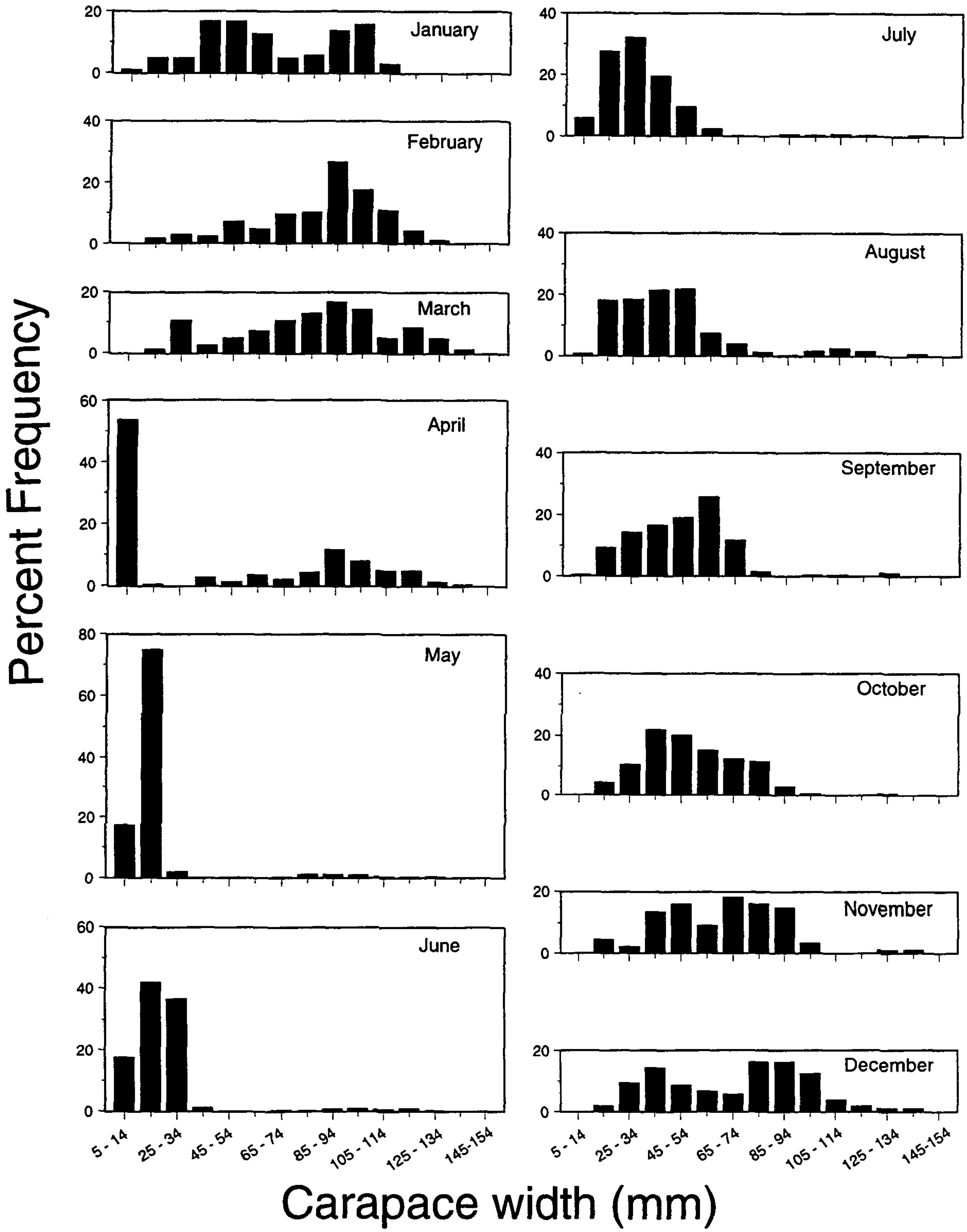

Figure 2 Size frequency of *C. magister* by month collected with the otter trawl. Size classes are every 10 mm, from 5 to 155 mm.

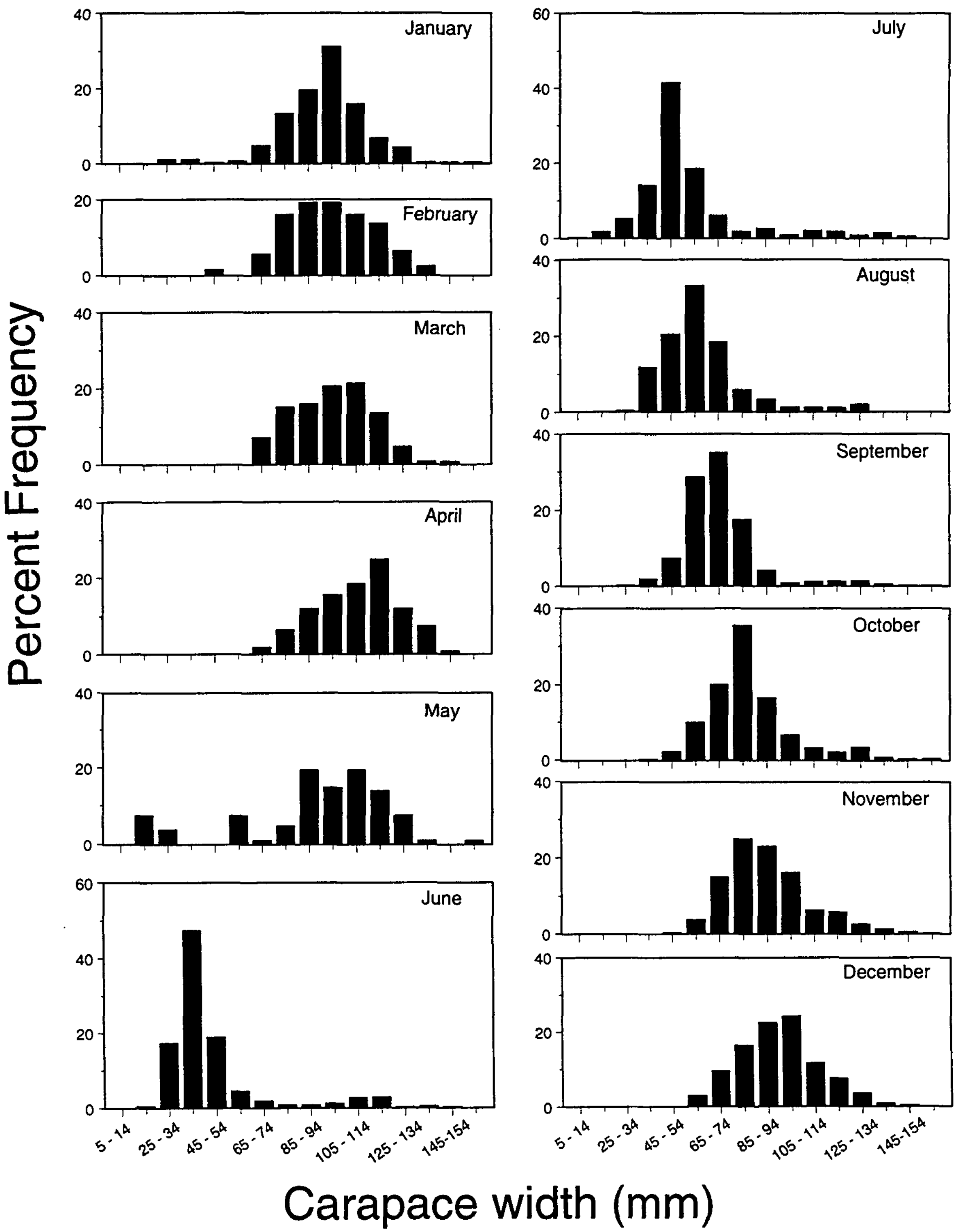

Figure 3 Size frequency of *C. magister* by month collected with the ringnets. Size classes are every 10 mm, from 10 to 165 mm.

The annual index periods selected were as follows: May through July for age–0 *C. magister* from the otter trawl, July through December for age–0 crabs from the ringnets, February through August for age–1+ crabs from the otter trawl, and January through August for age–1+ crabs from the ringnets. Note that the age–1+ indices from the ringnets were calculated only for 1983 through 1989, years in which we sampled all 12 months. For the seasonal distribution analyses, 1985 was selected as a representative year for age–0 crabs and 1985 and 1986 as representative "dry" and "wet" years for age–1+ crabs.

Results

Size Frequency

The largest female *C. magister* we collected was 136 mm and the largest male 200 mm. Twelve males were >150 mm and were probably age–2 crabs. No ovigerous females were collected. Most of the smallest *C. magister* (5 to 14 mm) entered the estuary from April through June (see Figure 2). Growth was rapid, and by December the median size was approximately 75 to 94 mm in the otter trawl (see Figure 2) and 85 to 104 mm in the ringnets (see Figure 3). A few smaller crabs (<35 mm) were collected in all months, which is evidence of either continual larval hatching and recruitment to the estuary or more likely, sporadic immigration of ocean-reared crabs.

For all sizes and both gear types, male *C. magister* outnumbered females 1.4:1, but this was primarily due to the large number of larger (>90 mm) males collected by the ringnets. The male to female ratio was 1.1:1 for the 30 to 59 mm size class, approximately equal for the 60 to 89 mm size class, and 3:1 for crabs >90 mm.

Abundance

Although *C. magister* was overall the most commonly collected species in the otter trawl and ringnets (see Table 1), there were large interannual variations in its abundance in both gear types. For example, in the otter trawl, age–0 indices ranged from 0 in 1983 and 1992 to over 11,000 in 1988 (Figure 4A, Table 3). The next highest indices (approximately 3,000) occurred in 1984 and 1985, whereas the indices from all other years were substantially lower. The high 1988 index was primarily due to very high May abundance (see Table 3). After May, abundance declined rapidly and the July 1988 index was less than either the July 1984 or July 1985 indices. The age–0 ringnet indices generally corresponded to the otter trawl indices; the major difference was that the highest ringnet index occurred in 1985, followed by 1984 and 1988 (Figure 4B, Table 4). The age–1+ *C. magister* annual indices tended to follow the age–0 indices with a 1 year lag (Figure 5, Tables 5 and 6). The highest age–1+ indices occurred in 1985, 1986, and 1989 and the lowest indices occurred in 1984, 1993, and 1994.

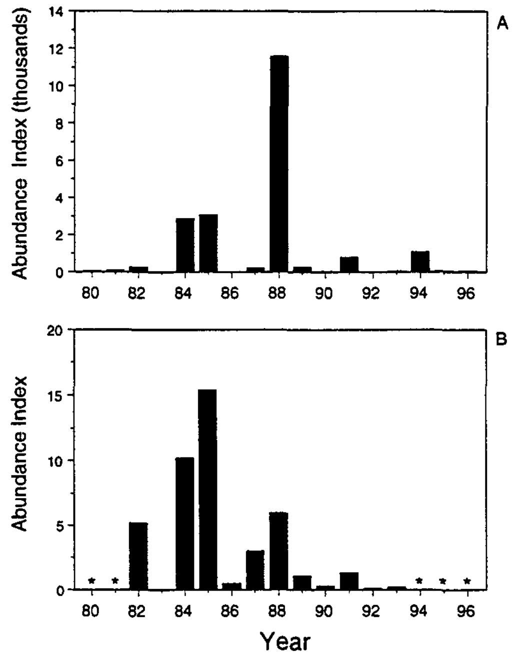

Figure 4 Annual abundance indices of age–0 *C. magister*: (A) otter trawl (1980 to 1996), the index period is May to July; (B) ringnets (1982 to 1993), the index period is July to December. Asterisk (*) indicates no survey.

Table 3 Monthly and annual abundance indices of age–0 *C. magister* collected with the otter trawl from 1980 to 1996. The index period is May to July.

	Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*May–Jul*
1980		0	0	0	0	117	19	19	173	142	58	31	45
1981	0	0	0	0	58	108	116	88	58	174	27	134	94
1982	0	0	0	115	556	189	58	0	0	162	0	19	268
1983	0	0	0	0	0	0	0	19	0	0	0	19	0
1984	0	0	0	388	2481	3673	2497	1489	1104	1643	92	193	2884
1985	0	0	0	31	640	6750	1825	668	1179	775	708	348	3072
1986	0	0	0	0	0	0	14	19	0	14	34	14	5
1987	0	0	0	0	85	377	121	162	21	41	138	168	194
1988	0	0	0	1601	26652	6698	1384	340	347	90	81	95	11578
1989	0	0	0	0	273	365	152	113					263
1990		0	0	0	0	65	27	0	14	14			31
1991		0	0	0	192	1511	685	141	236	305			796
1992		0	0	0	0	0	0	0	0	0			0
1993		0	0	0	0	108	54	0	7	0			54
1994		0	0	0	180	1957	1153	574	285	128			1097
1995	0	0	0	0	54	31	89		379	324	216	676	58
1996	0	0	0	0	54	0	144	26	48	68	0	61	66
1981–1988, 1996	0	0	0	237	3392	1977	684	312	306	330	120	117	

Table 4 Monthly and annual abundance indices of age–0 *C. magister* collected with the ringnets from 1982 to 1993. The index period is July to December. CPUE x 10.

	Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Jul–Dec*
1982					0	1	9	80	123	31	60	20	52
1983	0	0	0	0	0	0	0	0	0	1	0	0	0
1984	0	0	0	0	11	168	88	141	174	76	61	72	102
1985	0	0	0	0	0	8	3	56	283	201	191	188	154
1986	0	0	0	0	0	0	0	1	2	2	9	16	5
1987	0	0	0	0	0	0	21	18	40	63	18	19	30
1988	0	0	0	0	2	176	64	97	56	19	79	43	60
1989	0	0	0	0	0	1	2	3	5	28	18	19	11
1990							1	0	0	2	10	8	3
1991							7	9	10	21	19	13	13
1992							0	0	0	1	2	1	1
1993							2	3	1	0	4	3	2
1983–1989	0	0	0	0	2	50	26	46	81	58	54	51	

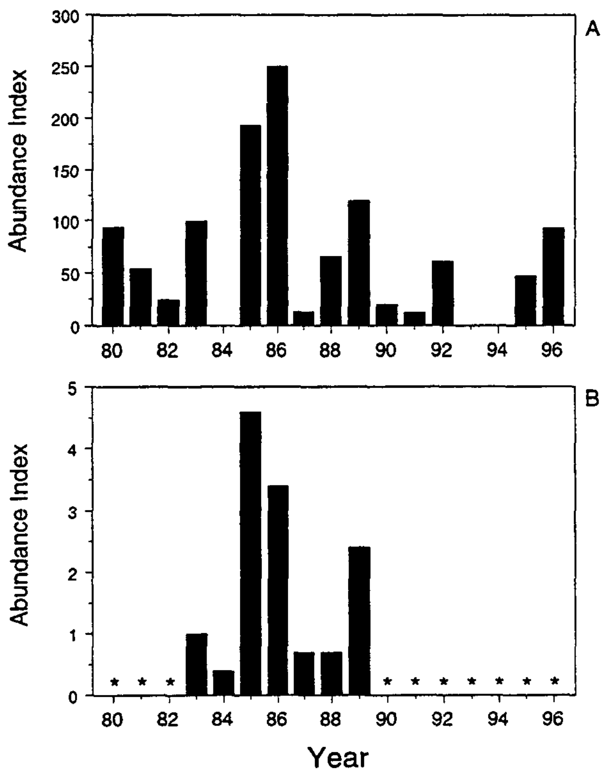

Figure 5 Annual abundance indices of age–1+ *C. magister*: (A) otter trawl (1980 to 1996), the index period is February to August; (B) ringnets (1983 to 1989), the index period is January to August. Asterisk (*) indicates no survey or no data.

Table 5 Monthly and annual abundance indices of age–1+ *C. magister* collected with the otter trawl from 1980 to 1996. The index period is February to August.

	Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Feb–Aug*
1980		414	44	77	77	19	27	0	0	0	0	0	94
1981	0	134	38	77	19	19	93	0	0	0	0	19	54
1982	22	19	0	0	93	0	0	54	0	0	0	19	24
1983	19	93	0	514	27	31	0	27	0	0	0	0	99
1984	0	0	0	0	0	0	0	0	0	0	0	0	0
1985	223	454	126	227	330	153	34	27	19	0	0	27	193
1986	566	683	220	154	366	208	27	92	0	7	0	0	250
1987	7	40	0	19	26	0	7	0	0	0	27	0	13
1988	74	111	48	183	7	91	0	19	0	0	0	0	66
1989	177	74	211	190	47	127	154	38					120
1990		28	21	59	19	14	0	0	0	0			20
1991		21	14	7	14	27	0	0	7	0			12
1992		198	26	125	68	7	0	0	0	0			61
1993		0	0	0	0	0	0	0	0	0			0
1994		0	0	0	0	0	0	0	0	0			0
1995	47	146	81	27	27	0	0		0	0	27	0	47
1996	541	227	153	0	216	0	0	54	54	0	0	0	93
1981–1988, 1996	161	196	65	130	120	56	18	30	8	1	3	7	

Table 6 Monthly and annual abundance indices of age–1+ *C. magister* collected with the ringnets from 1983 to 1989. The index period is January to August. CPUE x 10.

	Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Jan–Aug*
1982					19	6	1	8	14	8	10	4	
1983	24	28	1	19	0	1	2	1	0	1	3	0	10
1984	1	1	0	0	0	19	3	6	2	1	1	0	4
1985	133	62	76	40	40	7	3	3	13	16	13	7	46
1986	148	1	31	22	38	8	0	21	8	11	13	8	34
1987	21	13	4	10	1	2	4	1	4	6	8	6	7
1988	8	9	16	0	4	8	4	4	3	2	4	2	7
1989	56	24	12	33	10	17	23	19	10	18	10	0	24
1990							2	1	1	2	7	3	
1991							2	0	1	0	1	0	
1992							1	0	1	0	1	0	
1993							2	0	0	0	0	1	
1983–1989	57	20	20	17	13	9	6	8	6	7	8	3	

Table 7 Monthly catch of *C. magister* zoeae (1980 to 1985) and megalopae (1980 to 1988)

Month	*Zoeae*	*Megalopae*
January	142	0
February	10	0
March	0	1
April	0	24
May	0	11
June	0	2
July	0	0
August	0	0
September	0	0
October	0	0
November	0	0
December	0	0

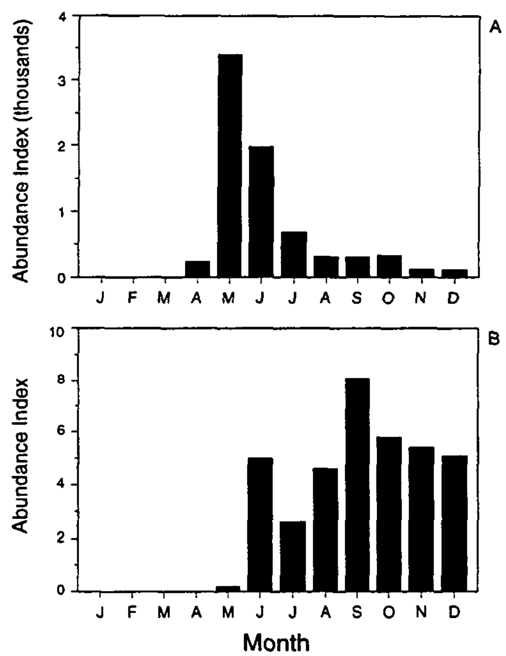

Figure 6 Monthly abundance indices of age–0 *C. magister*: (A) otter trawl (1981 to 1988 and 1996) and (B) ringnets (1983 to 1989)

Cancer magister zoeae were collected only in January and February but megalopae were collected from March through June (Table 7). The first age–0 crabs were usually collected with the otter trawl in April or May (see Table 3), although in years with low abundance the first collections were as late as August (for example, 1983). Age–0 *C. magister* were typically most abundant from May through July in the otter trawl (Figure 6A). The most notable exception was in 1995, when abundance peaked in December (see Table 3). This peak was comprised of crabs 25 to 60 mm that had recently immigrated to the estuary from the ocean rather than recently settled crabs. Age–0 catches in the ringnets increased over the summer and usually peaked in September or October (Figure 6B), except in 1988 when ringnet abundance peaked in June (see Table 4).

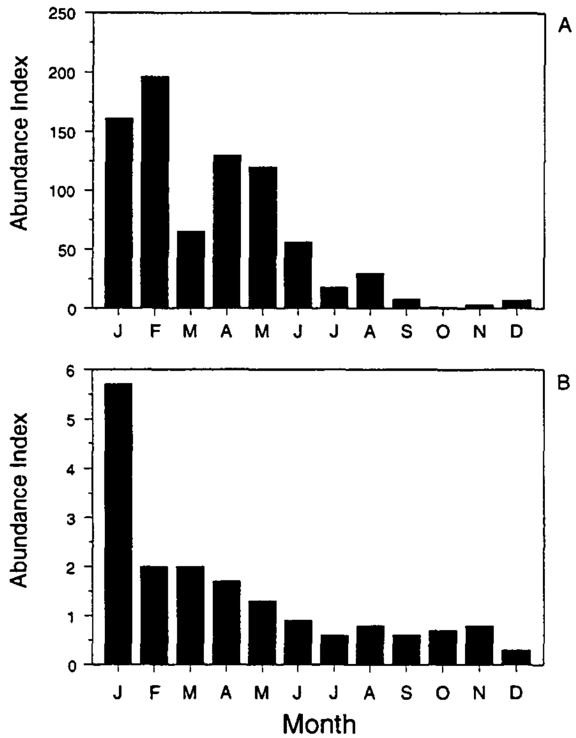

Figure 7 Monthly abundance indices of age–1+ *C. magister*: (A) otter trawl (1981 to 1988 and 1996) and (B) ringnets (1983 to 1989)

Abundance of age–1+ *C. magister* in the otter trawl was relatively high until May and few crabs were collected after August (Figure 7A, see Table 5). In the ringnets, abundance appeared to decrease dramatically from January to February and then slowly through July (Figure 7B, see Table 6). It remained at low but stable levels through December. The monthly indices did not decrease steadily every year; some of the extreme fluctuations in catch may have been because crabs moved from the sampling area or were less vulnerable to the sampling gear during high outflow events. For example, the ringnet CPUE decreased precipitously from 148 to 1 from January to February 1986 (see Table 6) during an extremely high outflow event (see Introduction chapter, Figure 2). Although CPUE increased in March, it never recovered to the pre-outflow event level. Examination of the size frequency data also indicated that a small number of ocean-reared age–1+ crabs immigrated to the estuary in some years.

Distribution

Cancer magister zoeae were restricted to Central Bay, but megalopae were collected from South Bay near Oakland to upper San Pablo Bay (stations #104 and #320, see Methods chapter, Figure 1). Age–0 *C. magister* were most commonly collected in Central, San Pablo, and Suisun bays during the index period of May through July (Figure 8). Because of the months and gear type, these data most accurately represent the distribution of early instar crabs within the estuary. There was little interannual difference in distribution during these months—crabs were concentrated in Central Bay in all years except 1981, 1984, and 1994, when CPUE was highest in San Pablo Bay. Crabs used Suisun Bay primarily in years with low freshwater outflow (for example, 1988 and 1994) and were collected in the west delta only in 1988.

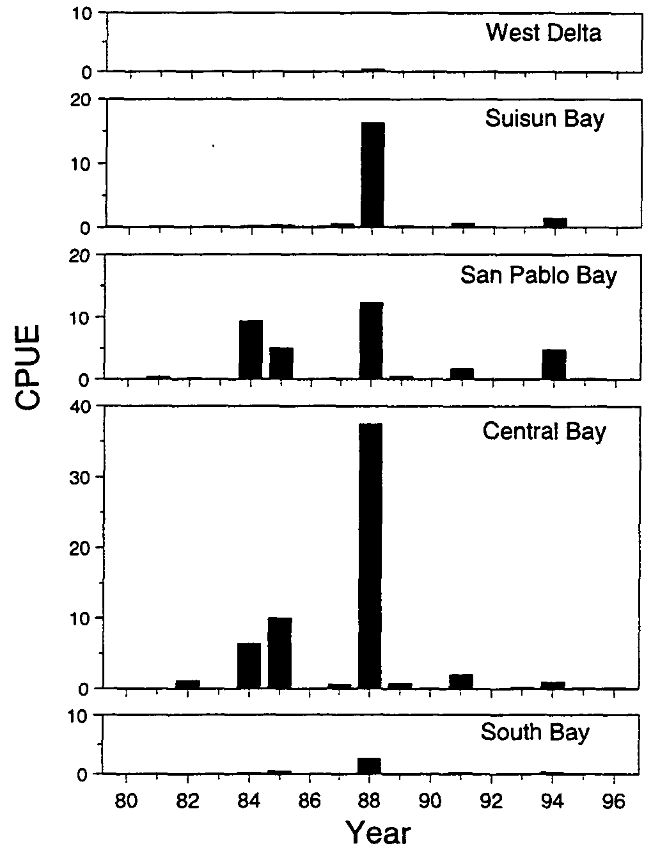

Figure 8 Annual distribution (CPUE) of age–0 *C. magister* collected with the otter trawl for May to July from 1980 to 1996

The annual distribution of age–1+ *C. magister* varied more with outflow than the distribution of age–0 *C. magister*, probably because winter and spring months were used to calculate the average CPUE. Age–1+ crabs were concentrated in Central Bay during the high outflow years 1982, 1983, 1986, 1995, and 1996, in San Pablo Bay in 1980, 1981, and 1985, and in Suisun Bay during the 1987 to 1992 drought (Figure 9).

The first age–0 *C. magister* were usually collected by the otter trawl in Central Bay and lower San Pablo Bay in April or May (Figure 10). Over a period of 1 to 2 months they moved upstream, and their distribution was centered in San Pablo or Suisun bays through December. Although not shown in Figure 10, age–0 crabs were first collected in the channels and moved to the shoals through summer. In years with high outflow, age–1+ *C. magister* moved to San Pablo and Central bays in winter before emigrating to the ocean (Figure 11). In years with low outflow, age–1+ crabs remained in San Pablo and Suisun bays (primarily Carquinez Strait) through winter and emigrated in late spring and summer (Figure 12). Examination of the sex and size frequency data revealed that female *C. magister* emigrated when they reached maturity, but males stayed in the estuary for at least 1 molt past maturity. Consequently, most of the age–1+ *C. magister* collected in the estuary were males and a few males remained in the estuary at least 2 years.

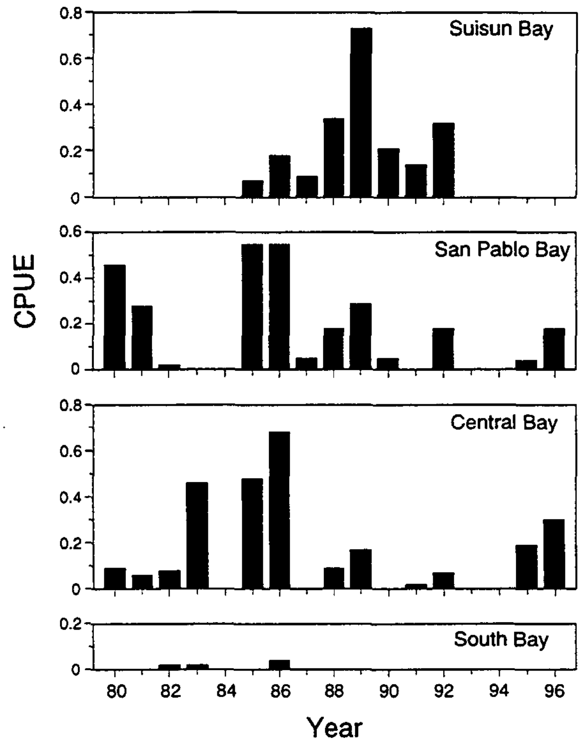

Figure 9 Annual distribution (CPUE) of age–1+ *C. magister* collected with the otter trawl for February to August from 1980 to 1996

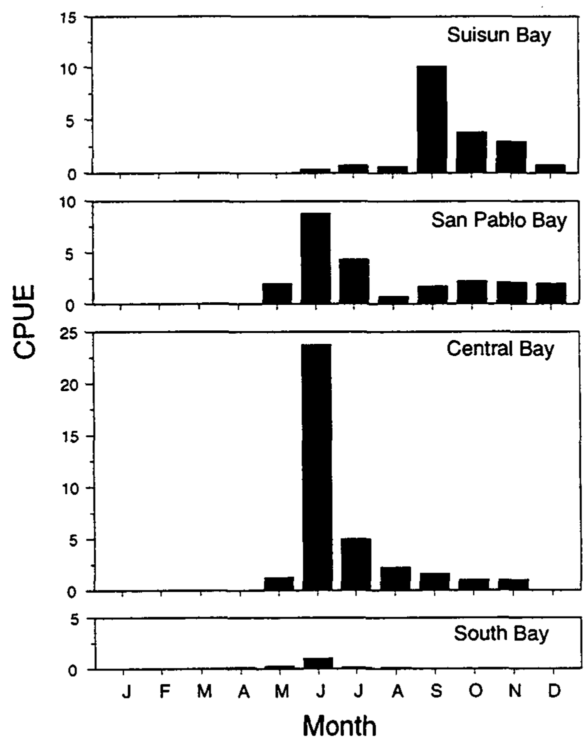

Figure 10 Monthly distribution (CPUE) of age–0 *C. magister* collected with the otter trawl in 1985

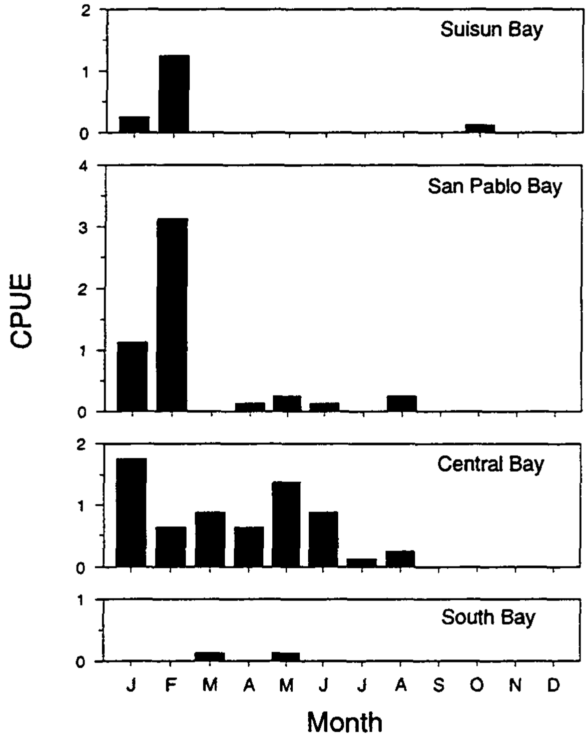

Figure 11 Monthly distribution (CPUE) of age–1+ *C. magister* collected with the otter trawl in 1986

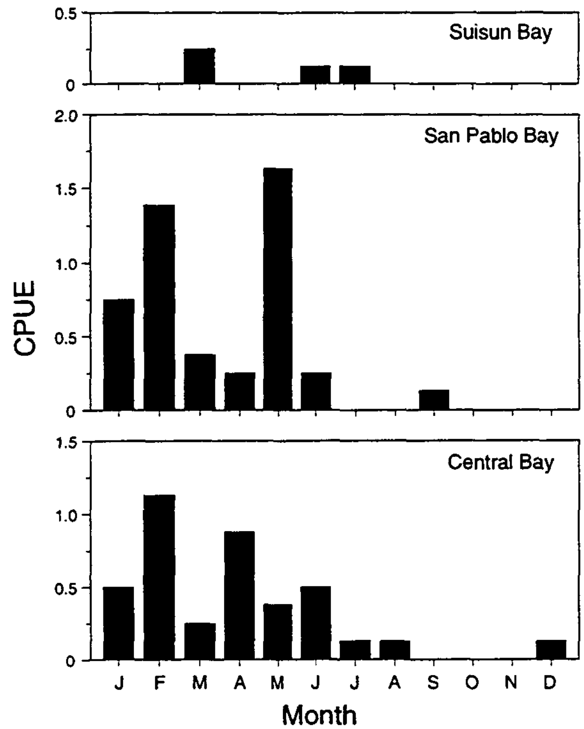

Figure 12 Monthly distribution (CPUE) of age–1+ *C. magister* collected with the otter trawl in 1985

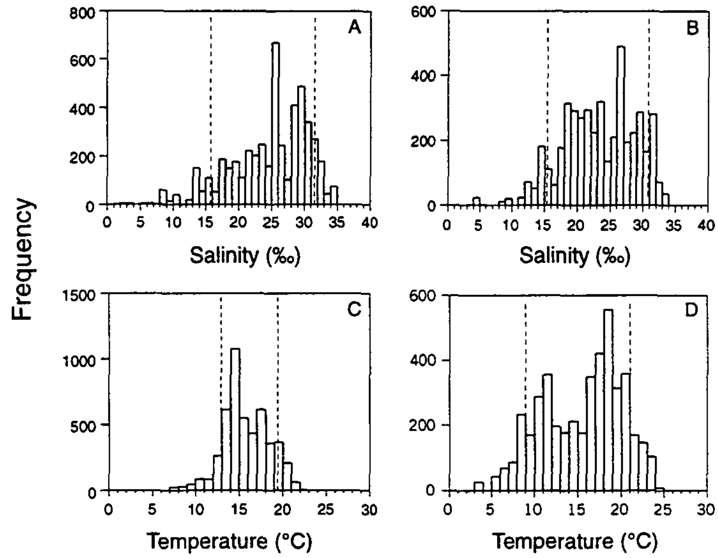

Figure 13 Salinity (‰) and temperature (°C) distributions of all sizes of *C. magister* collected with the otter trawl (1980 to 1996) and ringnets (1982 to 1994): (A) salinity, otter trawl; (B) salinity, ringnets; (C) temperature, otter trawl; (D) temperature, ringnets. Dashed vertical lines are the 10th and 90th percentiles.

Table 8 Salinity (‰) and temperature (°C) statistics for all sizes of *C. magister* from the otter trawl (1980 to 1996) and ringnets (1982 to 1994)

	Mean (Standard Deviation)	*Minimum*	*Maximum*	*10th Percentile*	*90th Percentile*
Salinity					
Otter trawl	24.7 (6.0)	1.2	34.3	15.7	31.5
Ringnets	23.3 (5.6)	1.9	33.4	15.4	30.8
Temperature					
Otter trawl	15.8 (2.6)	7.3	22.7	12.9	19.4
Ringnets	15.8 (4.6)	6.0	24.5	9.0	21.0

Salinity and Temperature

Cancer magister was common over a relatively wide range of salinities and temperatures; most individuals were collected from 15‰ to 32‰ and 9 to 20 °C (Figure 13). The mean salinities were very similar for the otter trawl and ringnets (mean = 24.7‰ and 23.3‰, respectively), as were the ranges and the 10th and 90th percentiles (Table 8). Although the mean temperatures were identical for both gear types (mean = 15.8 °C, see Table 8), *C. magister* was collected over a somewhat wider range of temperatures in the ringnets than in the otter trawl. In the ringnets, 80% of the individuals were collected from 9.0 to 21.0 °C, whereas in the otter trawl, 80% were collected from 12.9 to 19.4 °C (10th and 90th percentiles respectively).

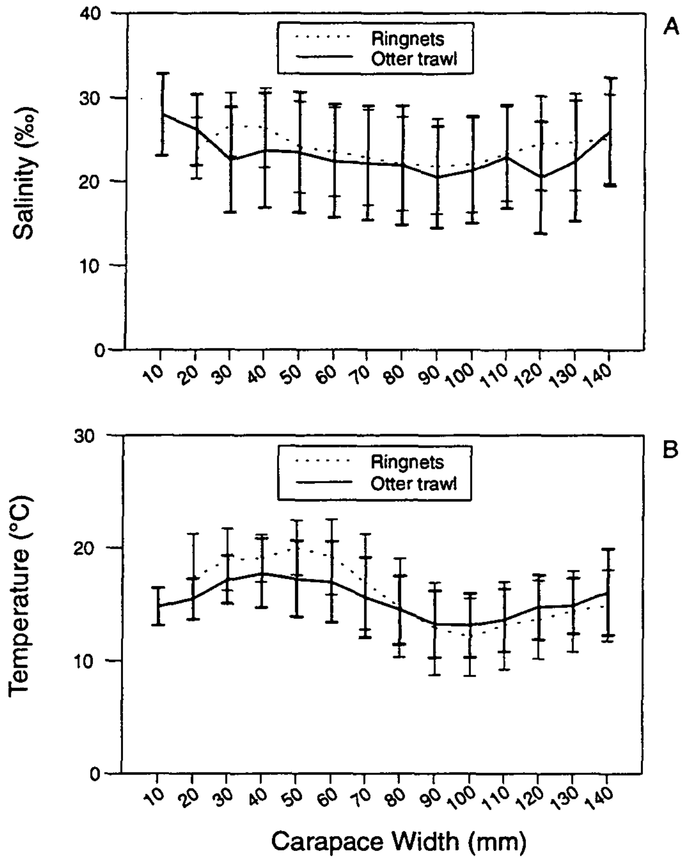

Figure 14 Mean salinity and temperature (±1 standard deviation) of *C. magister* by size class collected with the otter trawl and the ringnets: (A) salinity (‰), (B) temperature (°C). Size classes are every 10 mm, from 5 to 145 mm.

Male *C. magister* were collected at slightly higher mean salinities than females by both gear types (males at 22.7‰, females at 22.4‰ in the otter trawl, males at 23.4‰, females at 22.9‰ in the ringnets). The mean temperature at point of capture was slightly higher for males than for females in the otter trawl (males at 16.2 °C, females at 16.0 °C), but lower in the ringnets (males at 15.5 °C, females at 16.2 °C).

The mean salinity and temperature at point of capture varied by size class and to some extent, gear type. In general, the mean salinity gradually decreased with size until the crabs reached 85 to 114 mm and then increased with size (Figure 14A). In the otter trawl, the smallest size class (5 to 14 mm) was collected at a mean salinity of 28.0‰, the 85 to 94 mm size class at 20.5‰, and the 135 to 144 mm size class at 26.0‰.

Temperature at point of capture increased as size increased to 35 to 44 mm, then decreased for crabs 85 to 114 mm, and again increased as crabs grew to 135 to 144 mm (Figure 14B). In the otter trawl, the smallest crabs (5 to 14 mm) were collected at a mean temperature of 14.7 °C; the mean temperature increased to 17.7 °C for crabs 35 to 44 mm and gradually decreased for each size group to a low of 13.1 °C for crabs 95 to 104 mm before increasing again to 19.3 °C for the 135 to 144 mm size class. *Cancer magister* collected with the ringnets were consistently captured at higher temperatures than those collected with the otter trawl until they were 75 to 84 mm; above this size, they were captured at lower temperatures.

Discussion

The general distribution patterns of *C. magister* in the San Francisco Estuary by season, salinity, and temperature agree with literature results (Collier 1983, Tasto 1983). First and second instar crabs were first collected in April or May from Central Bay and the San Pablo Bay channel. Over several months, age–0 crabs moved upstream and to shoals and intertidal areas. These crabs were collected at some of the highest temperatures and the lowest salinities of all *C. magister* collected. Most females emigrated from the estuary when they matured in late fall or winter. Males generally remained in the estuary longer than females and some males remained through their second summer and fall. This differential emigration by sex agrees with the findings of Orensanz and Gallucci (1988) in Garrison Bay, Puget Sound, except that crabs in the San Francisco Estuary grew at a much faster rate than in Garrison Bay and the timing of emigration differed.

Cancer magister distribution was affected by the magnitude of freshwater outflow and to some extent, year class strength. Age–0 crabs were distributed farther upstream in low outflow years than in high outflow years, although all years with high outflow had low abundance. Freshwater outflow also affected the timing of immigration and emigration, as immigration to the estuary was apparently delayed in some high outflow years, and crabs emigrated from the estuary before they were mature if winter outflow was relatively high.

The large interannual variation in abundance of *C. magister*, from 0 in some years to very high abundance in others is notable. Tasto (1983) concluded that the year class strength of *C. magister* in the estuary was directly related to the year class strength of megalopae in the Gulf of the Farallones during spring. The effects of ocean temperature and currents on the hatching success, survival, and distribution of *C. magister* larvae are well documented—years with warm ocean temperatures or frequent winter storms resulted in poor recruitment of *C. magister* to the estuary (Lough 1976, Reilly 1983a, Wild 1983, Johnson and others 1986). During this study, there were several warm water periods (see Salinity and Temperature chapter, Figure 11), years with frequent winter storms, and years with very warm ocean temperatures combined with frequent winter storms (for example, 1982, 1983, and 1993). Abundance of age–0 *C. magister* in the estuary was never high in any of these years. But not every year with relatively cool ocean temperatures and few winter storms resulted in a strong year class (for example, 1991).

There is also evidence of interannual differences in survival of age–0 *C. magister*. Abundance of early instar crabs in the otter trawl was highest in 1988, but the 1988 ringnet index was lower than the 1984 and 1985 indices. As the ringnet index represents older crabs, this difference in relative abundance was probably due to a lower survival rate of early instar crabs in 1988. The contribution of each year class to the fishery is additional evidence that the 1988 year class was ultimately smaller than either the 1984 or 1985 year classes. The large 1984 and 1985 year classes undoubtedly contributed to the increased commercial landings in 1987 to 1988 (see Figure 1), but neither the 1990–1991 nor 1991–1992 landings increased, indicating the 1988 year class did not make a significant contribution.

Cancer magister uses the San Francisco Estuary almost strictly as a nursery area, which is unique among the *Cancer* crabs discussed in this chapter. Age–0 crabs apparently osmoregulate readily in brackish water, which is reflected by the relatively wide range of salinities *C. magister* occupied compared to *C. antennarius*, *C. gracilis*, and *C. productus*. Although *C. magister* uses San Pablo and Suisun bays to a greater extent than either *C. antennarius*, *C. gracilis*, or *C. productus*, it was not collected at substantially warmer temperatures than these 3 species.

Cancer gracilis

Cancer gracilis, the slender crab, ranges from Alaska to Baja California (Schmitt 1921). It is sometimes found intertidally on mudflats, but is more common subtidally on sandy or muddy bottoms and in eelgrass beds (Knudsen 1964, Orensanz and Gallucci 1988). *Cancer gracilis* is considered to be a stenohaline species, as it is intolerant of low salinities (Gross 1957). It is the smallest of the *Cancer* species included in this report; males have been reported to reach a maximum size of 115 mm, females 106 mm (Orensanz and Gallucci 1988).

Ovigerous *C. gracilis* are most common from December through April in Puget Sound, although many females produce more than 1 brood per year (Knudsen 1964). The reproductive season is apparently protracted: in Puget Sound, ovigerous females are present from February through August, larval hatching occurs from March through September, and juvenile settlement occurs in late summer (Orensanz and Gallucci 1988). There is limited information about the *C. gracilis* reproductive cycle in California. In Monterey Bay, peak larval abundance is from January through March (Hsueh 1991).

Reproductive aggregates, dominated by females and with a maximum aggregate density of 50 crabs/m^2, occur in summer in Puget Sound (Orensanz and others 1995). Peak mating activity occurs in August, towards the end of the larval hatching season. The minimum ovigerous size in Puget Sound is 48 mm; 50% of the females are mated at 54 mm, and the smallest mated male was 77 mm (Orensanz and others 1995). Both sexes mature at instar 10 or 11, which is within 1 year after settlement in Puget Sound. Both sexes remain in the same area all year and neither mature crabs nor ovigerous females migrate to nearshore waters (Orensanz and Gallucci 1988).

Bivalves, polychaetes, and barnacles are the primary prey items of *C. gracilis*; it is occasionally a pest in oyster beds (Knudsen 1964, Orensanz and Gallucci 1988, Jensen 1995). A variety of fishes prey on *C. gracilis* in the San Francisco Estuary. Major predators include brown smoothhound, big skate, green sturgeon, rubberlip seaperch, pile perch, and starry flounder. Minor predators include spiny dogfish, Pacific tomcod, white sturgeon, striped bass, redtail surfperch, white seaperch, staghorn sculpin, bonehead sculpin, and white croaker (CDFG, unpublished data). Boothe (1967) also reported that staghorn sculpin and starry flounder prey upon *C. gracilis*.

Methods

Male and female *C. gracilis* <35 mm were classified as age 0 and all larger crabs as age 1+. The annual index periods selected were as follows: May through October for age–0 *C. gracilis* from the otter trawl, February through October for age–1+ crabs from the otter trawl, and July through December for crabs (all age classes) from the ringnets. Age–1+ crabs from the otter trawl were used for analysis of seasonal sex ratio trends. For analysis of channel-shoal distribution, stations #215 (channel) and #243 (shoal) were selected based on the relatively high otter trawl catches of *C. gracilis*.

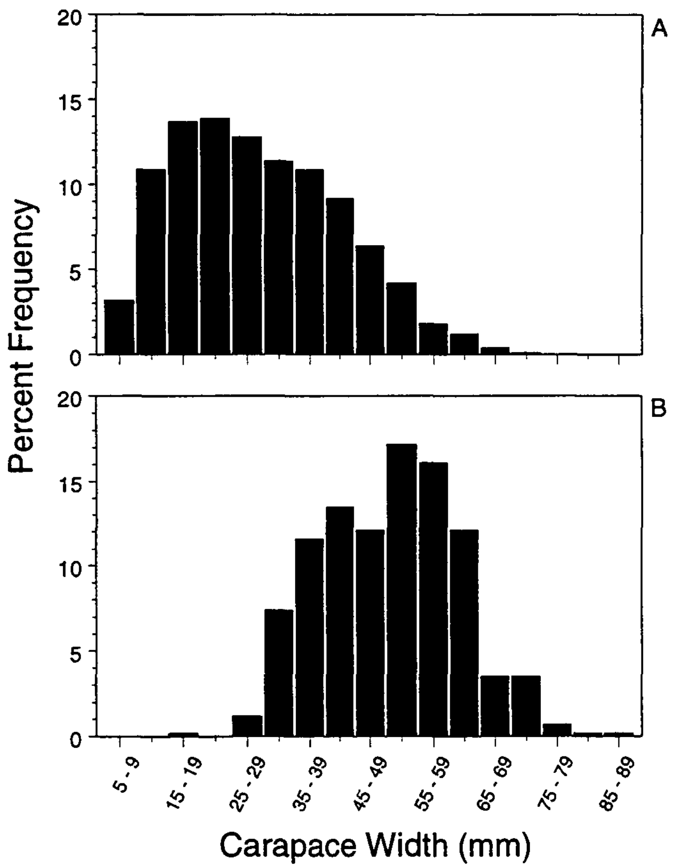

Figure 15 Size frequency of *C. gracilis*: (A) otter trawl, 1980 to 1996; (B) ringnets, 1982 to 1994. Size classes are every 5 mm, from 5 to 90 mm.

Results

Size and Size Frequency

The largest male *C. gracilis* collected by this study was 85 mm, the largest female 70 mm. A total of 57 ovigerous females was collected, ranging from 25 to 54 mm; 10 were from 25 to 34 mm and the remainder were larger. Based on the minimum ovigerous size, age–1+ *C. gracilis* from the San Francisco Estuary were mature. The otter trawl collected age–0 and age–1+ crabs (Figure 15A), whereas the ringnets collected primarily age–1+ crabs (Figure 15B). Two size groups were distinguishable in the March, April, and December otter trawl data (Figure 16). Small crabs (<15 mm) were collected every month and the mode of age–0 crabs could be readily followed from March through December.

The ratio of male to female *C. gracilis* collected by the otter trawl changed with size. For crabs 20 to 24 mm, females slightly outnumbered males; the ratio was 0.8:1. As the crabs approached maturity, even more females were collected than males and the ratio changed to 0.5:1 for crabs 30 to 34 mm. The number of males increased in the larger size classes—the sex ratio was approximately equal for *C. gracilis* 45 to 49 mm and males outnumbered females by 5:1 for crabs >50 mm. In contrast to the otter trawl, the ringnet catch was dominated by male *C. gracilis* for all size classes >30 mm. The male to female ratio was 1.5:1 for the 30 to 34 mm size class, 2.7:1 for the 45 to 49 mm size class, and 9:1 for crabs >50 mm.

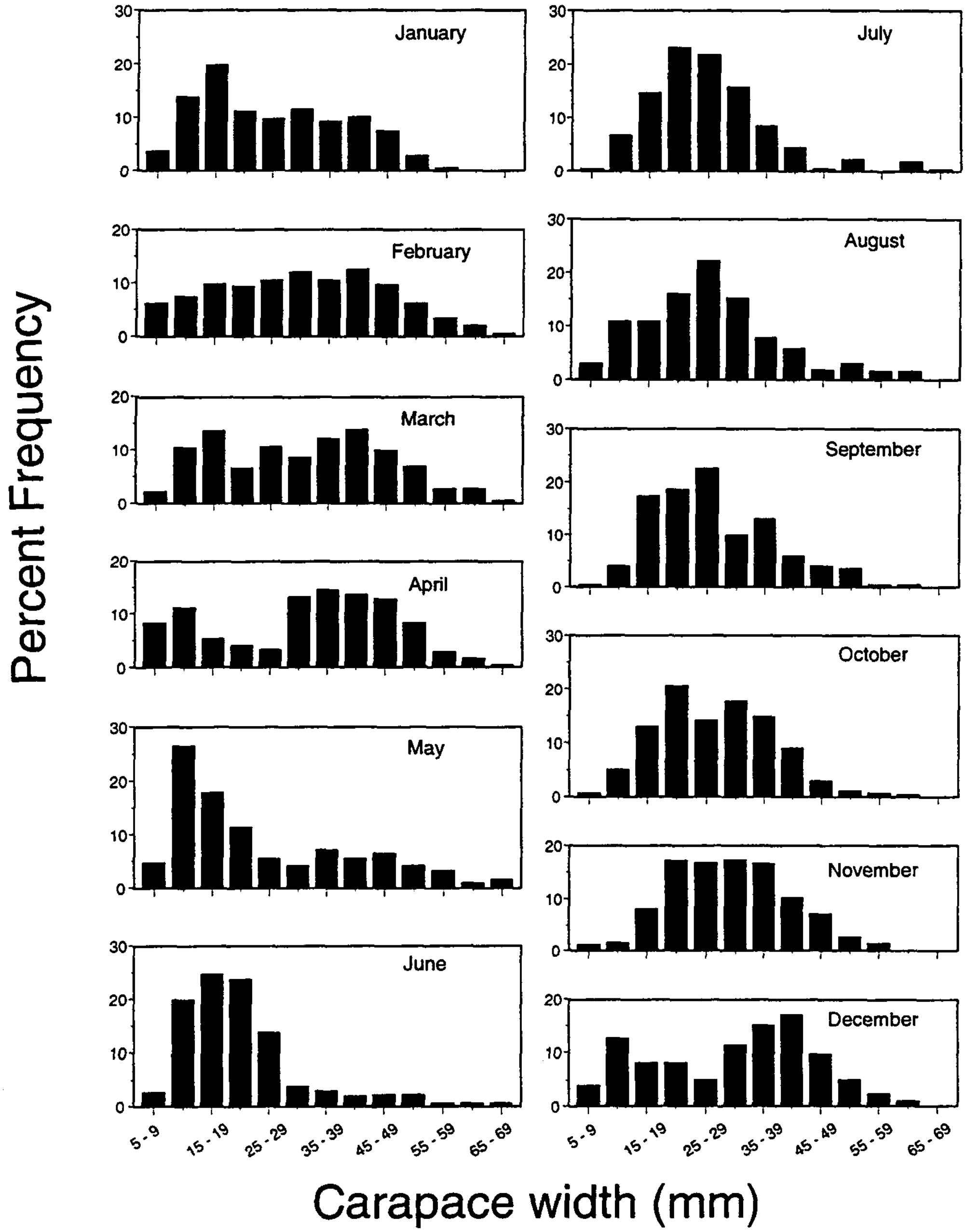

Figure 16 Size frequency of *C. gracilis* by month collected with the otter trawl. Size classes are every 5 mm, from 5 to 70 mm.

Abundance

Cancer gracilis was the 2nd most common species of *Cancer* crab collected by the otter trawl, but ranked 4th in the ringnets (see Table 1). The annual abundance of age–0 crabs was relatively low through the 1980s and increased in the early 1990s; the highest index was in 1994, followed by 1991 and 1993 (Figure 17A, Table 9). The abundance trend of age–1+ *C. gracilis* was similar to the trend for age–0 crabs, with the highest indices during the 1990s (Figure 17B, Table 10). This trend was not shared by the ringnet data, where the annual highest indices were in 1987, 1988, and 1992 (Figure 18, Table 11). Note the ringnet sampling stopped in 1993, so the otter trawl and ringnet indices are not entirely comparable.

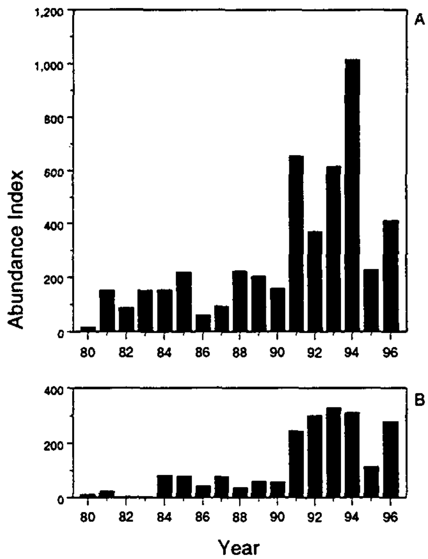

Figure 17 Annual abundance indices of *C. gracilis* collected with the otter trawl from 1980 to 1996: (A) age 0, the index period is May to October; (B) age 1+, the index period is February to October

Table 9 Monthly and annual abundance indices of age–0 *C. gracilis* collected with the otter trawl from 1980 to 1996. The index period is May to October.

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*May–Oct*
1980		36	0	0	0	27	0	27	0	46	0	0	17
1981	0	0	0	0	0	50	181	494	27	162	27	0	152
1982	0	0	0	0	309	0	31	27	0	155	0	0	87
1983	185	0	216	0	0	31	54	216	54	552	568	108	151
1984	514	784	243	243	243	328	189	27	135	0	73	58	154
1985	0	27	54	27	212	471	173	108	85	270	27	27	220
1986	127	842	0	0	0	166	27	81	0	81	27	54	59
1987	212	127	189	27	54	0	0	54	81	366	730	595	93
1988	568	108	162	189	529	437	235	135	0	0	54	216	223
1989	54	27	135	135	90	414	166	144					204
1990		982	1383	139	77	143	117	220	324	73			159
1991		1023	1866	634	771	1402	561	577	418	208			656
1992		227	139	166	298	229	687	54	543	413			371
1993		379	545	379	541	252	942	541	491	930			616
1994		297	135	204	846	2192	417	1248	1067	328			1016
1995	539	572	301	27	54	0	27		838	216	2947	622	227
1996	1776	144	27	135	410	406	139	588	216	707	85	807	411
1981–1988, 1996	376	226	99	69	195	210	114	192	66	255	177	207	

Table 10 Monthly and annual abundance indices of age–1+ *C. gracilis* collected with the otter trawl from 1980 to 1996. The index period is February to October.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Feb–Oct
1980		108	0	0	0	0	0	0	0	0	91	0	12
1981	0	0	54	0	0	0	88	0	0	62	0	85	23
1982	0	31	0	0	0	0	0	0	0	0	0	0	3
1983	0	0	36	0	0	0	0	0	0	0	27	54	4
1984	0	54	27	27	27	27	243	0	162	162	27	162	81
1985	27	0	54	0	0	81	65	189	54	247	81	92	77
1986	19	379	0	0	0	0	0	0	0	0	81	38	42
1987	135	216	100	54	154	0	27	81	54	0	127	127	76
1988	108	54	135	0	27	54	0	54	0	0	0	27	36
1989	27	27	270	54	31	27	0	0					58
1990		81	270	100	27	0	27	0	0	0			56
1991		649	626	433	100	127	81	81	81	38			246
1992		541	1554	324	216	27	27	0	19	0			301
1993		496	433	1085	464	144	54	108	100	81			329
1994		356	502	166	533	54	193	297	460	235			311
1995	225	491	216	85	0	0	0		81	27	2055	1676	113
1996	901	595	351	220	54	135	27	162	189	784	146	185	280
1981–1988, 1996	132	148	84	33	29	33	50	54	51	139	54	86	

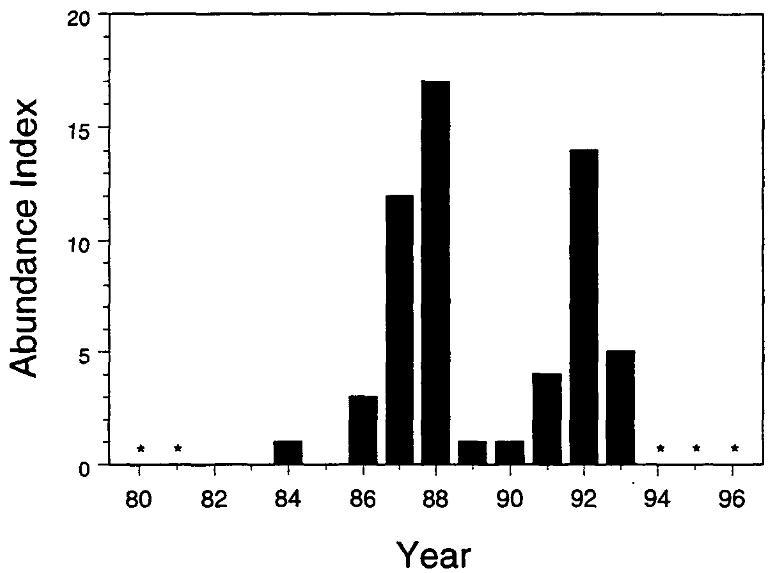

Figure 18 Annual abundance indices (CPUE x 10) of all sizes of *C. gracilis* collected with the ringnets from 1982 to 1993. The index period is July to December. Asterisk (*) indicates no survey.

Table 11 Monthly and annual abundance indices of age–1+ *C. gracilis* collected with the ringnets from 1982 to 1993. The index period is July to December. CPUE × 10.

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Jul–Dec*
1982					0	0	0	0	0	0	1	0	0
1983	0	0	0	0	0	0	0	0	0	0	2	0	0
1984	0	0	0	0	0	0	4	0	0	0	0	0	1
1985	0	0	0	0	0	0	0	0	0	1	0	0	0
1986	0	0	0	0	0	0	2	9	2	3	0	0	3
1987	1	0	0	6	26	21	47	8	10	2	0	4	12
1988	0	1	0	0	0	3	90	12	1	0	1	0	17
1989	0	0	0	0	0	1	1	0	1	0	1	0	1
1990							4	0	0	0	0	0	1
1991							12	0	1	1	7	0	4
1992							1	42	22	11	6	2	14
1993							12	8	11	0	0	0	5
1983–1989	0	0	0	1	4	4	21	4	2	1	1	1	

Table 12 Monthly catch of *C. gracilis* stage 2 to 5 zoeae (1980 to 1985) and megalopae (1980 to 1988)

Month	*Zoeae*	*Megalopae*
January	84	28
February	382	3
March	1076	52
April	1556	59
May	111	5
June	73	34
July	80	121
August	100	24
September	61	13
October	100	0
November	352	2
December	331	4

Ovigerous females were collected in all months except August and November and were most common from January through May. Zoeae were collected all year but abundance appeared to be bimodal; the highest catches were from February through April and in November and December (Table 12). Megalopae were collected in all months except for October, with the highest catches in March, April, and July (see Table 12). Although age–0 *C. gracilis* were relatively abundant in most months (Figure 19), in many years there were 1 or 2 distinct abundance peaks, usually from late spring to summer or from fall to winter. For example, in 1987 and 1988, age–0 crabs were most abundant from October 1987 through January 1988 and in May and June 1988 (see Table 9).

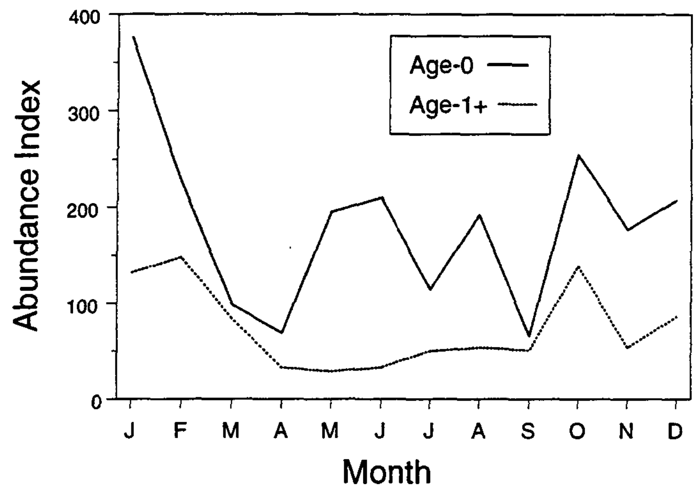

Figure 19 Monthly abundance of age–0 and age–1+ *C. gracilis* collected with the otter trawl from 1981 to 1988 and 1996

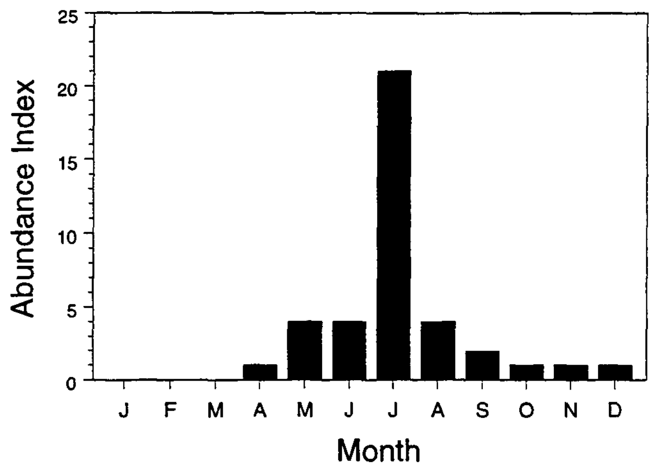

Figure 20 Monthly abundance (CPUE x 10) of all sizes of *C. gracilis* collected with the ringnets from 1983 to 1989

Age–1+ *C. gracilis* were generally most abundant from October through March in the otter trawl (see Figure 19), but in several years abundance was high through May (for example, 1993 and 1994) and increased as early as August or September (see Table 10). In contrast to the otter trawl, abundance was highest in the ringnets from May through September (Figure 20). There is no evidence of a winter abundance peak in any year (see Table 11), although year-round sampling was limited to 1983 through 1989 with this gear.

Age–1+ males outnumbered females from February through September in the otter trawl (Figure 21), but females comprised at least 60% of the age–1+ catch from November through January. In the ringnets, males outnumbered females in all months, although total catch was very low in winter.

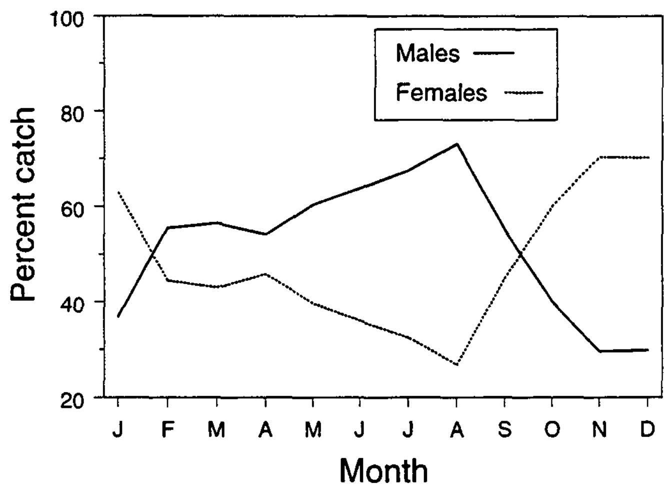

Figure 21 Monthly percent catch of male and female age–1+ *C. gracilis* collected with the otter trawl

Distribution

Cancer gracilis was common from northern South Bay to lower San Pablo Bay. None were collected upstream of San Pablo Bay. Smaller crabs (<40 mm) were more widely distributed than larger crabs. Over all the months and years, the otter trawl collected more *C. gracilis* at channel stations than at shoal stations. Catches were highest at the channel stations south of Treasure Island and east of Tiburon (stations #110 and #215, see Methods chapter, Figure 1). In the ringnets, most *C. gracilis* were collected at the Paradise station #294 (see Methods chapter, Figure 3).

Cancer gracilis zoeae were concentrated in Central Bay, but there were relatively high catches of early stage zoeae in the southernmost part of South Bay. A few early stage zoeae were collected in San Pablo Bay and as far upstream as Carquinez Strait. Late stage zoeae and megalopae were most commonly collected in Central Bay.

Age–0 *C. gracilis* were concentrated in Central Bay in all years (Figure 22). This age class used San Pablo Bay to a greater extent in low outflow years than in high outflow years (for example, 1994 and 1995). There was also a general trend of expanding distribution with increasing abundance. The center of distribution of age–1+ *C. gracilis* was also in Central Bay in all years (Figure 23). As for age–0 crabs, the use of San Pablo Bay was greater in low outflow years.

Neither age–0 nor age–1+ *C. gracilis* showed strong evidence of seasonal movements between regions of the estuary (Figures 24 and 25). Age–0 crabs probably used San Pablo Bay seasonally, as CPUE was highest there in summer and fall.

Although *C. gracilis* used channels more than shoals, crabs moved seasonally between these habitats. For the selected channel-shoal pair of stations, catches of age–1+ *C. gracilis* were higher at the channel station (#215) from November through April and at the shoal station (#243) from May through October (Figure 26). The shoal catch in summer and fall was primarily composed of male *C. gracilis*. Females were common in the channel in winter, but total catch of females at both the channel and shoal stations decreased in summer.

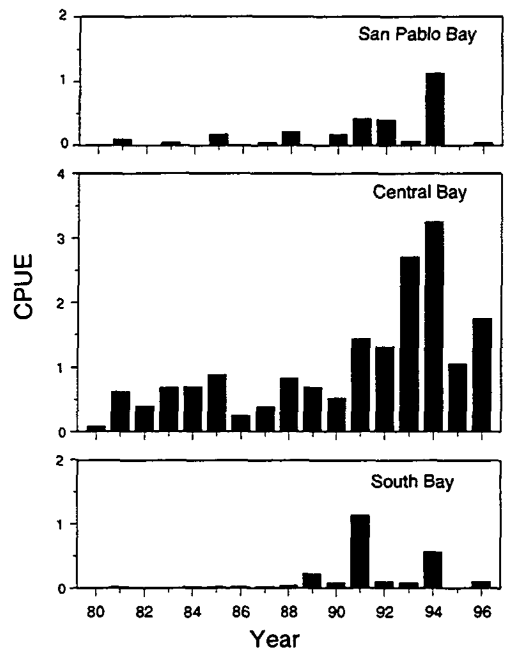

Figure 22 Annual distribution (CPUE) of age–0 *C. gracilis* collected with the otter trawl for May to October from 1980 to 1996

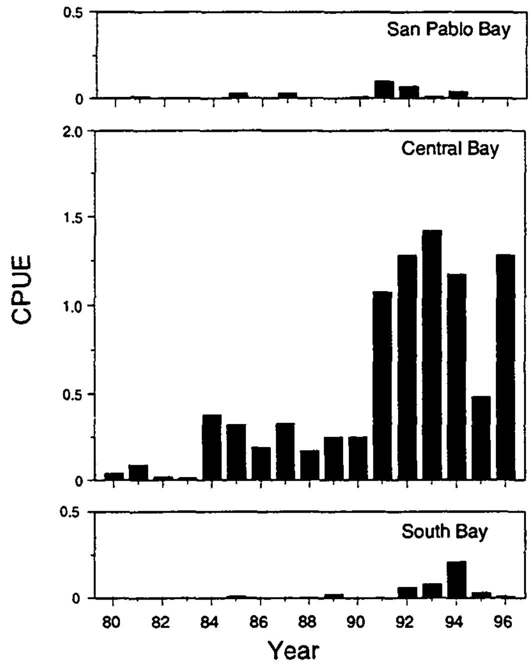

Figure 23 Annual distribution (CPUE) of age–1+ *C. gracilis* collected with the otter trawl for February to October from 1980 to 1996

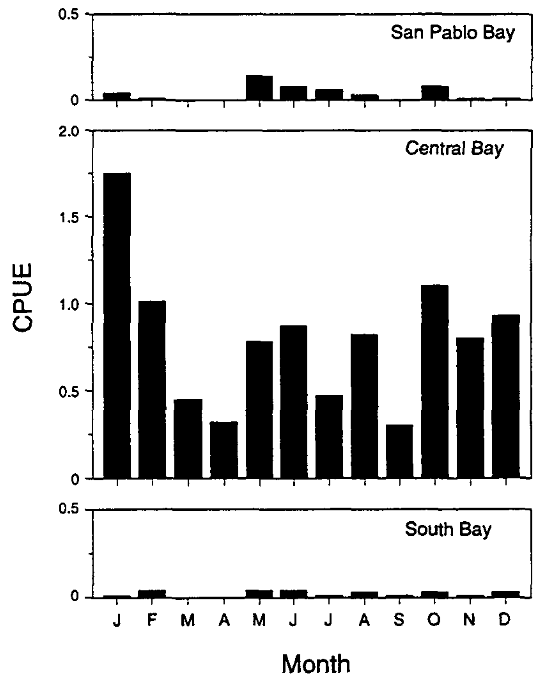

Figure 24 Monthly distribution (CPUE) of age–0 *C. gracilis* collected with the otter trawl from 1981 to 1988 and in 1996

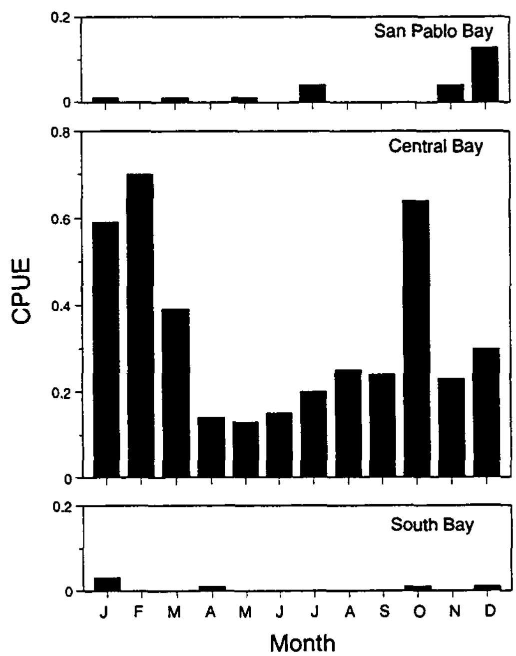

Figure 25 Monthly distribution (CPUE) of age–1+ *C. gracilis* collected with the otter trawl from 1981 to 1988 and in 1996

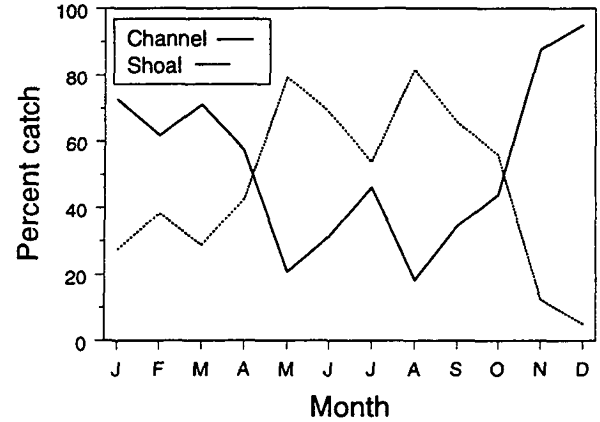

Figure 26 Channel-shoal percent catch of *C. gracilis* by month from 1988 to 1996 at station #215 (channel) and station #243 (shoal)

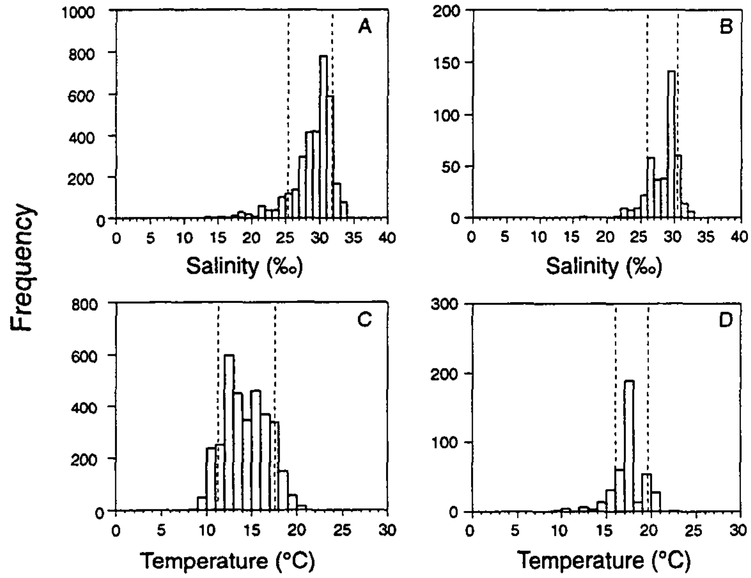

Figure 27 Salinity (‰) and temperature (°C) distributions of all sizes of *C. gracilis* collected with the otter trawl (1980 to 1996) and ringnets (1982 to 1994): (A) salinity, otter trawl; (B) salinity, ringnets; (C) temperature, otter trawl; (D) temperature, ringnets. Dashed vertical lines are the 10th and 90th percentiles.

Salinity and Temperature

Most *C. gracilis* were collected at salinities ranging from 25‰ to 32‰ and temperatures from 11 to 18 °C (Figure 27). *Cancer gracilis* was collected at very similar mean salinities in the otter trawl and ringnets (mean = 29.1‰ and 28.4‰, respectively) (Table 13), but was collected at a substantially lower mean temperature in the otter trawl than in the ringnets (mean = 14.3 °C and 17.3 °C, respectively) (see Table 13). Males and females were collected at almost identical mean salinities and temperatures in the otter trawl, but females were collected at a slightly lower mean salinity and temperature and than males in the ringnets. There were no salinity or temperature trends with size (Figure 28).

Table 13 Salinity (‰) and temperature (°C) statistics for all sizes of *C. gracilis* collected with the otter trawl (1980 to 1996) and ringnets (1982 to 1994)

	Mean (Standard Deviation)	*Minimum*	*Maximum*	*10th Percentile*	*90th Percentile*
Salinity					
Otter trawl	29.1 (3.0)	13.7	34.3	25.4	31.8
Ringnets	28.4 (2.2)	16.0	33.0	25.9	30.5
Temperature					
Otter trawl	14.3 (2.4)	8.7	20.8	11.3	17.6
Ringnets	17.3 (1.7)	9.8	22.5	16.0	19.6

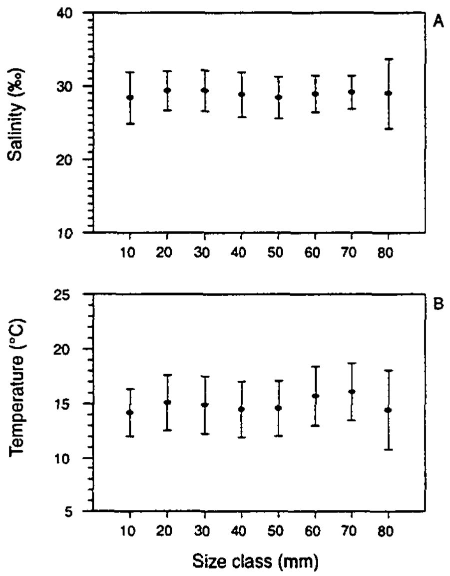

Figure 28 Mean salinity and temperature (±1 standard deviation) for *C. gracilis* by size class collected with the otter trawl and ringnets: (A) salinity (‰) and (B) temperature (°C). Size classes are every 10 mm, from 5 to 85 mm.

Discussion

Cancer gracilis was most common in the relatively cool, euhaline waters of Central Bay, as is typical of a "marine" species. Of the 4 species of *Cancer* crabs included in this report, *C. gracilis* was collected at the highest mean salinity and the lowest mean temperature in the otter trawl, although the mean salinity was only <1‰ higher than the mean salinity for *C. antennarius* and *C. productus*. The San Francisco Estuary probably functions more as an extension of the preferred nearshore coastal habitat of *C. gracilis* than as a nursery. This is similar to how *C. antennarius* and *C. productus* are proposed to use the estuary in this report. The relatively high number of ovigerous females collected combined with limited evidence of a seasonal emigration indicates that at least some *C. gracilis* are resident in the estuary. This observation is also supported by the conclusion that mature *C. gracilis* did not emigrate to the ocean from Garrison Bay, Washington (Orensanz and Gallucci 1988).

Although mature *C. gracilis* do not move extensively in the San Francisco Estuary, age–0 crabs are more widely distributed than age–1+ crabs. Age–1+ crabs also move seasonally between the channels and shoals, with catches higher on shoals in summer and in channels in winter. The peak ringnet abundance in summer corresponds with this movement from channels to shoals.

The relatively high catches of *C. gracilis* in the otter trawl relative to the ringnets probably reflects a preference for open sandy and muddy substrates rather than pilings and other protected areas. Also, it may be displaced from rocky or protected areas by the larger species of *Cancer* crabs common to the estuary (R. Tasto, personal communication, see "Notes").

Although *C. gracilis* abundance decreased in high outflow years, this trend is somewhat masked by increasing abundance through the 1990s. The high salinities present all year in Central Bay during the 1987–1992 drought (see Introduction chapter, Figure 2) created a stable environment which may have resulted in the initial increase of *C. gracilis* abundance in 1991. Other factors, yet unknown, may have contributed to the continued high abundance after the drought ended. Interestingly, abundance of *C. antennarius* and *C. productus* also increased over the study period, although not all peak abundance years were common for all 3 species.

There were multiple cohorts of *C. gracilis* in most years and evidence of a protracted breeding season, which agrees with the literature. Age–1+ males were more common in summer, especially over the shoals, and females were more common in winter. The ringnet catch was also dominated by age–1+ males in summer. This distributional pattern indicates a spatial segregation of the sexes, especially in summer. Breeding aggregates of females, as found in Puget Sound during the summer (Orensanz and others 1995), could result in this pattern of sex segregation if the female-dominated aggregates were infrequently sampled.

Cancer productus

Cancer productus, the red rock crab, ranges from Alaska to San Diego, California. It is primarily found in bays and protected coastal waters, associated with rocky areas, gravel, and coarse sand (Schmitt 1921, Garth and Abbott 1980). Juveniles settle on spatially complex substrates, but move to more open areas as they grow (Orensanz and Gallucci 1988). Although *C. productus* is most common in intertidal and shallow subtidal areas, it has been collected to at least 91 m. The largest reported male was 190 mm and the largest female 168 mm (CDFG unpublished data, as cited in Carroll and Winn 1989).

In Puget Sound, *C. productus* mates from June to August, ovigerous females are most abundant from December to March, and peak larval hatching is in March and April (Knudsen 1964). Female *C. productus* migrate to deeper water in winter for larval hatching and return to shallow water, including estuaries, in May and June to join the males (Orensanz and Gallucci 1988). In the intertidal zone of Puget Sound, males dominated the catch from January to May, but females were more common than males from July to October (Knudsen 1964). The larval period is relatively long—97 days at 11 °C (Trask 1970). Peak juvenile settlement occurs in April and May in Coos Bay, Oregon, (Selby 1980) and in July and August in Friday Harbor, Washington (Orensanz and Gallucci 1988). Most *C. productus* mature within 1 year after settlement in Puget Sound (about 60 mm, instar 10) and pass though a maximum of 13 instars (Orensanz and Gallucci 1988).

In southern California coastal waters the highest catches of *C. productus* were in fall and the lowest in summer (Winn 1985). In Coos Bay the highest catches were also in the fall, but the lowest catches were from November to January (Selby 1980). The low winter catches in Oregon were hypothesized to be a result of a downstream migration in response to decreasing salinities.

The large chelae of *C. productus* make it adept at preying upon hard-shelled organisms such as snails, clams, mussels, and barnacles (Carroll and Winn 1989, Robles and others 1989). In the San Francisco Estuary, *C. productus* is a major prey item of brown smoothhound, big skate, green sturgeon, and rubberlip seaperch, and a minor prey item of leopard shark, bat ray, staghorn sculpin, cabezon, white croaker, and starry flounder (CDFG, unpublished data).

Methods

Male and female *C. productus* <50 mm were classified as age 0 and all larger crabs as age 1+. The annual index periods selected were as follows: April through October for age–0 *C. productus* from the otter trawl, February through October for age–1+ crabs from the otter trawl, and July through December for crabs (all age classes) from the ringnets. Age–1+ crabs from the otter trawl and ringnets were used for analysis of seasonal sex ratio trends. *Cancer productus* catches were not sufficient at any of the otter trawl stations for a channel-shoal analysis.

Results

Size and Size Frequency

The largest male collected by this study was 160 mm and the largest female 137 mm. Only 3 ovigerous females, ranging from 88 to 92 mm, were collected. The otter trawl collected mostly age–0 crabs <45 mm (Figure 29A), whereas the ringnet catch was dominated by crabs >40 mm (Figure 29B). Small (5 to 19 mm) *C. productus* were most numerous from May through August in the otter trawl.

Cancer productus catches were strongly biased toward males from 20 to 49 mm, with a male to female ratio of 2.3:1 for this size class. Females slightly outnumbered males from 55 to 79 mm (ratio 0.9:1), whereas males dominated all size classes >80 mm (ratio 2:1).

Abundance

Cancer productus was the 4th most commonly collected species of *Cancer* crab in the otter trawl but ranked 2nd in the ringnet survey (see Table 1). Age–0 abundance was low during the early 1980s, increased in 1986, and fluctuated through the mid-1990s (Figure 30A, Table 14). The highest annual index was in 1996, followed closely by 1994, 1990, 1988, and 1991. All of these years, except for 1996, had relatively low freshwater outflow (see Introduction chapter, Figure 2). Age–1+ indices were relatively low through 1988 and the highest indices were in 1991, 1992, and 1994 (Figure 30B, Table 15). Usually the years with the highest outflow had the lowest age–1+indices (for example, 1980, 1982, 1983, 1986, and 1995). The ringnet indices, which were dominated by age–1+ crabs, were also usually lower in years with high outflow (1982, 1983, 1986) than in years with low outflow (Figure 31, Table 16). The exception was 1992, which had a low abundance index but also low outflow.

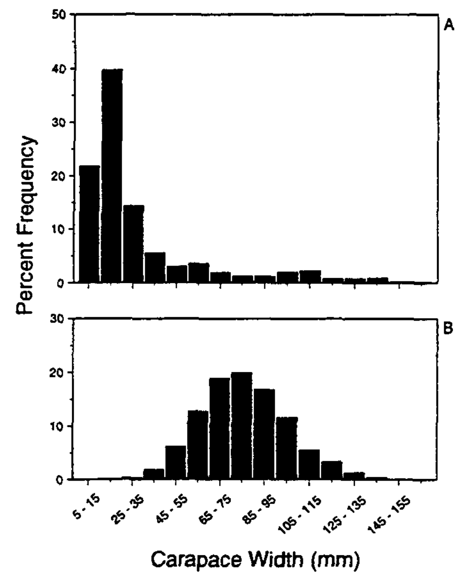

Figure 29 Size frequency of *C. productus*: (A) otter trawl, 1980 to 1996; (B) ringnets, 1982 to 1994. Size classes are every 10 mm, from 5 to 165 mm.

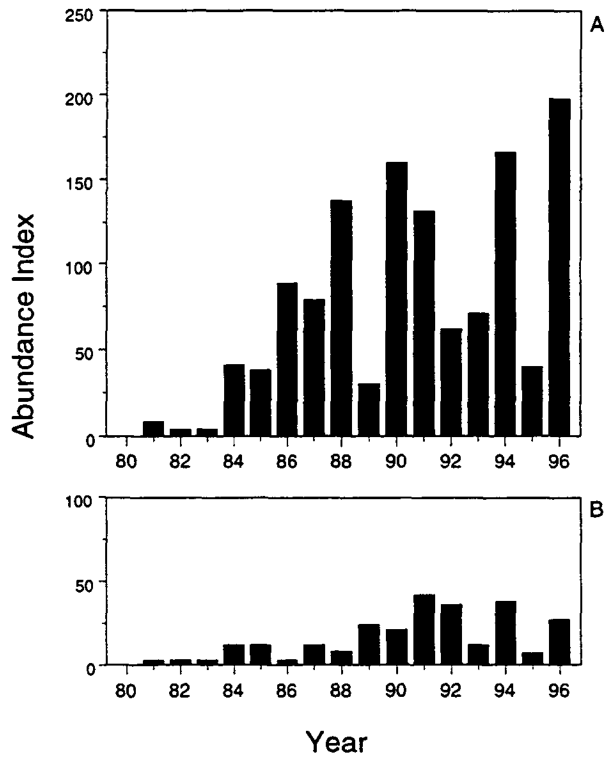

Figure 30 Annual abundance indices of *C. productus* collected with the otter trawl from 1980 to 1996: (A) age 0, the index period is April to October; (B) age 1+, the index period is February to October

Table 14 Monthly and annual abundance indices of age–0 *C. productus* collected with the otter trawl from 1980 to 1996. The index period is April to October.

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Apr–Oct*
1980		85	0	0	0	0	0	0	0	0	0	0	0
1981	19	0	0	0	0	0	0	66	0	0	0	31	9
1982	0	0	0	0	0	27	0	0	0	0	0	0	4
1983	31	0	0	0	0	31	0	0	0	0	0	0	4
1984	0	0	54	0	0	117	0	50	0	121	63	82	41
1985	125	0	63	27	0	46	148	19	27	0	19	94	38
1986	31	156	0	0	0	19	69	380	94	58	0	0	89
1987	0	0	94	27	19	154	81	54	81	135	212	31	79
1988	0	90	54	81	193	116	100	363	58	54	46	108	138
1989	0	58	81	27	19	19	0	85					30
1990		108	27	0	136	414	128	239	54	146			160
1991		104	58	0	63	266	190	139	139	127			132
1992		54	162	155	108	54	27	0	65	27			62
1993		54	54	27	27	85	31	100	112	112			71
1994		268	27	81	224	247	177	69	220	144			166
1995	92	54	81	0	0	0	0		58	179	117	310	40
1996	463	31	0	297	283	58	279	144	200	127	273	220	198
1981–1988, 1996	74	31	29	48	55	63	75	120	51	55	68	63	

Table 15 Monthly and annual abundance indices of age–1+ *C. productus* collected with the otter trawl from 1980 to 1996. The index period is February to October.

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Feb–Oct*
1980		0	0	0	0	0	0	0	0	0	0	0	0
1981	0	0	0	0	0	31	0	0	0	0	0	0	3
1982	0	0	0	0	31	0	0	0	0	0	0	0	3
1983	0	0	0	0	0	0	27	0	0	0	0	54	3
1984	0	0	0	0	0	0	0	27	0	81	0	54	12
1985	27	0	0	0	0	54	27	0	27	0	100	0	12
1986	54	31	0	0	0	0	0	0	0	0	0	0	3
1987	0	0	0	27	0	0	0	0	27	54	0	27	12
1988	0	0	0	27	0	46	0	0	0	0	0	0	8
1989	0	0	0	35	0	0	81	54					24
1990		27	81	27	27	27	0	0	0	0			21
1991		27	0	0	81	162	0	0	81	27			42
1992		0	54	54	0	108	81	0	0	27			36
1993		0	0	58	27	0	0	0	0	27			12
1994		58	121	27	81	0	0	0	27	27			38
1995	85	0	27	0	0	27	0		0	0	0	81	7
1996	19	0	31	27	0	54	27	27	27	54	0	0	27
1981–1988, 1996	11	3	3	9	3	21	9	6	9	21	11	15	

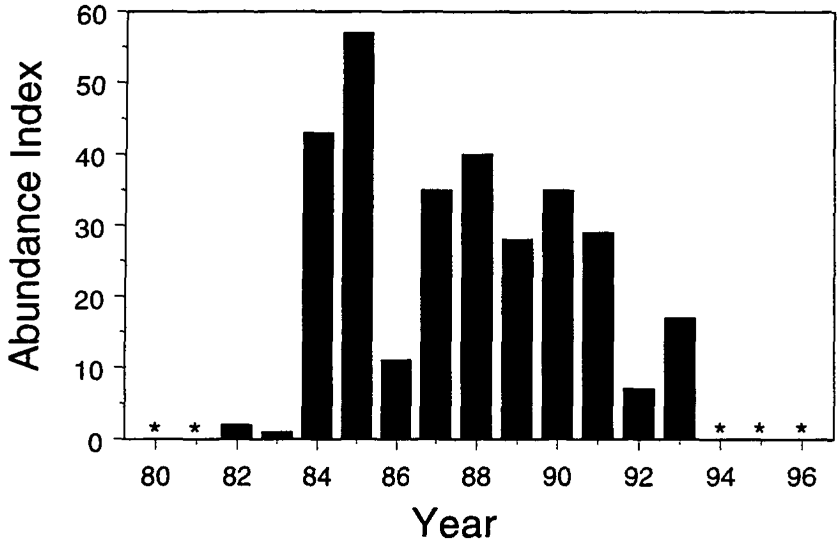

Figure 31 Annual abundance indices (CPUE x 10) of all sizes of *C. productus* collected with the ringnets from 1982 to 1993. The index period is July to December. Asterisk (*) indicates no survey.

Table 16 Monthly and annual abundance indices of all sizes of *C. productus* collected with the ringnets from 1982 to 1993. The index period is July to December. CPUE x 10.

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Jul–Dec*
1982					0	0	0	0	10	1	0	2	2
1983	0	0	0	0	1	0	0	0	0	1	6	0	1
1984	33	6	7	2	0	2	33	21	24	103	17	57	43
1985	43	17	24	20	40	40	29	43	104	67	51	46	57
1986	27	0	0	0	1	0	1	16	13	16	6	18	11
1987	10	10	34	17	47	30	40	40	37	37	21	35	35
1988	21	11	10	13	21	31	83	40	23	49	24	20	40
1989	26	1	1	7	8	14	30	28	38	42	19	18	28
1990							40	29	24	50	43	20	35
1991							63	20	39	22	20	11	29
1992							14	9	4	7	3	8	7
1993							2	20	12	24	29	16	17
1983–1989	23	6	11	8	16	17	31	27	34	45	20	28	

Table 17 Monthly catch of *C. productus* zoeae (1980 to 1985) and megalopae (1980 to 1988)

Month	*Zoeae*	*Megalopae*
January	5288	0
February	3969	1
March	3621	2
April	8130	19
May	9975	1
June	3355	10
July	1377	1
August	1247	1
September	1433	0
October	1526	0
November	6883	21
December	7290	0

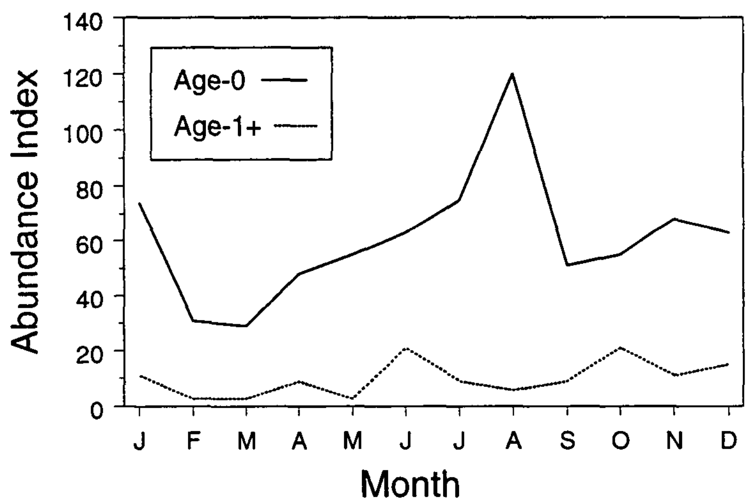

Figure 32 Monthly abundance of age–0 and age–1+ *C. productus* collected with the otter trawl from 1981 to 1988 and in 1996

Cancer productus zoeae were most abundant from November through January and in April and May, and megalopae were most abundant from March through June (Table 17). Age–0 *C. productus* were least abundant in February and March; the indices increased steadily from April though August (Figure 32, see Table 14). Abundance may be bimodal, as the index increased again from November to January. Age–1+ *C. productus* from the otter trawl were generally least abundant from February through May and most abundant from July through October (see Figure 32, see Table 15). The lowest ringnet indices were from February through April; the indices then increased slowly to a peak in October (Figure 33, see Table 16).

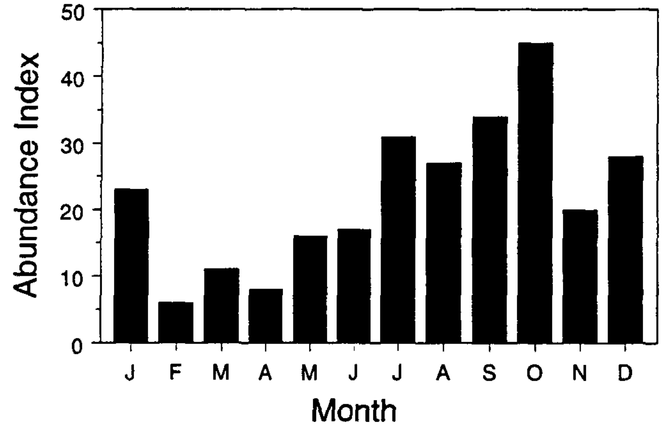

Figure 33 Monthly abundance (CPUE x 10) of all sizes of *C. productus* collected with the ringnets from 1983 to 1989

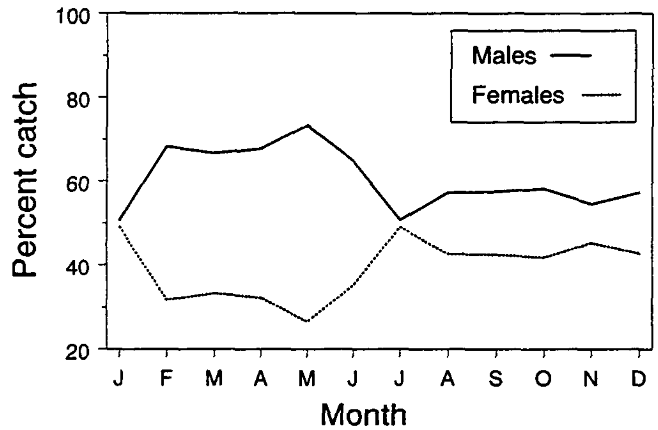

Figure 34 Monthly percent catch of male and female age–1+ *C. productus* collected with the otter trawl and ringnets

Overall, male *C. productus* outnumbered females approximately 3:2, but the magnitude of this dominance changed with time. Males accounted for at least 65% of the age–1+ catch from February through June but only 50% to 60% of the catch all other months (Figure 34).

Distribution

Cancer productus zoeae were concentrated in Central Bay, but were occasionally collected as far upstream as Carquinez Strait. Most megalopae were collected in Central Bay. Although age–0 and age–1+ crabs were collected with the otter trawl from South Bay, near the Dumbarton Bridge to Carquinez Strait, they were most common in the northern portion of South Bay (stations #108 and #109), Central Bay (especially station #213), and lower San Pablo Bay (station #323) (see Methods chapter, Figure 1). Smaller crabs (<35 mm) were more widely distributed than larger crabs and crabs >75 mm were generally restricted to Central Bay. The highest ringnet catches were at the Point Pinole (#396), Paradise (#294), and Muni Pier (#293) stations (ordered by catch).

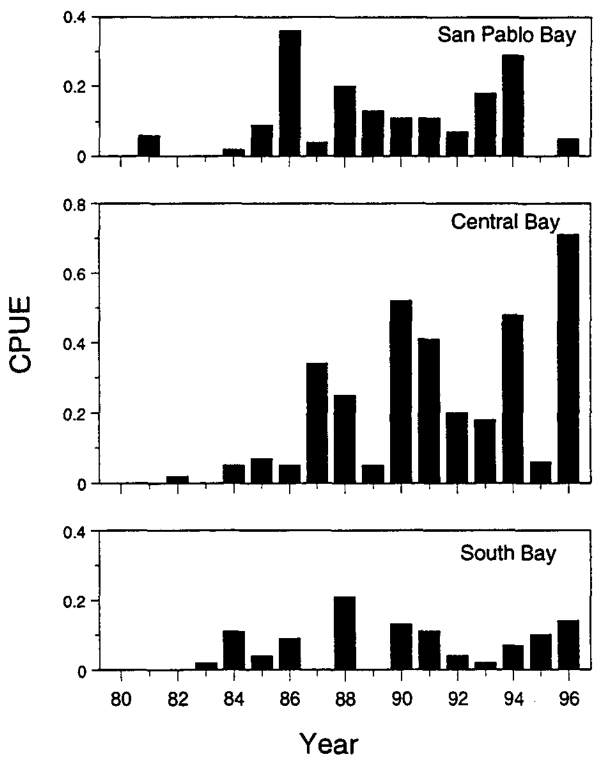

Figure 35 Annual distribution (CPUE) of age–0 *C. productus* collected with the otter trawl for April to October from 1980 to 1996

Distribution of age–0 *C. productus* was centered in Central Bay most years (Figure 35). In years with relatively low abundance, CPUE was often highest in South Bay (1983, 1984, 1995) or San Pablo Bay (1981, 1985, 1985, and 1989), which may reflect low, sporadic catches. Age–1+ crabs were concentrated in Central Bay in all years except for 1981, when CPUE was highest in South Bay (Figure 36).

There was some seasonal movement of age–0 *C. productus*, as CPUE was highest in South Bay in winter and Central Bay in spring and summer (Figure 37). Distribution expanded to San Pablo Bay in summer and to South Bay in fall. There is little evidence of seasonal movements of age–1+ *C. productus*; some crabs may move from Central Bay to South Bay in winter (Figure 38).

Salinity and Temperature

Most *C. productus* were collected at salinities ranging from 23‰ to 32‰ and temperatures from 10 to 20 °C (Figure 39). The otter trawl mean salinity (28.4‰) was slightly higher than the ringnet mean salinity (27.5‰), while the otter trawl mean temperature (15.4 °C) was slightly lower than the ringnet mean temperature (15.7 °C) (Table 18). Male and female *C. productus* were collected at nearly identical salinities and temperatures by both gear types. The major difference was in the otter trawl, where females were collected at a somewhat lower mean salinity than males (14.6‰ compared to 15.2‰).

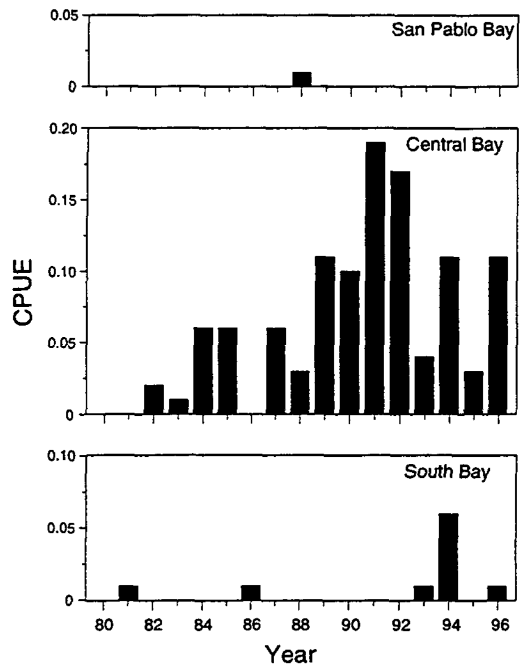

Figure 36 Annual distribution (CPUE) of age–1+ *C. productus* collected with the otter trawl for February to October from 1980 to 1996

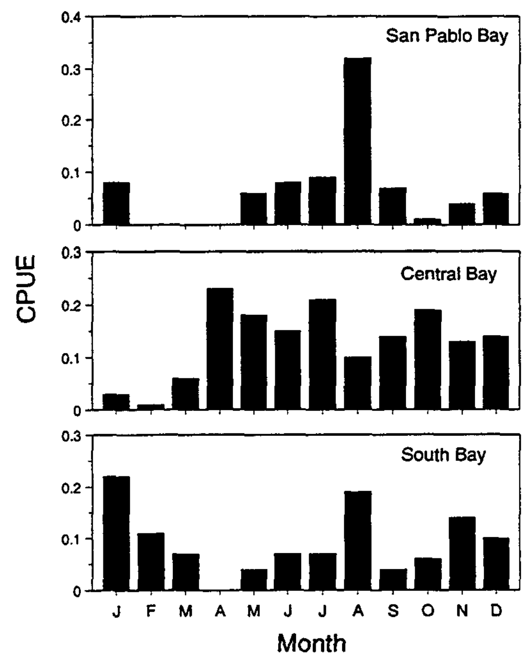

Figure 37 Monthly distribution (CPUE) of age–0 *C. productus* collected with the otter trawl from 1981 to 1988 and in 1996

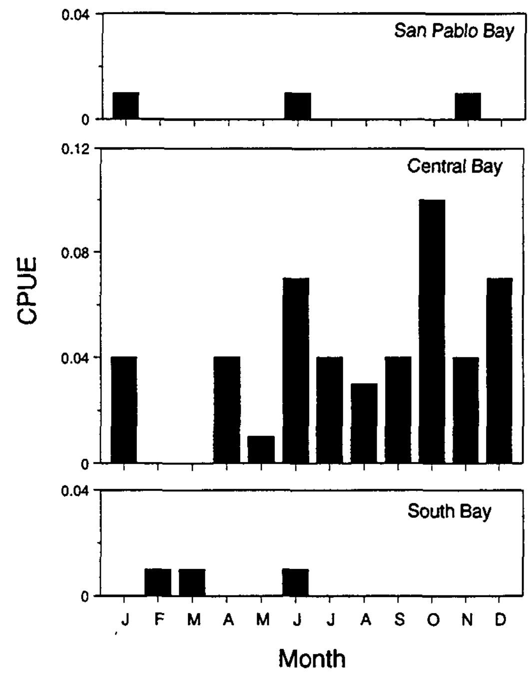

Figure 38 Monthly distribution (CPUE) of age–1+ *C. productus* collected with the otter trawl from 1981 to 1988 and in 1996

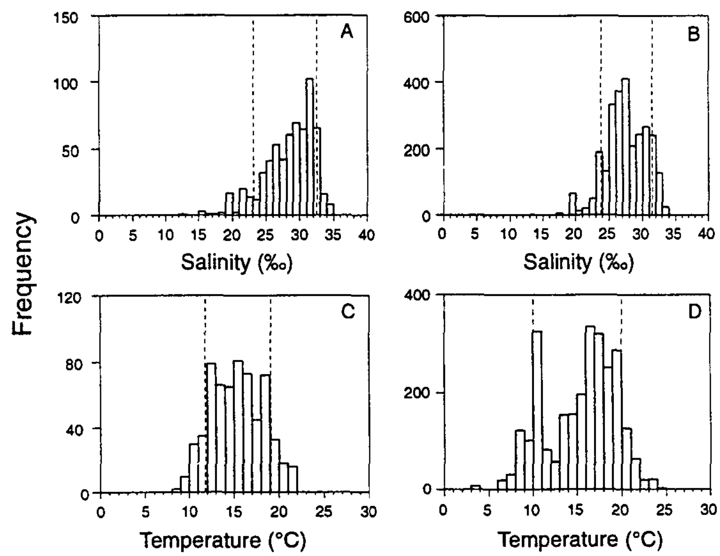

Figure 39 Salinity (‰) and temperature (°C) distributions of all sizes of *C. productus* collected with the otter trawl (1980 to 1996) and ringnets (1982 to 1994): (A) salinity, otter trawl; (B) salinity, ringnets; (C) temperature, otter trawl; (D) temperature, ringnets. Dashed vertical lines are the 10th and 90th percentiles.

Table 18 Salinity (‰) and temperature (°C) statistics for all sizes of *C. productus* from the otter trawl (1980 to 1996) and ringnets (1982 to 1994)

	Mean (Standard Deviation)	*Minimum*	*Maximum*	*10th Percentile*	*90th Percentile*
Salinity					
Otter trawl	28.4 (3.7)	12.5	34.4	23.1	32.5
Ringnets	27.5 (3.1)	14.0	34.0	23.8	31.4
Temperature					
Otter trawl	15.4 (2.9)	8.3	22.0	11.8	19.1
Ringnets	15.7 (3.9)	6.0	24.5	10.0	20.0

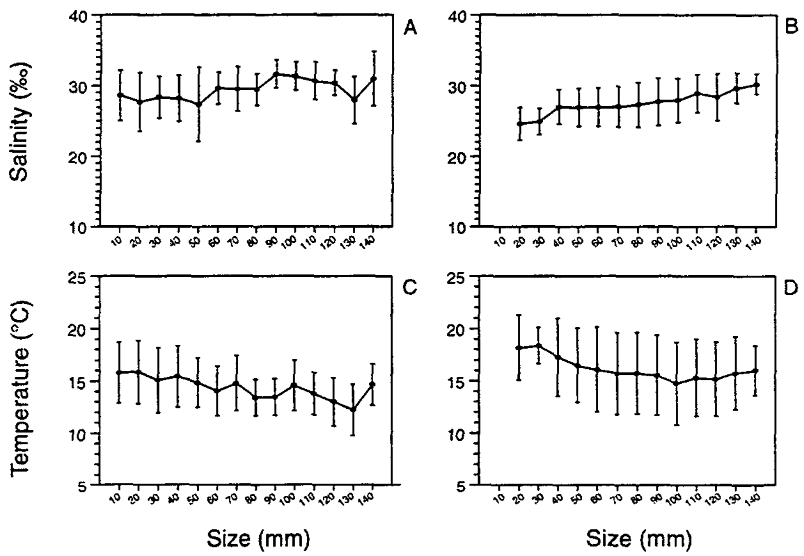

Figure 40 Mean salinity (‰) and temperature (°C) (±1 standard deviation) for *C. productus* by size class collected with the otter trawl and ringnets: (A) salinity, otter trawl; (B) salinity, ringnets; (C) temperature, otter trawl; (D) temperature, ringnets. Size classes are every 10 mm, from 5 to 145 mm for the otter trawl, and 15 to 145 mm for the ringnets.

The mean salinity at point of capture increased slightly with size, especially in the ringnets (Figures 40A and 40B). In contrast, the mean temperature at point of capture decreased with size (Figures 40C and 40D). This trend was also stronger for the ringnet collected crabs.

Discussion

Most *C. productus* use the San Francisco Estuary opportunistically, as an extension of the preferred near-shore coastal habitat. Although some *C. productus* probably rear in the estuary, it is not an important nursery area. *Cancer productus* is widely distributed in the estuary, but it is most common in Central and lower San Pablo bays. This distributional pattern combined with the relatively high salinities at which *C. productus* was collected is consistent with *Cancer* species which do not readily osmoregulate in brackish water (for example, *C. antennarius* and *C. gracilis*). Note that based on the 10th and 90th percentiles, *C. produc-*

tus was collected over a slightly wider salinity range in the otter trawl and ringnets than either *C. antennarius* or *C. gracilis.*

Annual abundance indices were low in the early 1980s and increased through the mid-1990s, a trend which is shared with *C. antennarius* and *C. gracilis*. However, the year in which abundance first increased and was highest differed by species. All 3 species had several years of high abundance (for example, 1994 and 1996) and low or decreased abundance (for example, 1982, 1983, and 1995) in common. Freshwater outflow apparently affects *C. productus* abundance to some extent, as indices were generally lower in high outflow years than in low outflow years. This is probably due to decreased salinities in the estuary, but may also be related to unfavorable ocean currents associated with frequent winter storms.

The relatively high abundance of *C. productus* in the ringnets compared to the otter trawl is probably because crabs of all sizes prefer areas with structure rather than open channels or shoals. Although *C. productus* was not common enough in the otter trawl to analyze seasonal movement from channel to shoals, the increased abundance in the ringnets in summer may reflect a movement from deeper water. Alternatively, this abundance increase may be due to immigration to the estuary from the ocean. Some *C. productus* undoubtedly emigrate from the estuary in response to decreased salinities in winter and immigrate to the estuary as salinities increase in summer. A similar migration pattern has been reported in Coos Bay, Oregon (Selby 1980).

Seasonal abundance trends of zoeae, megalopae, and small juveniles correspond with the findings of other researchers. The dominance of males from February to May is similar to the Puget Sound results, where males outnumbered females from January to May (Knudsen 1964). The most likely scenario is that females emigrate from the estuary for larval hatching in the winter and immigrate back to the estuary starting in June. This female migration has been hypothesized to facilitate estuarine use by *C. productus* (Orensanz and Gallucci 1988) and is probably initiated by decreasing salinities. The dominance of males in the smaller, pre-puberty size classes (<50 mm), and females in the size classes associated with puberty (55 to 79 mm) has not been reported in the literature, but is reported for *C. antennarius* in this chapter.

Cancer antennarius

Cancer antennarius, the brown rock crab, ranges from Oregon to Baja California and is most common from Point Conception to San Francisco (Carroll and Winn 1989). It mainly inhabits rocky intertidal and subtidal areas along the outer coast (Garth and Abbott 1980) and has been collected to 79 m (Jensen 1995). In southern California coastal waters *C. antennarius* is most abundant at rock-sand interfaces and extensive rocky reefs (Winn 1985). It is reported to be a strictly marine species which does not readily osmoregulate in brackish water (Jones 1941, Gross 1957). *Cancer antennarius* lives to 7 years and males reach a maximum size of 160 mm and females about 150 mm (Carroll 1982).

In central California, ovigerous *C. antennarius* are present in all months, but are most common in winter (Carroll 1982). Females produce at least 2 broods per instar and 1 brood per season (Shields 1984). Larvae are most abundant in spring and early summer and 1st instar crabs are most common in late spring and summer (Carroll 1982, Winn 1985). Both sexes mature at 60 to 80 mm (the 10th to 12th instars), which is 2 years after settlement in central California (Carroll 1982).

The highest catches of *C. antennarius* in southern California occurred in October and November and the lowest catches from June to August (Winn 1985). Similar seasonal trends were reported from central California, where the fall abundance peak was attributed to an increase in females (Carroll 1982). Male abundance remained relatively stable throughout the year and, overall, males outnumbered females 1.4:1.

Carroll hypothesized that females migrated inshore in fall in response to warmer water temperatures, but a concurrent tagging study showed no seasonal trends in crab movement. From a literature review, Orensanz and Gallucci (1988) concluded that both male and female *C. antennarius* remain in the same area all year.

The large chelae of *C. antennarius* are efficient in crushing mollusk shells. Gastropods (for example, *Tegula*), cockles, barnacles, hermit crabs, and abalone are common prey items along the open coast (Carroll and Winn 1989). In the San Francisco Estuary, *C. antennarius* was frequently consumed by brown smoothhound and rubberlip seaperch, and occasionally consumed by big skate, pile perch, staghorn sculpin, and starry founder (CDFG, unpublished data). Staghorn sculpin and starry flounder were also reported to prey upon *C. antennarius* by Boothe (1967).

Methods

Male and female *C. antennarius* <50 mm were classified as age 0 and all larger crabs as age 1+. The annual index periods selected were as follows: May through October for age–0 *C. antennarius* from the otter trawl, February through October for age–1+ crabs from the otter trawl, and July through December for crabs (all age classes) from the ringnets. Age–1+ crabs from the otter trawl and ringnets were used for analysis of seasonal sex ratio trends. For analysis of channel-shoal distribution, stations #109 (channel) and #142 (shoal) were selected based on the relatively high catches of *C. antennarius*.

Results

Size and Size Frequency

The largest male *C. antennarius* collected by this study was 134 mm, the largest female was 129 mm. Only 12 ovigerous females were collected, ranging from 44 to 117 mm. Three were from 44 to 52 mm and the remainder >64 mm. The otter trawl primarily collected age–0 crabs <35 mm (Figure 41A), while the ringnets primarily collected age–1+ crabs (Figure 41B). From June through December, a mode of smaller crabs was readily distinguishable in the otter trawl (Figure 42). Larger crabs were collected by the otter trawl in most months, but were most common from January through June.

Overall, male *C. antennarius* were more common than females, but this dominance changed with size. The male to female ratio was 2:1 for crabs 20 to 49 mm, 1.4:1 for crabs 50 to 74 mm, 0.6:1 for crabs 75 to 109 mm, and 1.5:1 for crabs >110 mm. The ratio of males to females was 1:1 in the ringnets, which collected more large crabs, and 1.7:1 in the otter trawl, which collected more small crabs.

Abundance

Cancer antennarius was the 3rd most commonly collected species in the otter trawl and the ringnets but was rarely collected in the beach seine (see Table 1). Overall, it was the least common of the 4 *Cancer* crabs included in this report. The annual abundance indices of age–0 crabs in the otter trawl were relatively low from 1980 to 1992, but increased significantly in 1993 (Figure 43A, Table 19). Because the otter trawl catch of age–1+ crabs was relatively low in all years (total annual catch ranged from 0 to 24), the abundance and distributional trends should be interpreted cautiously. The abundance indices of age–1+ crabs from the otter trawl increased later in the study period, with the highest indices in 1991, 1993, 1994, and 1996 (Figure 43B, Table 20). In contrast, the annual abundance trend from the ringnets (dominated by age–1+ crabs) was bimodal, with the highest indices from 1985 to 1988 and in 1992 (Figure 44, Table 21).

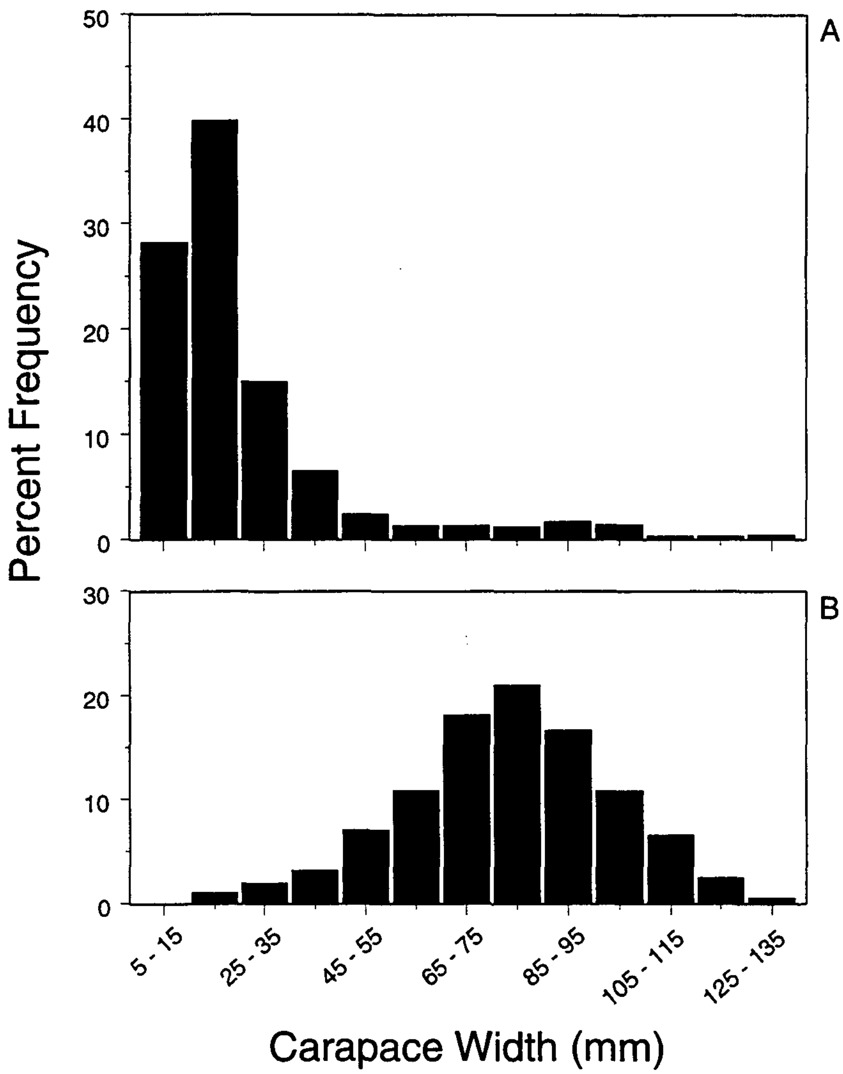

Figure 41 Size frequency of *C. antennarius*: (A) otter trawl, 1980 to 1996; (B) ringnets, 1982 to 1994. Size classes are every 10 mm, from 15 to 135 mm.

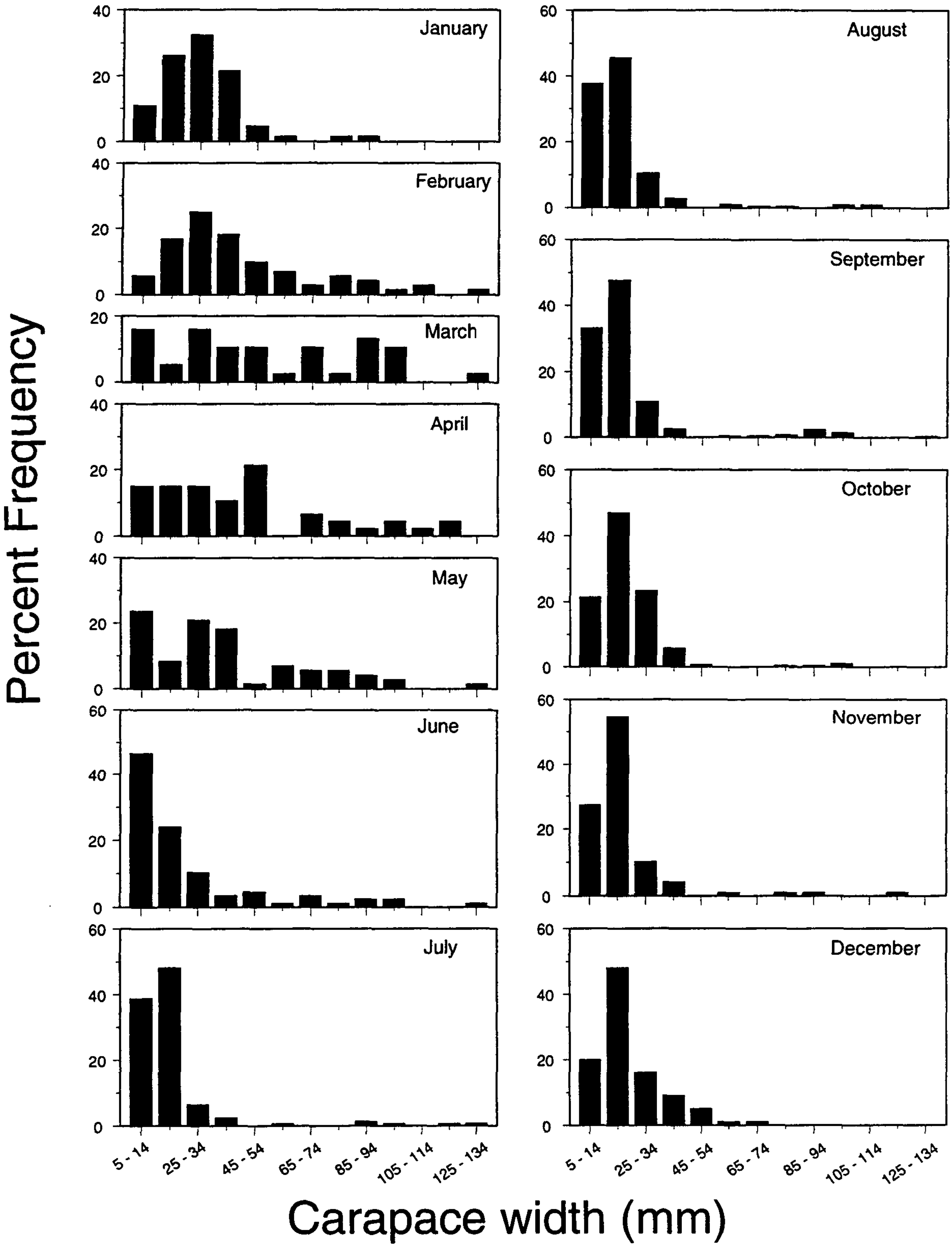

Figure 42 Size frequency of *C. antennarius* by month collected with the otter trawl. Size classes are every 10 mm, from 5 to 135 mm.

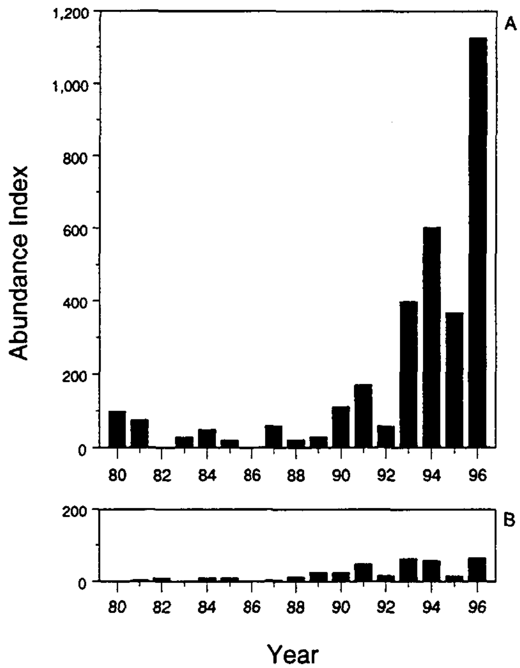

Figure 43 Annual abundance indices of *C. antennarius* collected with the otter trawl from 1980 to 1996: (A) age 0, the index period is May to October; (B) age 1+, the index period is February to October

Table 19 Monthly and annual abundance indices of age–0 *C. atennarius* from the otter trawl from 1980 to 1996. The index period is May to October.

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*May–Oct*
1980		31	0	27	0	0	0	0	0	594	19	31	99
1981	27	0	0	0	43	31	0	313	31	36	0	0	76
1982	36	0	0	0	0	0	0	0	0	0	0	31	0
1983	0	0	0	0	54	0	27	0	85	0	0	0	28
1984	54	54	31	27	0	27	58	85	132	0	242	85	50
1985	117	0	58	0	0	89	0	0	31	0	0	0	20
1986	0	0	0	0	0	0	0	0	0	0	63	31	0
1987	109	177	31	0	0	58	150	27	0	132	246	58	61
1988	54	54	0	0	50	0	27	0	19	31	0	0	21
1989	0	27	0	0	85	0	0	31					29
1990		0	0	27	27	0	135	146	216	150			112
1991		144	46	54	216	19	219	119	296	158			171
1992		96	104	81	131	46	19	0	58	104			60
1993		171	54	243	0	81	660	601	576	467			398
1994		192	117	109	31	731	332	659	1174	688			603
1995	651	58	27	54	27	0	58		735	1015	210	491	367
1996	310	108	0	108	189	58	1097	1957	1754	1699	1332	1184	1126
1981–1988, 1996	79	44	13	15	37	29	151	265	228	211	209	154	

Table 20 Monthly and annual abundance indices of age–1+ *C. atennarius* from the otter trawl from 1980 to 1996. The index period is February to October.

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Feb–Oct*
1980		0	0	0	0	0	0	0	0	0	36	0	0
1981	0	0	0	0	0	0	0	0	31	0	0	0	3
1982	0	0	0	0	0	0	0	27	0	53	0	0	9
1983	0	0	0	0	0	0	0	0	0	0	0	0	0
1984	0	0	0	0	0	0	27	54	0	0	0	27	9
1985	0	27	0	27	27	0	0	0	0	0	0	0	9
1986	0	0	0	0	0	0	0	0	0	0	0	0	0
1987	0	27	0	0	0	0	0	0	0	0	81	0	3
1988	0	31	0	0	27	27	0	0	0	27	0	0	12
1989	0	27	0	122	0	0	27	0					25
1990		0	81	0	27	27	0	0	27	54			24
1991		27	54	0	0	0	27	54	270	0			48
1992		27	0	0	0	81	0	27	0	0			15
1993		135	270	27	27	27	0	27	54	0			63
1994		135	27	81	162	81	0	0	27	0			57
1995	81	27	54	0	27	0	0		0	0	0	27	14
1996	27	85	0	81	225	81	27	0	27	54	0	27	64
1981–1988, 1996	3	19	0	12	31	12	6	9	6	15	9	6	

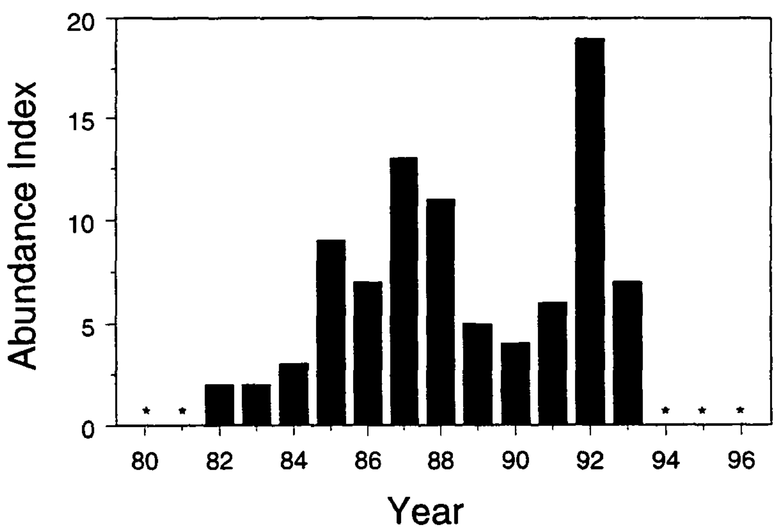

Figure 44 Annual abundance indices (CPUE x 10) of all sizes of *C. antennarius* collected with the ringnets from 1982 to 1993. The index period is July to December. Asterisk (*) indicates no survey.

Table 21 Monthly and annual abundance indices of *C. antennarius* collected with the ringnets from 1982 to 1993. The index period is July to December. CPUE x 10.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jul–Oct
1982					0	0	1	4	0	1	0	2	2
1983	0	0	0	0	0	0	0	0	0	1	9	1	2
1984	5	2	1	0	3	4	1	2	3	8	1	4	3
1985	4	1	0	0	3	0	0	2	9	3	29	8	9
1986	3	0	0	0	0	8	0	9	12	3	7	9	7
1987	2	1	9	10	17	4	11	9	21	18	11	6	13
1988	0	7	9	4	4	9	8	12	7	10	18	9	11
1989	6	1	2	1	3	12	10	3	11	0	1	3	5
1990							12	4	4	1	1	2	4
1991							20	3	2	1	6	2	6
1992							15	3	10	16	27	41	19
1993							0	9	14	7	4	7	7
1983–1989	3	2	3	2	4	5	4	5	9	7	11	6	

Table 22 Monthly catch of *C. antennarius* stage 2 to 5 zoeae (1980 to 1985) and megalopae (1980 to 1988)

Month	Zoeae	Megalopae
January	277	18
February	1609	17
March	748	62
April	36905	88
May	387	98
June	160	169
July	174	427
August	30	19
September	155	6
October	360	4
November	454	1
December	320	67

Cancer antennarius zoeae and megalopae were collected all year, but zoeae were most common from February through April and megalopae were most common from March through July (Table 22). Eight of the 12 ovigerous females were collected from December through April and the remainder from June through August. Age–0 crabs were most abundant from July through December in the otter trawl (Figure 45, see Table 19). Seasonal abundance of age–1+ crabs from the otter trawl was possibly bimodal, with peaks in fall and spring (see Figure 45, see Table 20). But in the ringnets, *C. antennarius* was most abundant in fall (Figure 46, see Table 21). Age–1+ male *C. antennarius* outnumbered females from February through May, while females generally outnumbered males from July though January (Figure 47).

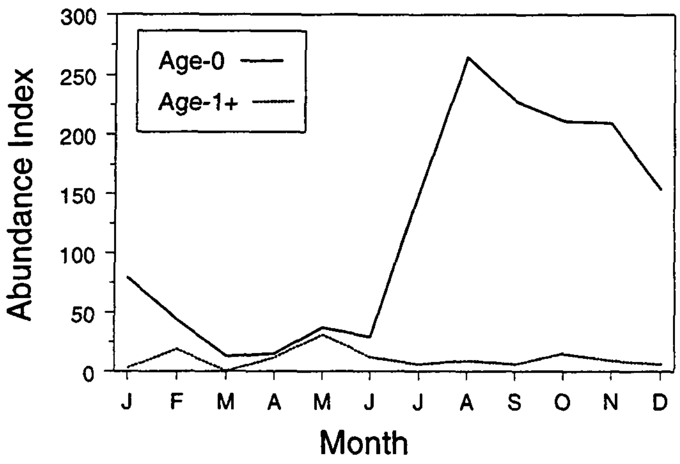

Figure 45 Monthly abundance indices of age–0 and age–1+ *C. antennarius* collected with the otter trawl from 1981 to 1988 and in 1996

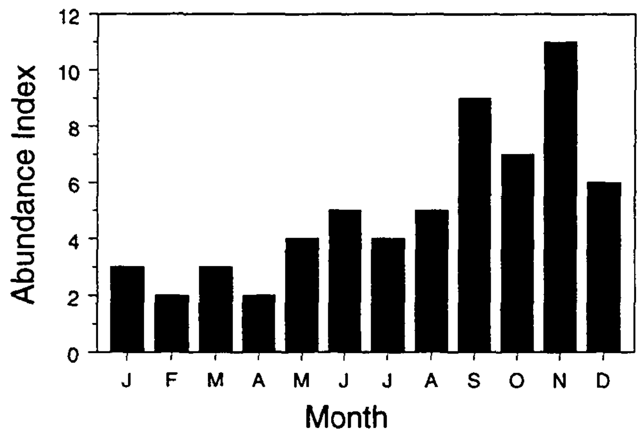

Figure 46 Monthly abundance indices (CPUE x 10) of all sizes of *C. antennarius* collected with the ringnets from 1983 to 1989

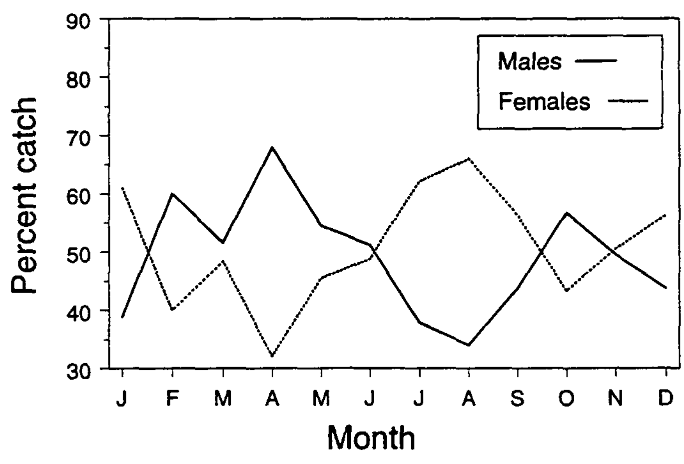

Figure 47 Monthly percent catch of male and female age–1+ *C. antennarius* collected with the otter trawl and ringnets

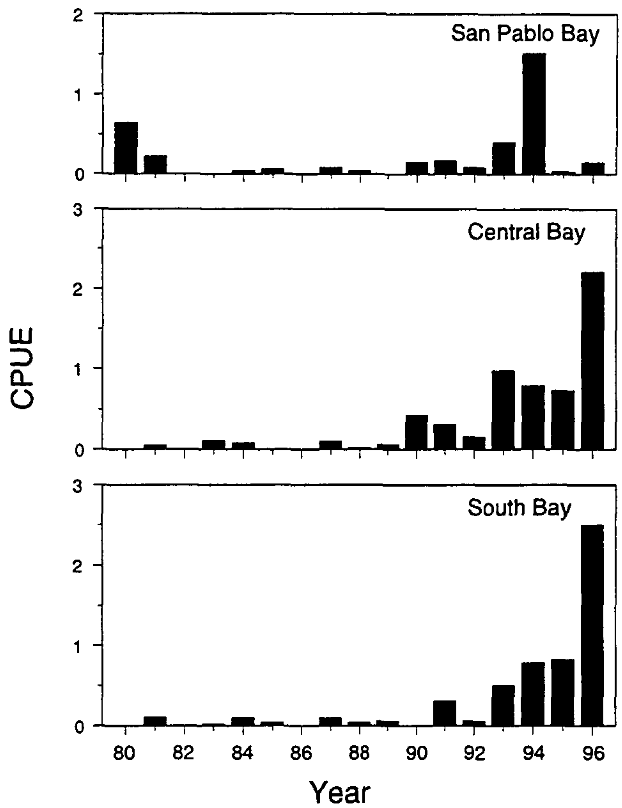

Figure 48 Annual distribution (CPUE) of age–0 *C. antennarius* collected with the otter trawl for May to October from 1980 to 1996

Distribution

Cancer antennarius zoeae were concentrated in South and Central bays; only a few zoeae were collected in San Pablo Bay and Carquinez Strait. Later stage zoeae and megalopae were most common in Central Bay. Age–0 *C. antennarius* were more widely distributed in the estuary than age–1+ crabs, as age–0 crabs were commonly collected from mid-South Bay through lower San Pablo Bay and age–1+ crabs were common only in Central Bay and lower San Pablo Bay. Age–0 crabs were most common near San Leandro and Oakland, with the highest catches at 2 shoal stations (#105 and #142) and 2 nearby channel stations (#108 and #109) (see Methods chapter, Figure 1). In the otter trawl, age–1+ crabs were most common at the Central Bay channel stations, especially station #213, and in the ringnets they were most commonly collected at the Muni Pier (#293) and Point Pinole (#396) stations.

The distribution of age–0 *C. antennarius* prior to 1993, when abundance was low, was very mixed relative to outflow (Figure 48). But from 1993 to 1996, when abundance was high, the center of distribution of age–0 crabs changed with outflow: CPUE was highest in South Bay in 1995 and 1996 (both "wet" years), in Central Bay in 1993 (an "above normal" year), and in San Pablo Bay in 1994 (a "critical" year). The distribution of age–1+ crabs from the otter trawl apparently did not shift upstream in low outflow years, as this age class was most common in Central Bay in all years except for 1981, when CPUE was highest in South Bay (Figure 49). But there was evidence of an upstream shift of larger crabs in the ringnet data, as *C. antennarius* was collected at the Point Pinole (#396) station in lower San Pablo Bay in all years except 1982 and 1983 (both "wet" years) and as far upstream as Crockett (Carquinez Strait) in several of the "dry" or "critical" years.

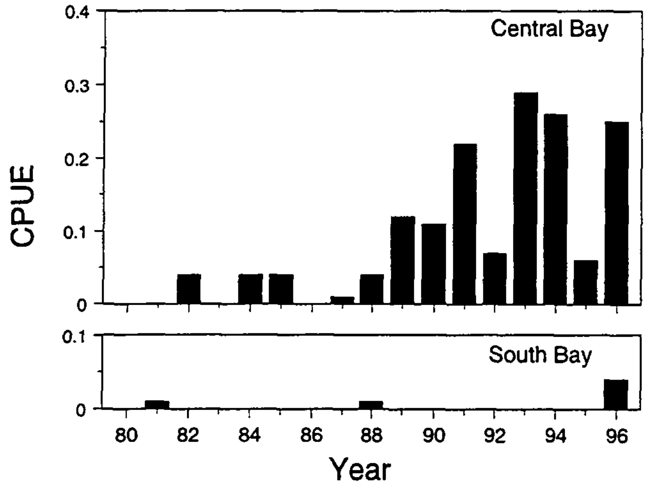

Figure 49 Annual distribution (CPUE) of age–1+ *C. antennarius* collected with the otter trawl for February to October from 1980 to 1996

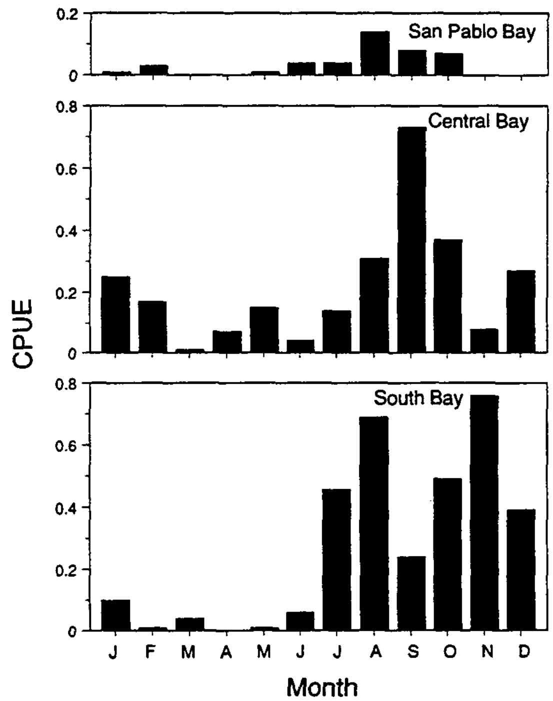

Figure 50 Monthly distribution (CPUE) of age–0 *C. antennarius* collected with the otter trawl from 1981 to 1988 and in 1996

Age–0 *C. antennarius* may move seasonally in the estuary, as they were more common in Central Bay from January through May and in South Bay from July through December (Figure 50). There is also some seasonal use of San Pablo Bay, where the highest CPUE was from June through October. But the otter trawl data show no evidence of a seasonal movement of age–1+ *C. antennarius*, as CPUE was highest in Central Bay in all months (Figure 51). However, there was a trend of increasing ringnet catches in San Pablo Bay from June through November.

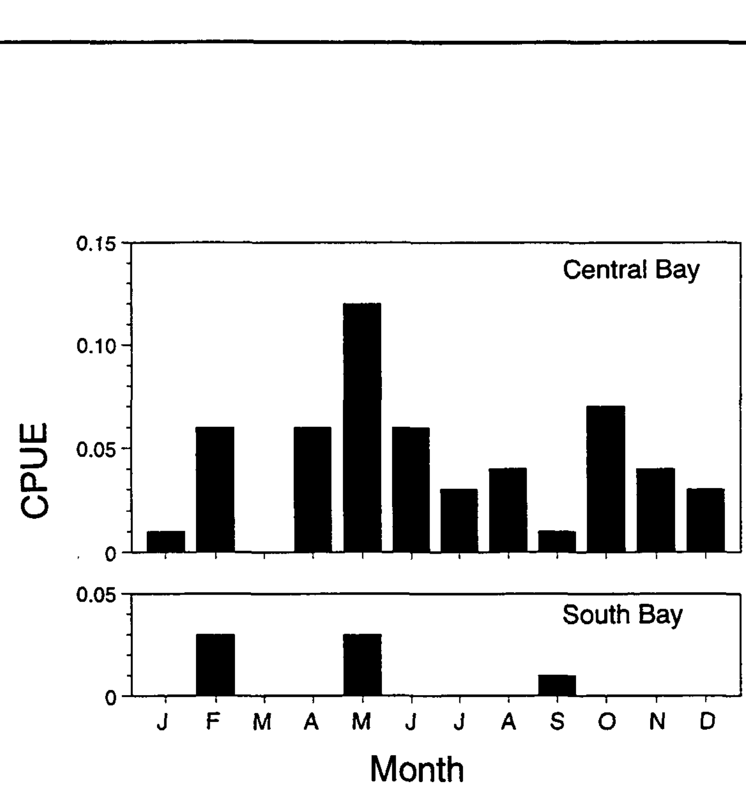

Figure 51 Monthly distribution (CPUE) of age–1+ *C. antennarius* collected with the otter trawl from 1981 to 1988 and in 1996

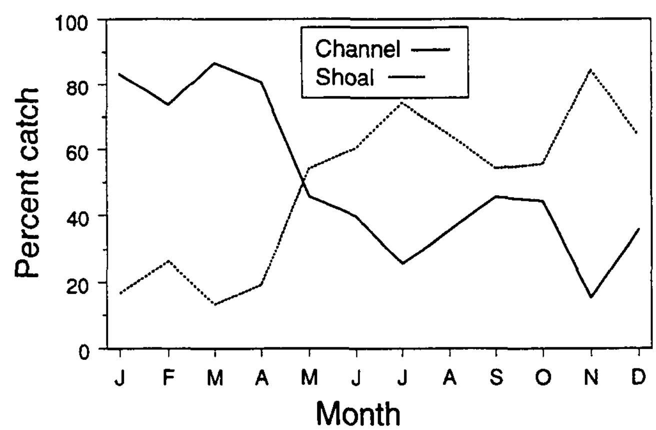

Figure 52 Channel-shoal percent catch of *C. antennarius* by month from 1988 to 1996 at station #109 (channel) and station #142 (shoal)

Cancer antennarius apparently move seasonally from channels to shoals within the estuary. For the selected channel-shoal station pair (stations #109 and #142), crabs were more common at the channel station from January through April and at the shoal station from June through December (Figure 52).

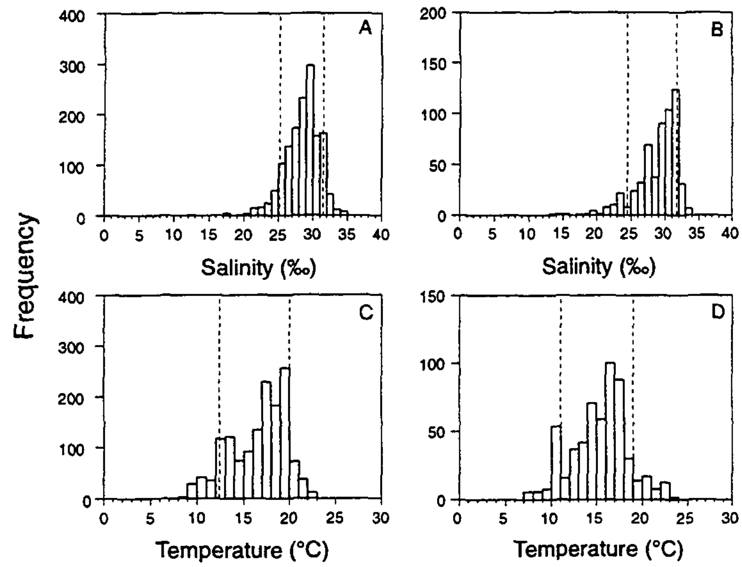

Figure 53 Salinity (‰) and temperature (°C) distributions of all sizes of *C. antennarius* collected with the otter trawl (1980 to 1996) and ringnets (1982 to 1994): (A) salinity, otter trawl; (B) salinity, ringnets; (C) temperature, otter trawl; (D) temperature, ringnets. Dashed vertical lines are the 10th and 90th percentiles.

Table 23 Salinity (‰) and temperature (°C) statistics for all sizes of *C. antennarius* from the otter trawl (1980 to 1996) and ringnets (1982 to 1994)

	Mean (Standard Deviation)	*Minimum*	*Maximum*	*10th Percentile*	*90th Percentile*
Salinity					
otter trawl	28.5 (2.5)	12.5	34.4	25.2	31.5
ringnets	29.0 (3.0)	13.6	34.0	24.5	31.7
Temperature					
otter trawl	16.7 (3.0)	8.1	22.6	12.4	20.0
ringnets	15.7 (3.1)	8.0	24.0	11.0	19.0

Salinity and Temperature

Most *C. antennarius* were collected at salinities ranging from 25‰ to 32‰ and temperatures from 11 to 20 °C (Figure 53). *Cancer antennarius* was collected at similar salinities in the otter trawl and ringnets (mean = 28.5‰ and 29.0‰, respectively), but at slightly higher temperatures in the otter trawl than the ringnets (mean = 16.7 °C and 15.7 °C, respectively) (Table 23). Female *C. antennarius* were collected at slightly higher salinities and lower temperatures than males in both gear types.

There was a slight increase in salinity with size (Figure 54A); the mean salinity was 28.5‰ for the 15 to 24 mm size group (n = 591) and 30.0‰ for the 95 to 104 mm size group (n = 81). There was also a decrease in temperature with size (Figure 54B), as the mean temperature was 17.4 °C for the 15 to 24 mm size group and 15.2 °C for the 95 to 104 mm size group.

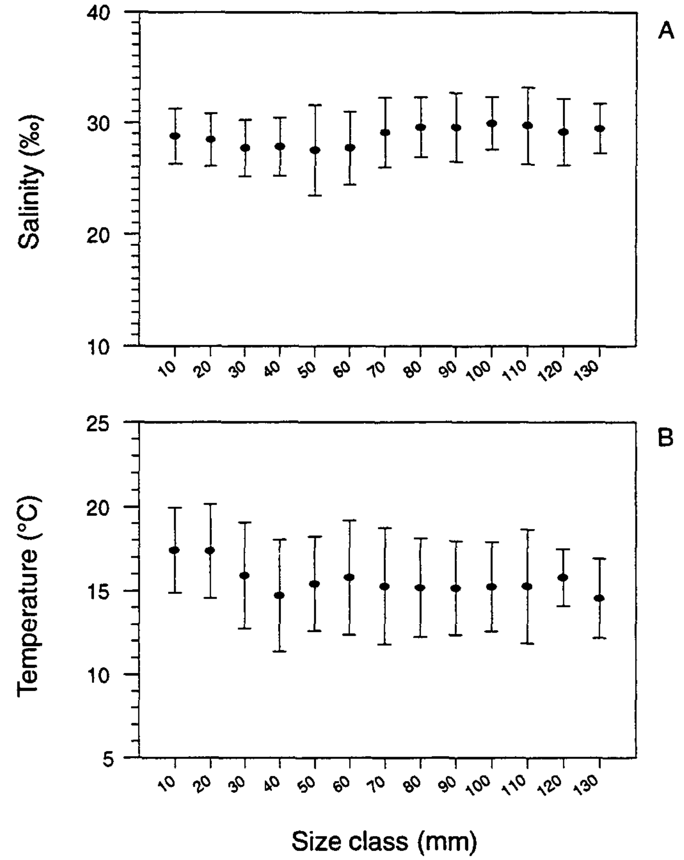

Figure 54 Mean salinity and temperature (±1 standard deviation) for *C. antennarius* by size class collected with the otter trawl and ringnets: (A) salinity (‰) and (B) temperature (°C). Size classes are every 10 mm, from 5 to 135 mm.

Discussion

It has been proposed that *C. antennarius*, which is considered to be a "marine" species, is not a successful inhabitant of estuaries (Orensanz and Gallucci 1988). Our data appear to partially support this conclusion for the San Francisco Estuary, as the abundance of *C. antennarius* was relatively low compared to *C. magister* and *C. gracilis* from the otter trawl and *C. magister* and *C. productus* from the ringnets. The low otter trawl catches are not unexpected, as *C. antennarius*, like *C. productus*, prefers rocky substrates which are not sampled effectively by this gear. The relatively low ringnet catches may be a function of limited estuarine use by *C. antennarius* due to salinity tolerance or exclusion from preferred protected habitats by the larger rock crab, *C. productus*. Although *C. antennarius* was collected at slightly higher salinities than *C. productus* in both the otter trawl and ringnets, it was collected at slightly lower salinities than *C. gracilis* in the otter trawl. For whatever reasons, *C. antennarius* apparently uses the estuary opportunistically as an extension of its nearshore coastal habitat and is usually not resident in the estuary.

Because *C. antennarius* was not as commonly collected in the otter trawl as the other species of *Cancer* crabs included in this chapter, it is difficult to interpret some of the abundance and distribution data. The trend of increasing annual abundance indices through the 1990s is similar to the abundance trends reported for *C. gracilis* and *C. productus*, with some high abundance years in common (for example, 1994 and

1996). The same factors may affect year class strength of *C. antennarius*, *C. gracilis* and *C. productus*, but not *C. magister*, in the estuary.

Based on the peak abundance of zoeae, megalopae, and small age–0 crabs, peak settlement of 1st instar *C. antennarius* is in late spring. There is a gradual movement of age–0 crabs to the shoals, especially in the northern portion of South Bay. Older crabs move back to the channels in late fall and by winter age–1+ crabs are concentrated in Central Bay, where most remain. Some age–1+ *C. antennarius*, especially females, may emigrate from the estuary in winter and early spring. This emigration is probably in response to decreasing salinities. Some age–1+crabs probably immigrate to the estuary as salinities again increase through summer and early fall.

An overall male to female ratio which favors males has been previously reported (Carroll 1982), but the dominance of males in the smaller, pre-puberty size classes (<75 mm), and females in the post-puberty size classes (80 to 110 mm) has not. We may have incorrectly identified some of the smaller females (<30 mm) as males, but this would explain only a portion of the bias towards males. The increase in the number of females in June and the relatively large number of mature females collected may be due to a migration of mature female *C. antennarius* to shallower waters, including the estuary, after egg incubation and hatching. An increase in female *C. antennarius* along the central California coast in the fall was attributed to a migration from deeper, cooler waters to warmer, shallower waters (Carroll 1982). Water temperatures in Central Bay are usually warmer than ocean temperatures from March through November (see Salinity and Temperature chapter, Figure 12), which includes most of the months in which mature female *C. antennarius* were more common than males.

Other *Cancer* Species

In addition to the 4 species discussed in this chapter, the San Francisco Bay Study monitoring program collected 46 *C. anthonyi* and 2 *C. jordani* (see Table 1). *Cancer anthonyi* ranges from Baja California to Humboldt Bay, and is most common south of Point Conception (Carroll and Winn 1989). Specimens collected by this study ranged from 7 to 122 mm, and all but 8 were <50 mm. One ovigerous female (113 mm) was collected. No *C. anthonyi* were collected or were identified prior to 1987 and the otter trawl catches were highest from 1990 to 1994 (Table 24). This trend of increasing catches in the early 1990s was also reported for *C. antennarius*, *C. gracilis*, and *C. productus* in this chapter. Although *C. anthonyi* were distributed from mid-South Bay to lower San Pablo Bay, the majority were collected in Central Bay. Salinity at point of collection ranged from 23.9‰ to 33.0‰ and temperature from 10.5 to 19.6 °C.

Cancer jordani ranges from Baja California to Neah Bay, Washington, but is not common north of Oregon (Jensen 1995). Both specimens were 14 mm and were collected from the northern portion of South Bay stations (#108 and #142). Because *C. jordani* is easily confused with *C. antennarius* in the field, it is probably more common in the San Francisco Estuary than indicated by our collections.

Table 24 Annual catch of *Cancer anthonyi* in the otter trawl and ringnets

Year	*Otter trawl*	*Ringnets*
1987	0	1
1988	3	2
1989	1	0
1990	11	1
1991	9	0
1992	5	0
1993	5	0
1994	5	
1995	1	
1996	1	

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Notes

Robert Tasto (California Department of Fish and Game, Menlo Park, California). 1989. Phone conversation with author.

Caridean Shrimp

Kathryn Hieb

Introduction

Caridean shrimp are an important component of the San Francisco Estuary's aquatic resources. They are a food source for many species of fish, crabs, and marine mammals and support a commercial fishery in the estuary. Shrimp are omnivores and prey upon a variety of organisms and plant material. Because of their numerical abundance and position in the food web, they play an important ecological role in the estuary. The San Francisco Bay Study collected 15 species of caridean shrimp from 5 families in the San Francisco Estuary from 1980 to 1996 (Table 1). Because we did not sample rocky habitats or vegetated areas, such as eelgrass beds, this is not a complete list of all species present in the estuary. The 6 most common species of shrimp, *Crangon franciscorum*, *C. nigricauda*, *C. nigromaculata*, *Heptacarpus stimpsoni*, *Palaemon macrodactylus*, and *Lissocrangon stylirostris* are the focus of this chapter. The 4 species of *Crangon* and *H. stimpsoni* are native, but *P. macrodactylus* was accidentally introduced to the estuary from the Orient in the 1950s (Newman 1963).

Table 1 Caridean shrimp catch from the otter trawl, by year, from 1980 to 1996. All surveys and stations sampled are included.

	Year																	
Species	*80*	*81*	*82*	*83*	*84*	*85*	*86*	*87*	*88*	*89*	*90*	*91*	*92*	*93*	*94*	*95*	*96*	*80–96*
Betaeus longidactylus				5		3		1		1	3	6			1			20
Betaeus spp.								1	6		1			2				10
Crangon franciscorum	156466	99029	278402	235743	233313	50763	212716	146024	95814	89151	57732	63831	24656	78464	60093	130387	235881	2248465
Crangon munitella					2	1		1			1	14		1	2		4	26
Crangon nigricauda	25054	11784	7924	16233	6304	8554	26901	50787	75385	52695	79577	92292	70597	60068	53710	35229	77094	750188
Crangon nigromaculata	977	297	562	7149	2884	1233	3568	6785	9552	6307	16931	24579	26759	30440	21196	16656	21429	197304
Exopalamon carinicauda																1		1
Heptacarpus spp.	1																	1
Heptacarpus brevirostris	1			2												3		6
Heptacarpus palpator				1														1
Heptacarpus pictus			6															6
Heptacarpus stimpsonii	1665	574	724	972	1093	1391	1424	5307	5954	8878	8247	16835	7858	8471	6000	4495	9499	89387
Heptacarpus taylori	10			1				1		1	1	1						15
Lissocrangon stylirostris			1	2	1245	333	2100	856	103	32	214	89	43	560	169	933	1010	7690
Lysmata californica					1													1
Palaemon macrodactylus	6165	6376	3282	896	7958	4181	4185	3070	2491	5332	4640	5935	5040	4298	2894	3410	3338	73491
Pandalus danae	1		1	1	1	1	5	8	1	2		2	2		5	4	31	65

Crangon spp. are commonly referred to as "bay shrimp" and *P. macrodactylus* as "pile shrimp"; collectively they are often referred to as "grass shrimp." These species (primarily *C. franciscorum*) are fished commercially by trawlers in the San Francisco Estuary and are currently sold as bait to sport anglers. Since 1980, this fishery has landed between 100,000 and 200,000 pounds per year, although landings approached 3 million pounds per year in the late 1920s and 1930s when bay shrimp were sold for human consumption. From the late 1980s through the early 1990s, the fishery was concentrated in the Alviso Slough and Redwood Creek areas of South Bay. Shrimp were probably abundant in these areas because of the lower salinity water present all year in the vicinity of several sewage treatment plant discharges. Occasionally commercial fishermen are not able to meet demand because of a scarcity of large shrimp suitable for bait (P. Reilly, personal communication, see "Notes").

The life cycles of Crangonidae and Palaemonidae that inhabit shallow coastal waters and estuaries are similar, and they migrate seasonally in response to salinity, temperature, and maturity or life stage (Allen 1966). For example, most *C. franciscorum* larvae hatch in winter and early spring in Central Bay or the Gulf of the Farallones from eggs carried by the females. Post-larvae and juveniles migrate upstream to lower salinity, warmer areas, such as San Pablo and Suisun bays, to rear through the summer. Adult shrimp migrate downstream in fall and winter to higher salinity, cooler waters to complete the life cycle.

All the species included in this report use the estuary as a nursery area, but in varying degrees. They have a slightly different timing of larval hatching and juvenile recruitment to the estuary and use different nursery areas based partly on salinity and temperature preferences (CDFG 1992). All have a short life span—male *Crangon* are generally reported to live for 1 to 1.5 years and females 1 to 2 years, with females growing to a larger size than males. However, *C. franciscorum* has been reported to be a protandrous hermaphrodite, with males transitioning to females at approximately 1 year (Gavio 1994).

All species of shrimp common to the estuary are undoubtedly opportunistic feeders, with diet varying by location and size. For example, *C. franciscorum* from Suisun Bay and the western delta primarily preyed upon *Neomysis mercedis* (Sitts 1978, Siegfried 1980). But in San Pablo Bay, where *N. mercedis* is usually not common, amphipods, bivalve, polychaetes, and isopods dominated the diet of *C. franciscorum* (Wahle 1985). Prey also varied with size: smaller *C. franciscorum* (<30 mm total length, TL) consumed mostly foraminiferans, ostracods, and copepods; intermediate size shrimp consumed mostly amphipods and bivalves; and larger shrimp (>60 mm TL) consumed mostly bivalves, caridean shrimp, and polychaetes (Wahle 1985).

Caridean shrimp are preyed upon by many fishes in the estuary, including striped bass (Johnson and Calhoun 1952, Ganssle 1966), staghorn sculpin (Ganssle 1966, Boothe 1967, Kinnetic Laboratories and Larry Walker Associates 1987), green sturgeon, white sturgeon, brown smoothhound, and Pacific tomcod (Ganssle 1966). They are also consumed by harbor seals and several species of diving ducks (Cottam 1939, Yocom and Keller 1961, Vermeer 1982).

Crangon franciscorum

Crangon franciscorum, the California bay shrimp, is a euryhaline species that is the dominant caridean shrimp in most Pacific coast estuaries (Emmett and others 1991) and the most common species in the San Francisco Estuary (Schmitt 1921, Bonnot 1932, Israel 1936, Ganssle 1966, Hatfield 1985, CDFG 1992). It ranges from southeastern Alaska to San Diego, California (Rathbun 1904), and has been collected from the intertidal to 91 m (Jensen 1995). In the San Francisco Estuary *C. franciscorum* is usually found from South to Suisun and Honker bays, but has been collected as far upstream as the San Joaquin River at Middle River (Israel 1936). Juveniles prefer shallow (<5 m), low salinity waters and migrate to deeper, higher salinity waters as they grow (Israel 1936). A maximum size of 110 mm TL had been reported from the

Columbia River (Emmett and others 1991), but the largest reported sizes from the San Francisco Estuary are 82 mm TL for females and 62 mm TL for males (Israel 1936).

In the San Francisco Estuary, the reproductive season extends from December through June, although some ovigerous females have been collected in all months (Israel 1936). Ovigerous females migrate to higher salinities and in most years they are concentrated in the nearshore ocean area rather than in the estuary (Hatfield 1985). In Yaquina Bay, Oregon, reproduction is bimodal, with older females reproducing from December to March and first time and repeat breeders reproducing from April to August (Krygier and Horton 1975). Ovigerous females were concentrated in the lower portion of Yaquina Bay and adjacent coastal waters, and none were collected at salinities <14.6‰ (Krygier and Horton 1975). Larvae hatch in 10 to 12 weeks in the spring and 8 to 10 weeks in summer. In the laboratory, *C. franciscorum* usually passed through 7 larval stages, although some larvae metamorphosed after only 5 stages. Larvae developed to post-larvae in 14 to 20 days at 20 °C, but at typical estuary or ocean temperatures larval development probably takes 30 to 40 days (Mondo 1980).

The minimum time to reach maturity and life span of *C. franciscorum* varies by location and study. In Yaquina Bay, Oregon, *C. franciscorum* mature within 9 to 12 months from hatching; males mature at 34 mm TL and live to 1 year and females mature at 48 mm TL and live to 1.5 years (Krygier and Horton 1975). In the San Francisco Estuary, male *C. franciscorum* mature at 37 mm TL, females at 53 mm TL, and both sexes live 1 year (Israel 1936). But Kinnetic Laboratories (1987) reported males to live to 1.5 years and some females to 2.5 years in the estuary. Alternatively, if *C. franciscorum* is indeed a protandrous hermaphrodite, males transition to females at approximately 1 year and could live to 2 to 2.5 years as females (Gavio 1994). This life history strategy would account for the apparent shorter life span and smaller size of males reported by previous researchers.

Methods

Juvenile *Crangon franciscorum* were separated from adults based on a size of maturity of 37 mm TL for males (Israel 1936, CDFG unpublished data) and 48 mm TL for females (approximately 1% of the ovigerous females we collected were <48 mm). Juvenile and adult categories were used for the abundance and distribution analyses, while 5 mm size groups by sex were used for the salinity and temperature analyses. The annual index periods selected were May through October for juveniles and February through September for adults. The February through September index period omitted months when there was often a high abundance of adult *C. franciscorum*, but was necessary for the inclusion of the 1989 to 1994 data in the annual analyses. For analysis of seasonal distribution patterns, 1983 and 1988 were selected as representative high and low outflow years for both juvenile and adult *C. franciscorum*. Length frequency data from 1988 were used to demonstrate the typical monthly length frequency distributions. All sizes reported are total length.

Results

Length Frequency

Crangon franciscorum is the largest common shrimp species in the estuary. This study collected females to 87 mm and males to 68 mm. Adult shrimp usually dominated our catches from January through March; in 1988 several cohorts of adult females were collected in January and February, but by March, only 1 cohort was detectable in the length frequency histograms (Figure 1). This adult female cohort continued to be collected at least through September, but the adult male cohort essentially disappeared from our catches after April 1988.

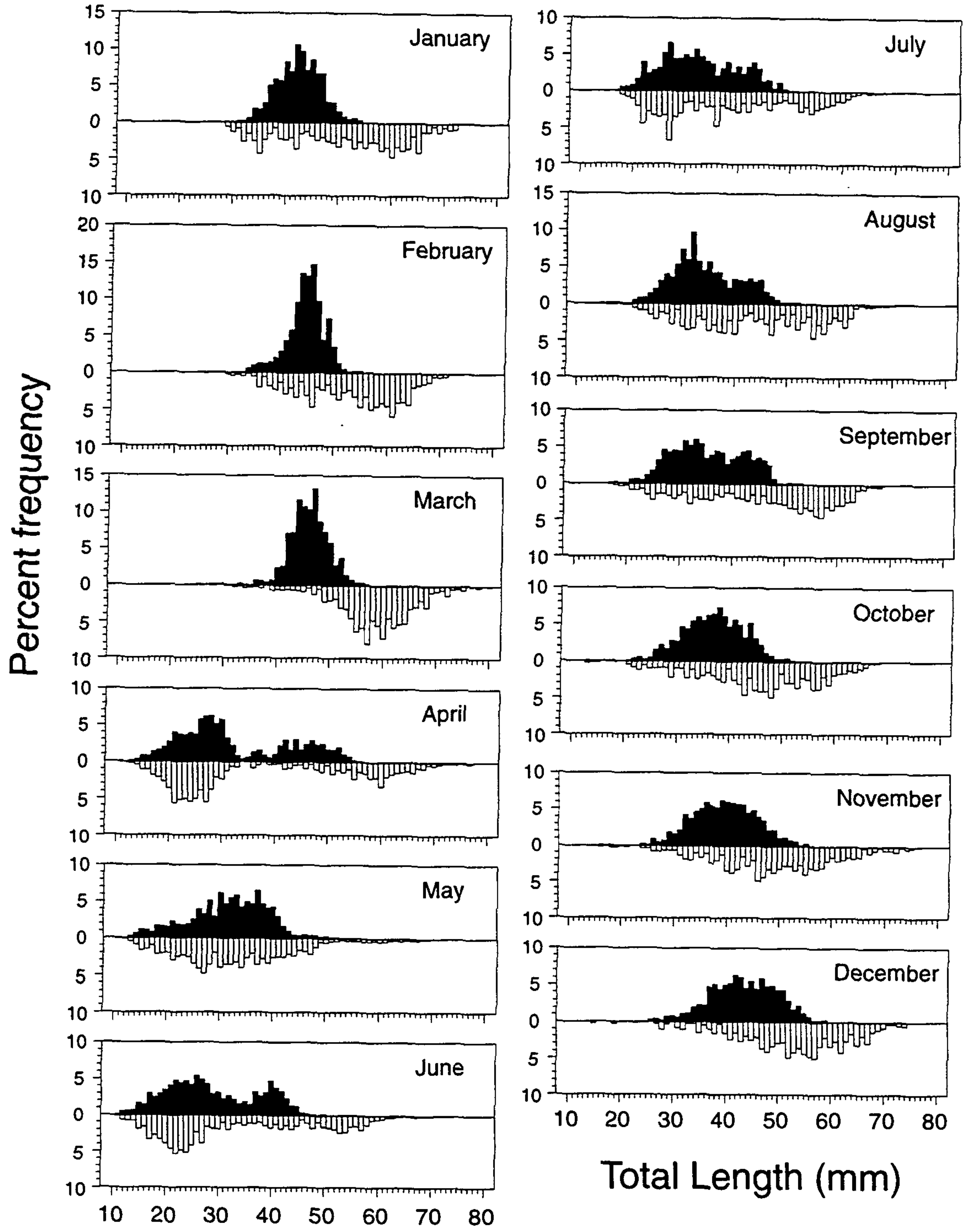

Figure 1 Monthly percent length frequencies of male (closed bars) and female (open bars) *C. franciscorum* **collected with the otter trawl in 1988.** Size classes are every 1 mm, from 11 to 80 mm.

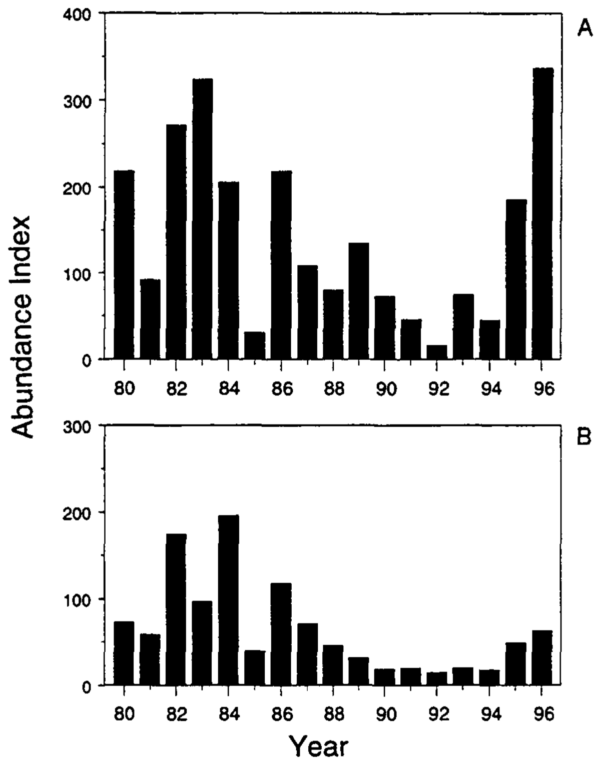

Figure 2 Annual abundance indices of *C. franciscorum* collected with the otter trawl: (A) juveniles (1980 to 1996), the index period is May to October and the indices are divided by 1000; (B) adults (1980 to 1996), the index period is February to September and the indices are divided by 1000

Often, multiple juvenile cohorts were collected in spring and early summer; in 1988, the first cohort was collected in April and a second cohort appeared in June. By late fall these multiple cohorts were difficult to distinguish and many shrimp were mature or approaching maturity. By December, the male modal length was about 40 mm and the female modal length was about 50 mm.

Abundance

Crangon franciscorum was the most commonly collected species of caridean shrimp over the study period and was the most common species in all years except from 1990 to 1992, when it ranked 2nd to *C. nigricauda* (see Table 1). The annual abundance of juvenile *C. franciscorum* varied by a factor of almost 20 from 1980 to 1996 (Figure 2A, Table 2). The highest annual index was in 1996, followed closely by 1983 and 1982. The lowest indices were in 1985 and 1992 and there was a general trend of declining abundance during the 1987–1992 drought.

The annual abundance trend of adult *C. franciscorum* either mirrored the juvenile trend or had a 1 year lag. The highest indices were in 1982 and 1984 and the lowest indices were in 1985 and from 1988 through 1994 (see Figure 2B, Table 3). A strong year class of juveniles resulted in a relatively large number of adult shrimp in the estuary in winter and spring of the following year.

Table 2 Monthly and annual abundance indices of juvenile *C. franciscorum* collected with the otter trawl from 1980 to 1996. The index period is May to October and the indices are divided by 1,000.

	Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*May–Oct*
1980		2	1	1	44	378	166	294	320	113	39	26	219
1981	3	8	4	9	101	72	159	47	152	19	11	5	92
1982	5	2	1	146	318	478	175	328	230	105	72	76	272
1983	110	40	43	28	5	422	834	269	195	220	355	181	324
1984	55	15	34	101	175	488	200	184	78	111	8	19	206
1985	4	3	1	0	20	57	41	40	19	8	3	1	31
1986	1	0	0	0	56	236	294	367	286	72	43	31	219
1987	18	10	10	15	68	140	233	104	62	46	18	6	109
1988	6	4	1	21	89	154	156	52	22	7	5	2	80
1989	3	1	1	11	151	141	161	86					135
1990		2	1	3	71	123	115	74	41	13			73
1991		5	1	1	8	58	87	60	42	21			46
1992		3	1	1	19	28	23	14	7	5			16
1993		0	0	4	111	122	111	65	30	13			75
1994		0	0	3	34	65	65	62	36	12			45
1995	1	0	1	3	148	283	218		235	46	19	17	186
1996	9	8	7	25	427	753	483	254	74	31	17	11	337
1981–1988, 1996	24	10	11	38	140	311	286	183	124	69	59	37	

Strong seasonal trends in the abundance of juvenile and adult *C. franciscorum* occurred in the estuary. Juvenile abundance was strongly unimodal with a single peak from May through September in most years (Figure 3, see Table 2). In any given year, the period of peak abundance extended from 3 to 5 months, depending on the relative size and timing of the cohorts (see Table 2). Small fall cohorts occurred in several years, and in 1983 there was a large fall cohort with an abundance peak that extended through December.

Adult *C. franciscorum* abundance was bimodal; peaks occurred from November through March and from May through September (see Figure 3, see Table 3). The largest winter-spring peaks occurred in years following high juvenile abundance (1981, 1983, 1984, and 1987) and the smallest winter-spring peaks occurred in years following low juvenile abundance (1982, 1986, 1989, and 1985). There was no distinguishable summer-fall abundance peak of adults in either 1983 or 1992.

Distribution

Adult and juvenile *C. franciscorum* were widely distributed throughout the estuary, although they were more commonly collected in the northern reach (San Pablo Bay through the west delta) than in South and Central bays. The center of distribution of juvenile *C. franciscorum*, on an annual basis (May to October), ranged from San Pablo Bay to the west delta (Figure 4). In 1983 and 1995, the highest CPUE was in San Pablo Bay. In 1988 and from 1990 through 1992, CPUE was highest in the west delta area, and in all other years highest in Suisun Bay. The average CPUE was very low in San Pablo Bay in low outflow years and low in the west delta in high outflow years.

The center of distribution of adult *C. franciscorum* also varied annually, but not as much as for juveniles. In high outflow years (for example, 1982, 1983, 1986, and 1995), the highest annual CPUE (February though September) was in San Pablo Bay and in low outflow years (for example, 1981 and 1987) the highest annual CPUE was in Suisun Bay (Figure 5). Although the distribution of adult *C. franciscorum* was broadest in years with low outflow, CPUE was never highest in the west delta as it was for juveniles.

Table 3 Monthly and annual abundance indices of adult *C. franciscorum* collected with the otter trawl from 1980 to 1996. The index period is February to September and the indices are divided by 1,000.

	Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Feb–Sep*
1980		44	25	8	8	68	93	114	221	129	53	82	73
1981	92	70	41	46	51	15	53	33	153	41	25	48	58
1982	53	34	23	8	170	253	346	360	208	110	88	136	175
1983	227	171	154	93	69	89	84	68	46	124	163	133	97
1984	103	140	534	164	134	427	102	43	23	23	14	48	196
1985	47	143	21	14	7	34	54	28	18	11	9	15	40
1986	27	15	7	9	18	44	273	293	285	70	171	109	118
1987	82	119	74	33	198	47	44	23	33	29	36	60	71
1988	51	50	24	24	29	82	88	52	22	9	13	15	46
1989	23	12	17	14	27	51	63	43					32
1990		19	28	16	11	14	29	22	13	10			19
1991		25	15	11	10	17	20	26	35	23			20
1992		36	34	10	8	7	9	5	8	7			15
1993		4	6	3	5	18	58	46	24	14			20
1994		12	12	3	7	25	21	34	29	13			18
1995	16	41	25	11	13	76	95		79	25	38	80	49
1996	101	49	81	56	29	72	74	85	58	17	42	52	63
1981–1988, 1996	87	88	107	50	78	118	124	109	94	48	62	68	

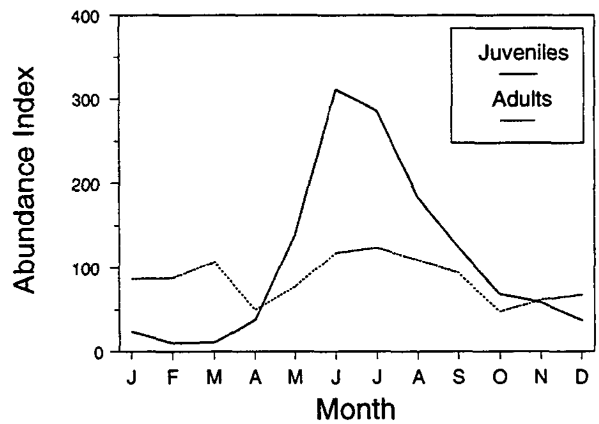

Figure 3 Monthly abundance indices of juvenile and adult *C. franciscorum* collected with the otter trawl from 1981 to 1988 and in 1996. The indices are divided by 1000.

There were strong seasonal trends in the distribution of juvenile and adult *C. franciscorum* in the estuary. In 1983, a "wet" year, the center of distribution of juveniles was in San Pablo Bay from January to July, shifted to Suisun Bay in August and September, and shifted back to San Pablo Bay for the remainder of the year (Figure 6). This general pattern of an upstream distribution shift occurred in all years, although the initiation and extent of the upstream movement varied with freshwater outflow. For example, in 1988, a "critically dry" year, the center of distribution shifted from Suisun Bay to the west delta in March and essentially remained there for the rest of the year (Figure 7).

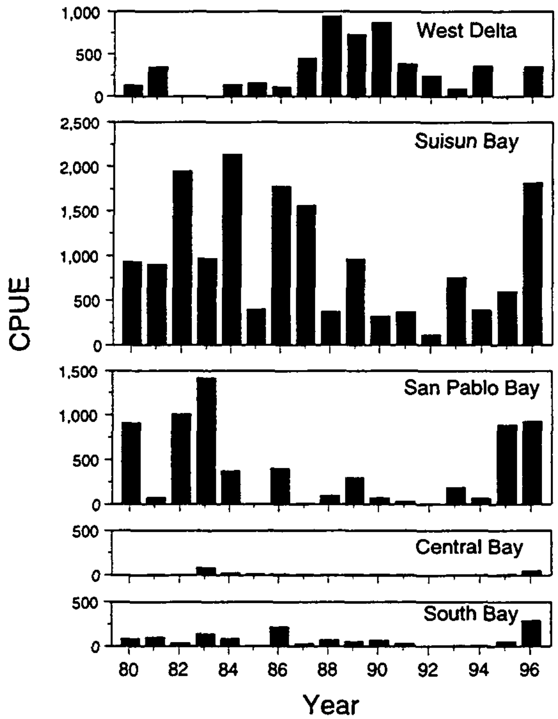

Figure 4 Annual distribution (CPUE) of juvenile *C. franciscorum* for May through October from 1980 to 1996

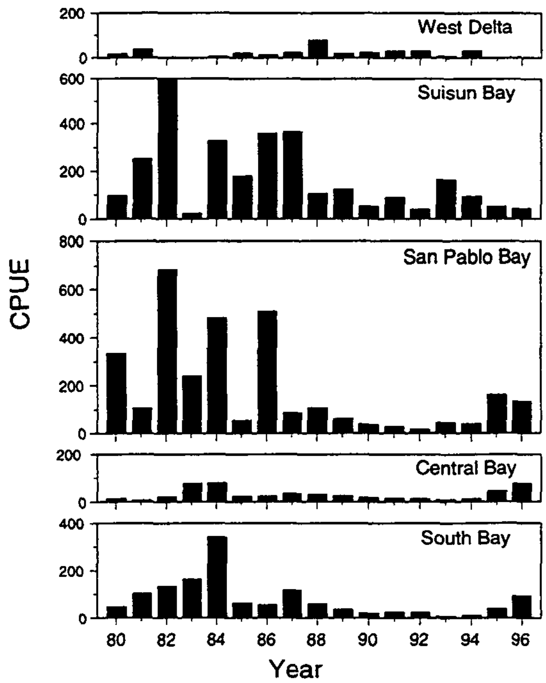

Figure 5 Annual distribution (CPUE) of adult *C. franciscorum* for February through September from 1980 to 1996

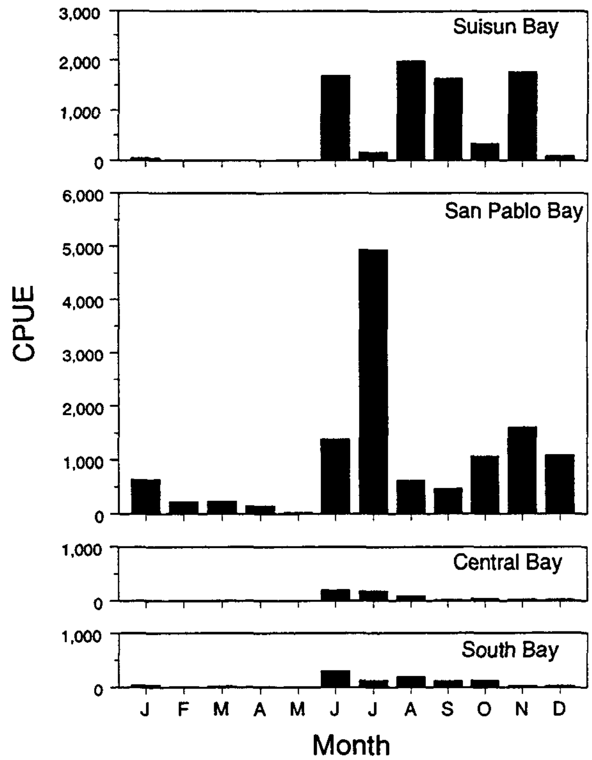

Figure 6 Monthly distribution (CPUE) of juvenile *C. franciscorum* in 1983

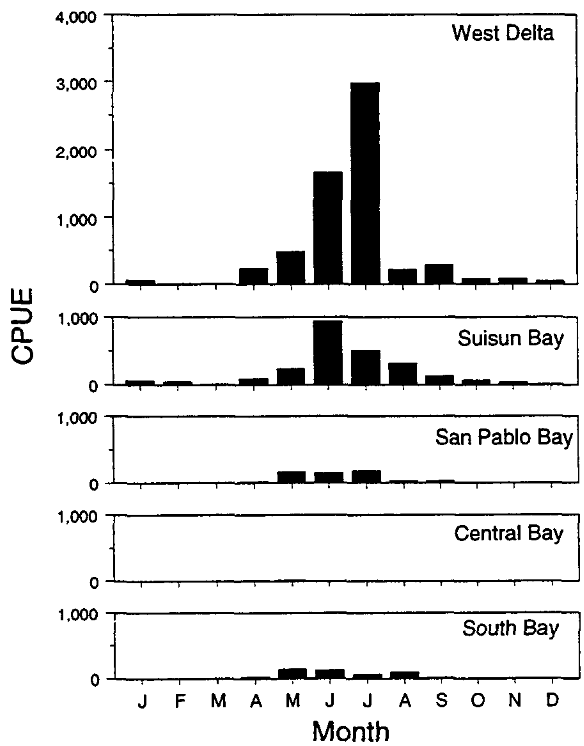

Figure 7 Monthly distribution (CPUE) of juvenile *C. franciscorum* in 1988

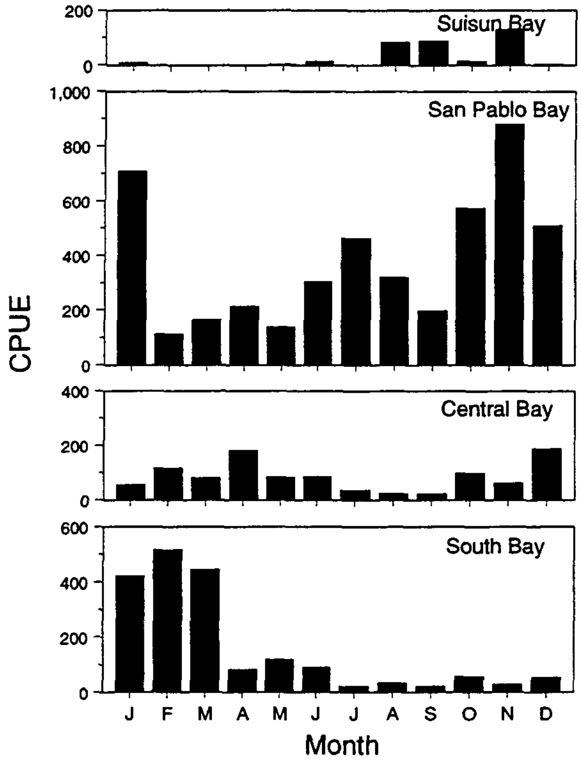

Figure 8 Monthly distribution (CPUE) of adult *C. franciscorum* in 1983

Although adult *C. franciscorum* also moved upstream seasonally, the extent and timing of this movement differed from the juvenile movement. For example, in 1983, adult distribution was centered in San Pablo Bay in January (Figure 8), shifted to South Bay in February and March when outflow increased (see Introduction chapter, Figure 2), and moved back to San Pablo Bay in April as outflow decreased. The highest CPUE was in San Pablo Bay through the remainder of the year, although it did increase in Suisun Bay in late summer and fall. In 1988, a year with much lower outflow than 1983, the adult distribution was initially centered in San Pablo Bay but shifted to Suisun Bay in March (Figure 9). Although CPUE was highest in San Pablo Bay in May and June, the center of distribution again shifted to Suisun Bay in July and to the west delta in November and December.

Salinity and Temperature

Crangon franciscorum was collected over a wide range of salinities (Figure 10A); the mean salinity was 13.9‰, with 90% collected between 2.8‰ and 25.9‰ (10th and 90th percentiles, respectively). It was also collected at relatively warm temperatures (Figure 10B); the mean temperature was 18.2 °C with 90% collected between 13.2 and 21.3 °C.

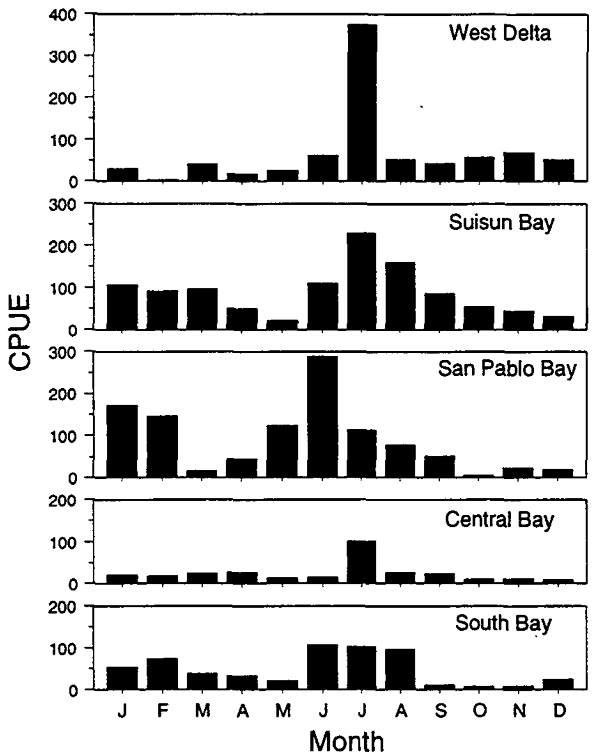

Figure 9 Monthly distribution (CPUE) of adult *C. franciscorum* in 1988

Salinity and temperature at point of capture varied with size and sex. The smallest juvenile *C. franciscorum* (11 to 15 mm) were collected at a mean salinity of 13‰ (Figure 11A). The mean salinity decreased slightly with size to 10‰ for shrimp 21 to 25 mm. The mean salinity increased steadily with size for female and male *C. franciscorum* >25 mm (Figures 11A and 11B). Females were collected at a maximum mean salinity of about 24‰ (76 to 80 mm) and males at a maximum mean salinity of about 23‰ (56 to 60 mm). The decrease in salinity for males in the 61 to 65 mm size group may be an aberration, as shrimp from only 3 tows (n = 525) in Carquinez Strait dominated this group. Males were consistently collected at a higher mean salinity than females of the same size up to 51–55 mm. For some size groups, this difference was >5‰. But at the approximate size of maturity, which is the 36 to 40 mm size group for males and the 46 to 50 mm size group for females, both sexes were collected at a similar mean salinity of about 15‰.

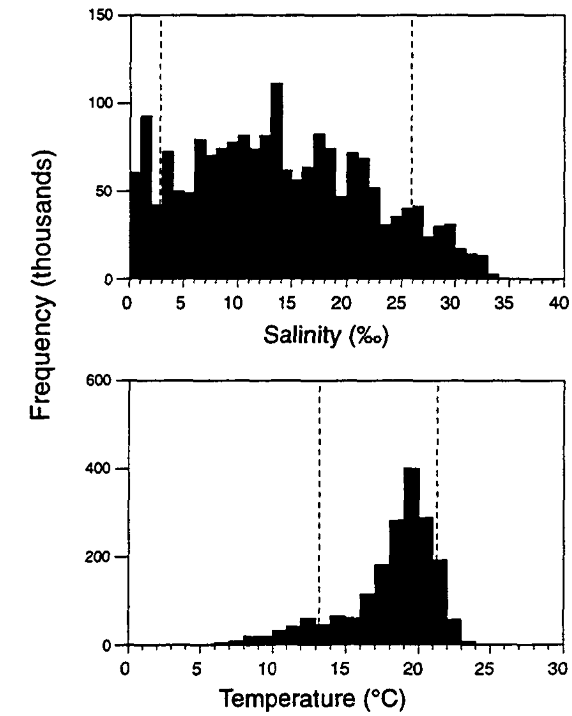

Figure 10 Salinity (‰) and temperature (°C) distributions of all sizes of *C. franciscorum* collected with the otter trawl (1980 to 1996). Dashed vertical lines are the 10th and 90th percentiles.

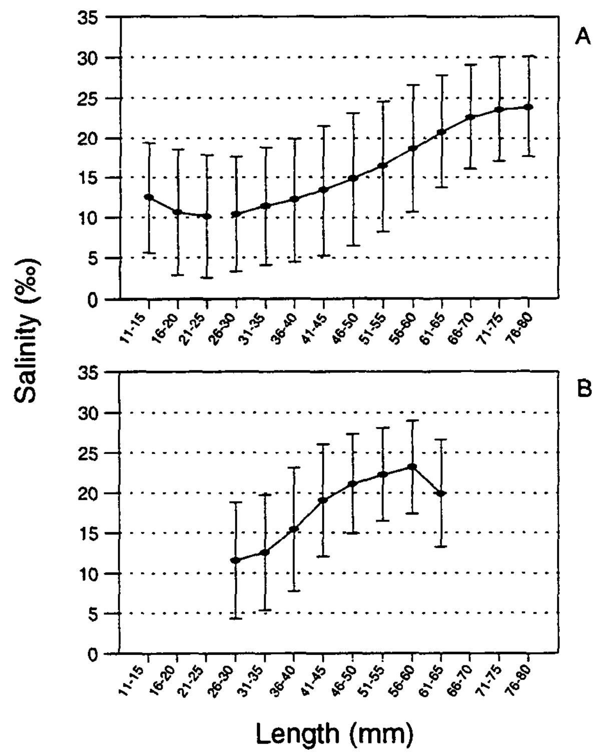

Figure 11 Mean salinity (±1 standard deviation) of *C. franciscorum* by size class collected with the otter trawl: (A) juveniles (11 to 25 mm) and females and (B) males. Size classes are every 5 mm, from 11 to 80 mm.

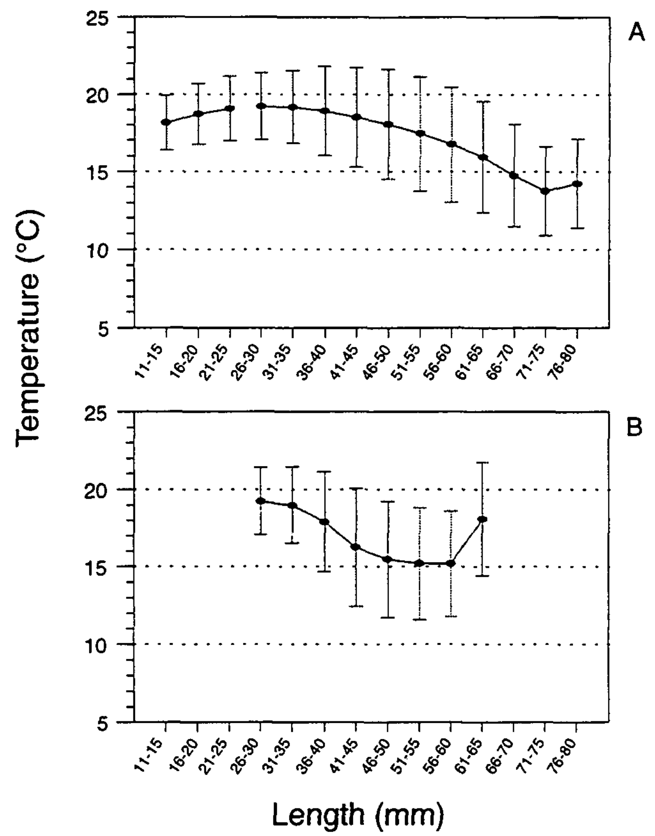

Figure 12 Mean temperature (±1 standard deviation) of *C. franciscorum* by size class collected with the otter trawl: (A) juveniles (11 to 25 mm) and females and (B) males. Size classes are every 5 mm, from 11 to 80 mm.

The smallest juvenile *C. franciscorum* (11 to 15 mm) were collected at a mean temperature of about 23 °C (see Figure 12A). The mean temperature increased slightly with size to about 19 °C for shrimp in the 21 to 25 and 26 to 30 mm size groups and then decreased with size for both sexes (Figures 12A and 12B). For any given size group, females were collected at a higher temperature than males (note the exception for the 61 to 65 mm males discussed in the previous paragraph). For some size groups, females were collected at a mean temperature which was 3 °C warmer than for the males, but this difference decreased with size. At the approximate sizes of maturity, males and females were collected at a similar mean temperature of about 18 °C.

Discussion

Crangon franciscorum is an estuarine species that dominated our shrimp catches in most years. The general life cycle of *C. franciscorum* as reported by other researchers is supported by this study's data. Peak abundance of juveniles occurred between May and September, when temperatures were typically warmest in the mesohaline nursery areas. Depending on the magnitude of freshwater outflow and the resulting salinities, the center of distribution of juvenile *C. franciscorum* ranged from San Pablo Bay to the west delta. Juveniles from the spring and early summer cohorts grew rapidly and apparently reached maturity by fall of the same year, and by November or December adult shrimp dominated our catches. As *C. franciscorum* matured, they moved downstream to cooler, polyhaline areas to reproduce. The center of distribution of adults, especially ovigerous females, is probably outside of the estuary in years with high freshwater outflow, as proposed by Hatfield (1985).

The highest annual juvenile abundance indices were in years with relatively high freshwater outflow in winter and spring whereas the lowest indices were in low outflow years. There is a strong positive relationship between the annual abundance of juvenile *C. franciscorum* and freshwater outflow which has been discussed in detail in previous reports (CDFG 1987, 1992). Annual abundance was strongly related to distribution, as juvenile *C. franciscorum* were concentrated in San Pablo or Suisun bays in high abundance years and concentrated in Suisun Bay or the west delta area, but never in San Pablo Bay, in low abundance years.

Although male *C. franciscorum* were consistently collected from cooler, more saline waters than females of the same size, at the onset of maturity, both sexes were collected at almost identical mean salinities. The salinity and temperature data indicate that, except for the sizes associated with the onset of maturity, males were generally distributed downstream of females. Analyses have confirmed that juvenile males are distributed downstream of juvenile females (CDFG unpublished data). Males may be located downstream from females so maturing females will pass by them during their downstream migration. Males of some species of caridean shrimp move to deeper water after mating, and females follow them after the larvae hatch (Allen 1966).

Crangon nigricauda

Crangon nigricauda, the blacktail bay shrimp, ranges from Prince William Sound, Alaska (Squires and Figueira 1974), to Baja California (Rathbun 1904) and is found in estuaries and the nearshore ocean area from the intertidal to 57 m (Jensen 1995). *Crangon nigricauda* is less tolerant of low salinities than *C. franciscorum* (Israel 1936, Ganssle 1966, Siegfried 1980) and is not common upstream of western Suisun Bay even during low outflow years (Israel 1936, CDFG 1987).

Crangon nigricauda is reported to have a single reproductive season from April through September in the San Francisco Estuary, although ovigerous females were collected all year (Israel 1936). Some females produce 2 broods during the reproductive season. In Yaquina Bay, Oregon, reproduction extends from December through mid-August but is bimodal, with peaks from December through March and May through August (Krygier and Horton 1975). Hatching time was estimated to be 10 to 14 weeks in winter and 8 to 10 weeks in summer. Most juveniles hatched in winter settle in June, while those hatched in summer settle in December. In the San Francisco Estuary, juveniles were most common in shallow water (<6 m) but were collected from deeper areas than juvenile *C. franciscorum* (Israel 1936). *Crangon nigricauda* are limited to low temperature, polyhaline waters in Yaquina Bay, with juveniles collected from warmer, lower salinity waters than adults. Most ovigerous *C. nigricauda* were collected at salinities >33‰ and temperatures ranging from 8 to 11 °C (Krygier and Horton 1975).

Female *C. nigricauda* were estimated to mature at 37 mm in the San Francisco Estuary (Israel 1936). In Yaquina Bay, females mature at 40 mm and males at 28 mm (Krygier and Horton 1975). Maximum reported size from the estuary is 60 mm for females and 45 mm for males (Israel 1936). Although Israel (1936) did not report a life span for *C. nigricauda*, he did report that it could reach its maximum size in 1 year. In Yaquina Bay, females reportedly live to 1.5 years and males to 1 year. Both sexes mature at 1 year and males probably spawn once and die (Krygier and Horton 1975). If *C. nigricauda* is a protandrous hermaphrodite as reported for *C. franciscorum*, males would transition to females at approximately 1 year and would live to at least 1.5 years as females. As for *C. franciscorum*, this life history strategy would account for the apparent shorter life span and smaller size of male *C. nigricauda* reported by other researchers.

Methods

Crangon nigricauda juveniles were separated from adults based on a size of maturity of 28 mm for males (Krygier and Horton 1975, CDFG unpublished data) and 33 mm for females (only 1% of the ovigerous females we collected were less than 33 mm). The juvenile and adult categories were used for abundance and distribution analyses and 5 mm size groups by sex were used for the salinity and temperature analyses. The annual index periods selected were May through September for juveniles and February through September for adults. Although the February through September period omitted months when the abundance of adult *C. nigricauda* was often high, it was necessary so the 1989 through 1994 data could be included in the annual analyses. For analysis of seasonal distribution patterns, 1983 and 1988 were selected as representative high and low outflow years for both juvenile and adult *C. nigricauda*. Length frequency data from 1988 were used to demonstrate the monthly length frequency distributions.

Results

Length Frequency

The maximum sizes of *C. nigricauda* collected by our study were 64 mm for females and 60 mm for males (only 4 males were >55 mm). Monthly length frequency histograms for 1988 give a general picture of the timing of cohorts and growth rates, but the number and timing of cohorts of *C. nigricauda* varied so much that no single year represented a norm. In January 1988, there were 2 male cohorts and possibly several female cohorts of *C. nigricauda* in the estuary (Figure 13). The smaller male cohort was primarily juveniles and the larger cohort adults. By March, there was little evidence of multiple cohorts and the modal length for both sexes was greater than the size of maturity. In April, a cohort of juvenile *C. nigricauda* appeared, but the adult mode remained distinct. In May, the larger *C. nigricauda* all but disappeared, although some adult females from the previous year continued to be collected through summer. During the rest of the year, several cohorts of juvenile *C. nigricauda* entered the estuary—a relatively large cohort in June and smaller cohorts from September through November. The shrimp from each cohort eventually overlapped in size as they reached maturity and the occurrence of several cohorts from spring through fall broadened the length frequency histograms. There appeared to be 2 distinct cohorts from September through November, and by November the modal length of the larger cohort was at or larger than the size of maturity of both sexes.

Abundance

Crangon nigricauda was the second most common species of caridean shrimp collected during the study period and was the most common species from 1990 to 1992 (see Table 1). The annual abundance of juvenile *C. nigricauda* was relatively low from 1980 to 1987, increased from 1988 to 1990, and remained relatively high from 1991 to 1996 (Figure 14A, Table 4). The highest indices were in 1990 and 1996 and the lowest indices were in 1981, 1982, 1984, and 1985. The juvenile and adult annual abundance trends were similar, although the highest adult index was in 1991 (Figure 14B, Table 5), the year after the highest juvenile index. The lowest adult *C. nigricauda* indices were from 1981 through 1985.

Seasonal abundance of juvenile *C. nigricauda* was bimodal, with the larger peak from May through August, and a smaller peak from December through February (Figure 15, see Table 4). The winter cohort was relatively large in some years (for example, 1986 to 1987 and 1987 to 1988). The monthly abundance of adult *C. nigricauda* was also bimodal (see Figure 15, see Table 5), with the major peak from November through February and a secondary peak from May through August. In years with 12 months of data, the winter peak was always larger than the following summer peak except for winter 1985–1986.

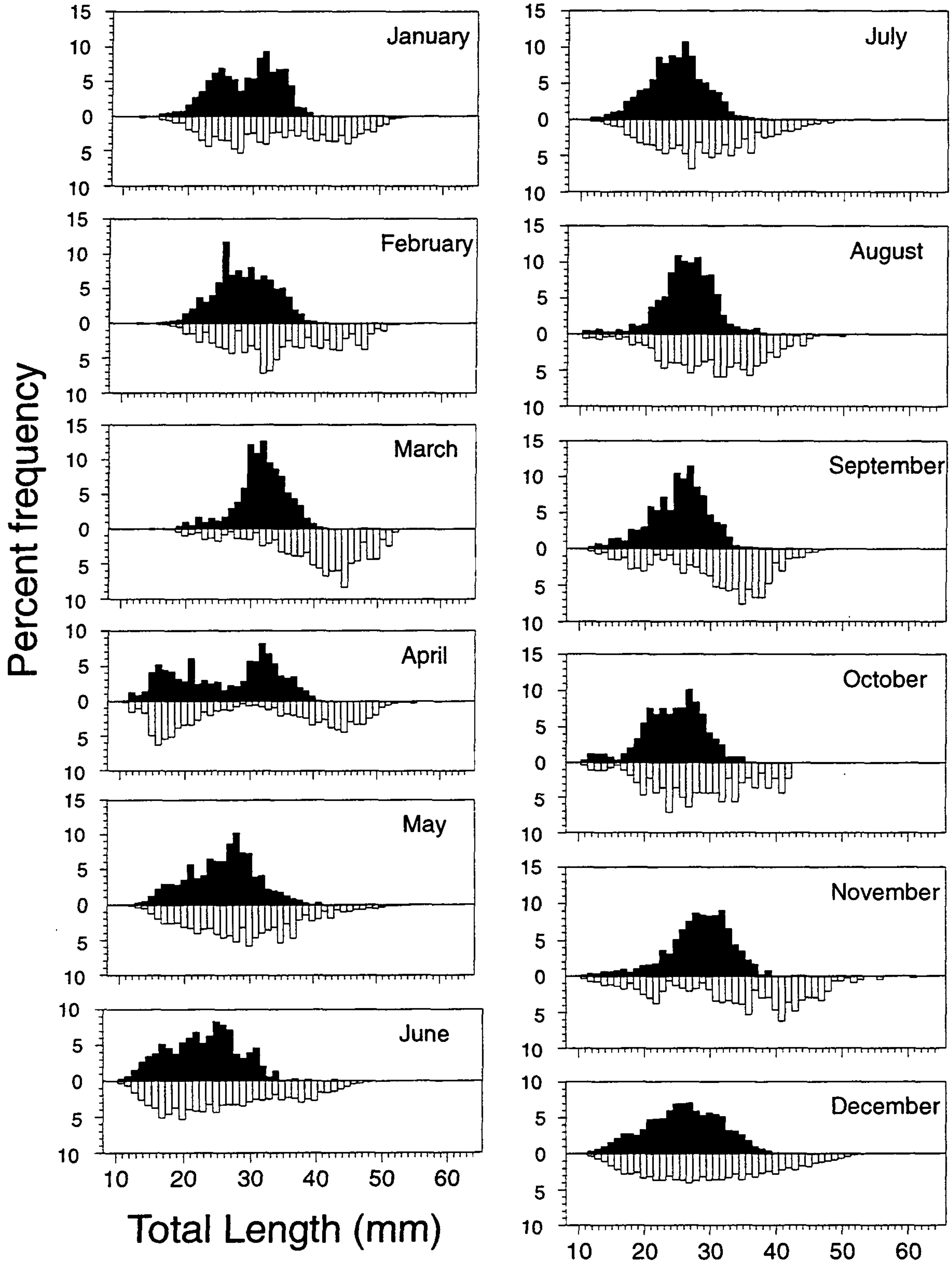

Figure 13 Monthly percent length frequencies of male (closed bars) and female (open bars) ***C. nigricauda*** **collected with the otter trawl in 1988.** Size classes are every 1 mm, from 11 to 65 mm.

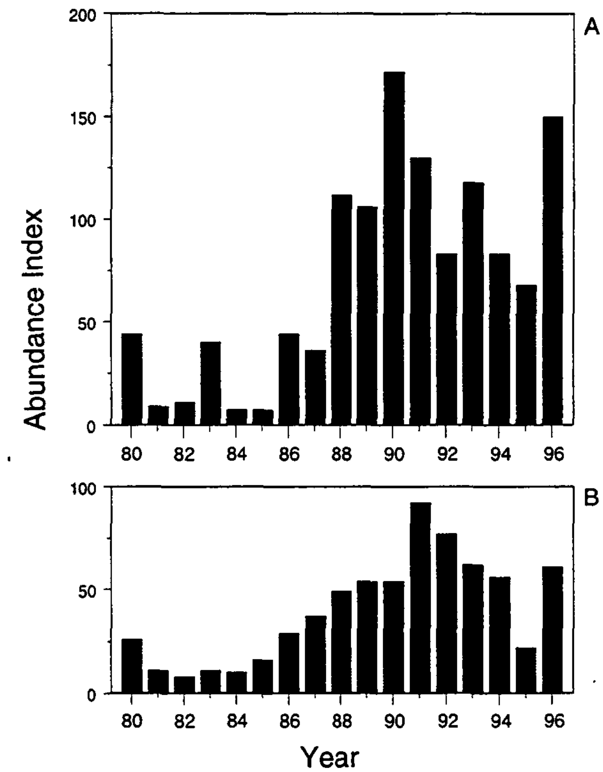

Figure 14 Annual abundance indices of *C. nigricauda* collected with the otter trawl: (A) juveniles (1980 to 1996), the index period is May to September and the indices are divided by 1000; (B) adults (1980 to 1996), the index period is February to September and the indices are divided by 1000

Table 4 Monthly and annual abundance indices of juvenile *C. nigricauda* collected with the otter trawl from 1980 to 1996. The index period is May to September and the indices are divided by 1,000.

	Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*May–Sep*
1980		24	18	9	3	137	33	28	18	2	7	8	44
1981	14	19	15	17	27	1	5	3	8	10	0	12	9
1982	17	3	2	5	29	14	1	1	8	6	9	5	11
1983	25	16	9	22	2	28	16	153	1	8	9	12	40
1984	8	2	3	6	14	7	7	6	1	2	2	2	7
1985	3	4	0	0	5	14	11	1	4	4	2	3	7
1986	2	1	12	2	5	107	29	47	32	16	20	44	44
1987	36	38	14	6	1	18	38	50	73	57	57	63	36
1988	86	22	2	29	176	233	103	26	22	3	5	5	112
1989	18	22	45	54	169	102	57	95					106
1990		37	109	27	119	290	211	152	90	31			172
1991		39	94	87	61	222	111	113	142	59			130
1992		54	34	9	69	197	71	41	37	43			83
1993		23	12	18	51	215	277	35	12	3			118
1994		6	5	15	44	190	65	77	37	7			83
1995	12	14	72	9	35	145	50		42	9	4	18	68
1996	59	29	51	83	214	154	190	157	34	15	10	14	150
1981–1988, 1996	28	15	12	19	53	64	45	49	20	13	13	18	

Table 5 Monthly and annual abundance indices of adult *C. nigricauda* collected with the otter trawl from 1980 to 1996. The index period is February to September and the indices are divided by 1,000.

	Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Feb–Sep*
1980		59	29	9	11	29	26	31	12	2	12	8	26
1981	41	21	15	25	7	1	10	5	3	8	1	41	11
1982	34	6	7	4	16	19	1	4	9	9	3	9	8
1983	44	22	11	19	10	5	6	16	2	4	8	20	11
1984	14	3	9	6	19	21	12	9	1	3	5	7	10
1985	13	56	4	4	3	36	21	3	3	4	3	10	16
1986	20	29	29	11	6	20	47	67	25	15	18	62	29
1987	52	63	41	11	9	13	42	58	62	86	123	154	37
1988	147	35	23	51	122	78	43	18	19	2	8	12	49
1989	27	52	65	47	64	46	50	56					54
1990		65	123	36	66	54	43	26	20	18			54
1991		145	143	70	83	101	60	62	75	45			92
1992		226	76	32	100	87	36	18	43	39			77
1993		83	50	21	36	71	134	67	30	14			62
1994		27	18	24	37	79	66	123	78	19			56
1995	42	25	28	10	22	18	16		32	16	36	102	22
1996	78	26	60	62	103	65	63	43	67	18	46	66	61
1981–1988, 1996	49	29	22	22	33	29	27	25	21	16	24	43	

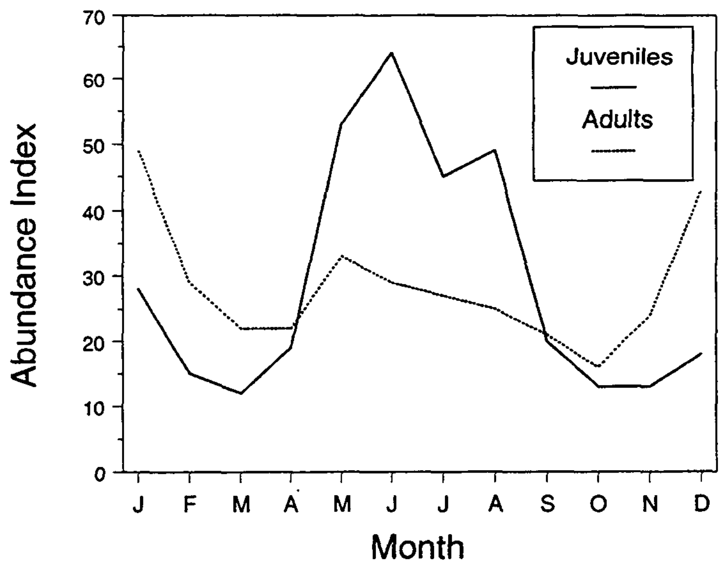

Figure 15 Monthly abundance indices of juvenile and adult *C. nigricauda* collected with the otter trawl from 1981 to 1988 and 1996. The indices are divided by 1,000.

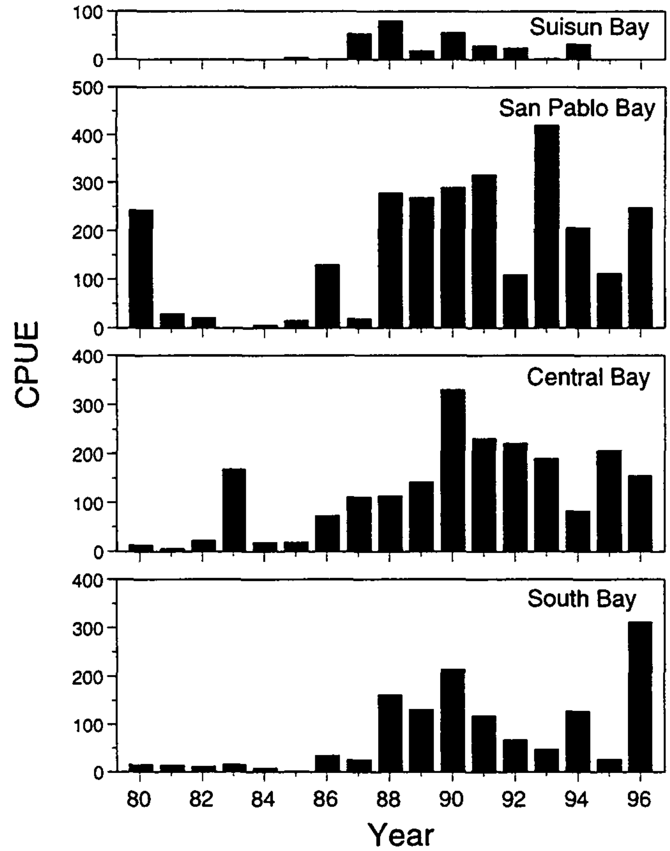

Figure 16 Annual distribution (CPUE) of juvenile *C. nigricauda* for May through September from 1980 to 1996

Distribution

Juvenile and adult *C. nigricauda* were collected from South to Suisun bays, although the extension to Suisun Bay primarily occurred during the drought years 1987–1992 (Figures 16 and 17). On an annual basis (May to September), the center of distribution of juveniles was usually in San Pablo Bay in low outflow years and Central Bay in high outflow years (see Figure 16). Major exceptions include 1980 and 1986, high outflow years when CPUE was highest in San Pablo Bay, and 1987, 1990, and 1992, low outflow years when CPUE was highest in Central Bay. Juvenile CPUE was highest in South Bay in 1996, a high outflow year, and higher in South Bay than Central Bay in 1988 and 1994, both low outflow years.

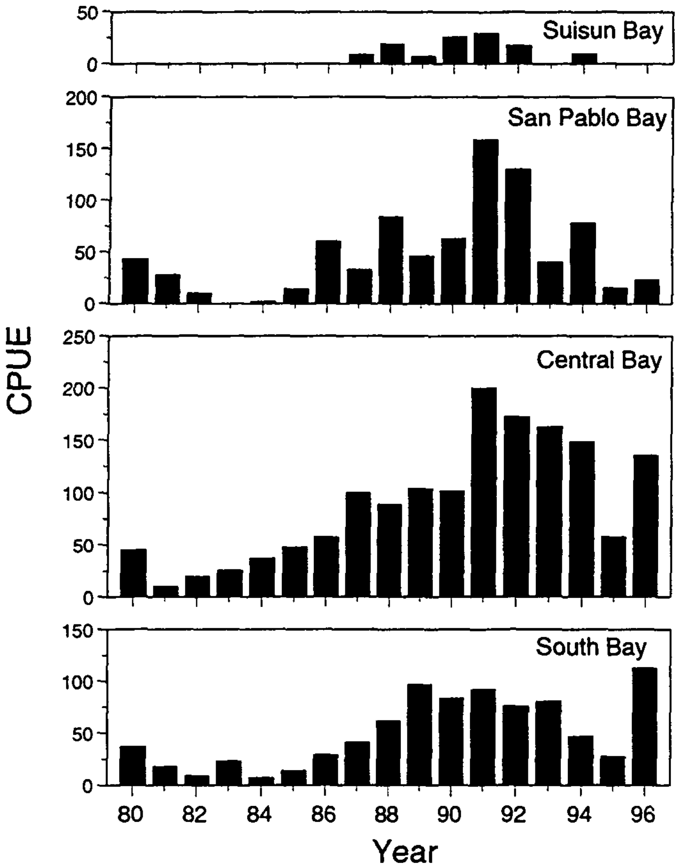

Figure 17 Annual distribution (CPUE) of adult *C. nigricauda* for February through September from 1980 to 1996

Annually, the center of distribution of adult *C. nigricauda* was in Central Bay all years except 1981, when CPUE was highest in San Pablo Bay (see Figure 17). Although South Bay never had the highest annual CPUE of adult *C. nigricauda*, it often had the 2nd highest CPUE of all embayments. Surprisingly, South Bay CPUE was relatively high in both high outflow (1983 and 1996) and low outflow (1981 and 1989) years.

Juvenile *C. nigricauda* moved seasonally between South, Central, and San Pablo bays, but the extent and timing of this movement varied with outflow. In 1983, a "wet" year, CPUE was highest in South Bay from January though June (Figure 18). The center of distribution shifted to Central Bay in July and remained there through December. Some movement to San Pablo Bay occurred in November and December. In lower outflow years, the center of distribution of juveniles was in San Pablo Bay from January to June, although as abundance increased in May, CPUE was also relatively high in South Bay (Figure 19). From July through September, CPUE decreased in South, San Pablo and Suisun bays and distribution was centered in Central Bay. From October to December, CPUE decreased in Central Bay and the center of distribution shifted to either South or San Pablo bays.

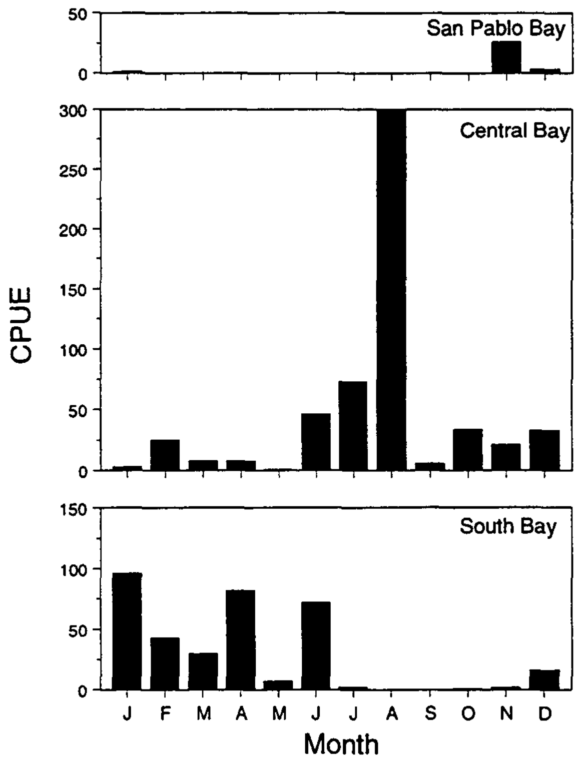

Figure 18 Monthly distribution (CPUE) of juvenile *C. nigricauda* in 1983

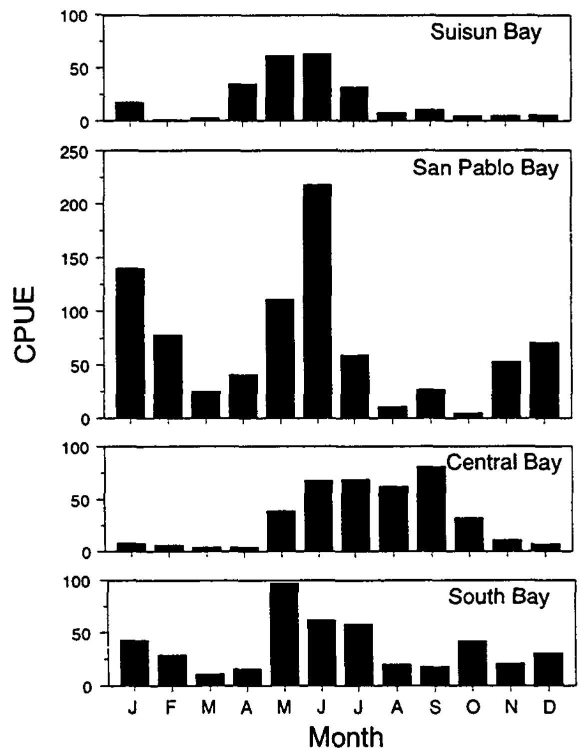

Figure 19 Monthly distribution (CPUE) of juvenile *C. nigricauda* in 1981, 1985, 1987, and 1988

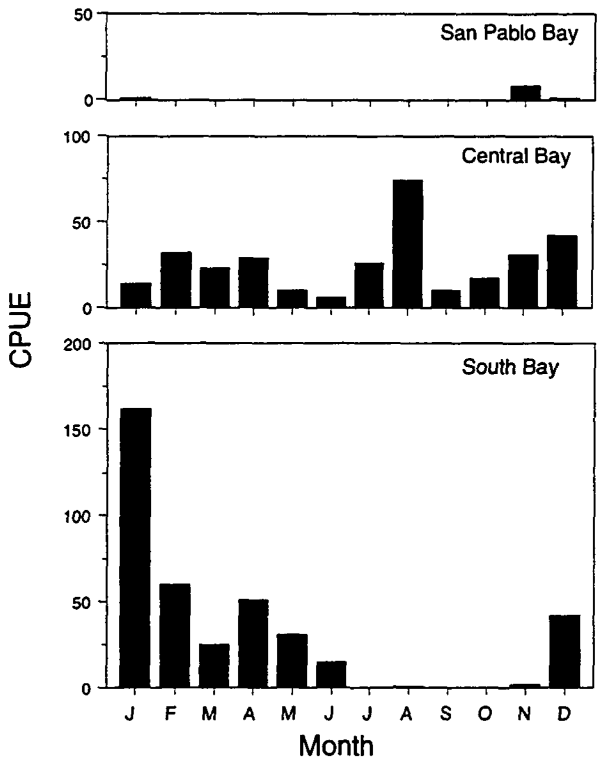

Figure 20 Monthly distribution (CPUE) of adult *C. nigricauda* in 1983

In 1983, adult *C. nigricauda* were concentrated in South Bay from January to June (Figure 20). The center of distribution shifted to Central Bay in July, and remained there until December, when CPUE again increased in South Bay. Some limited movement to San Pablo Bay occurred in November and December. In low outflow years, adult *C. nigricauda* CPUE was highest in South Bay in January (Figure 21); CPUE was also high in San Pablo Bay in January. From February through June, there was a somewhat erratic trend of CPUE decreasing in South and San Pablo bays and the center of distribution shifting to Central Bay. But from July to October, adult *C. nigricauda* were definitely concentrated in Central Bay. In November and December, CPUE increased in South and San Pablo bays and decreased in Central Bay. The December distribution was very similar to the January distribution.

Salinity and Temperature

Crangon nigricauda was collected over a wide range of salinities and temperatures; 80% were found from 18.0‰ to 31.7‰ and 10.7 and 19.3 °C (10th and 90th percentiles, respectively, Figure 22). For all sizes, the mean salinity was 25.9‰ and the mean temperature was 15.5 °C.

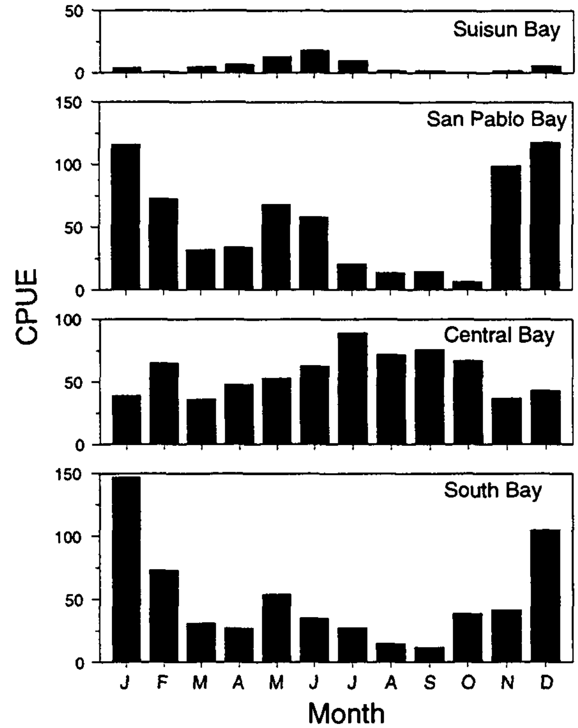

Figure 21 Monthly distribution (CPUE) of adult *C. nigricauda* in 1981, 1985, 1987, and 1988

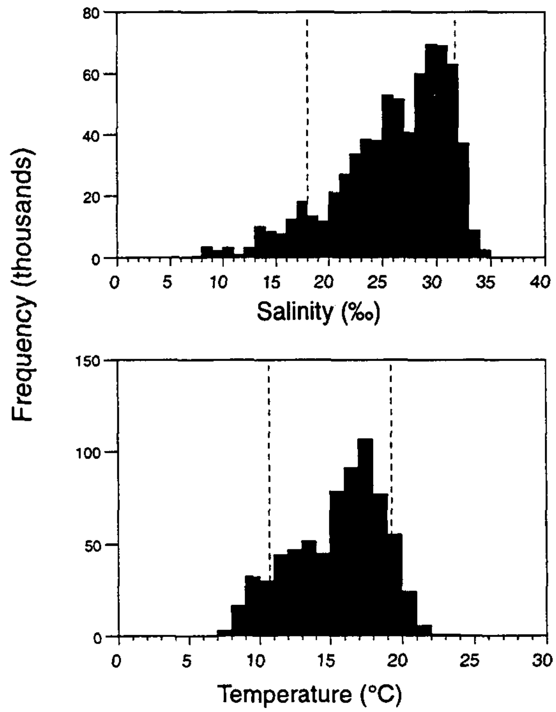

Figure 22 Salinity (‰) and temperature (°C) distributions of all sizes of *C. nigricauda* collected with the otter trawl (1980 to 1996). Dashed vertical lines are the 10th and 90th percentiles.

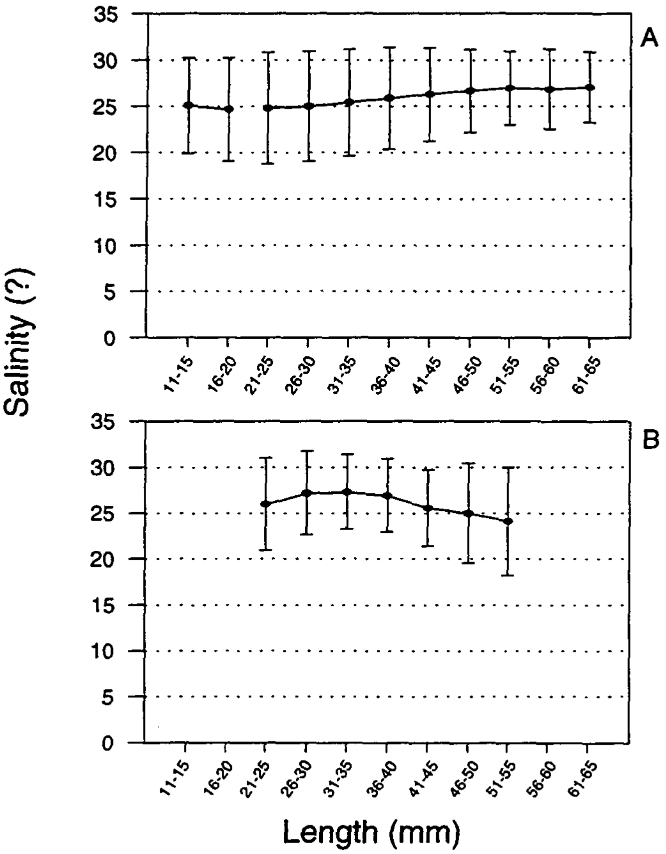

Figure 23 Mean salinity (±1 standard deviation) of *C. nigricauda* by size class collected with the otter trawl: (A) juveniles (11 to 20 mm) and females and (B) males. Size classes are every 5 mm, from 11 to 65 mm.

Unlike *C. franciscorum*, the mean salinity did not change appreciably with size (Figure 23). The smallest juvenile *C. nigricauda* (11 to 15 mm) were collected at a mean salinity of about 25‰ (see Figure 23A). The mean salinity decreased slightly for juveniles in the 16 to 20 mm size group and then slowly increased with size for females (see Figure 23A); the largest female size classes were collected at the highest mean salinity (about 27‰). The mean salinity for males was about 27‰ for the 26 to 35 mm size group and decreased to about 25‰ for the 51 to 55 mm size group (see Figure 23B). Males were collected at a higher mean salinity than same-sized females until 41 to 45 mm. The smallest juveniles (11 to 15 mm) were collected at a mean temperature of about 17 °C (Figure 24B). The mean temperature slowly decreased with size for females 21 to 40 mm and decreased more rapidly for females >40 mm. The largest females were collected at a mean temperature of about 12 °C. Male *C. nigricauda* were also collected at decreasing temperature with size (Figure 24A), although the decline was somewhat erratic for males >45 mm. From 26 to 45 mm, males were collected at a lower mean temperature than same sized females. But at the size classes which encompass the onset of maturity (26 to 30 mm for males, 31 to 35 mm for females), both sexes were collected at a mean temperature of about 16 °C.

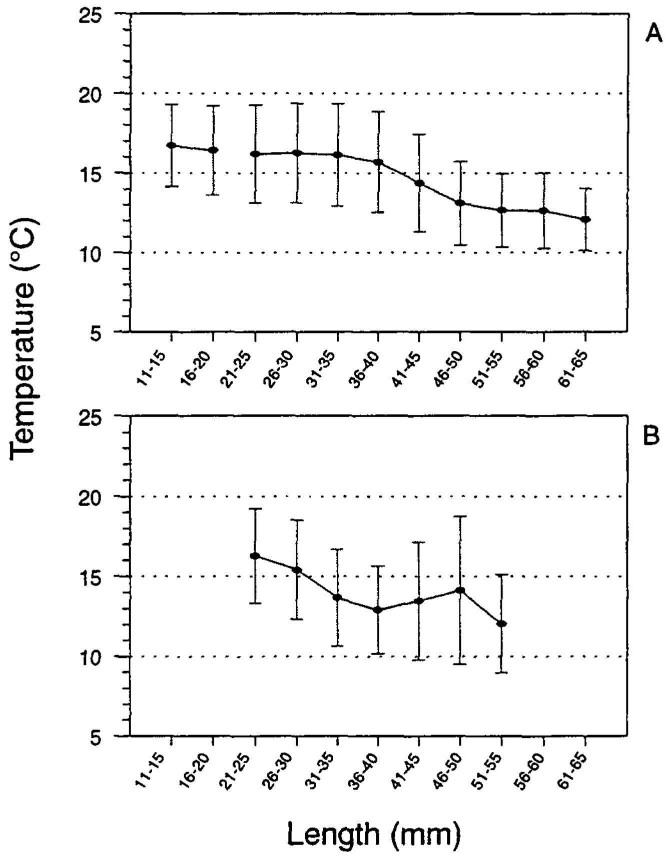

Figure 24 Mean temperature (±1 standard deviation) of *C. nigricauda* by size class collected with the otter trawl: (A) juveniles (11 to 20 mm) and females; (B) males. Size classes are every 5 mm, from 11 to 65 mm.

Discussion

Crangon nigricauda is an important component of the San Francisco Estuary's caridean shrimp community; it was the 2nd most common species collected during the study period and in some years the most common. It was widely distributed in the cooler, polyhaline areas of the estuary. Although not as euryhaline as *C. franciscorum*, it is well adapted to conditions downstream of Carquinez Strait. During extended periods of low outflow, *C. nigricauda* possibly completes its entire life cycle in the estuary.

Crangon nigricauda annual abundance increased steadily from 1986 through 1991 and remained well above the pre–1987 levels through 1996. This increase in abundance was partly due to large contributions by fall and winter cohorts during 1986 to 1987, 1987 to 1988, and possibly subsequent years. As data was not collected from winter 1989–1990 to winter 1994–1995, it is unknown if abundance was relatively high in these winters and how the annual abundance indices would be affected if 12 months of data were available. Despite the data gaps from 1989 through 1994, *C. nigricauda* abundance was definitely high these years relative to previous years.

It is possible that *C. nigricauda* increased its use of the estuary during the 1987–1992 drought because of the increased availability of polyhaline (18‰ to 30‰) habitat, especially in winter when temperatures were cooler. But this hypothesis does not account for the continued high abundance after the drought—the 2nd highest index of juvenile *C. nigricauda* was in 1996, which was classified as a "wet" year.

Abundance of juvenile *C. nigricauda* usually peaked from May through August, but was bimodal in some years, with a 2nd fall-winter peak. Compared to *C. franciscorum*, fall cohorts were relatively large in some years. Adult *C. nigricauda* were most abundant in winter with a 2nd smaller peak in summer of most years. As *C. nigricauda* are reported to mature within 1 year, most of the adult females and males present in the winter are assumed to have hatched in spring of the same year. Adult *C. nigricauda* collected in summer were probably a mixture of older females hatched the previous spring (that is, 1.5 years old) and younger shrimp from the fall-winter cohort. The length frequency data from 1988 somewhat confirms this age structure, although the appearance of multiple cohorts through the spring and summer served to broaden the modes in several months. Israel (1936) noted that the breeding population of *C. nigricauda* present in the estuary from April through September were shrimp hatched the previous year. He reported a modal length of 14 mm in December 1933; by April 1934, the male mode was 31 mm and the female mode 41 mm.

Juvenile *C. nigricauda* were collected further upstream and at lower salinities and higher temperatures than adults, but the mean salinity did not appreciably increase with size as for *C. franciscorum*. Mean temperature did decrease with size for both sexes, which may reflect a movement to deeper, cooler water with age and decreasing temperatures concurrent with maturation through winter.

Crangon nigricauda ranged from South to San Pablo bays in all years except 1983, when low salinity limited them to South and Central bays. Juveniles and adults expanded their distributions to Suisun Bay in years with low freshwater outflow, particularly from 1987 through 1992. The use of Central Bay was also influenced by decreased salinities during periods of high outflow. During the winter and spring of 1983, juvenile and adult *C. nigricauda* were concentrated in South Bay and as outflow decreased and salinities increased, they moved to Central Bay. Use of South, San Pablo, and Suisun bays appears to be limited by temperature in summer and fall. From July through September, mean bottom temperatures in these embayments are usually >19 °C (see Salinity and Temperature chapter, Figures 7, 8, and 10), which is warmer than most *C. nigricauda* were collected at. This response to temperature and salinity is similar to what was reported in Yaquina Bay (Krygier and Horton 1975). Abundance of *C. nigricauda* decreased at the upstream sites in Yaquina Bay from June through October as temperatures increased and increased again in the fall as temperatures decreased. Krygier and Horton hypothesized that temperature in the summer and salinity in the winter controlled the distribution of *C. nigricauda* in Yaquina Bay.

Crangon nigromaculata

Crangon nigromaculata, the blackspotted bay shrimp, ranges from the Farallon Islands, California to Turtle Bay, Baja California (Rathbun 1904) and is more common in the nearshore ocean area than in estuaries. It is found on sand bottoms at depths ranging from 5 to 174 m and reaches a maximum size of approximately 70 mm (Jensen 1995). During an early survey of San Francisco Bay and the Gulf of the Farallones, *C. nigromaculata* was collected from South Bay in the vicinity of Hunter's Point to Central Bay and in the Gulf of the Farallones to 55 m; all specimens were collected at temperatures from 8.8 to 17.2 °C and salinities from 27.8‰ to 34.1‰ (Schmitt 1921). Based on nearshore ocean sampling by the City of San Francisco, *C. nigromaculata* is the most abundant species of *Crangon* in the Gulf of the Farallones (Michael Kellog, personal communication, see "Notes"). Only sparse information exists on the life history of *C. nigromaculata* in the estuary and the nearshore ocean.

Methods

Crangon nigromaculata juveniles were separated from adults based on a size of maturity of 28 mm for males (CDFG, unpublished data) and 42 mm for females (approximately 1% of the ovigerous *C. nigromaculata* we collected were <42 mm). The juvenile and adult categories were used for abundance and distribution analyses and 5 mm groups by sex were used for salinity and temperature analyses. The annual index periods selected were April through October for juveniles and February through October for adults. The February through October period omitted months when the abundance of adult *C. nigromaculata* was often high, but was necessary for the inclusion of the 1989 through 1994 data in the annual analyses. For seasonal distribution analyses, 1996 was selected as a representative year for both juvenile and adult *C. nigromaculata,* and length frequency data from 1988 were used to demonstrate the typical monthly length frequency patterns.

Results

Length Frequency

We collected male *C. nigromaculata* to 59 mm and females to 72 mm. In January 1988, a large number of juvenile shrimp remained from a cohort which first appeared in late 1987 (Figure 25). Catches decreased significantly in February and March but the same cohort was collected in higher numbers in April. In May, a new cohort of juvenile shrimp appeared while a few shrimp from the older cohort were still present and had reached maturity. From June through August few *C. nigromaculata* of any cohort were collected. Another cohort of juvenile shrimp appeared in September and was again followed by very low catches. In November and December juvenile and adult cohorts were again distinguishable.

Abundance

Crangon nigromaculata was the 3rd most common species of caridean shrimp collected in the San Francisco Estuary over the study period (see Table 1). In 1992, it was the 2nd most common species, but from 1980 to 1982 and 1984 to 1986 is was either the 4th or 5th most common species. The annual abundance trends of juvenile and adult *C. nigromaculata* were very similar. Abundance of juvenile *C. nigromaculata* was relatively low from 1980 through 1989 and consistently increased from 1990 through 1993 (Figure 26A, Table 6). The highest annual index was in 1993 and the lowest indices were from 1980 to 1982 and in 1985. The highest indices for adult *C. nigromaculata* were from 1991 through 1994 and the lowest indices from 1980 to 1986 (Figure 26B, Table 7). Juveniles were more abundant than adults in every year except 1985 and over all the years, juveniles comprised 69% of the total *C. nigromaculata* index. The annual indices for adult *C. nigromaculata* were biased low in most years because the adults were usually most abundant in late fall and winter and the annual indices excluded November through January.

The seasonal abundance of juvenile *C. nigromaculata* was unimodal, with a peak in August and high abundance from May through September (Figure 27, see Table 6). But when the individual years are examined, the period of peak abundance ranged from late spring to winter (see Table 6). Several years had multiple abundance peaks; for example, in 1988 juvenile abundance peaked in January, April to May, September, and November to December. The length frequency data (above) indicates that each peak was a distinct cohort. Adult *C. nigromaculata* were most abundant from November through January, with a secondary peak in summer of some years (see Figure 27, see Table 7).

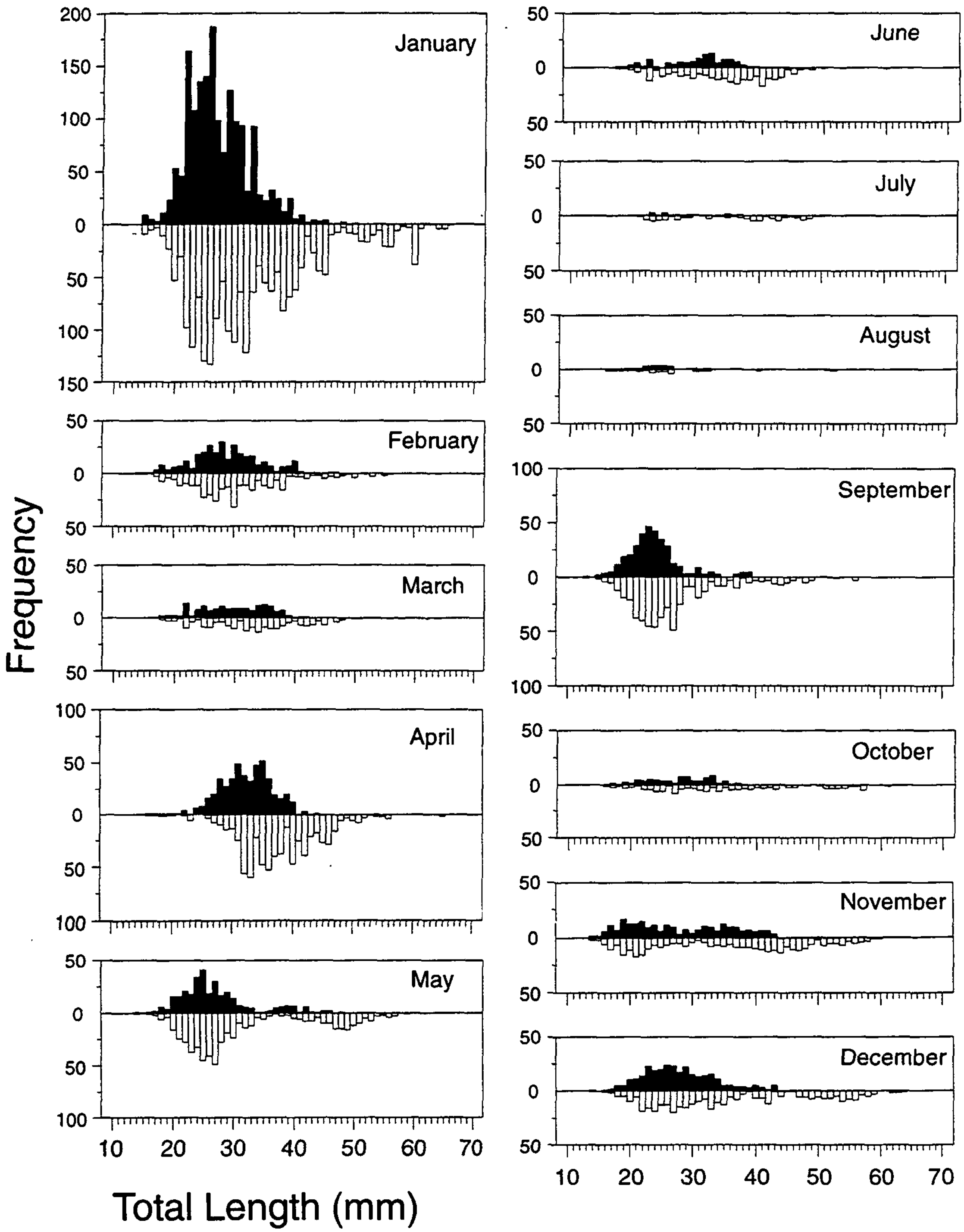

Figure 25 Monthly length frequencies of male (filled bars) and female (open bars) *C. nigromaculata* **collected with the otter trawl in 1988.** Size classes are every 1 mm, from 11 to 70 mm.

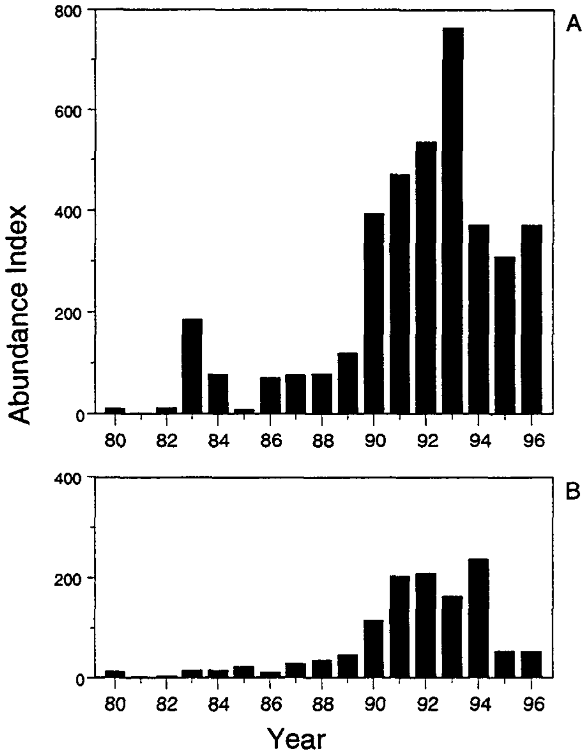

Figure 26 Annual abundance indices of *C. nigromaculata* collected with the otter trawl: (A) juveniles (1980 to 1996), the index period is April to October and the indices are divided by 100; (B) adults (1980 to 1996), the index period is February to October and the indices are divided by 100

Table 6 Monthly and annual abundance indices of juvenile *C. nigromaculata* collected with the otter trawl from 1980 to 1996. The index period is April to October and the indices are divided by 100.

	Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Apr–Oct*
1980		47	3	1	18	24	6	12	13	3	4	0	11
1981	7	2	1	0	0	0	8	2	0	6	0	16	2
1982	8	1	0	0	31	29	3	2	14	12	5	5	13
1983	4	1	0	0	0	0	102	1108	34	54	168	49	185
1984	32	8	6	4	191	335	7	9	1	0	1	8	78
1985	4	13	1	7	0	28	15	0	4	7	3	4	9
1986	23	3	0	1	8	19	60	265	125	28	6	30	72
1987	16	50	3	2	25	30	12	74	85	313	216	220	77
1988	189	51	30	125	119	53	9	12	205	34	85	85	79
1989	152	42	69	161	121	132	128	57					120
1990		103	130	93	240	249	158	425	826	770			394
1991		225	309	238	293	426	502	258	719	861			471
1992		147	198	37	408	1209	123	322	816	837			536
1993		152	95	282	1735	998	1497	495	50	295			765
1994		120	189	56	534	653	201	603	420	130			371
1995	164	168	198	45	291	1361	76		35	40	65	133	308
1996	168	38	57	81	272	222	708	734	410	170	285	463	371
1981–1988, 1996	35	10	9	13	72	90	129	303	84	40	67	82	

Table 7 Monthly and annual abundance indices of adult *C. nigromaculata* collected with the otter trawl from 1980 to 1996. The index period is February to October and the indices are divided by 100.

	Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Feb–Oct*
1980		47	6	0	10	32	8	4	5	7	2	0	13
1981	16	3	2	0	0	0	9	3	0	4	0	11	2
1982	11	1	0	0	2	18	1	2	9	8	1	4	4
1983	11	0	0	0	0	0	12	78	11	37	161	108	15
1984	20	8	6	3	22	85	6	8	0	0	1	17	15
1985	26	140	19	7	3	24	9	0	0	2	4	18	23
1986	87	10	0	0	2	9	11	25	16	25	39	176	11
1987	70	77	9	1	4	6	11	38	43	85	147	163	30
1988	114	33	28	130	55	28	7	2	20	22	58	50	36
1989	130	32	35	41	64	79	45	25					46
1990		88	60	28	95	113	26	21	128	482			116
1991		300	75	96	63	125	168	99	157	754			204
1992		256	214	74	141	266	17	17	515	383			209
1993		316	231	97	198	218	183	67	13	158			164
1994		328	283	138	210	213	124	404	324	110			237
1995	368	236	95	16	24	15	2		14	32	163	306	54
1996	195	30	12	11	38	59	45	67	125	96	464	457	53
1981–1988, 1996	52	27	6	3	9	28	13	26	23	24	96	113	

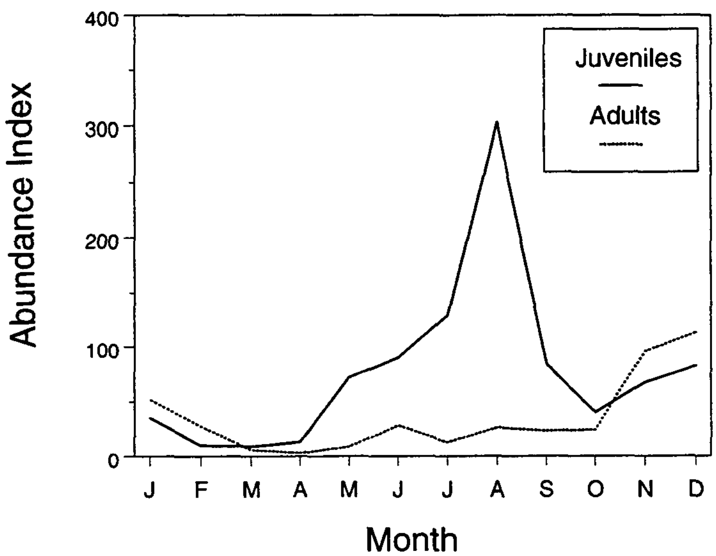

Figure 27 Monthly abundance indices of juvenile and adult *C. nigromaculata* collected with the otter trawl from 1981 to 1988 and 1996. The indices are divided by 100.

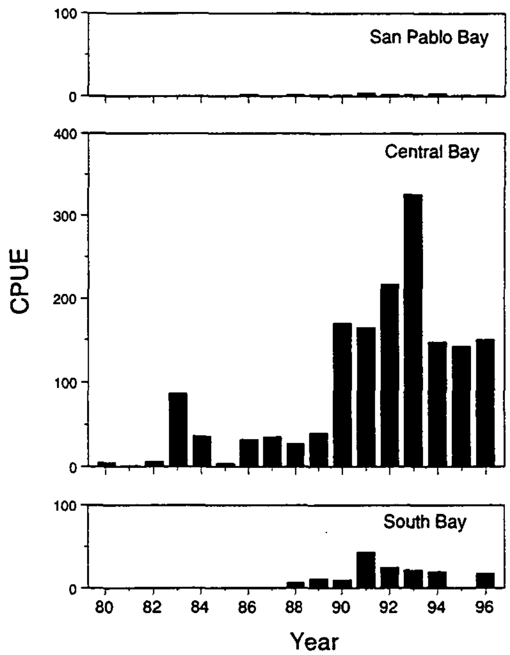

Figure 28 Annual distribution (CPUE) of juvenile *C. nigromaculata* for April to October from 1980 to 1996

Distribution

The center of distribution of *C. nigromaculata* was usually in Central Bay, and annual and seasonal changes in distribution were not as pronounced as for either *C. franciscorum* or *C. nigricauda*. Both juveniles and adults extended their distribution to South Bay and, to a lesser extent, San Pablo Bay, especially from 1988 through 1992 (Figures 28 and 29). In San Pablo Bay, *C. nigromaculata* was primarily restricted to the channel and the shoals of its southern part.

There were no strong seasonal trends in the distribution of either juvenile or adult *C. nigromaculata* (Figures 30 and 31), as their distribution was centered in Central Bay in all months. South Bay CPUEs were highest in winter and relatively low in summer. CPUEs increased slightly in San Pablo Bay in late fall and winter but were essentially 0 through the summer.

Salinity and Temperature

Most *C. nigromaculata* were collected from a relatively narrow range of salinities and temperatures—80% were from 25.9‰ to 31.9‰ and 10.9 to 17.8 °C (10th and 90th percentiles, respectively, Figure 32). The mean salinity for all sizes of *C. nigromaculata* was 29.4‰ and the mean temperature was 14.9 °C. There was essentially no change in mean salinity with size for juvenile (11 to 20 mm), female, or male *C. nigromaculata*, and both sexes were collected at almost identical mean salinities (Figure 33). Mean temperature was about 15 °C for the smallest juveniles, increased slightly with size and then decreased (Figure 34). The largest females (66 to 70 mm) and males (51 to 55 mm) were collected at a mean temperature of about 12 °C. Males >30 mm were collected at lower mean temperatures than same-sized females, but at the size classes which encompass the onset of maturity (26 to 30 mm for males, 41 to 45 mm for females), the mean temperatures were almost identical.

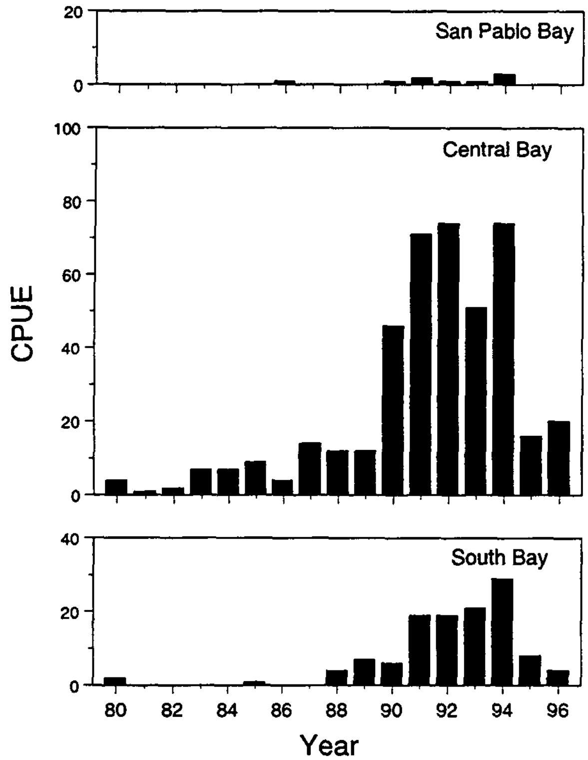

Figure 29 Annual distribution (CPUE) of adult *C. nigromaculata* for February to October from 1980 to 1996

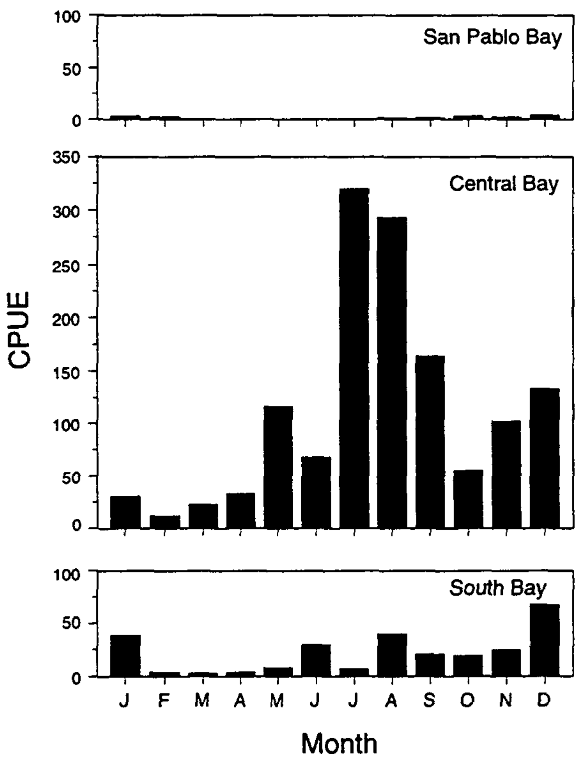

Figure 30 Monthly distribution (CPUE) of juvenile *C. nigromaculata* in 1996

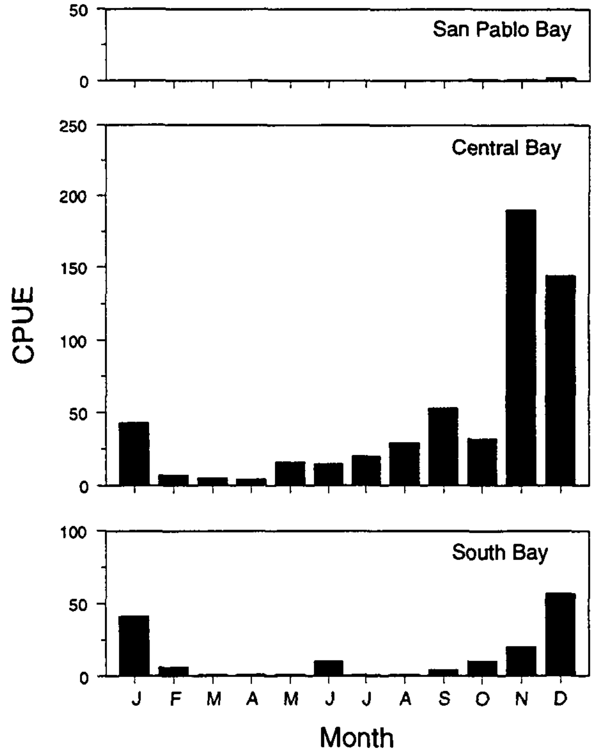

Figure 31 Monthly distribution (CPUE) of adult *C. nigromaculata* in 1996

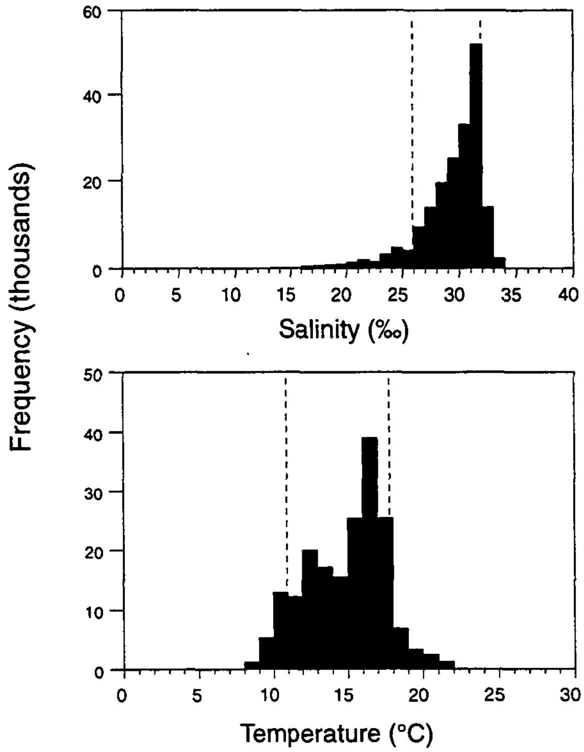

Figure 32 Salinity (‰) and temperature (°C) distributions of all sizes of *C. nigromaculata* collected with the otter trawl (1980 to 1996). Dashed vertical lines are the 10th and 90th percentiles.

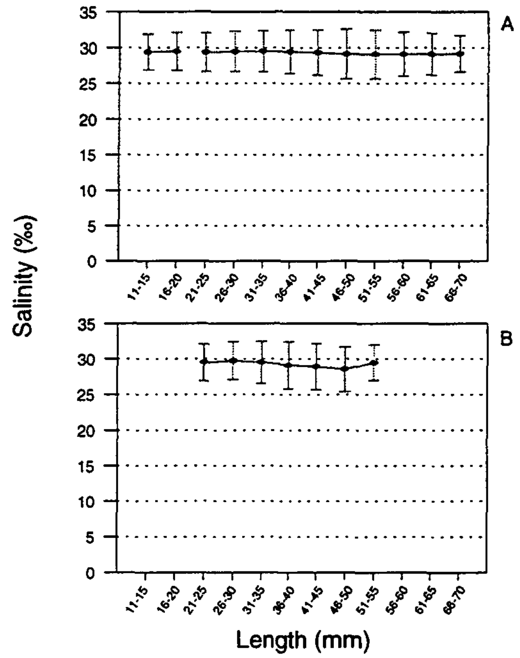

Figure 33 Mean salinity (±1 standard deviation) of *C. nigromaculata* by size class collected with the otter trawl: (A) juveniles (11 to 20 mm) and females and (B) males. Size classes are every 5 mm, from 11 to 70 mm.

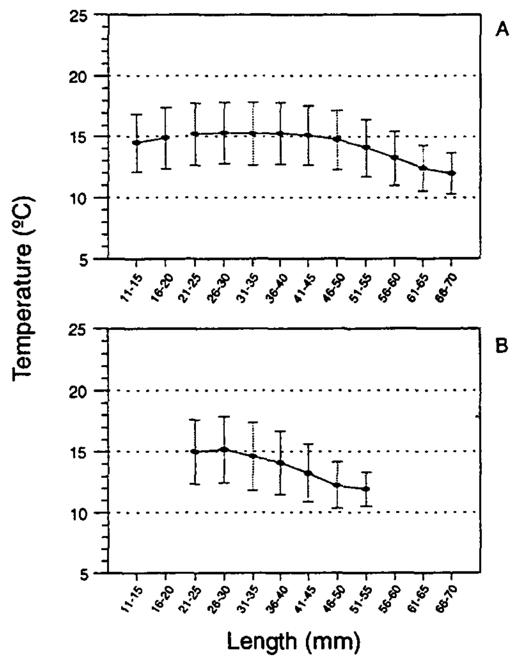

Figure 34 Mean temperature (±1 standard deviation) of *C. nigromaculata* by size class collected with the otter trawl: (A) juveniles (11 to 20 mm) and females and (B) males. Size classes are every 5 mm, from 11 to 70 mm.

Discussion

Crangon nigromaculata is generally limited to high salinity, cool areas of the San Francisco Estuary and based on collections by this study, City of San Francisco data, and Schmitt (1921) is more common in the nearshore coastal area than in the estuary itself. The estuary probably functions primarily as an expansion of the nearshore nursery area of *C. nigromaculata*, with juveniles opportunistically using the estuary when salinities and temperatures are appropriate. Juveniles dominated our catch and were collected at higher temperatures, but at essentially the same salinities as adults. Based on temperature preferences, juvenile *C. nigromaculata* are more tolerant of estuarine conditions than adults. The use of the estuary by juvenile *C. nigromaculata* was more sporadic than for either *C. franciscorum* or *C. nigricauda*, as abundance did not consistently peak during the same period each year, and multiple cohorts were common.

Early in the study, *C. nigromaculata* was a minor component of the estuary's shrimp community, but from 1990 through 1993, its abundance increased and it became the 3rd most common species collected overall. This increase in abundance is hypothesized to be a result of the 1987–1992 drought, as *C. nigromaculata* became well established in the higher salinity, cooler areas of the estuary in these years. But abundance remained relatively high through 1996, even during several years classified as either "above normal" or "wet." There may also be a relationship between increased ocean temperatures and abundance, as 2 of the most dramatic increases in abundance occurred in 1983 and 1993, concurrent with above average ocean temperatures (see Salinity and Temperature chapter, Figure 11). It is plausible that *C. nigromaculata* abundance would increase during warm ocean periods, as the San Francisco Estuary is near the northern limit of its range.

Crangon nigromaculata was most abundant in Central Bay in all years and seasons. The extension to South and San Pablo bays was usually limited to late fall through spring. This restricted distribution is supported by the salinity and temperature statistics, as only 10% were collected at salinities <25.9‰ or temperatures >17.8 °C. Although average bottom salinities in South and San Pablo bays were >26‰ for extended periods, especially during the drought (see Salinity and Temperature chapter, Figures 1 and 3), temperatures were >18 °C during the summer and early fall of all years in these embayments (see Salinity and Temperature chapter, Figures 8 and 10). In contrast, average Central Bay bottom salinities were >26‰ in many months and in all months from May 1987 through December 1992 (see Salinity and Temperature chapter, Figure 2). With a few exceptions, Central Bay temperatures were <18.0 °C in all months (see Salinity and Temperature chapter, Figure 9).

Palaemon macrodactylus

Palaemon macrodactylus, the oriental shrimp, was introduced to the San Francisco Estuary from Asia in the 1950s (Newman 1963) and is now common in lower salinity areas of the estuary, including South Bay below the Dumbarton Bridge (Kinnetic Laboratories 1987) and areas upstream of San Pablo Bay (Siegfried 1980, CDFG 1987). Few *P. macrodactylus* were collected by Siegfried (1980) at salinities <1‰. Most ovigerous *P. macrodactylus* were collected from May through August and many of the ovigerous females had ripe ovaries, indicating repeat reproduction. Based on the vertical distribution of larvae of an another species of Palaemonidae (Sandifer 1975), *P. macrodactylus* larvae have probably developed mechanisms that result in estuarine retention.

Methods

Palaemon macrodactylus were not separated into juvenile and adult categories for the abundance and distributional analyses, as a size of maturity is not available for males. But ovigerous and non-ovigerous categories were used for the seasonal abundance analyses. An index period of April through October was selected for the annual analyses and 1985 was selected as a representative year for the seasonal distribution analysis. The monthly length frequency histograms include all years and stations sampled. For salinity and temperature analyses, 5 mm groups by sex were used.

Results

Length Frequency

Female *P. macrodactylus* grow to a larger size than males; we collected males to 64 mm and females to 73 mm. There is some indication of 2 modes in the length frequency data through March, especially for males in February and March (Figure 35). Length data for both sexes were strongly unimodal from May through August, with a modal size of about 40 mm for males and about 55 mm for females in August. Another cohort of smaller shrimp, which are undoubtedly juveniles, made its first appearance in September. This cohort of smaller shrimp can be distinguished from the larger cohort through December, especially for males. Note that we collected very few small (<20 mm) *P. macrodactylus*; most shrimp <20 mm were collected from September through December.

Abundance

Palaemon macrodactylus was the 5th most common species of caridean shrimp collected from 1980 to 1996 and in some years ranked 3rd (see Table 1). The highest annual index of *P. macrodactylus* was in 1984 and the lowest indices were in 1983 and 1988 (Figure 36, Table 8). Abundance appears to have been somewhat cyclic in the 1980s, but there was less variation in the abundance indices in the 1990s.

Non-ovigerous *P. macrodactylus* were most abundant in the estuary from June through September (Figure 37, see Table 8). Abundance occasionally peaked outside of this period—the most notable occurrence was in January 1983 (see Table 8). Ovigerous females were most abundant from May through September, with few or none collected from November through March (see Figure 37).

Distribution

The center of distribution of *P. macrodactylus* was in either Suisun Bay or the west delta in every year (April through October) except 1983, when CPUE was highest in South Bay (Figure 38). There were annual shifts in distribution which were apparently associated with freshwater outflow. During years with high outflow (for example, 1982 and 1983), *P. macrodactylus* moved downstream, and few or no shrimp were collected in the west delta.

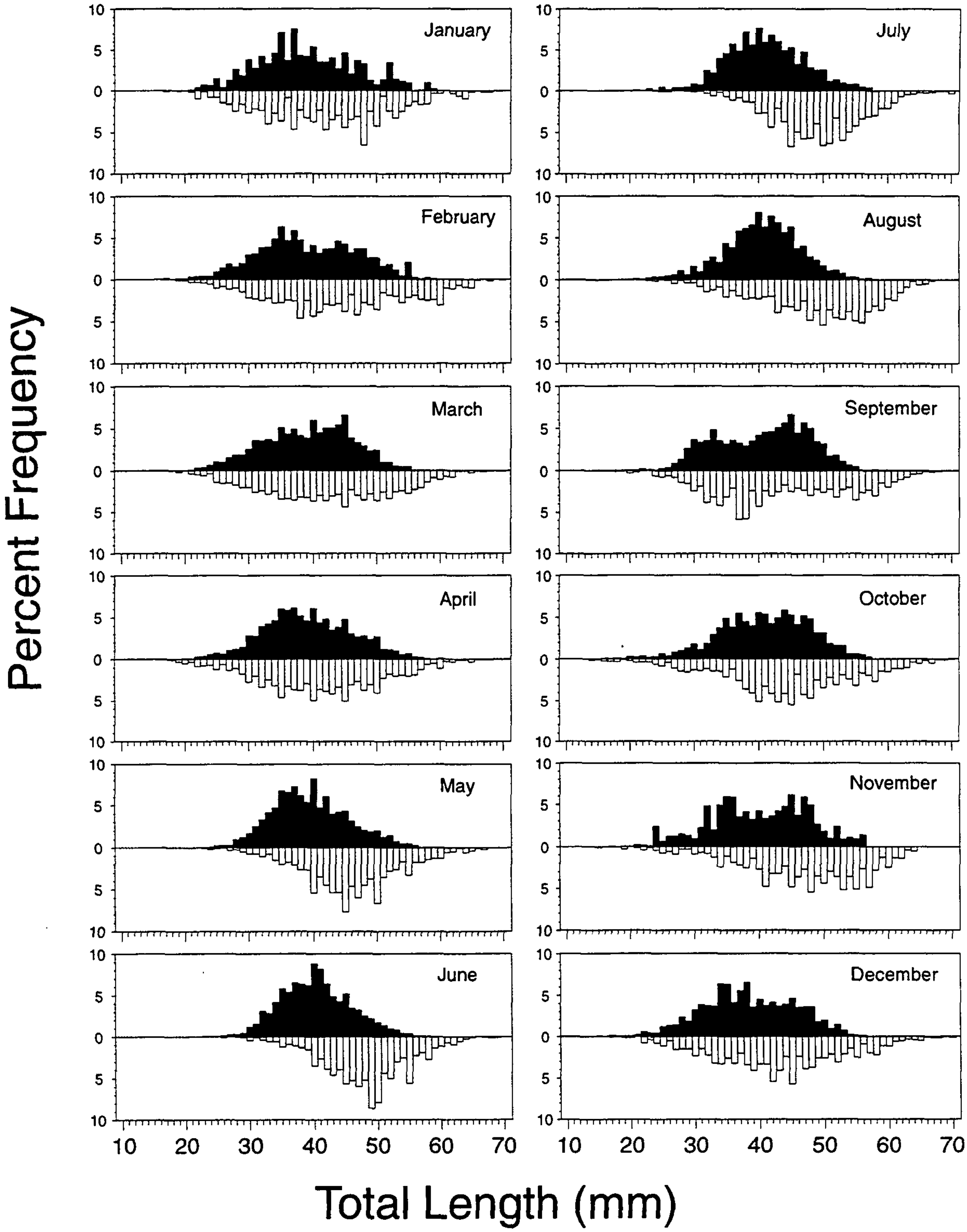

Figure 35 Monthly percent length frequencies of male (closed bars) and female (open bars) *P. macrodactylus* **collected with the otter trawl from 1980 to 1996.** Size classes are every 1 mm, from 11 to 70 mm.

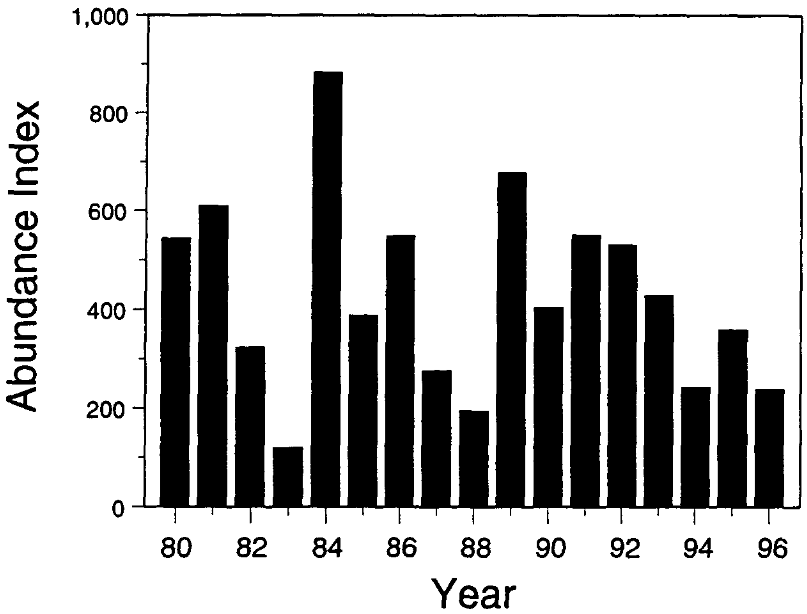

Figure 36 Annual abundance indices of *P. macrodactylus* collected with the otter trawl from 1980 to 1996. The index period is April to October and the indices are divided by 10.

Table 8 Monthly and annual abundance indices of all sizes of *P. macrodactylus* collected with the otter trawl from 1980 to 1996. The index period is April to October and the indices are divided by 10.

	Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Apr–Oct*
1980		259	178	247	601	1154	794	384	387	230	138	145	543
1981	76	160	124	203	204	706	1264	798	462	625	198	315	609
1982	397	209	208	428	380	232	576	461	74	115	103	35	324
1983	488	224	94	137	130	340	97	72	17	37	23	184	119
1984	26	23	90	642	413	685	277	212	2622	1328	165	593	883
1985	245	557	227	167	417	386	475	488	449	328	71	330	387
1986	147	521	556	237	384	804	651	901	645	212	401	159	548
1987	88	63	186	233	254	226	310	487	308	113	150	181	276
1988	100	88	121	170	325	250	286	181	85	61	74	101	194
1989	70	100	113	488	602	1006	628	666					678
1990		66	235	281	364	620	614	455	288	199			403
1991		95	245	435	556	295	338	1667	284	274			550
1992		114	281	458	600	650	742	284	854	119			530
1993		277	288	616	309	281	724	614	388	62			428
1994		87	96	144	210	384	383	319	152	102			242
1995	108	200	520	116	786	391	389		316	158	91	80	359
1996	109	48	265	272	384	277	219	353	128	33	84	50	238
1981–1988, 1996	186	210	208	277	321	434	461	439	532	317	141	216	

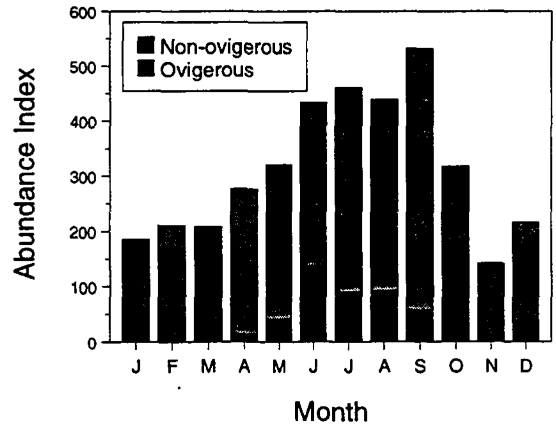

Figure 37 Monthly abundance indices of non-ovigerous and ovigerous *P. macrodactylus* collected with the otter trawl from 1981 to 1988 and 1996. The indices are divided by 10.

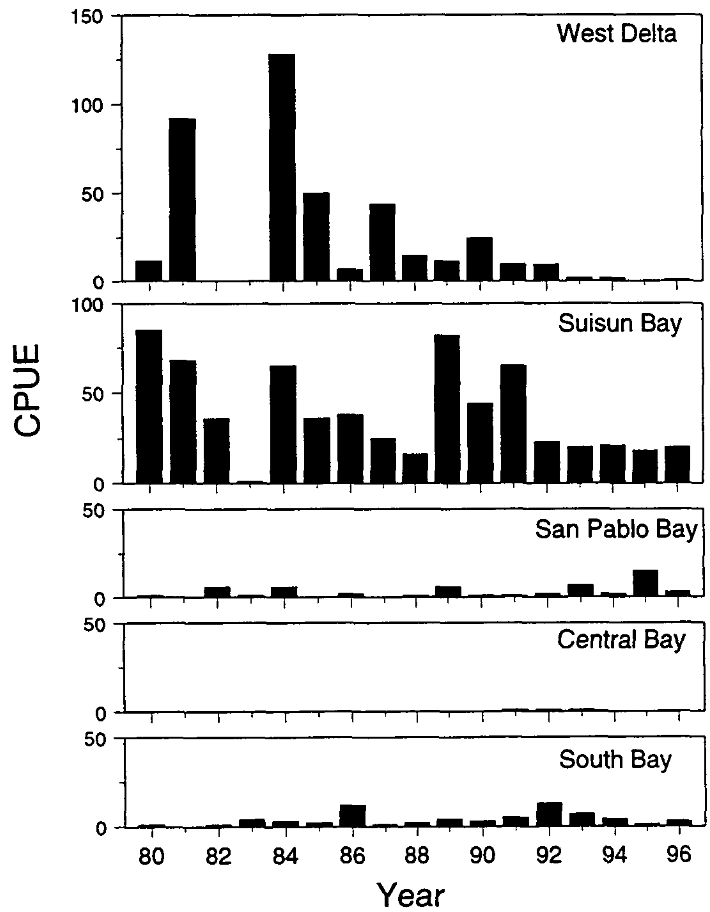

Figure 38 Annual distribution (CPUE) of all sizes of *P. macrodactylus* for April to October from 1980 to 1996

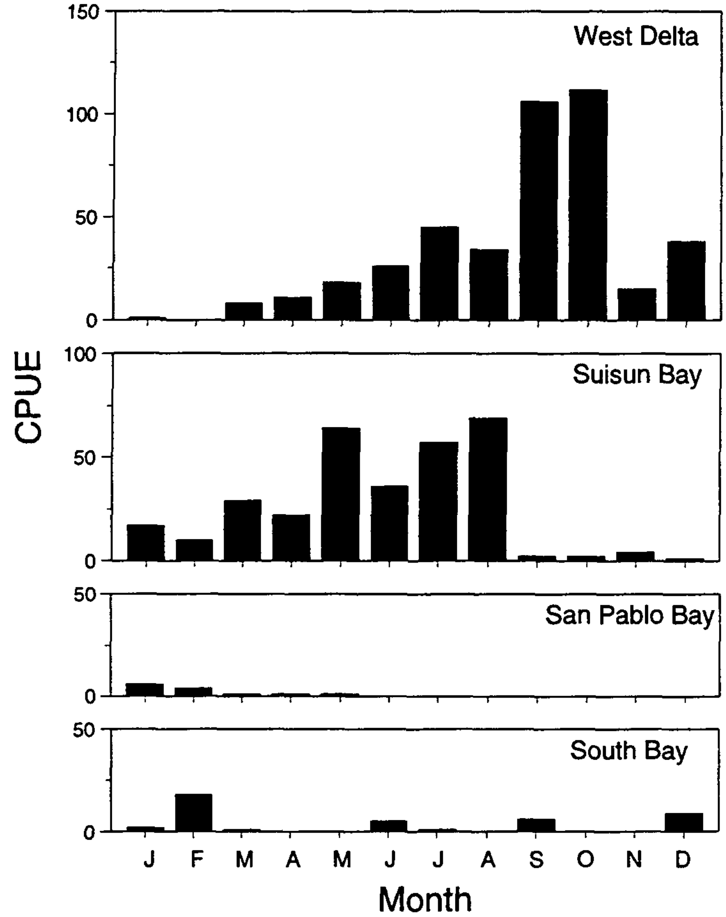

Figure 39 Monthly distribution (CPUE) of all sizes of *P. macrodactylus* collected with the otter trawl in 1985

Palaemon macrodactylus was concentrated in Suisun Bay from January through August (except for February, when CPUE was highest in South Bay), and the center of distribution shifted upstream to the west delta in September (Figure 39). This apparent distribution shift in fall was probably due to juvenile shrimp from the new cohort which either grew large enough to become catchable by the net or moved into the sampling area.

Salinity and Temperature

Palaemon macrodactylus was abundant over a very wide range of salinities and temperatures; 80% were collected from 1.9‰ to 28.1‰ and from 12.3 to 21.7 °C (10th and 90th percentiles, respectively, Figure 40). The mean salinity was 13.5‰ and the mean temperature was 18.0 °C.

The smallest size group (16 to 20 mm) was initially collected at a mean salinity of about 10‰ (Figures 41A and 41B). The mean salinity decreased with size, but more so for females than males. After 26 to 30 mm, salinity initially increased with size—the largest females (66 to 70 mm) were collected at a mean salinity of about 9‰ and the largest males (56 to 60 mm) were collected at a mean salinity of about 21‰. For any given size group, males were collected at a higher mean salinity than females.

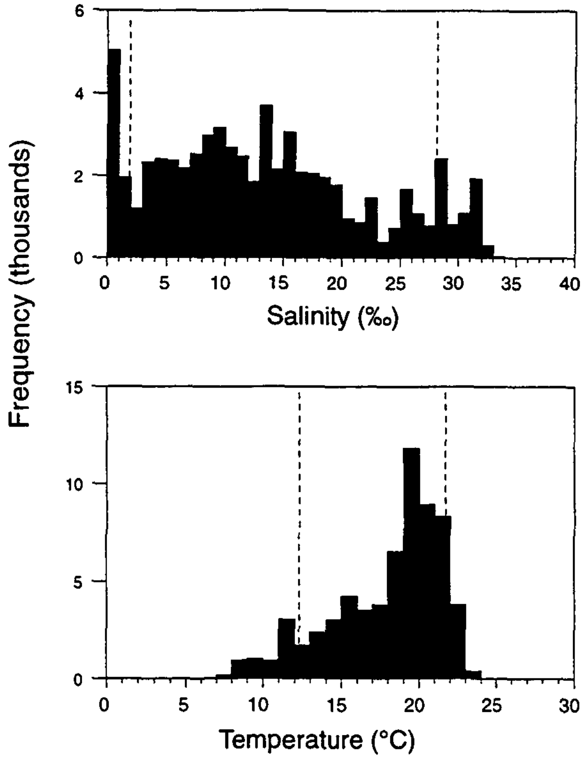

Figure 40 Salinity (‰) and temperature (°C) distributions of all sizes of *P. macrodactylus* collected with the otter trawl (1980 to 1996). Dashed vertical lines are the 10th and 90th percentiles.

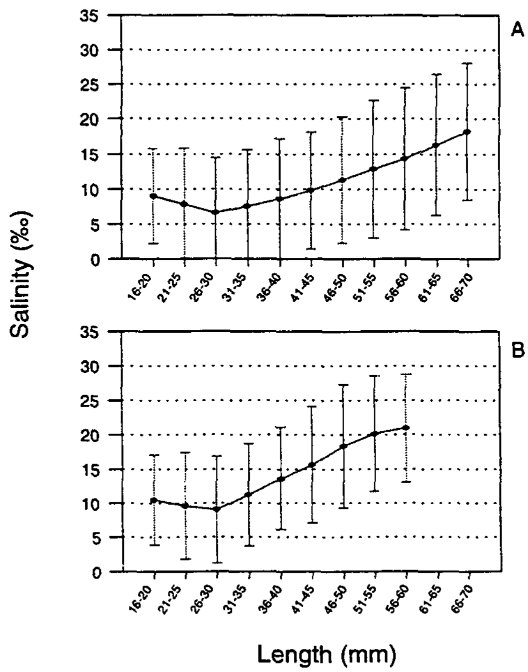

Figure 41 Mean salinity (±1 standard deviation) of *P. macrodactylus* by size class collected with the otter trawl: (A) females and (B) males. Size classes are every 5 mm, from 16 to 70 mm.

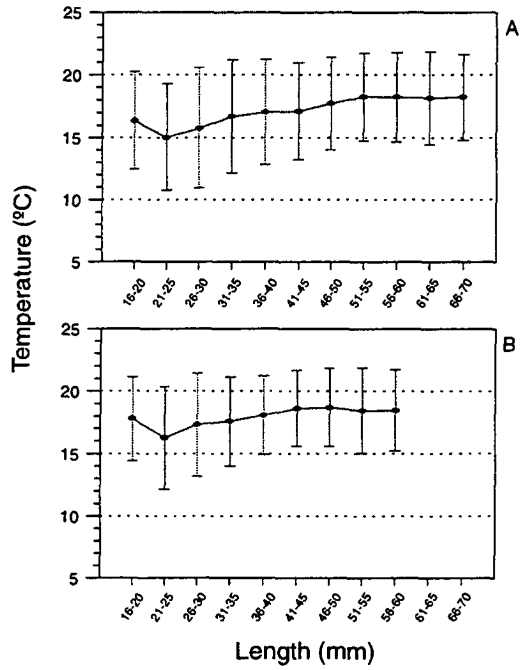

Figure 42 Mean temperature (±1 standard deviation) of *P. macrodactylus* by size class collected with the otter trawl: (A) females and (B) males. Size classes are every 5 mm, from 16 to 70 mm.

The mean temperature also initially decreased with size and them slowly increased (Figures 42A and 42B). Males were consistently collected at a higher mean temperature than females of the same size, up to 51 to 55 mm.

Discussion

Palaemon macrodactylus is an introduced species which apparently completes its entire life cycle in the estuary. It is well adapted to estuarine life, as it is abundant over a broader range of salinities and temperatures than any other species of caridean shrimp common to the estuary. Based on when ovigerous females were collected, most larvae hatch during the summer and early fall months when they are subject to the least amount of downstream transport by freshwater outflow. We collected few small juveniles in the otter trawl and hypothesize that they rear either in very shallow water areas or in tidal sloughs and creeks upstream of our sampling area.

Unlike *C. franciscorum*, *C. nigricauda*, and *C. nigromaculata*, *P. macrodactylus* abundance did not increase or decrease during the 1987–1992 drought. We may not have sampled a significant portion of the population, especially juveniles, during the drought and consequently the annual indices were biased low.

The distribution of *P. macrodactylus* shifted downstream in response to high outflow, but was never centered below Suisun Bay. There is also a population in the southern portion of South Bay, primarily south of the Dumbarton Bridge, which we evidently undersampled; some shrimp from this population were always collected, but accounted for a very small portion of the total index.

The initial, slight decrease in salinity and temperature with size is probably due to an upstream movement of juveniles and the collection of most juveniles in fall and winter, when salinities and temperatures decrease. An increase in salinity and temperature with size has been reported for other species of estuarine shrimp and is indicative of a downstream movement of maturing shrimp to higher salinities for reproduction. Male *P. macrodactylus* were collected at higher salinities and lower temperatures than females. This pattern has also been reported for *C. franciscorum* and *C. nigricauda* and is consistent with the observation that males of many species of caridean shrimp are distributed downstream of females.

Heptacarpus stimpsoni

Heptacarpus stimpsoni, Stimpson's coastal shrimp, ranges from Sheep Bay, Alaska, to Punta Abreojos, Baja California (Jensen 1995). It is common subtidally in eelgrass beds and in macroalgae (Smith and Carlton 1975) but also occurs on soft bottoms (Jensen 1995). It has been collected from the intertidal to 73 m (Jensen 1995). *Heptacarpus stimpsoni* was the most common member of the family Hippolytidae collected in San Francisco Bay by Schmitt (1921). In his collections it was abundant in Central and South bays and was only occasionally collected in lower San Pablo Bay. This is a relatively small species, with a maximum size of 32 mm (Jensen 1995).

Methods

Heptacarpus stimpsoni was not separated into juvenile and adult categories for the abundance and distributional analyses, because a size of maturity is not known for males. Also, after March 1987, *Heptacarpus* were no longer sexed and measured, but categorized as either ovigerous or non-ovigerous and counted. These ovigerous and non-ovigerous categories were used for the seasonal abundance analyses. An index period of February through October was selected for the annual analyses. For analysis of seasonal distribution, 1987 was selected as a representative year. The 1981 to 1986 length frequency data were used for the monthly length frequency histograms.

Results

Length and Length Frequency

The largest *H. stimpsoni* female collected was 35 mm and the largest male 32 mm. The smallest shrimp (<10 to 15 mm) were collected primarily in December and January and from May through August (Figure 43). Most large shrimp (>30 mm) were collected from December through February and in June. The maximum modal length of about 28 mm occurred in February.

Abundance

Heptacarpus stimpsoni was the 4th most common species of caridean shrimp collected over the study period; in 1989 it ranked 3rd and in 1984 and 1985 it ranked 5th (see Table 1). The annual abundance indices of *H. stimpsoni* were very low from 1980 thorough 1986, increased from 1987 to 1991, and, except for 1995, remained at relatively high levels through 1996 (Figure 44, Table 9). Ovigerous females comprised a very high proportion of the annual index, ranging from 33% in 1983 to 64% in 1984 (see Figure 44, Table 10).

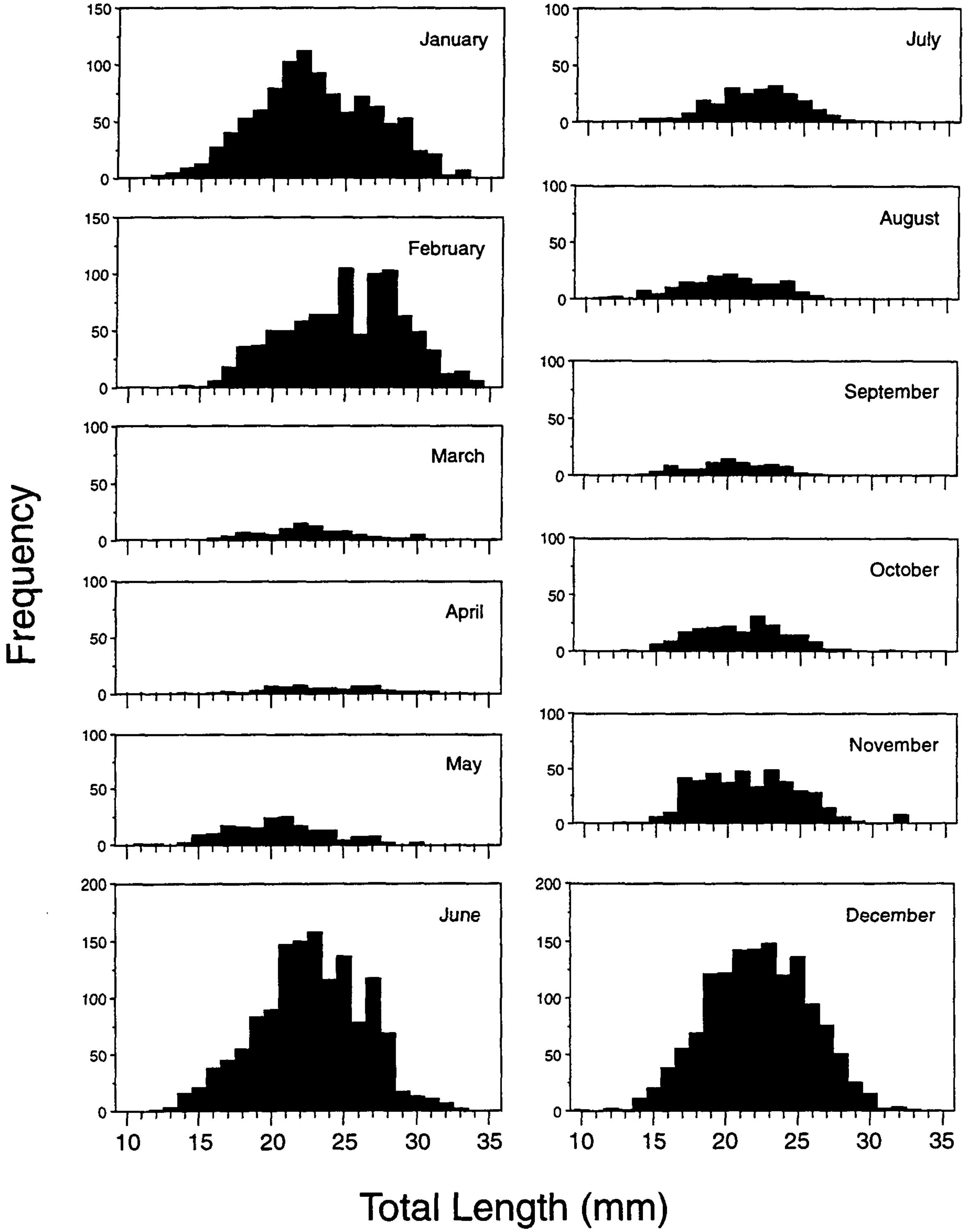

Figure 43 Monthly length-frequency histograms for male and female *H. stimpsoni* **combined from 1981 to 1986.** Size classes are every 1 mm, from 10 to 35 mm.

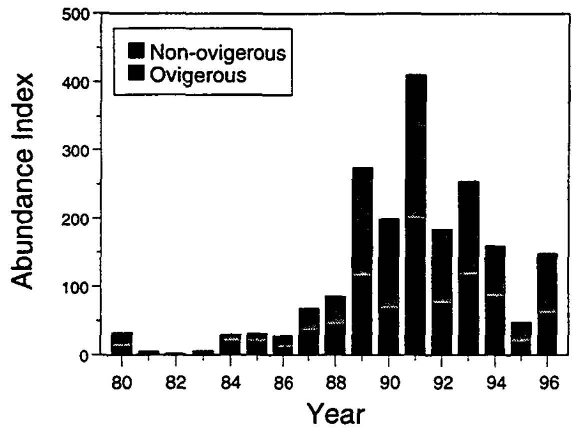

Figure 44 Annual abundance indices of ovigerous and non-ovigerous *H. stimpsoni* collected with the otter trawl from 1980 to 1996. The index period is February to October and the indices are divided by 10.

Table 9 Monthly and annual abundance indices of all sizes of *H. stimpsoni* collected with the otter trawl from 1980 to 1996. The index period is February to October and the indices are divided by 10.

	Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Feb–Oct*
1980		197	33	1	10	40	7	1	0	0	0	2	32
1981	60	7	13	1	8	1	4	1	3	10	0	65	5
1982	49	1	1	0	3	2	0	0	7	0	37	122	2
1983	118	16	0	0	0	0	2	14	3	22	40	68	6
1984	3	4	7	15	37	208	2	3	1	0	1	14	31
1985	42	158	5	3	1	82	16	0	2	8	14	60	31
1986	30	78	2	0	3	80	44	26	9	18	30	82	29
1987	54	128	83	13	8	29	24	46	124	159	230	362	68
1988	252	65	94	244	96	91	74	39	55	15	53	100	86
1989	71	83	74	709	313	491	102	147					274
1990		121	258	105	122	236	275	180	251	244			199
1991		388	688	466	378	554	161	385	162	521			411
1992		425	414	79	235	163	37	26	127	158			185
1993		757	299	253	193	334	351	68	5	28			254
1994		105	102	44	143	445	169	190	176	60			159
1995	222	140	146	1	6	68	4		5	10	68	348	47
1996	342	223	108	85	182	165	160	266	77	75	288	418	149
1981–1988, 1996	106	75	35	40	38	73	36	44	31	34	77	144	

Table 10 Annual abundance indices of ovigerous, non-ovigerous, and percent ovigerous *H. stimpsoni* collected the otter trawl from 1980 to 1996. The index period is February to October and the indices are divided by 10.

Year	*Ovigerous*	*Non-ovigerous*	*Percent Ovigerous*
1980	11	21	34.4
1981	2	3	40.0
1982	1	1	50.0
1983	2	4	33.3
1984	19	11	63.3
1985	18	13	58.1
1986	10	18	35.7
1987	35	33	51.5
1988	44	42	51.2
1989	115	159	42.0
1990	67	132	33.7
1991	199	212	48.4
1992	75	109	40.8
1993	116	138	45.7
1994	85	74	53.5
1995	18	30	37.5
1996	60	88	40.5

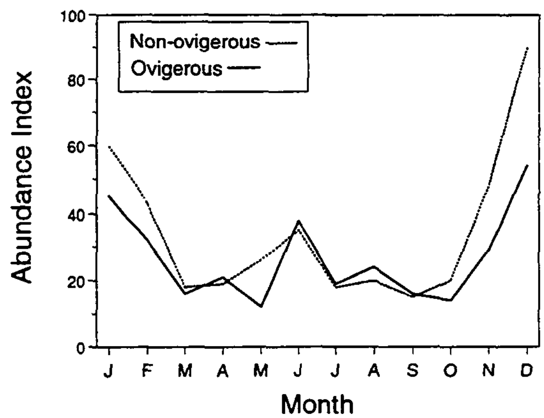

Figure 45 Monthly abundance indices of non-ovigerous and ovigerous *H. stimpsoni* collected with the otter trawl from 1981 to 1988 and in 1996. The indices are divided by 10.

Heptacarpus stimpsoni was most abundant from November through February with a smaller peak in June (Figure 45). The ovigerous and non-ovigerous trends were almost identical. In years we sampled for 12 months, a summer peak occurred in 1980, 1984, 1985, 1986, and 1996 (see Table 9). The winter peak was very small relative to the summer peak in 1984.

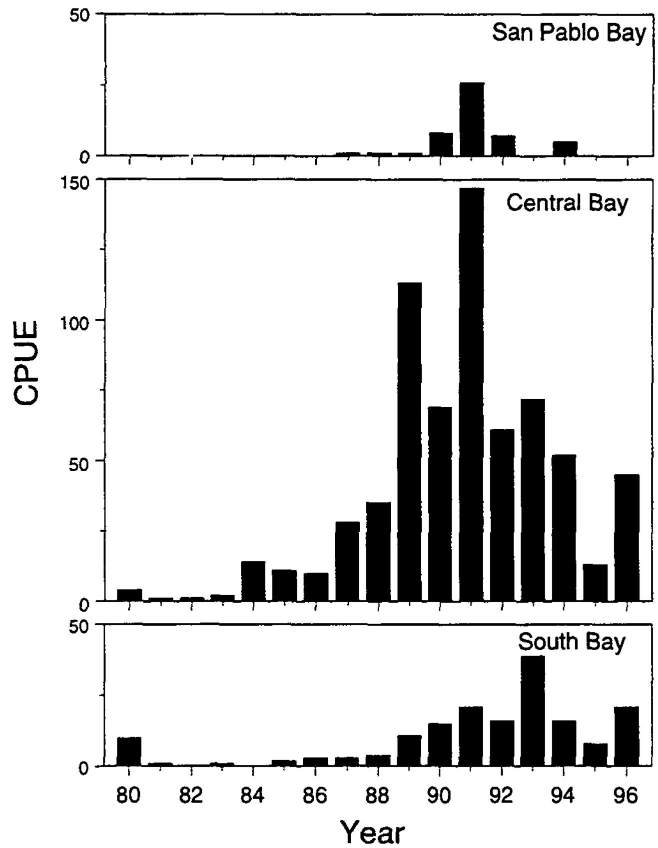

Figure 46 Annual distribution (CPUE) of all sizes of *H. stimpsoni* for February to October from 1980 to 1996

Distribution

The center of distribution of *H. stimpsoni* was in Central Bay in all years except 1980, when CPUE was highest in South Bay (Figure 46). Distribution expanded to San Pablo Bay primarily during the 1987–1992 drought. When *H. stimpsoni* was collected in San Pablo Bay, it was usually at the downstream stations. Although not apparent on the distribution graph, a few *H. stimpsoni* were collected in Carquinez Strait. Most of these collections were in the fall and spring of 1990, 1991, and 1992.

Heptacarpus stimpsoni was also concentrated in Central Bay all months, although the South and Central Bay CPUEs were almost equal in December (Figure 47). Central Bay CPUE was relatively high in fall, but *H. stimpsoni* typically did not expand its distribution to South or San Pablo bays until December.

Salinity and Temperature

Heptacarpus stimpsoni was collected at relatively high salinities and low temperatures, with 80% from 24.1‰ to 31.8‰ and 10.9 to 18.0 °C (10th and 90th percentiles, respectively, Figure 48). It was collected at a mean salinity of 28.7‰ and a mean temperature of 14.4 °C.

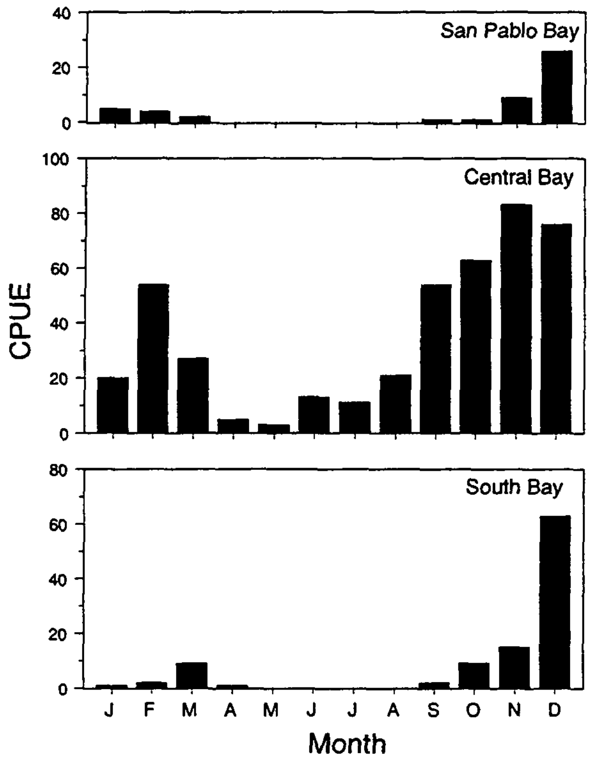

Figure 47 Monthly distribution (CPUE) of all sizes of *H. stimpsoni* in 1987

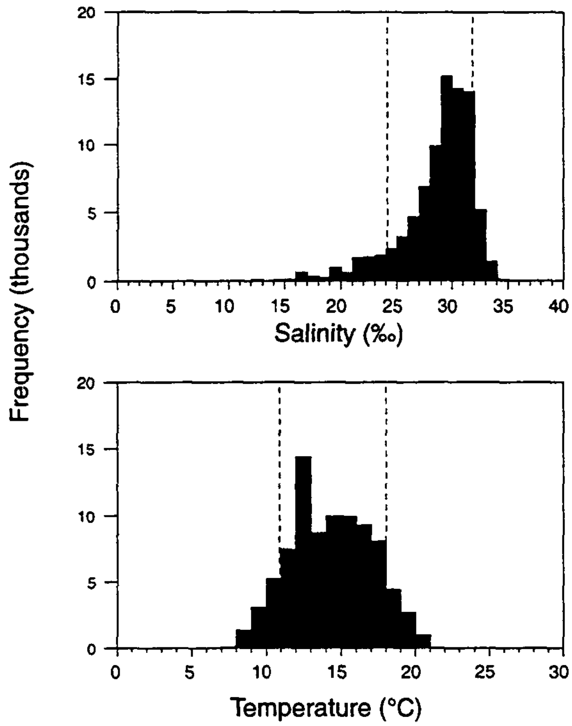

Figure 48 Salinity (‰) and temperature (°C) distributions of all sizes of *H. stimpsoni* collected with the otter trawl (1980 to 1996). Dashed vertical lines are the 10th and 90th percentiles.

Discussion

Heptacarpus stimpsoni is most common in cool, polyhaline to euhaline waters and is generally limited to South, Central, and lower San Pablo bays. It moved upstream during periods of low outflow, when higher salinities prevailed, and often during winter, when temperatures were cooler. Not surprisingly, the abundance of *H. stimpsoni* increased during the drought, with the highest abundance index in 1991. As for *C. nigricauda* and *C. nigromaculata*, abundance remained relatively high after the drought ended, in spite of some very high outflows.

Winter appears to be the major reproductive period of *H. stimpsoni*, with a 2nd, smaller reproductive period in summer. The peak abundance of ovigerous shrimp closely corresponds to the peak of non-ovigerous shrimp, indicating that a majority of the non-ovigerous shrimp we collected were adults. Any bias towards adults is probably due to the mesh selectivity of our gear—we rarely collected shrimp <10 mm in the otter trawl, which would exclude many juvenile *H. stimpsoni*. The high percentage of ovigerous females collected is notable, but is also probably due to a bias towards adult *H. stimpsoni* in our collections.

The relatively low abundance from March through October may also be due size selectivity of the gear. If peak reproductive activity is in winter, peak recruitment of juveniles would be in spring and summer. Many of these juveniles would not be collected by the otter trawl due to their small size. Alternatively, *H. stimpsoni* may emigrate from the estuary in late winter and remain in the nearshore ocean area until fall. However, there is no data from the Gulf of the Farallones or other nearshore ocean areas that supports such a migration.

Lissocrangon stylirostris

Lissocrangon stylirostris, the smooth bay shrimp, ranges from Chirikof Island, Alaska, to San Luis Obispo, California (Jensen 1995). It is common in the surf zone of relatively high energy sandy beaches and on sand or rock and sand bottoms subtidally and has been collected to 80 m (Jensen 1995). In an early survey of San Francisco Bay, *L. stylirostris* was collected from hard or sandy bottoms from Central Bay and lower San Pablo Bay, below Point San Pedro (Schmitt 1921). The largest reported size is 61 mm (Jensen 1995).

Methods

Lissocrangon stylirostris was not separated into juvenile and adult categories for the abundance and distributional analyses, because a size of maturity is not known for males. But ovigerous and non-ovigerous categories were used for the seasonal abundance analyses. An index period of February through October was selected for the annual analyses. No distributional figures are presented, as distribution rarely varied by year or season. The monthly length frequency histograms include all years and stations sampled, but the sexes were not plotted separately because so few males were collected. All sizes and both sexes were combined for the salinity and temperature analyses.

Results

Length Frequency

The size distribution of *L. stylirostris* was bimodal from January through March, with modal lengths of about 35 and 40 mm (Figure 49). The larger mode was detectable through June, when a large number of juvenile shrimp were also first collected. It is possible that several other cohorts entered the estuary during summer, as several modes were visible in the length frequency distributions in most months from August through December. Alternatively, the larger-sized mode could be females, which would be expected to grow more rapidly than males. In June, the modal length of juvenile shrimp was about 18 mm and by December it was 37 mm. Although the size of maturity is not reported in the literature, the smallest ovigerous female we collected was 29 mm and it appears that females are mature at about 33 mm, as <1% of the ovigerous females were <33 mm.

Abundance

Lissocrangon stylirostris was the 6th most common species of caridean shrimp collected from 1980 to 1996 by the Bay Study, and ranked 5th in 1984 (see Table 1). No *L. stylirostris* were collected (or recorded) in 1980 and 1981 and very few in 1982 and 1983. The highest annual abundance index was in 1986, followed by 1984 and 1996 (Figure 50, Table 11). Abundance appears to have been cyclic, with very low indices from 1988 through 1992. Juvenile *L. stylirostris* were estimated to comprise 68% of the total catch (this estimate is based on approximate sizes of maturity of 28 mm for males and 33 mm for females).

Abundance of *L. stylirostris* peaked from July to September, declined slowly through March, and was very low from April through June (Figure 51, see Table 11). The highest abundance of ovigerous females was from January through June, and the ovigerous index was slightly higher than the non-ovigerous index in April and May.

Distribution

Lissocrangon stylirostris was limited to Central Bay and the lower channel stations in San Pablo Bay. Most were collected at channel stations; 6,544 or 85% came from station #213 (Alcatraz Island), which has a rock-sand substrate. There may be a seasonal movement to San Pablo Bay in fall and winter, since the few *L. stylirostris* collected there were present from October through January.

Salinity and Temperature

Lissocrangon stylirostris was collected at relatively high salinities and low temperatures, with the majority collected from 25.4‰ to 33.6‰ and 11.8 to 16.6 °C (10th and 90th percentiles, respectively, Figure 52). The mean salinity was 30.2‰ and the mean temperature was 14.7 °C.

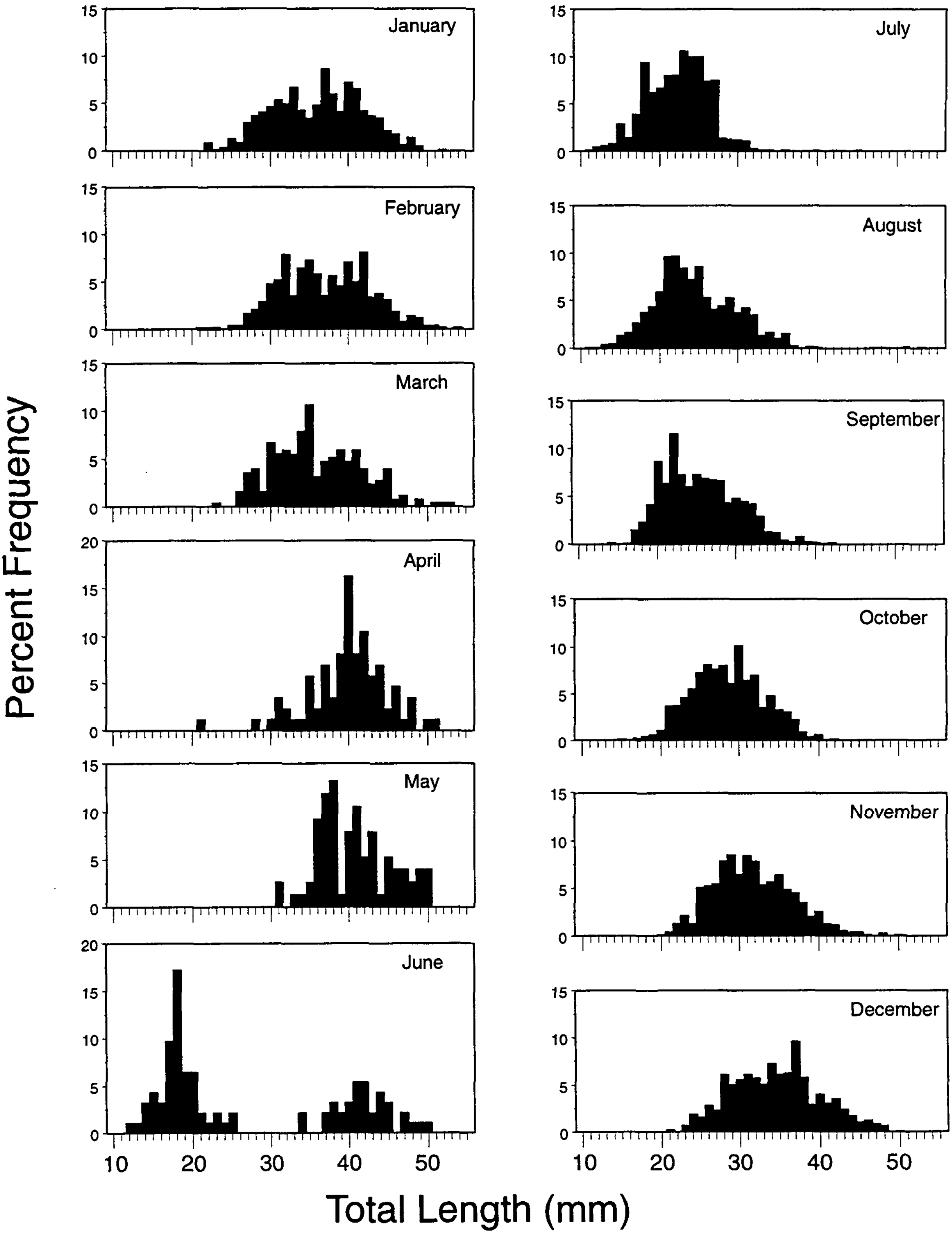

Figure 49 Monthly percent length-frequency histograms for male and female *L. stylirostris* **combined from 1980 to 1996.** Size classes are every 1 mm, from 11 to 55 mm.

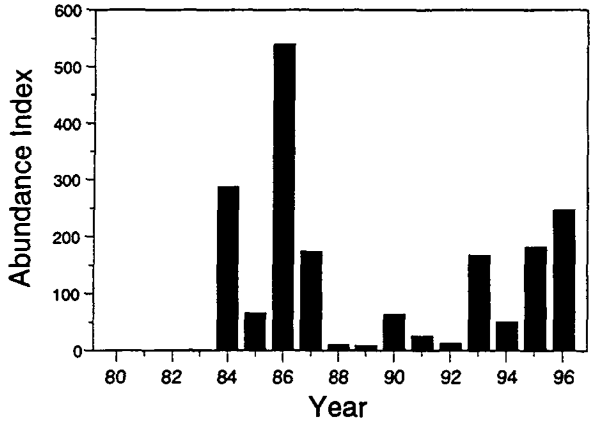

Figure 50 Annual abundance indices *L. stylirostris* **collected with the otter trawl from 1980 to 1996.** The index period is February to October and the indices are divided by 10.

Table 11 Monthly and annual abundance indices of all sizes of ***L. stylirostris*** **collected with the otter trawl from 1980 to 1996.** The index period is February to October and the indices are divided by 10.

	Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Feb–Oct*
1980		0	0	0	0	0	0	0	0	0	0	0	0
1981	0	0	0	0	0	0	0	0	0	0	0	0	0
1982	0	0	0	0	0	0	0	0	0	0	0	3	0
1983	0	0	0	5	0	0	0	0	0	0	0	0	1
1984	352	60	224	22	70	65	381	1395	251	111	303	133	287
1985	165	41	54	5	16	0	0	330	97	57	62	73	67
1986	235	138	89	24	8	135	1570	1712	584	600	589	189	540
1987	297	222	57	16	0	0	8	189	733	337	227	260	174
1988	105	14	30	0	0	11	5	5	24	11	11	61	11
1989	27	0	32	14	8	3	3	3					9
1990		65	32	0	0	0	0	57	114	311			64
1991		24	22	22	11	0	3	46	49	60			26
1992		87	5	16	0	0	0	0	0	8			13
1993		192	70	5	5	24	192	525	251	246			168
1994		95	19	68	32	3	5	65	146	24			51
1995	268	176	11	38	54	3	206		811	168	430	354	183
1996	38	187	38	0	0	8	108	384	1241	257	233	227	247
1981–1988, 1996	132	73	55	8	11	24	230	446	326	153	158	105	

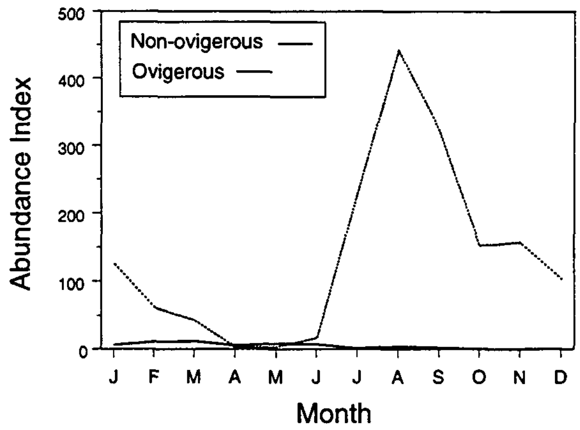

Figure 51 Monthly abundance indices of non-ovigerous and ovigerous *L. stylirostris* collected with the otter trawl from 1981 to 1988 and in 1996. The indices are divided by 10.

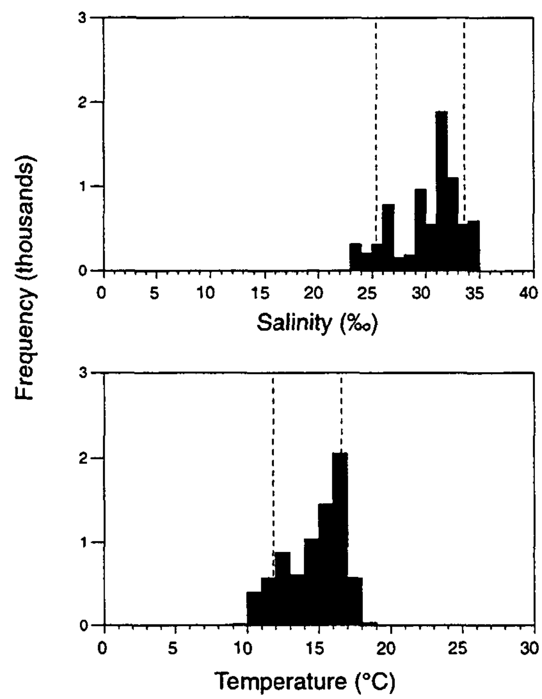

Figure 52 Salinity (‰) and temperature (°C) distributions of all sizes of *L. stylirostris* collected with the otter trawl (1980 to 1996). Dashed vertical lines are the 10th and 90th percentiles.

Discussion

Lissocrangon stylirostris is a minor component of the San Francisco Estuary's shrimp community, usually ranking 6th in total catch. It is limited to cool, high salinity areas and was rarely collected outside of Central Bay. Based on the peak abundance of juveniles and ovigerous females, larval hatching occurs in spring. As relatively few ovigerous females were collected, the reproductive population is probably concentrated in the nearshore ocean area. Although the estuary does serve as a nursery area for *L. stylirostris*, it appears that it is primarily an extension of the ocean habitat for both juveniles and adults.

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Notes

Michael Kellog (City and County of San Francisco, Public Utilities Commission, Water Quality Bureau, San Francisco, California). Telephone conversation with author on June 21, 1999.

Paul Reilly (California Department of Fish and Game, Monterey, California). 1990. Phone conversation with author.

Elasmobranchs

Kevin Fleming

Introduction

Five elasmobranchs were commonly collected in this survey from 1980 to 1995: brown smoothhound, *Mustelus henlei*; leopard shark, *Traikis semifasciatus*; bat ray, *Mylobatis californicus*; big skate, *Raja binoculata*; and spiny dogfish, *Squalus acanthias*. Members of this group share some common traits. In general, they are top marine predators, are long-lived and late maturing, and have long gestation periods.

Although otter trawl data were used for the description of elasmobranch abundance, our otter trawl is not efficient because most elasmobranchs are relatively large and capable of outmaneuvering or outswimming the trawl. Passive sampling gears such as trammel nets and long-lines are more efficient. More leopard sharks, bat rays, and six-gill sharks were collected during 2 weeks of a trammel net survey for sturgeon in San Pablo Bay than were caught in 15 years of monthly otter trawls (CDFG, unpublished).

Brown Smoothhound

Introduction

The brown smoothhound ranges from the Gulf of California to Humboldt Bay and from the intertidal zone to 110 m (Miller and Lea 1972). Throughout its range, it uses bays as nurseries (De Wit 1975, Russo 1975). The brown smoothhound is one of the most common shark species in San Francisco Bay (Herald and Ripley 1951, Russo 1975).

Mature brown smoothhounds give birth in spring (Roedel and Ripley 1950) to 3 to 5 pups (Compagno 1984), between 190 and 230 mm TL (De Wit 1975, Eschmeyer and others 1983). They mature in 2 to 3 years, between 510 and 660 mm TL (Compagno 1984, Yudin and Cailliet 1990) and may reach a maximum of about 950 mm TL (Miller and Lea 1972).

The brown smoothhound is primarily a bottom feeder and consumes mostly small crustaceans and fish (Herald and Ripley 1951, De Wit 1975, Russo 1975). The smaller sharks appear to feed in the intertidal while the larger ones feed in deeper water (Talent 1982).

Methods

Otter trawl data were used to describe abundance and distribution. Age–0 and age–1+ brown smoothhounds were separated based on visual examination of the length frequency data. Cutoff lengths used for separating age–0 fish from age–1+ fish were as follows for January through December: 300, 300, 300, 300, 310, 330, 360, 390, 400, 410, 420 and 430 mm. Different index periods were used for the 2 life stages: April to October for the age 0 and February to October for age 1+.

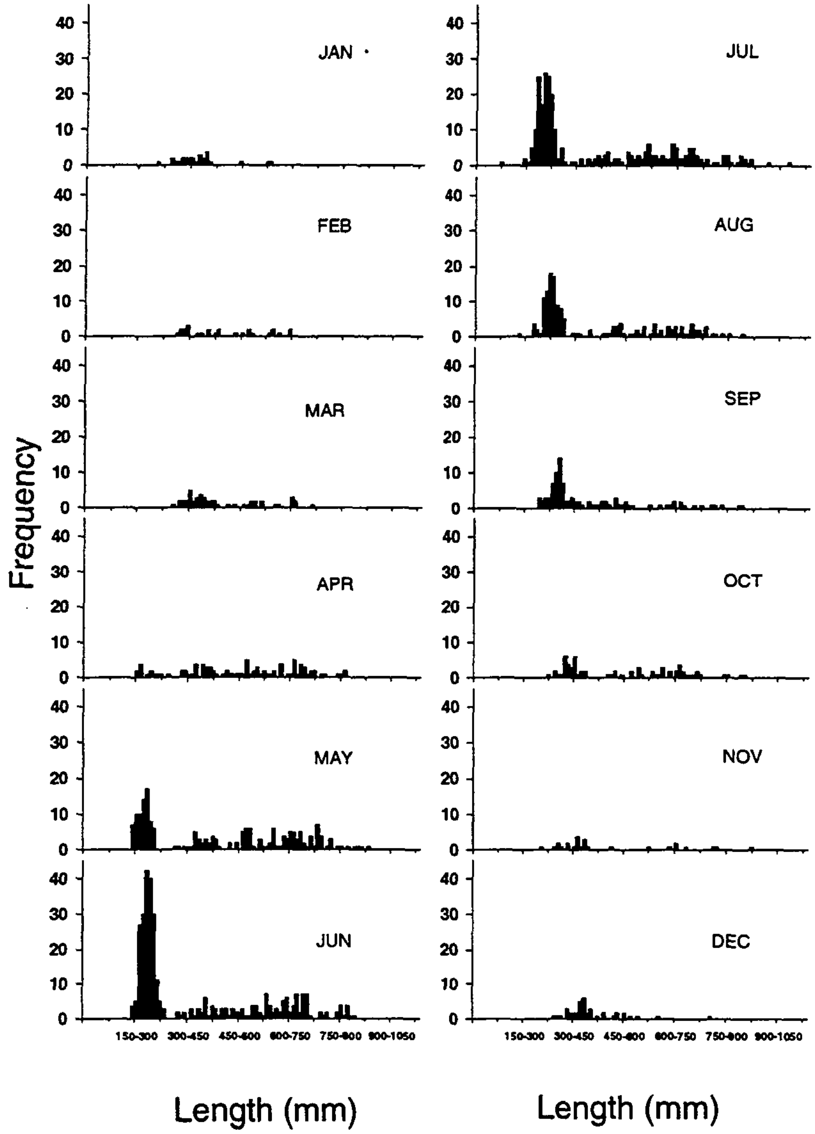

Figure 1 Length distribution of brown smoothhounds by month

Results

Length

There were clear distinctions between the abundance modes of age–0 and age–1+ brown smoothhounds (Figure 1). Both the smallest and largest sharks were collected in spring and early summer. The smallest brown smoothhounds were collected in April or May, soon after their birth. Examination of annual length frequencies reveals several modes (Figure 2). These modes correspond well with estimated ages from the literature (Yudin and Cailliet 1990). From year to year, the numbers and sizes of the age classes varied and appear to be related to water year type. In some dry years (for example, 1988 and 1989), over 5 age classes were discernible and young brown smoothhounds made up a large proportion of the annual catch. In wet years (for example, 1986 and 1995), few age classes were well represented.

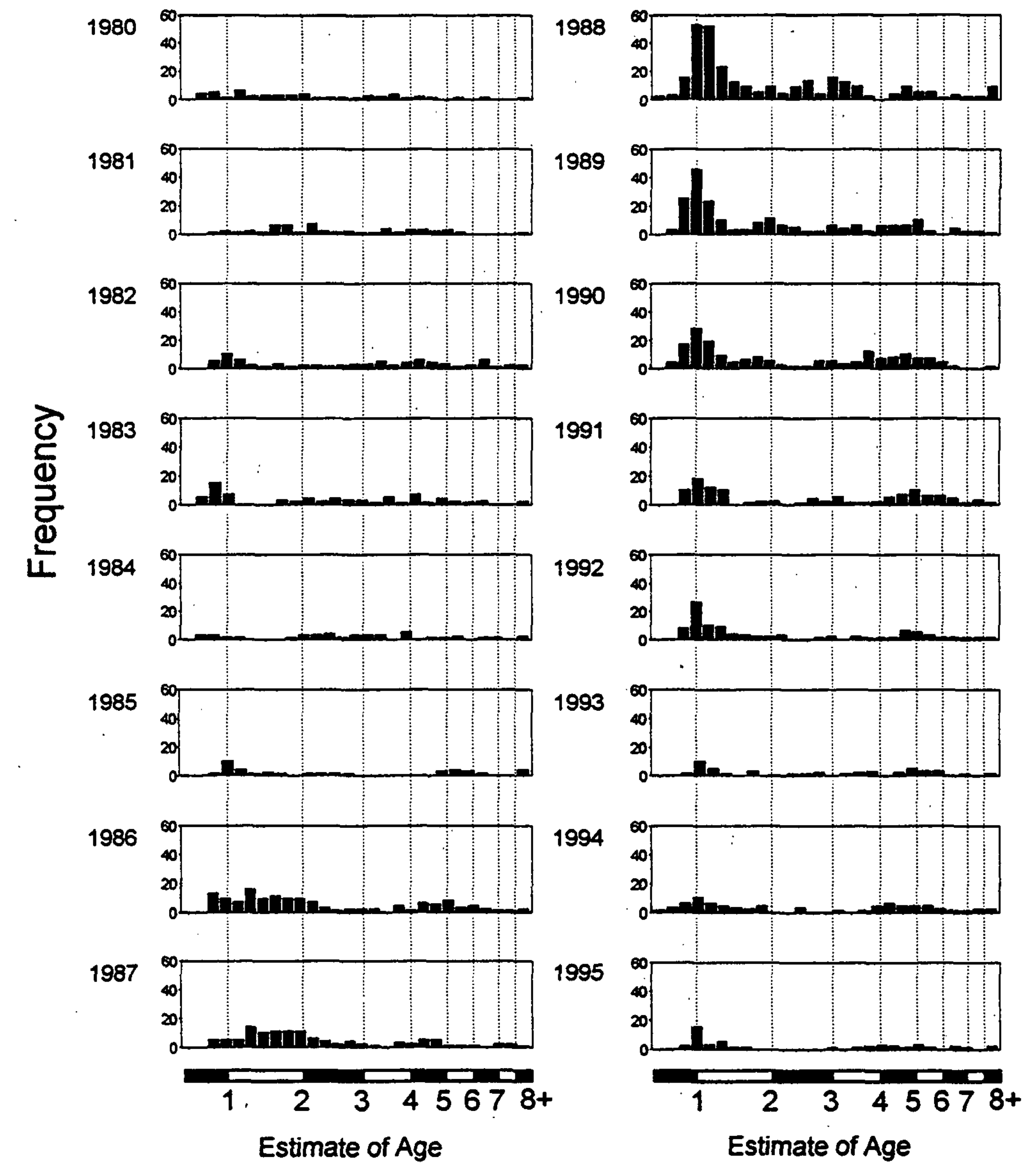

Figure 2 Length distribution of brown smoothhounds by year

Annual Abundance

The age–0 and age–1+ annual abundance indices of brown smoothhounds were significantly correlated (Pearson's $r = 0.908$, $P < 0.05$, $n = 16$). Abundance appeared to be cyclic and modes occurred in 1983 and 1989 (Figure 3, Tables 1 and 2). The abundance indices for both age groups were highest in 1989. The abundance of age–0 brown smoothhounds was lowest in 1984, and the lowest abundance of age–1+ sharks was in 1985.

Seasonal Abundance

The abundance of age–0 brown smoothhounds peaked in late spring or early summer (Figure 4) and was lowest in winter. Age–1+ brown smoothhounds were often collected all year. Their abundance also peaked in spring or summer and was lowest in winter.

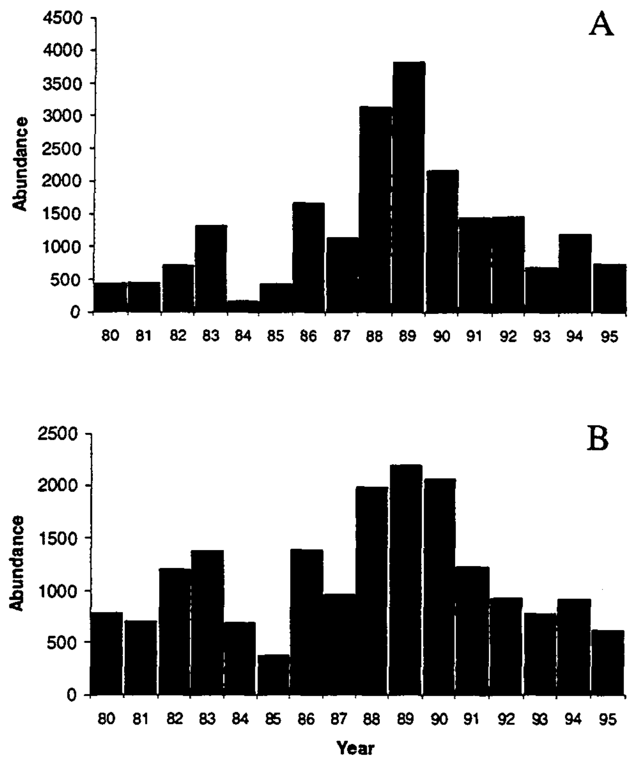

Figure 3 Annual abundance of brown smoothhounds: (A) age 0 and (B) age 1+

Table 1 Monthly abundance indices of age–0 brown smoothhound captured in the otter trawl from 1980 to 1995. The last column is the annual index, the mean abundance from February to October. The bottom row is the average seasonal abundance from 1981 to 1988.

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Index*
1980		0	0	0	1150	816	121	579	275	0	0	617	420
1981	194	0	0	0	0	267	0	449	1572	759	0	824	435
1982	0	0	0	0	1953	1013	1451	138	233	235	1064	531	717
1983	0	0	0	0	1106	6811	1067	147	0	57	0	462	1313
1984	0	0	0	0	0	183	699	138	0	0	0	0	146
1985	0	0	0	0	0	391	2271	0	164	176	0	441	429
1986	0	0	0	0	0	4392	580	3372	1630	1684	981	1178	1665
1987	0	0	0	0	0	2898	705	657	2926	696	1516	1199	1126
1988	0	0	0	267	1432	9838	4945	4310	873	315	260	214	3140
1989	0	0	0	308	305	6728	6545	5207					3819
1990		0	0	247	3636	4067	3347	2340	1455	0			2156
1991		0	0	0	1182	1894	1906	1486	2895	736			1442
1992		0	0	893	3846	1362	2402	918	57	681			1451
1993		0	0	1582	1369	1330	445	0	0	0			675
1994		0	0	542	0	2579	1243	2586	795	603			1193
1995	0	0	0	0	144	610	1454		1909	251	0	267	728
1981–1988	24	0	0	33	561	3224	1465	1151	925	490	478	606	

Table 2 Monthly abundance indices of age–1+ brown smoothhound captured in the otter trawl from 1980 to 1995. The last column is the annual index, the mean abundance from February to October. The bottom row is the average seasonal abundance from 1981 to 1988.

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Index*
1980		1333	1547	535	1686	889	810	0	186	0	206	0	776
1981	534	0	1112	1014	904	190	1192	1461	0	454	0	536	703
1982	813	813	0	705	3712	3519	564	699	244	564	0	195	1202
1983	188	0	0	0	158	4590	4186	2457	356	712	0	237	1384
1984	225	937	1647	898	295	1181	598	464	164	0	0	344	687
1985	0	0	514	164	0	617	855	0	550	654	237	0	373
1986	807	176	559	1829	2572	1596	1417	2884	655	838	397	183	1392
1987	2230	569	684	0	719	2297	444	632	2417	858	671	900	958
1988	284	0	2054	1961	4530	5471	2593	316	475	533	588	0	1993
1989	305	426	0	4514	3663	3526	2715	542					2198
1990		698	2208	5586	1845	3390	2590	535	190	1518			2062
1991		260	908	1245	1497	2510	2417	1148	303	754			1227
1992		637	213	893	1097	1124	1682	290	1087	1296			924
1993		427	0	0	754	641	3503	1439	0	247			779
1994		0	0	356	493	1202	1318	1749	1793	1327			915
1995	0	0	0	213	247	197	3473		388	476	0	0	624
1981-1988	635	312	821	821	1611	2433	1481	1114	608	577	237	299	

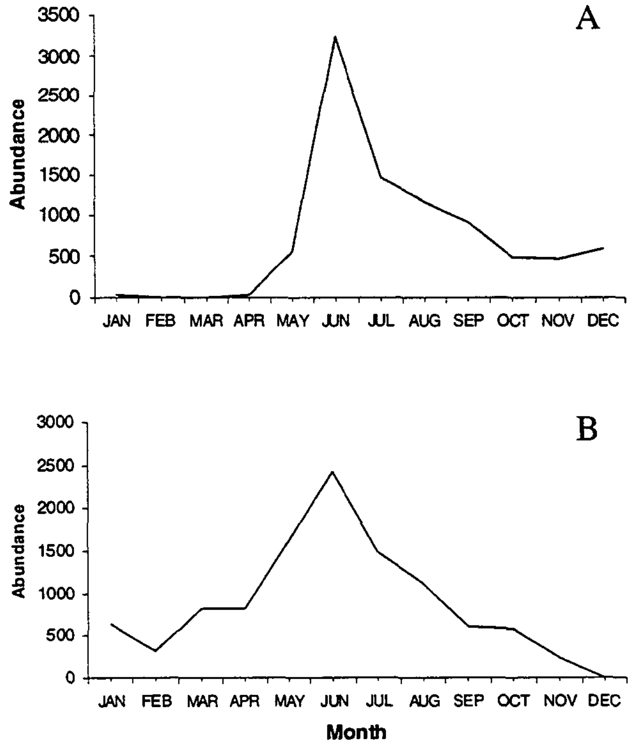

Figure 4 Seasonal abundance of brown smoothhounds from 1981 to 1988: (A) age 0 and (B) age 1+

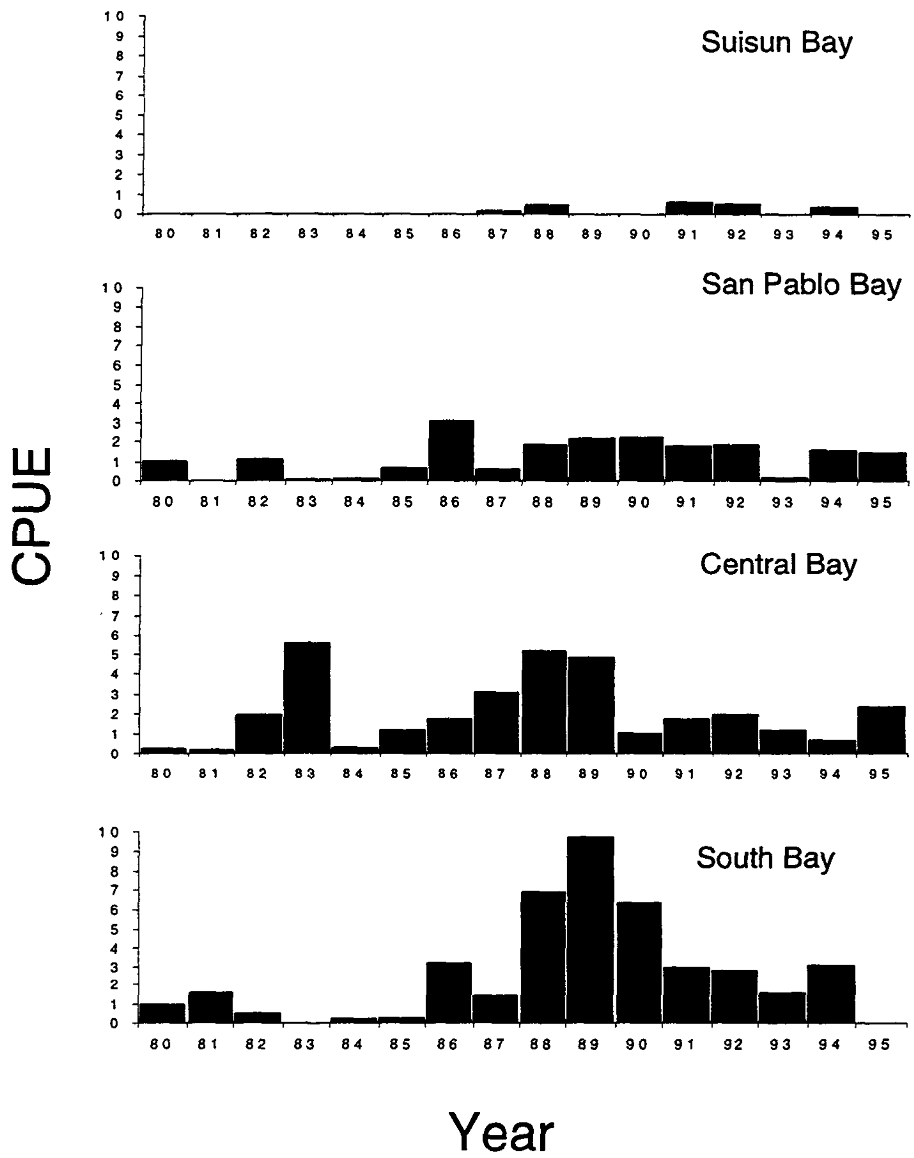

Figure 5 Annual distribution of age–0 brown smoothhounds by region. Values are the average CPUE for April to October.

Annual Distribution

Age–0 brown smoothhounds ranged from South to Suisun bays, but were most common in South and Central bays (Figure 5). In dry years, the CPUE increased in South and San Pablo bays, and the range extended into Suisun Bay. During wet years the CPUE tended to be higher in Central Bay and the range did not extend into Suisun Bay.

Unlike age–0 brown smoothhounds, age–1+ fish were not collected in Suisun Bay and their annual distribution did not vary as much. The highest CPUE, regardless of water year type, was always in Central Bay (Figure 6).

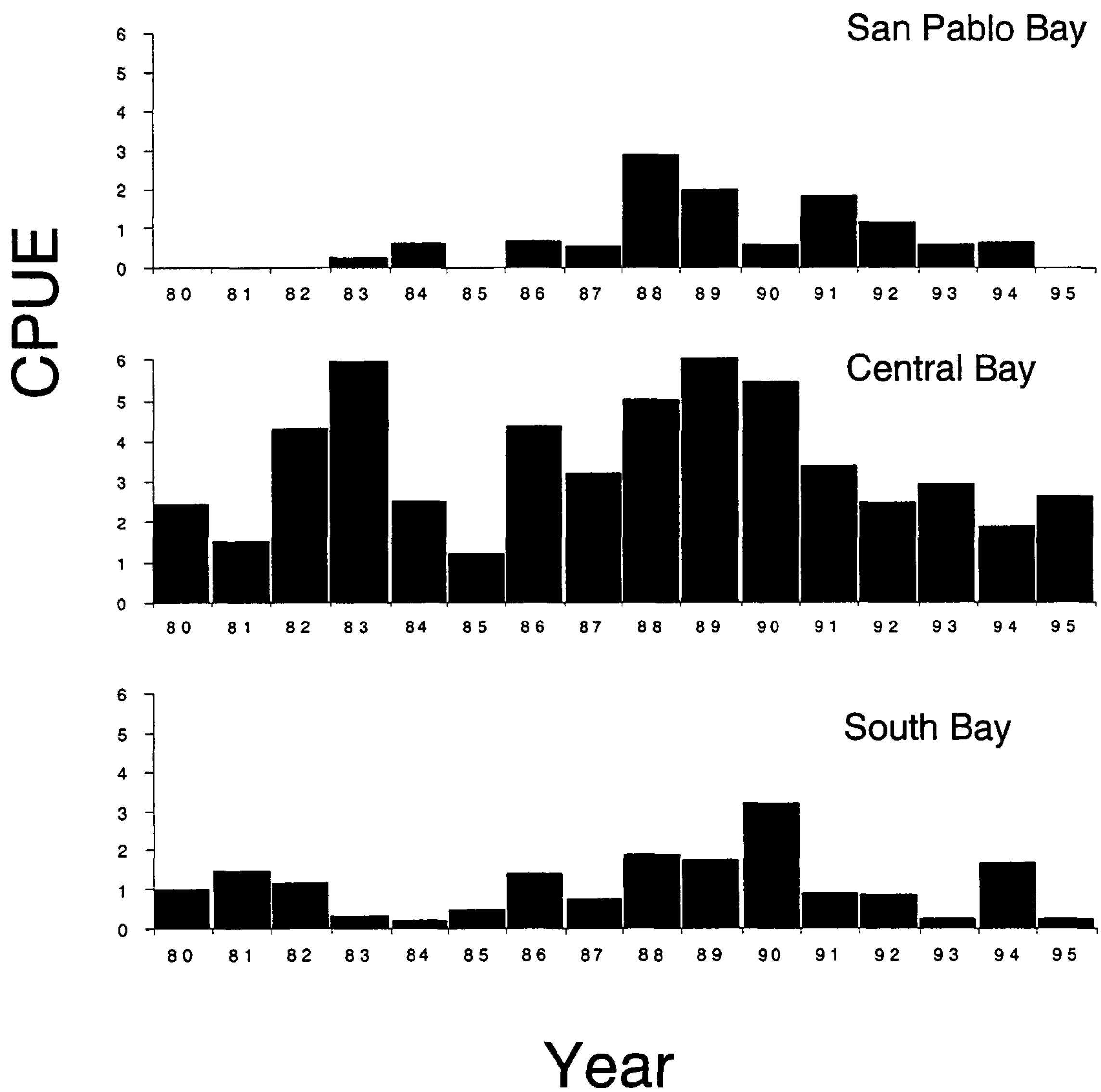

Figure 6 Annual distribution of age–1+ brown smoothhounds by region. Values are the average CPUE for February to October.

Seasonal Distribution

Age–0 brown smoothhounds were first caught in the trawl in spring (Figure 7). Densities, which tended to be higher in Central Bay, peaked in early summer.

Age–1+ brown smoothhounds were collected throughout year in Central and South bays, although many of those collected in winter were stragglers from the previous year class (Figure 8). In San Pablo Bay, age–1+ sharks were collected during spring and summer. The CPUE peaked in June throughout the estuary.

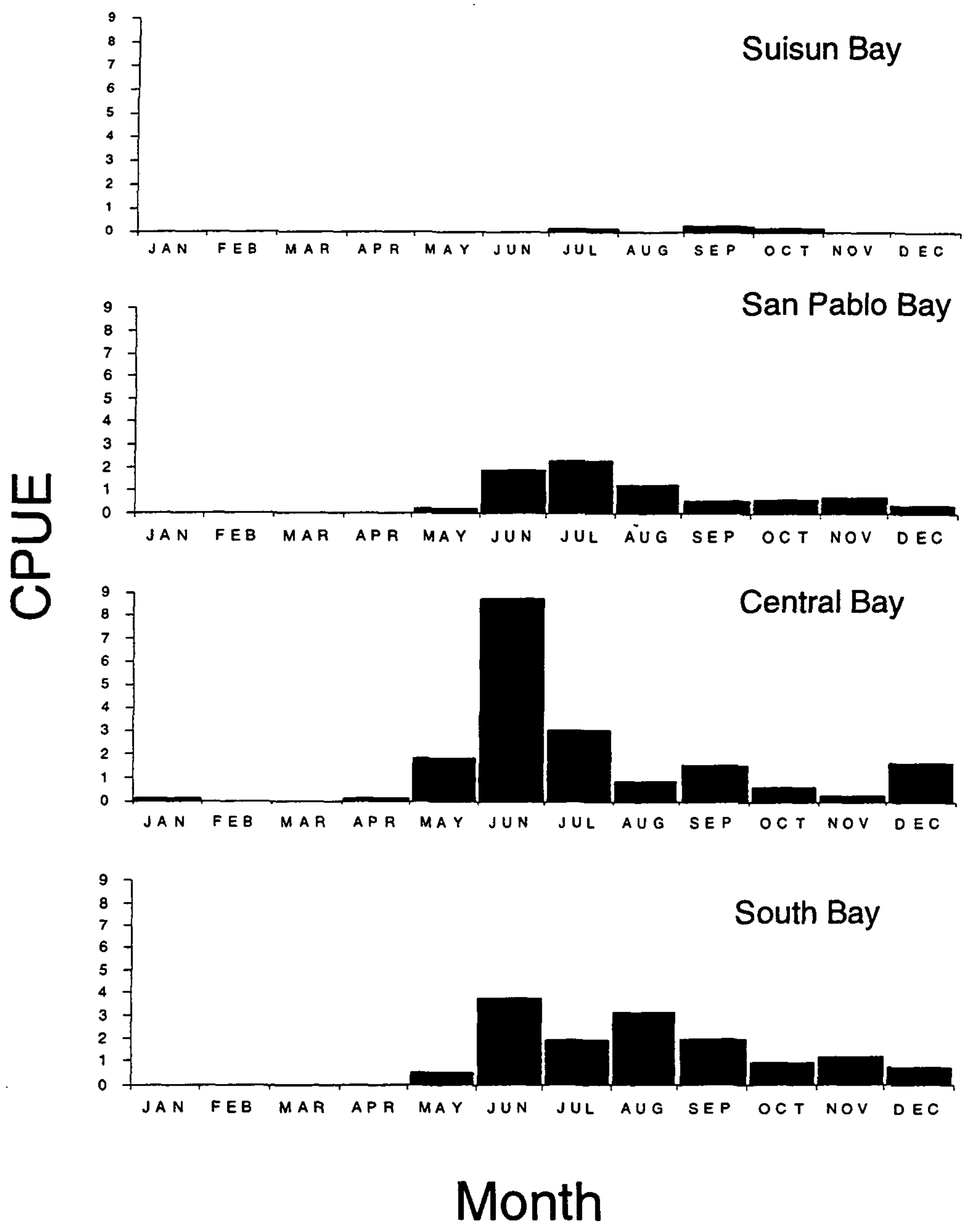

Figure 7 Seasonal distribution of age–0 brown smoothhounds by region. Values are the average CPUE for 1981 to 1988.

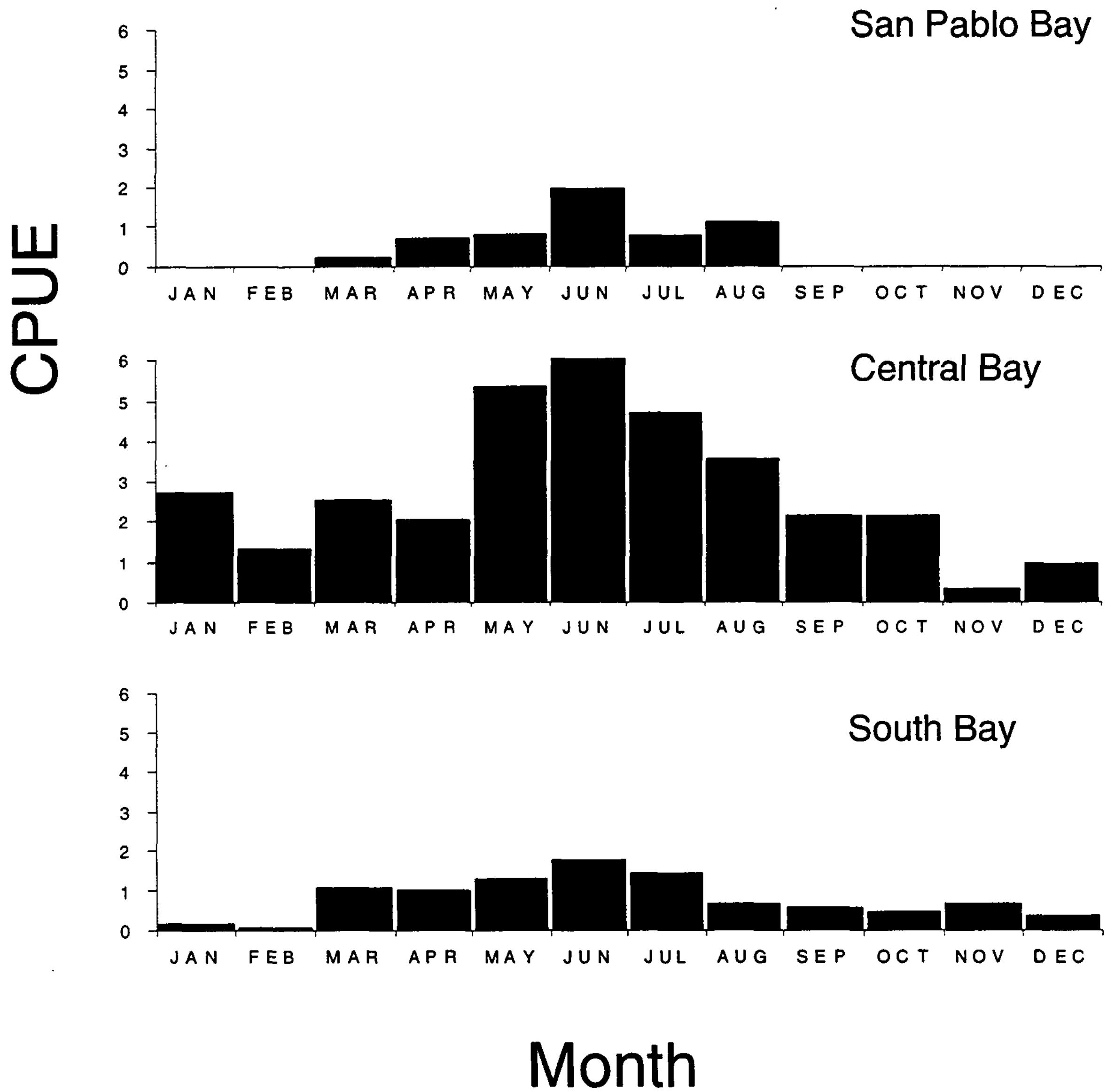

Figure 8 Seasonal distribution of age–1+ brown smoothhounds by region. Values are the average CPUE for 1981 to 1988.

Temperature and Salinity

Brown smoothhounds were primarily restricted to the warmer areas of the estuary (about 14 to 19 °C) that were in upper polyhaline to euhaline salinities (about 24‰ to 32‰) (Figures 9 and 10). Age–0 sharks were found at somewhat warmer temperatures than the age 1+; the mean temperature for age–0 sharks was 17.6 °C and for age–1+ it was 15.7 °C. The mean salinity for age–0 sharks (28.0‰) was close to the mean for age–1+ sharks (28.5‰).

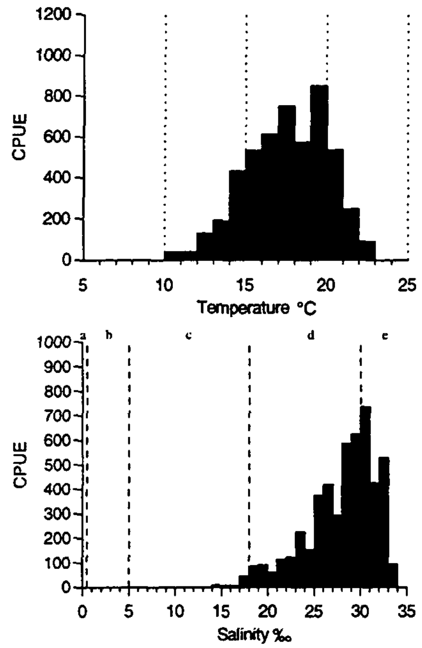

Figure 9 Temperature and salinity distributions of age–0 brown smoothhounds. The vertical lines on the salinity graph mark the boundaries of the Venice system ranges: (a) limnetic, (b) oligohaline, (c) mesohaline, (d) polyhaline, and (e) euhaline.

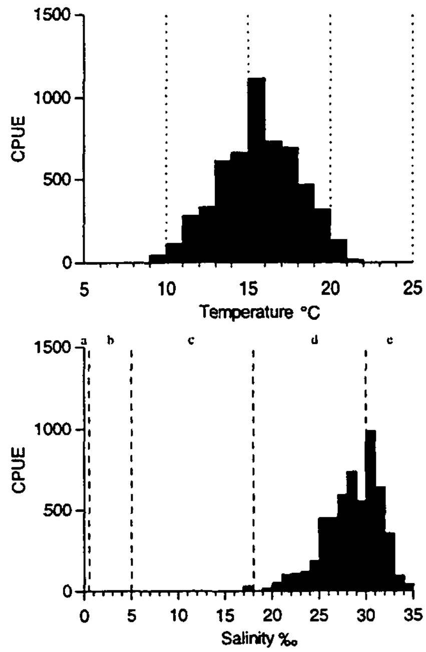

Figure 10 Temperature and salinity distributions of age–1+ brown smoothhounds. The vertical lines on the salinity graph mark the boundaries of the Venice system ranges: (a) limnetic, (b) oligohaline, (c) mesohaline, (d) polyhaline, and (e) euhaline.

Discussion

The brown smoothhound was the most abundant shark collected. Brown smoothhounds were found primarily in relatively warm, polyhaline to euhaline waters of South and Central bays. During dry years, their estuarine abundance increased and the age structure appeared more stable.

Brown smoothhounds entered the estuary in spring and summer prior to pupping and left during the fall and winter. This seasonal migration has also been noted in earlier studies (De Wit 1975, Compagno 1984, Yudin and Cailliet 1990). Although (Compagno 1984) suggested that the seasonal movements are in response to changes in salinity, the present data indicates that temperature may also stimulate the migration. During most years, these factors covary closely, decreasing during winter and increasing in summer, and so the movements of brown smoothhounds may be attributed to either factor. However, during the 1987–1992 drought, salinity remained fairly high in winter but the sharks emigrated to the ocean, suggesting that temperature was the stimulus. In all years, their emigration occurred when temperatures dropped below about 14 °C.

High outflows regulated the distribution of mature brown smoothhounds by reducing the salinity of the upper reaches of the estuary and thereby restricting pupping to Central and South bays.

Leopard Shark

Introduction

The leopard shark is common in bays and nearshore areas from Mazatlan, Mexico to Oregon. A small shark, it attains a maximum length of about 195 cm (Miller and Lea 1972). In the San Francisco Estuary, most leopard sharks are resident but some emigrate from the estuary in fall (Smith and Abramson 1990). Leopard sharks are fished both commercially and recreationally, with the recreational fishery accounting for the majority of the catch (Smith and Abramson 1990). Concern over the potential for overfishing led to a sport size and bag limit in 1991.

Primarily a benthic feeder, the leopard shark changes its food habits with growth. Crustaceans are the most important food items for small leopard sharks but as they grow, their diet shifts towards fish (Talent 1976). Although they are often found in the intertidal zone, they apparently spend little time feeding there (Russo 1975).

The leopard shark reproduces only once per year (Smith and Abramson 1990) and has a litter of 4 to 29 pups (Eschmeyer and others 1983), which are born live in April and May (Talent 1985). The males reach maturity between 70 to 119 cm and about 7 years of age, and females between 100 to 129 cm and about 10 years (Ackerman 1971, Compagno 1984, Kusher and others 1992).

Methods

Otter trawl data were used to describe abundance and distribution. Separation of leopard sharks into 2 age classes was based on visual inspection of length frequency data. Cutoff lengths were 230, 230, 230, 270, 320, 360, 370, 380, 390, 410, 420 and 430 mm TL for January through December, respectively.

Results and Discussion

Based upon the literature (Smith 1984), most of the leopard sharks collected appeared to be 3 or 4 years old. Forty-seven age–0 leopard sharks were collected from 1980 to 1995. With the exception of 1982, the catch of age–0 leopard sharks tended to be highest in dry years (Table 3). The highest catches were in 1982 (9) and 1988 (13). No age–0 leopard sharks were collected in 1984, 1985, 1993, and 1995. Age–0 leopard sharks were restricted to South and Central bays and most were collected in South Bay.

The catch trend for the age–1+ leopard sharks was contrary to expectations for a marine species because, generally, more age–1+ sharks were caught in wet years. The highest catch was in 1980 and the lowest in 1985 (see Table 3). Age–1+ leopard sharks were collected all year in South and Central bays, although catches were highest in winter and early spring. Collections in San Pablo Bay occurred only in late spring and summer.

The temperature distribution of leopard sharks was bimodal, which may be an artifact of the low numbers collected. The mean collection temperature was 14.8 °C. Leopard sharks were collected in polyhaline and euhaline salinities at a mean of 26.6‰ (Figure 11).

Table 3 Annual otter trawl catch of sharks and rays

	Year															
Species	*80*	*81*	*82*	*83*	*84*	*85*	*86*	*87*	*88*	*89*	*90*	*91*	*92*	*93*	*94*	*95*
Leopard shark, Age–0	1	1	9	5	1	0	2	5	13	1	2	3	1	0	3	0
Leopard shark, Age–1+	52	24	50	42	19	3	20	4	26	37	15	7	7	12	11	22
Leopard shark, All ages	53	25	59	47	20	3	22	9	39	38	17	10	8	12	14	22
Bat ray	13	34	22	12	18	9	36	8	32	18	36	18	26	8	11	18
Big skate	18	17	32	31	16	17	23	40	32	21	19	20	13	6	7	5
Spiny dogfish	3	3	5	4	4	2	2	1	7	4	6	3	4	0	2	1

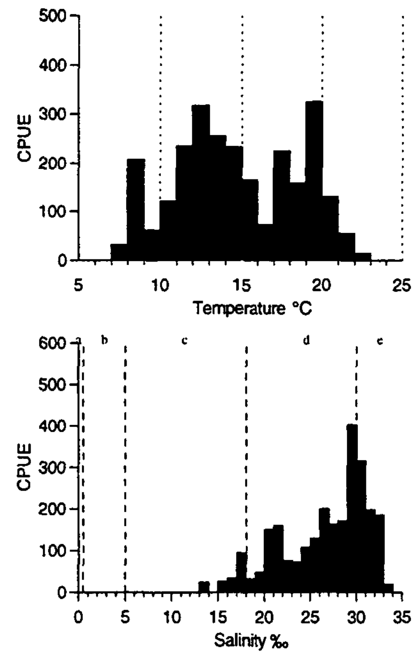

Figure 11 Temperature and salinity distributions of leopard sharks. The vertical lines on the salinity graph mark the boundaries of the Venice system ranges: (a) limnetic, (b) oligohaline, (c) mesohaline, (d) polyhaline, and (e) euhaline.

Bat Ray

Introduction

Bat rays are common to bays and shallow sandy areas from the Gulf of California to Oregon. They have been found to 46 m deep (Miller and Lea 1972) and are opportunistic bottom feeders, feeding on mollusks and crustaceans (Karl and Obrebski 1976, Karl 1979, Talent 1982). The pits dug by feeding rays open areas for infaunal recolonization and uncover food items for other fish (Karl 1979).

Mating occurs during the summer months and is followed by a gestation period of 9 to 12 months (Martin and Cailliet 1988a). The young are born alive at 305 to 356 mm disk width (DW) and weigh about 0.9 kg (Baxter 1980), although Martin and Cailliet (1988a) reported a disk width of 220 to 305 mm at birth. The largest bat ray reported was a 95 kg female taken in Newport Bay (Baxter 1980). The males mature at 450 to 622 mm DW (2 to 3 years). Half of the females are mature at 881 mm DW (about 5 years).

Methods

Otter trawl data was used to describe bay ray abundance and distribution. Because of the relatively low numbers of bat rays, an abundance index was not calculated.

Results and Discussion

From 1980 to 1995, 319 bat rays were collected in the otter trawl. Based on a disk width and age relationship (Martin and Cailliet 1988b), very few of these (about 21) were age 0. Annual catches were highest in 1986, 1990, and 1992 and were lowest in 1985 and 1987 (see Table 3).

Bat rays were collected all year in South and Central bays and during the spring and summer in San Pablo Bay. Their absence from San Pablo Bay in winter suggests that low salinity limits their upstream distribution. Bat rays were primarily collected in upper polyhaline to euhaline salinities; the average bottom salinity was 28.1‰ (Figure 12). Water temperature did not appear to influence their geographic distribution, as they were collected over a broad temperature range from 9 to 23 °C (mean 17.1 °C).

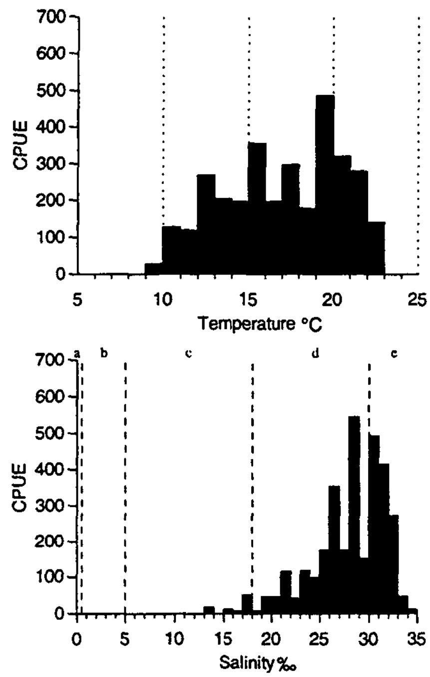

Figure 12 Temperature and salinity distributions of bat rays. The vertical lines on the salinity graph mark the boundaries of the Venice system ranges: (a) limnetic, (b) oligohaline, (c) mesohaline, (d) polyhaline, and (e) euhaline.

Big Skate

Introduction

Big skates are found from Baja California to the Bering Sea (Miller and Lea 1972) but are uncommon south of Point Conception (Roedel and Ripley 1950). They have been collected from 3 to 110 m deep (Miller and Lea 1972). Big skates consume both crustaceans and fish (Hart 1973) and are an important commercial species along the California coast (Martin and Zorzi 1993).

Male big skates mature between 7 and 8 years at 1,000 to 1,100 mm TL, and females mature at about 12 years and 1,300 mm TL (Zeiner and Wolf 1993). They can reach 2,400 mm, but fish over 1,800 mm are rare (Miller and Lea 1972). The male to female ratio is 1:1 (Hitz 1964). Big skates lay horny egg cases that are up to 300 mm long (Hart 1973) and contain 1 to 8 eggs (Hitz 1964).

Methods

Otter trawl catches were used to describe abundance and distribution of big skates. Because relatively few big skates were collected, annual abundance indices were not calculated.

Results and Discussion

From 1980 to 1995, 318 big skates were collected. The highest catch was in 1987 and the lowest in 1995 (see Table 3). Catches were highest in spring and summer. Almost two-thirds of the big skates were collected in Central Bay channels. Based upon literature growth curves (Zeiner and Wolf 1993), few big skates collected during this survey were either mature (57) or age 0 (49), most appeared to be between 3 and 5 years old.

Most of the big skates were found in the cooler waters of the estuary at upper polyhaline to euhaline salinities (Figure 13). Their distribution appeared to be restricted upstream by low salinity and in South Bay by high temperature. Big skates were collected at a mean temperature of 14.3 °C and a mean salinity of 27.9‰.

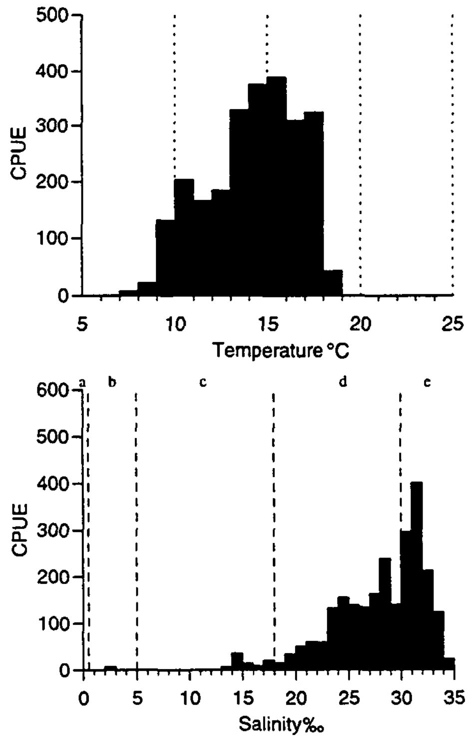

Figure 13 Temperature and salinity distributions of big skates. The vertical lines on the salinity graph mark the boundaries of the Venice system ranges: (a) limnetic, (b) oligohaline, (c) mesohaline, (d) polyhaline, and (e) euhaline.

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Clupeidae

Kevin Fleming

Members of the family Clupeidae are found worldwide and occupy a variety of environments from freshwater to marine. The adults of most species form pelagic schools that migrate extensively to feed and spawn (Blaxter and Holliday 1963). Four species, 2 native and 2 introduced, are common in the San Francisco Estuary. Each of the 4 clupeids has different environmental requirements and uses the estuary differently. This chapter describes the distribution and abundance of 3 of the 4 clupeids: Pacific herring, Pacific sardine, and American shad. The 4th species, the threadfin shad, *Dorosoma petenensis*, is not abundant in our sampling area.

Pacific Herring

Introduction

The Pacific herring, *Clupea harengus*, is found along the Pacific coast from northern Baja California to Japan (Miller and Lea 1972). It is a pelagic schooling fish that uses bays and estuaries as both spawning and nursery areas. San Francisco Bay represents the only significant spawning area south of Puget Sound (Alderdice and Velsen 1971). Herring return to spawn in the same bays in which they were hatched, and the spawning stocks probably remain separate even outside of their spawning bays (Moser 1990), indicating that there is little genetic mixing of spawning populations. Since 1973, Pacific herring have supported a commercial roe fishery in San Francisco Bay (Spratt 1992). Much of the adult Pacific herring commercially fished in the Monterey area may belong to the San Francisco spawning stock (Moser 1990).

In California, Pacific herring mature at an earlier age than the more northern stocks. Young fish begin to enter the spawning population at 2 years, and by the 3rd year, all are mature (Spratt 1981). Mature herring may spend up to 3 weeks in the estuary before spawning and spawn only once during a season. After spawning, spent herring return to the ocean (Miller and Schmidtke 1956).

The maximum spawning temperature is about 10 °C (Alderdice and Velsen 1971). Throughout their range, the occurrence and abundance of Pacific herring appear to be related to the availability and extent of spawning salinity between 8‰ and 28‰. Laboratory experiments conducted on Pacific herring eggs from the San Francisco estuary show that optimal hatching success occurs around 16‰ (Griffin and others 1998). Spawning in the estuary takes place from November through March (Spratt 1981). Spawned eggs are adhesive and are attached most often to eelgrass and occasionally to other algae in intertidal and subtidal areas (Hardwick 1973, Miller and Schmidtke 1956). The distribution of eggs depends on the vegetation type and the substrate slope (Heagele 1986).

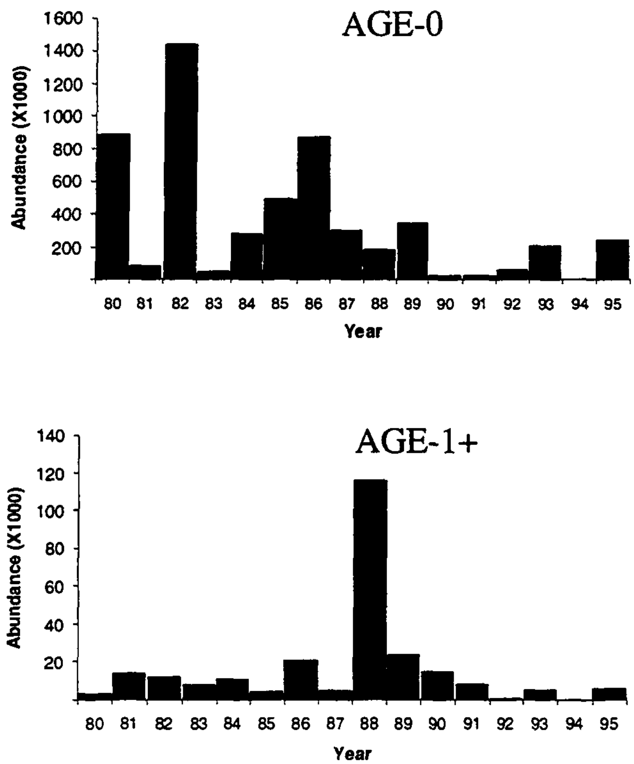

Figure 1 Annual abundance of Pacific herring: (A) age 0 and (B) age 1+. No index was calculated in 1994.

Methods

Data from the midwater trawl were used to describe abundance and distribution. Fish in the midwater trawl were categorized as age 0 or age 1+. The cutoff lengths used to separate these age classes were based on a visual inspection of the length frequency data. The following monthly cutoff lengths were used for January through December: 45, 50, 70, 85, 95, 105, 110, 120, 125, 125, 135, and 140 mm. The months used for the indices covered the periods when most of the age classes were collected. For age–0 fish, the index period was April through August and for age–1+ fish it was February through July.

Results

Abundance

The abundance index for age–0 fish varied from a high of 1,442 in 1982 to a low of 23 in 1990 (Figure 1, Table 1). There were secondary modes in 1980 and 1986 and an extended low from 1990 to 1992. Age–1+ fish were 5 times more abundant in 1988 than in the next highest year, 1989 (see Figure 1, Table 2). The lowest year was 1992. Abundance remained low from 1992 to 1995.

Table 1 Monthly abundance indices of age–0 Pacific herring captured in the midwater trawl from 1980 to 1995. The last column is the annual index, the mean abundance from April to August. The bottom row is the average seasonal abundance from 1981 to 1988.

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Index*
1980		0	0	48591	344565	508224	474121	3051669	222892	26344	2999	5112	885434
1981	0	0	22728	118228	28083	64292	146185	64146	113273	29995	5951	538	84187
1982	0	0	23796	416899	2606934	1719439	2123126	341151	505831	270881	43760	7736	1441510
1983	0	0	0	7753	85990	112630	31674	4331	267	11252	12341	1061	48475
1984	0	0	1425	352506	745012	223521	70191	4891	25667	1104	1644	0	279224
1985	0	0	1589	236915	306460	1128977	579829	193268	447857	115598	13398	2789	489090
1986	0	0	2474	225087	600410	1330340	2141340	50071	67530	13079	5704	2831	869449
1987	0	0	0	152796	529051	535731	48077	206874	30811	27496	5692	1249	294506
1988	0	0	0	671800	155702	43230	58020	2216	8898	30348	4318	0	186194
1989	0	0	0	495140	892011	190730	60606	97113					347120
1990		0	179	40984	44744	14850	8727	4308	3805	1100			22723
1991		0	8295	56257	52346	25474	3396	2802	2133	544			28055
1992		0	0	175461	104602	9400	9073	6540	1011	6343			61015
1993		0	0	609745	123944	93782	179134	19287	12682	16825			205178
1994		0	820	89475									NA
1995				29774	199278	333107	415032		21030	36339	39457	610	244298
1981–1988	0	0	6502	272748	632205	644770	649805	108368	150017	62469	11601	2025	

Table 2 Monthly abundance indices of age–1+ Pacific herring captured in the midwater trawl from 1980 to 1995. The last column is the annual index, the mean abundance from February to July. The bottom row is the average seasonal abundance from 1981 to 1988.

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Index*
1980		8374	1442	3785	1713	0	750	0	0	0	0	0	2677
1981	1593	9940	2360	33271	2252	0	36637	0	0	0	0	591	14077
1982	9600	11170	4537	17361	38622	0	0	418	0	636	8378	8927	11948
1983	135239	30331	8648	3728	426	1489	324	0	557	2335	496	2659	7491
1984	0	22122	3165	5308	9868	23793	729	0	551	0	0	0	10831
1985	3336	2285	7121	4703	2936	0	4278	0	0	0	0	0	3554
1986	5248	14039	1073	2749	3436	231	101351	0	0	0	0	2394	20480
1987	11309	9904	2781	12328	2258	0	1435	0	0	0	125	3866	4784
1988	17274	646880	7286	26461	1191	13306	2766	0	563	571	2111	6579	116315
1989	130645	54144	87750	1301	158	612	0	0					23994
1990		80496	2986	2053	982	0	538	0	0	0			14509
1991		48321	756	234	106	696	0	0	0	0			8352
1992		3119	615	0	0	0	0	0	0	0			622
1993		2162	6360	21650	692	0	0	0	0	0			5144
1994		2133	2495	0									NA
1995				4593	7986	10640	0		0	0	119	6600	5805
1981–1988	22950	93334	4621	13239	7624	4852	18440	52	209	443	1389	3127	

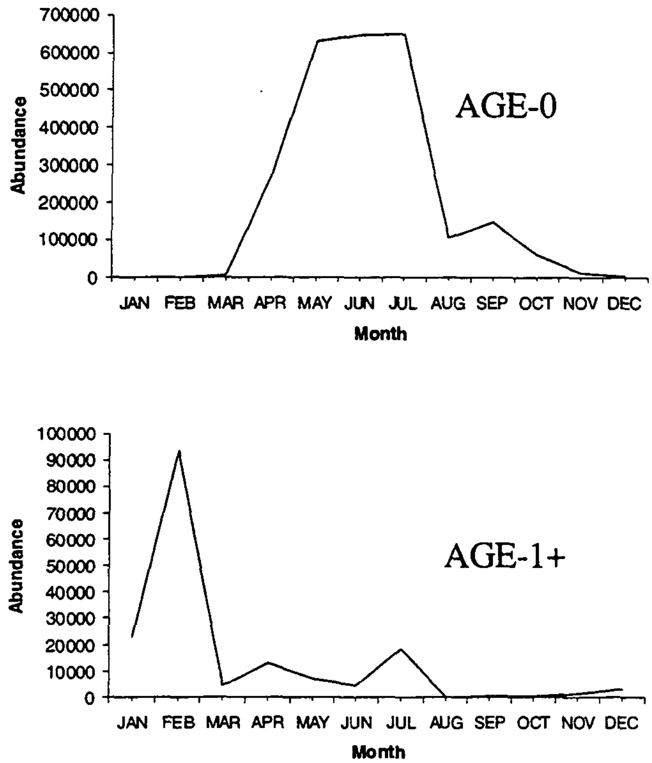

Figure 2 Seasonal abundance of Pacific herring from 1981 to 1988: (A) age 0 and (B) age 1+

Abundance showed different seasonal maxima for the 2 age classes. Age–0 Pacific herring peaked in late spring or early summer and were absent in January and February (Figure 2). The abundance of age–1+ fish peaked in January or February, except in 1986 when the peak came in July (see Table 2).

Distribution

The range of age–0 Pacific herring was greatest in May, concurring with their peak density (Figure 3). May was the only month they reached the west delta. They were usually most abundant in Central Bay and may have moved into Central Bay from South Bay in July. The Central Bay catch increased as catches in other regions decreased, peaked in June and July and then declined.

Age–1+ Pacific herring ranged farthest in January, the only month they were in the west delta (Figure 4). Most age–1+ fish were in Central or South bays. In all years except 1988, the age–1+ catch was highest in Central Bay (Figure 5). In 1988, catches were highest in South Bay. In several wet years, no age–1+ fish were caught in San Pablo Bay. Conversely, an upstream extension of age–1+ fish into Suisun Bay occurred in the dry years 1981, and from 1987 to 1992.

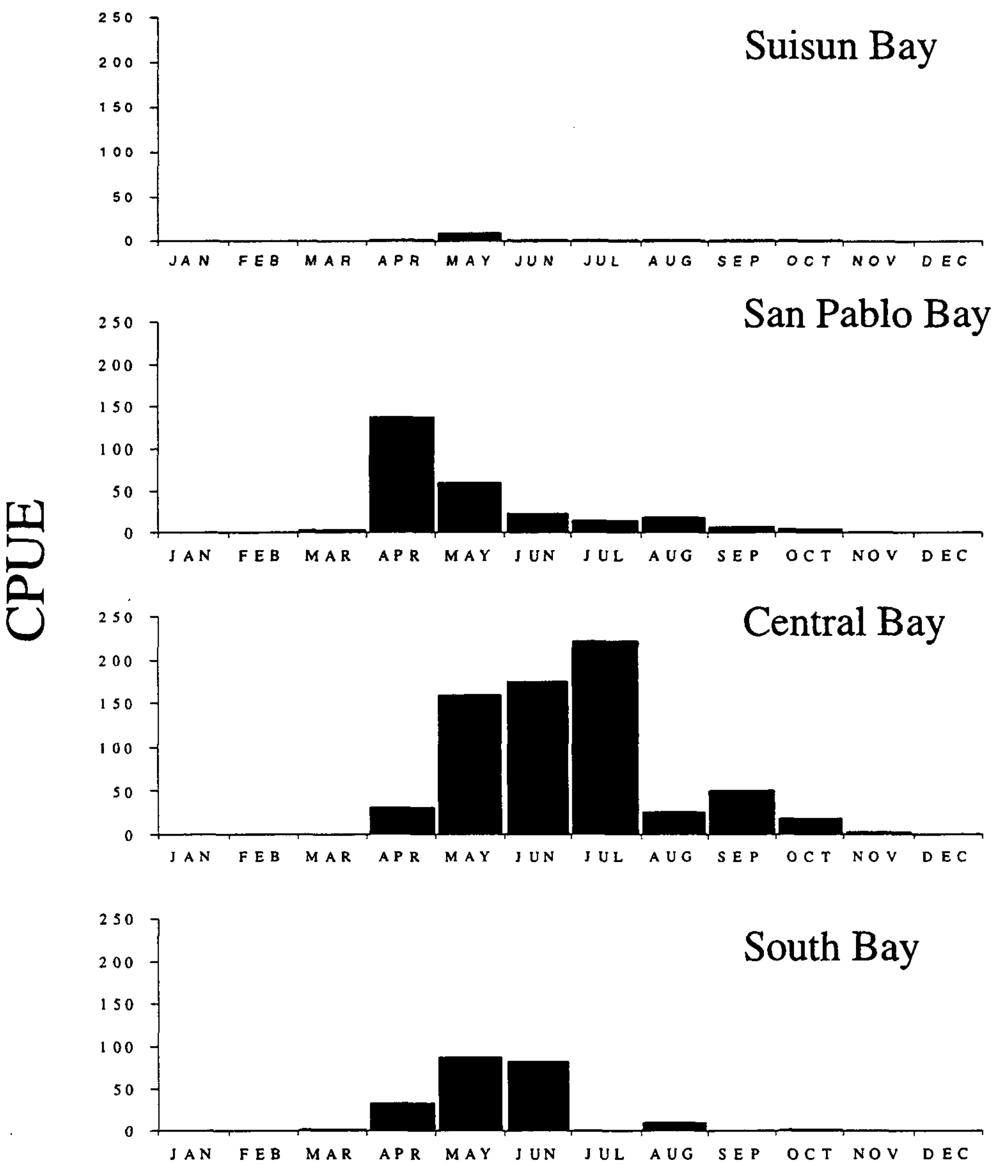

Figure 3 Seasonal distribution of age–0 Pacific herring by region. Values are the average CPUE for 1981 to 1988.

Temperature and Salinity

The salinities and temperatures that Pacific herring occurred in differed with fish size and time of year. The smallest age–0 fish (30 to 40 mm FL) were found most often at about 21‰ (Figure 6). As size increased so did the salinity at which they were found, up to 90 to 100 mm FL and about 28‰. Fish >100 mm FL were most often found in somewhat lower salinity. The decline in the salinity corresponded with the emigration of many of the larger age–0 fish to the ocean and reflects the salinities the "stragglers" were in. The age–1+ fish, whose residence time within the estuary is relatively brief, were found at a much narrower range of salinity from about 27‰ to 30‰. The temperature range of age–1+ fish varied from about 10.5 to 14.0 °C.

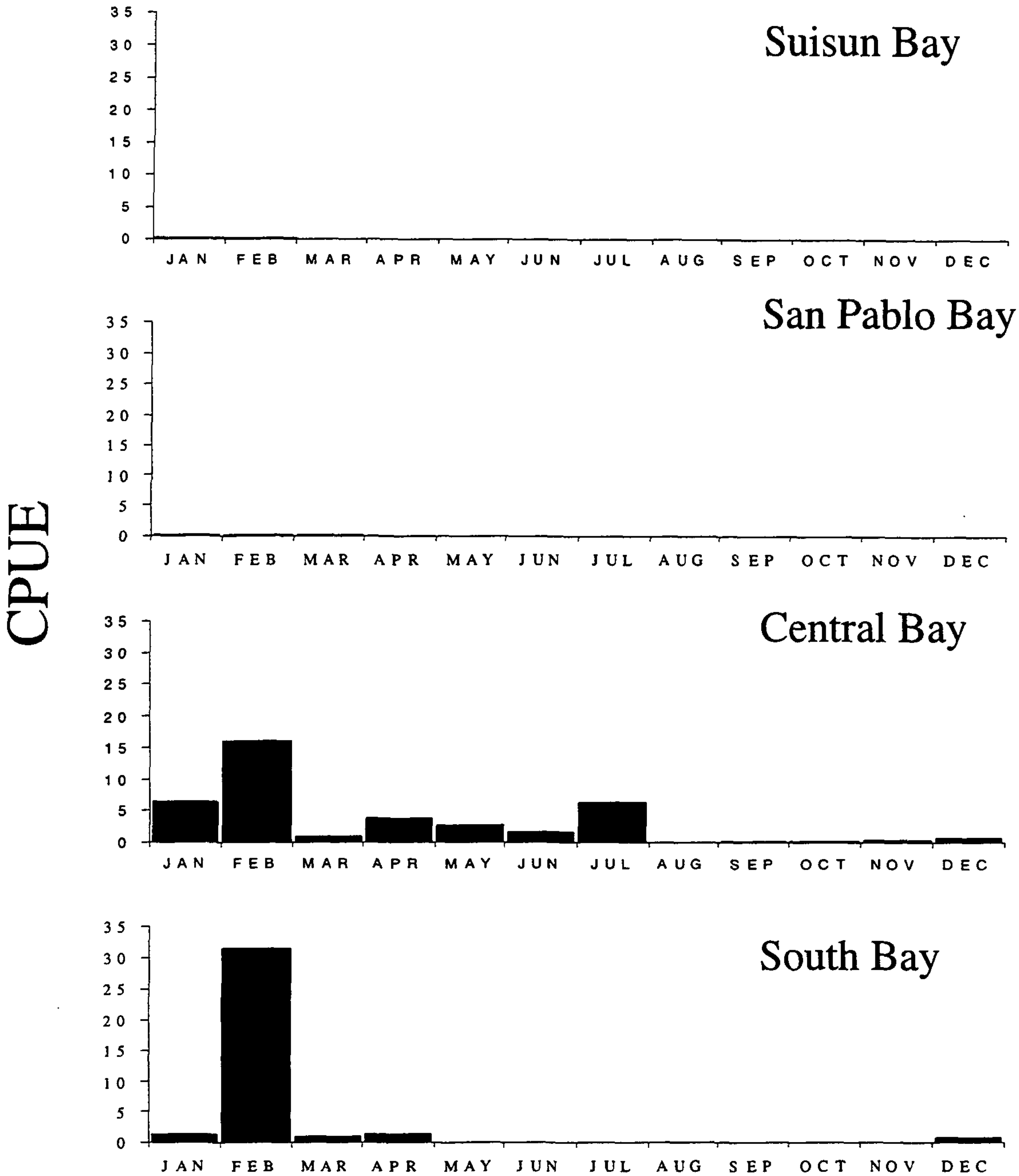

Figure 4 Seasonal distribution of age–1+ Pacific herring by region. Values are the average CPUE for 1981 to 1988.

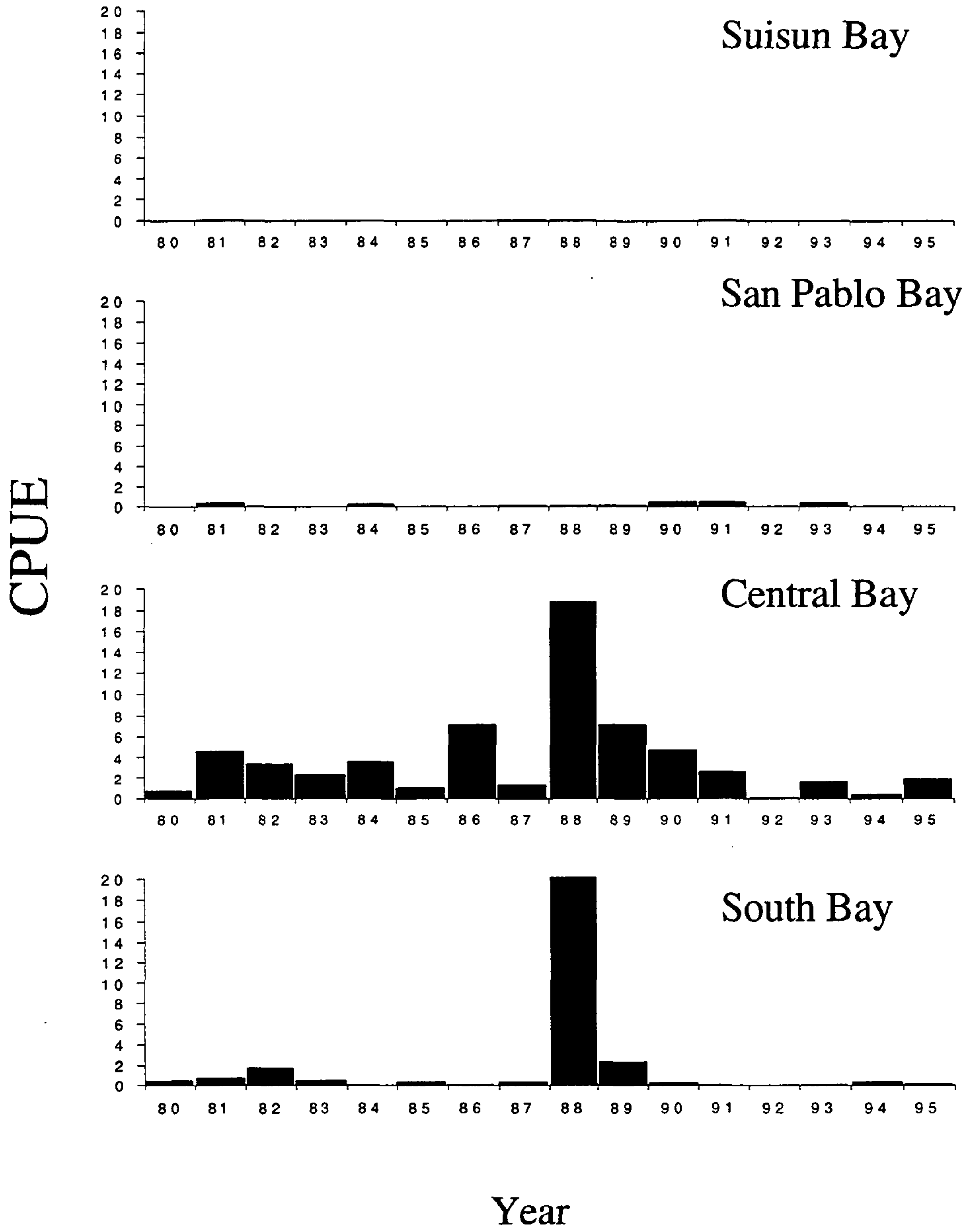

Figure 5 Annual distribution of age–1+ Pacific herring by region. Values are the average CPUE for February to October.

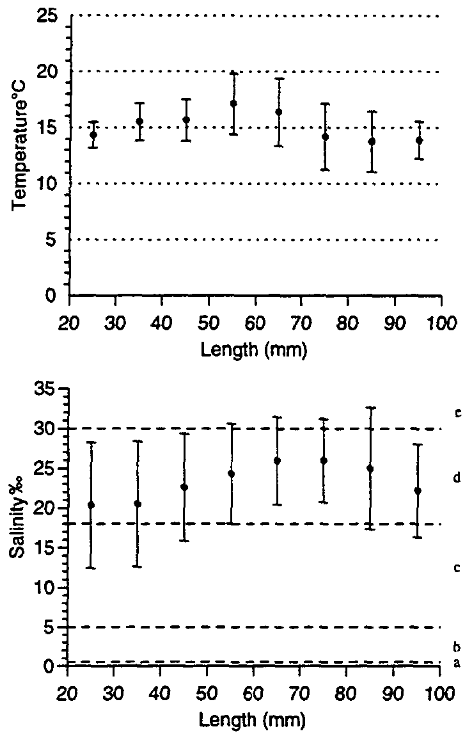

Figure 6 Temperature and salinity distributions of Pacific herring by length. The dots are the means and the bars are 1 standard deviation. The horizontal lines on the salinity graph mark the boundaries of the Venice system ranges: (a) limnetic, (b) oligohaline, (c) mesohaline, (d) polyhaline, and (e) euhaline.

Discussion

Freshwater flow directly affects the distribution of Pacific herring within the estuary. The distribution of age–1+ Pacific herring is limited by salinity. The age–1+ fish were typically found within the euhaline embayments of the estuary and were concentrated primarily in South and Central bays. Age–1+ fish were collected as far upstream as Suisun Bay during the drought when low winter outflows increased salinity in Suisun Bay to the mesohaline range.

Age–1+ fish had a predictable seasonal abundance pattern. Their seasonal abundance peak usually occurred in winter, but occasionally (for example in 1986) occurred later in the year. The interannual shifts in seasonal abundance reflected strengths of the various year classes within the age–1+ group. Mature Pacific herring (that is, 2 years and older), entered the estuary for only a short period during the winter to spawn. Juvenile (1 year old) herring stayed longer in the estuary. In most years, age–1+ fish were seldom found in the estuary beyond July and in 1992 were collected only in February and March.

Age–0 fish were found over a broader range of temperature and salinity than age–1+ fish, reflecting changes in their geographic distribution. Although spawned in Central and South bays, age–0 fish were often found in Suisun Bay and occasionally as far upstream as the west delta. Typically, peak catches of age–0 Pacific herring in regions other than the Central Bay occurred in spring. By summer, the catch of age–0 fish in these embayments decreased as the fish migrated towards Central Bay and abundance peaked there. Abundance in Central Bay decreased as age–0 fish left the estuary.

American Shad

Introduction

The American Shad, *Alosa sapidissima*, is native to the Atlantic coast. It was introduced to the Sacramento River in 1871 (Skinner 1962) and supported a commercial fishery until 1957. It ranges along the Pacific coast from Todos Santos Bay, Baja California, to Alaska and Kamchatka, Russia (Hart 1973, Miller and Lea 1972).

The American shad spends 3 to 5 years in the ocean before returning to the San Francisco Estuary to spawn in spring (Moyle 1976), after which a large percentage of adults die (Stevens 1966). The major spawning grounds are above Rio Vista in the Sacramento River and in its major tributaries, the Feather and American rivers. The San Joaquin River is not extensively used for spawning (Hatton 1940).

Methods

Midwater trawl catch data were used to describe abundance and distribution. Fish were separated into age–0 and age–1+ age groups based upon an examination of the length frequency data. The cutoff lengths for separating these groups were 30 mm FL for January to April and 70, 100, 130, 160, 200, 220, 240, 240 mm FL for May to December.

The annual abundance index period for the age–0 fish was July through October, the months with the greatest catches. Catches were too low to calculate an index for age–1+ fish. No sampling was done in 1994, nor from September to November in 1989.

Results

Length

During the 15 years of sampling, very few mature American shad were collected in these surveys. The large fish either avoided the nets or were in shallower water than is typically sampled in this survey. The largest American shad collected in the midwater trawl measured 550 mm FL and the smallest 27 mm FL.

Small shad began appearing in the midwater trawl in June and July. The smallest fish were collected in the west delta and were more numerous at shoal than channel stations. The mean size of the age–0 fish varied with location and increased downstream.

Outflow may have affected the size range of American shad in the estuary. In high outflow years, the mean size of the age–0 fish was smaller in all regions than in years with low outflows. This pattern was especially pronounced in 1983 and 1995, when the age–0 fish from Suisun Bay were on average about 20 mm smaller then age–0 fish from same area during the drought. High outflow may have reduced transit time of smaller fish through the estuary and moved them downstream faster.

Abundance

The annual abundance index of age–0 American shad was highest in 1982 and lowest in 1985 (Figure 7, Table 3). The indices tended to be higher in wet years. The peak in the monthly abundance index of age–0 fish varied from year to year. In 5 out of the 14 years that have an index, the peak occurred before September. In all of the years surveyed, a large proportion of the total annual index occurred catch during July and August.

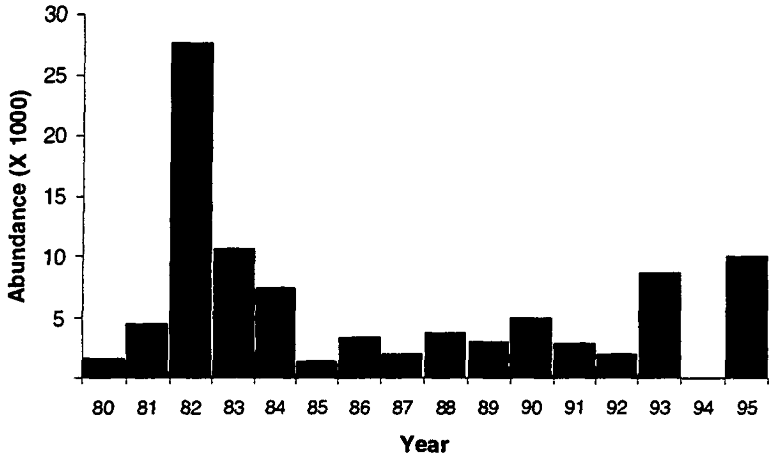

Figure 7 Annual abundance of age–0 American shad

Table 3 Monthly abundance indices of age–0 American shad captured in the midwater trawl from 1980 to 1995. The last column is the annual index, the mean abundance from July to October. The bottom row is the average seasonal abundance from 1981 to 1988.

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Index*
1980		0	0	0	0	0	289	924	4178	1460	5204	1668	1713
1981	0	0	0	0	0	0	0	3363	6105	8359	3127	1110	4457
1982	0	0	0	0	0	64	10496	53578	25929	20096	18422	13048	27525
1983	0	0	0	0	0	0	516	8313	23353	10077	4608	6389	10565
1984	0	0	0	0	0	0	18092	5955	3812	1957	851	1038	7454
1985	0	0	0	0	0	0	0	1840	1497	2188	2540	1150	1381
1986	0	0	0	0	0	0	0	1940	4668	6865	1829	3942	3368
1987	0	0	0	0	0	0	795	3088	2736	1718	1235	1478	2084
1988	0	0	0	0	0	0	3054	7208	1947	2855	2690	1786	3766
1989	0	0	0	0	0	0	540	5350					2945
1990		0	0	0	0	0	176	6408	11523	1711			4954
1991		0	0	0	0	0	0	2443	2763	5877			2771
1992		0	0	0	0	0	3229	1951	1761	958			1975
1993		0	0	0	0	0	548	16640	10412	6819			8604
1994		0	0	0									NA
1995				0	0	0	72		20370	9528	29921	3903	9990
1981–1988	0	0	0	0	0	8	4119	10661	8756	6764	4413	3743	

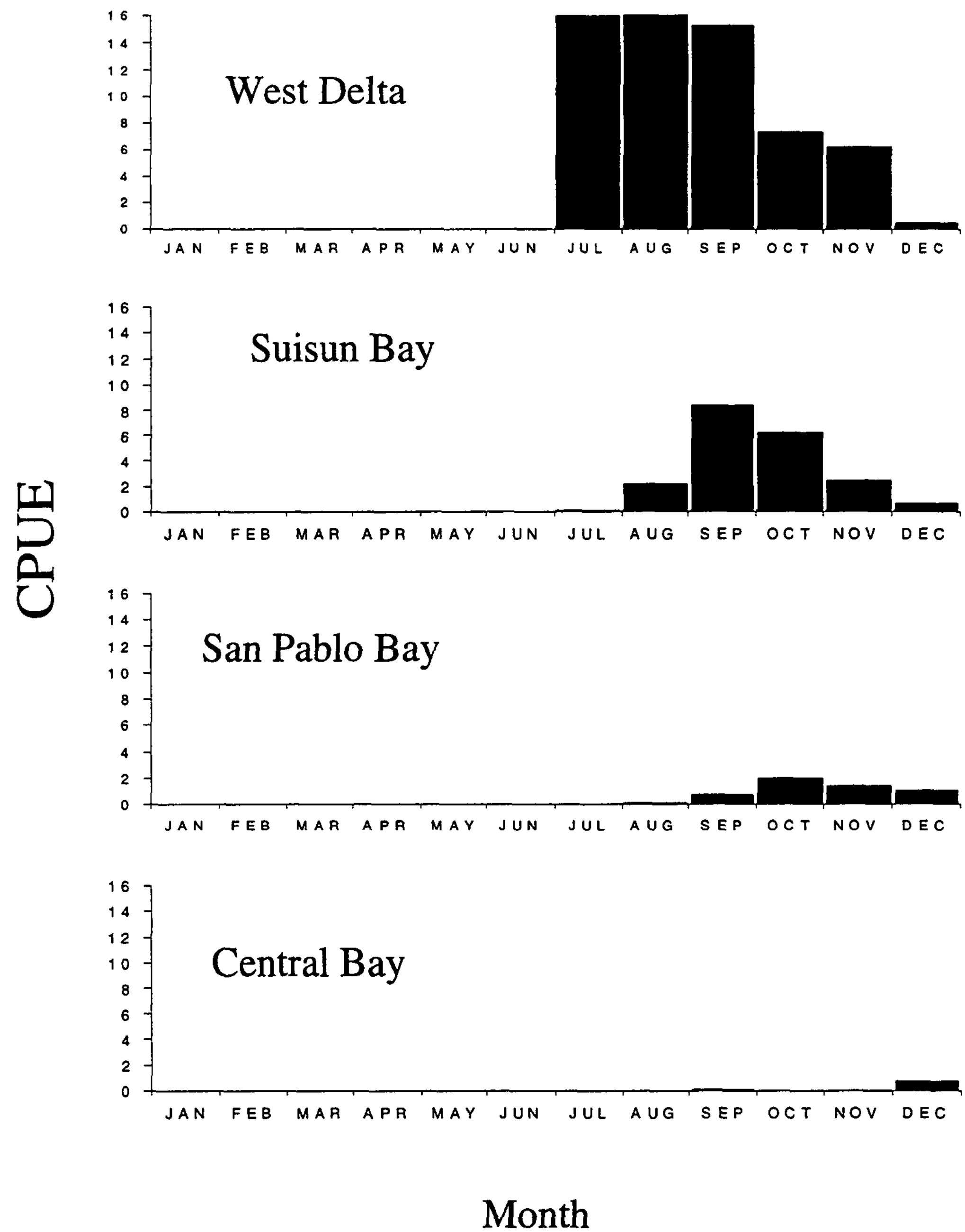

Figure 8 Seasonal distribution of age–0 American shad by region. Values are the average CPUE for 1981 to 1988.

Distribution

The distribution of age–0 American shad followed a recurring seasonal pattern. They first appeared in the west delta in July, where the catch usually peaked in July and August (Figure 8). As the year progressed, the catch in the west delta decreased and the downstream catch increased. Distribution varied little over the years (Figure 9). Most of the fish were collected in the west delta. The proportions of the total catches in regions downstream of the west delta increased in high outflow years.

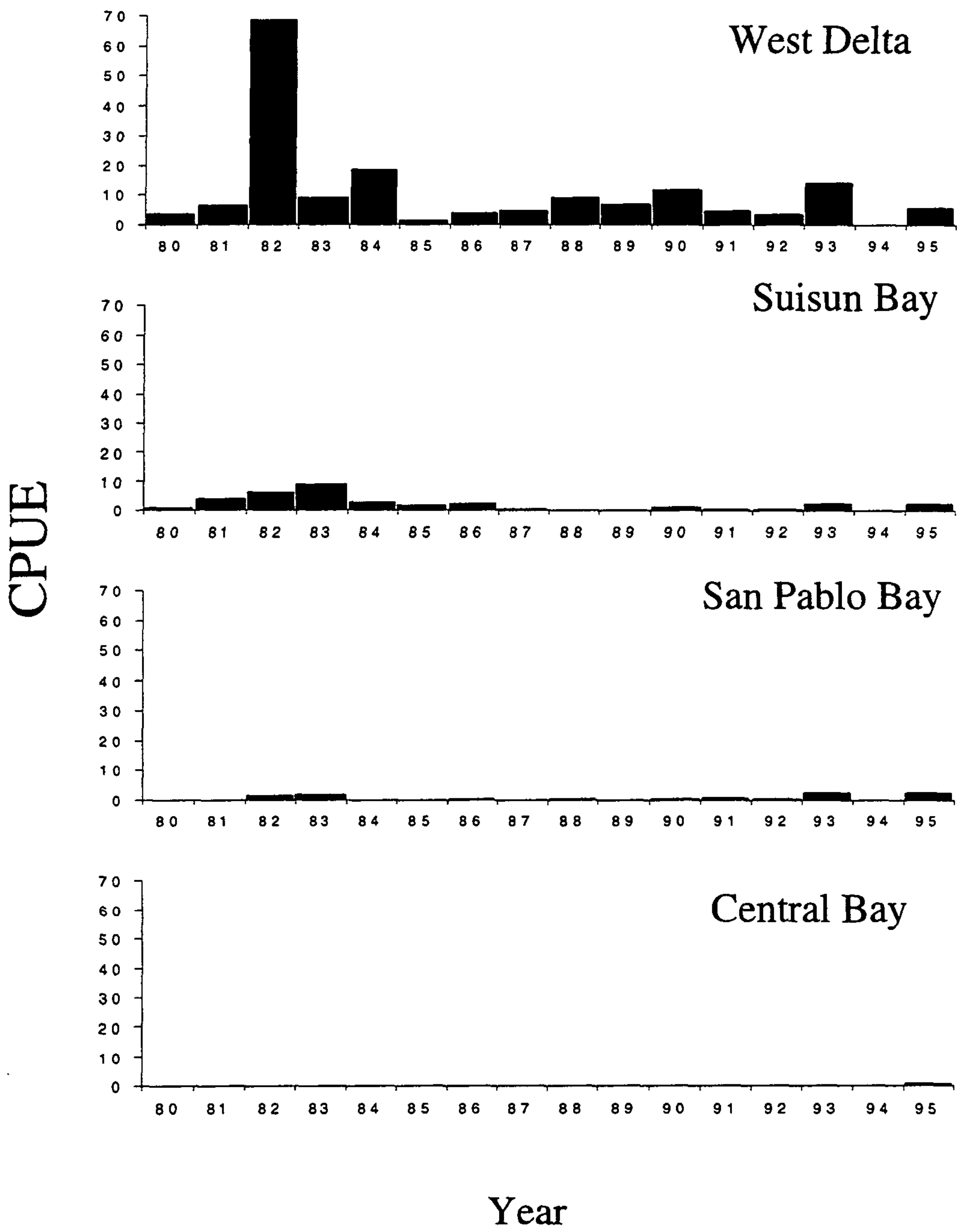

Figure 9 Annual distribution of age–0 American shad by region. Values are the average CPUE for July to October.

Temperature and Salinity

Age–0 American shad were collected over broad temperature and salinity ranges (Figure 10). The salinity the fish occurred in increased as they grew and emigrated. The smallest American shad were collected at a mean salinity of 0.16‰. The mean collection temperature showed an inverse relationship with size; the smallest fish were collected at a mean temperature of 21.3 °C.

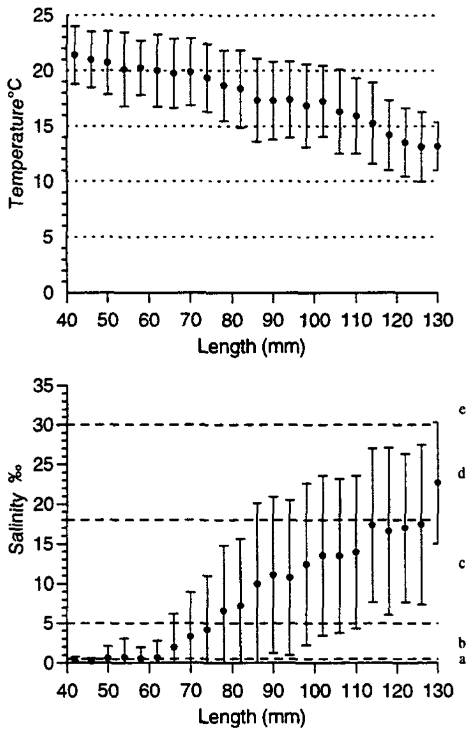

Figure 10 Temperature and salinity distributions of American shad by length. The dots are the means and the bars are 1 standard deviation. The horizontal lines on the salinity graph mark the boundaries of the Venice system ranges: (a) limnetic, (b) oligohaline, (c) mesohaline, (d) polyhaline, and (e) euhaline.

Discussion

Age–0 American shad migrated seaward through the estuary from June through December and experienced wide ranges of salinity and temperature. As they moved farther downstream the salinity at which they were caught increased and the temperature decreased. The annual abundance indices correlated significantly and positively with river flow ($r = 0.86$, $P < 0.05$, $n = 13$). This agrees with the relationship found by Stevens and Miller (1983) using data from the Fall Midwater Trawl Survey. Age–0 fish also appeared earlier in the year in our sampling area and were smaller during high outflow years.

The relationship between American shad abundance and outflow as measured by the Fall Midwater Trawl index was weakened during the early 1990s because the indices for these years were much greater than those predicted by the relationship based on earlier years. However, the Bay Study indices for the 1990s showed a continued significant relationship with outflow and differed significantly from the Fall Midwater Trawl indices ($r = 0.57$, $P < 0.05$, $n = 15$). The 2 studies produced different abundance indices because of differences in areas and months sampled. Neither study sampled the entire range of the fish nor all the months of peak abundance in all years. Hence, data from both studies need to be combined to obtain a complete picture of distribution and abundance.

Pacific Sardine

Introduction

The Pacific Sardine, *Sardinops sagax*, is primarily a coastal marine species. It ranges from Guaymas, Mexico to Kamchatka, Russia (Miller and Lea 1972). Individual fish travel long distances; fish tagged off southern California have been recovered a few months later in British Columbia. The speed of movement is related to the size of the fish. Larger sardines travel faster and farther than smaller fish (Clark and Janssen 1945). It is mostly older fish that make long journeys, up the coast during spring and summer and down the following winter. One- and two-year-old fish are generally not found in large numbers north of central California (Clark 1952).

The Pacific sardine spawns throughout its range but most spawning takes place off southern California (Scofield 1934) from January through September at temperatures between 12.5 to 16.0 °C (California Cooperative Sardine Research Program 1950).

The commercial fishery along the California coast was intensive and short-lived; after peaking in the mid-1930s, both the catch and effort declined. The fishery in San Francisco Bay began in 1916 and ended in the early 1950s. The fishery in the Pacific Northwest ended after 1948 (Murphy 1966).

Methods

Only midwater trawl data was used. Pacific sardines were not separated into age classes and because of the sporadic nature of the catch and the absence of several months of data, no index period for was set. Instead, the index was the sum of all the months available.

Results and Discussion

Prior to 1993, few Pacific sardine were caught in the estuary. From 1980 to 1992, only 21 Pacific sardines were collected and 12 of these were taken during a single tow within Central Bay. In 1993, the catch increased dramatically. Despite the curtailed sampling effort in 1994 the total catch of Pacific sardines from 1993 to 1995 far surpassed the total 15–year catch for many of the more "common" species that we normally encountered.

Although catches were somewhat higher during spring and summer, there was no strong seasonal trend. Commercial catches during the 1930s in San Francisco Bay also indicated little seasonal variation, with only a slight drop occurring in January and February.

Pacific sardines were collected over a broad salinity range from 15.7‰ to 31.7‰, mean 23.2‰, and were never collected upstream from San Pablo Bay. Most were in Central Bay; only in 1994 were they more abundant in South Bay. The collection temperatures ranged from 12.1 to 18.1 °C, mean 15.1 °C.

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Northern Anchovy

Kevin Fleming

Introduction

The northern anchovy, *Engralus mordax*, is a planktivorous, schooling fish that is common in bays and estuaries along the west coast of North America from Oregon to Baja California (Miller and Lea 1972).

Three subpopulations are recognized (Vrooman and others 1981). The distribution of the northern and central populations overlap outside the Golden Gate. Although fish from either population may be present in the estuary, the northern anchovies in the San Francisco Estuary seem to be more closely associated with the central population (Haugen and others 1969, Vrooman and others 1981). Members of the central population move north during the summer and south during the winter (Haugen and others 1969). Some of the movements have been extensive—tagged fish from San Francisco Bay were recovered in southern California. In addition to north-south movements, they also move offshore during fall and winter and return inshore in spring (Baxter 1967).

The northern anchovy is the most abundant species in the estuary and is an important forage fish for other resident and migratory species in the system, including salmon, jacksmelt, and striped bass. It supports a moderate commercial fishery for live bait (Smith and Kato 1979).

Although spawning occurs all year, resource limitations and environmental conditions constrain most reproduction to winter and spring at temperatures from 10 to 23 °C (Ahlstrom 1956, Brewer 1978). In the estuary, 2 spawning peaks occur, the 1st from February to April and the 2nd from July to September (Wang 1986).

Some northern anchovies mature after their 1st year at about 90 mm TL and all are mature after their 4th year and about 152 mm TL (Clark and Phillips 1952). Females may spawn batches of eggs and a large female may produce up to 130,000 eggs annually (Baxter 1967, Hunter and Macewicz 1980).

Methods

Midwater trawl data was used to describe distribution and abundance. No conspicuous cohorts were apparent from length frequency data, so separation of age–0 and age–1+ northern anchovies was based upon the length at earliest sexual maturity (about 90 mm) (Clark and Phillips 1952). Because of their low vulnerability to the net, fish <40 mm FL were not used in this analysis. Fish between 40 and 90 mm were considered age 0, and those >90 mm were considered age 1+.

The annual abundance index was calculated using February to October data. No index was calculated for 1994 because sampling with the midwater net was curtailed after April of that year.

Results

Abundance

Northern anchovy abundance was highly variable between years. The highest abundance for age–0 fish was in 1992 and the lowest in 1980. The difference was about 4 times (Figure 1A, Table 1). The indices for age–1+ fish were even more variable; the highest index in 1984 was approximately 10 times greater than the lowest in 1980 (Figure 1B, Table 2). Although no index was calculated in 1994, the above average February and March indices for both age classes suggests that the annual abundance index for that year would have been above average.

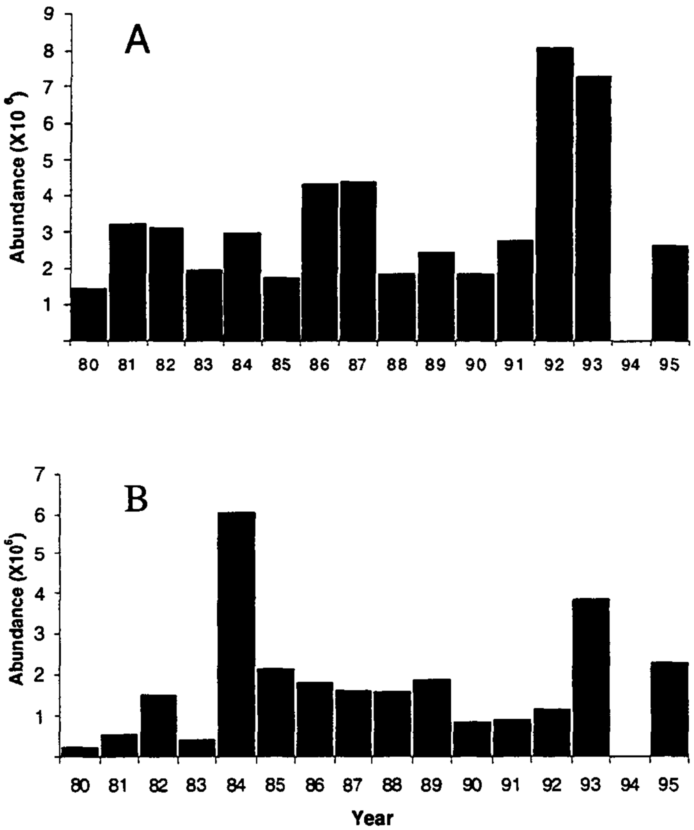

Figure 1 Annual abundance of northern anchovy: (A) age 0 and (B) age 1+. No abundance index was calculated in 1994.

Table 4 Monthly abundance indices (divided by 1000) of age-0 northern anchovy captured in the midwater trawl from 1980 to 1995. The last column is the annual index, the mean abundance from February to October. The bottom row is the average seasonal abundance from 1981 to 1988. No index was calculated for 1994.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Index
1980		54	4	53	201	7903	839	1006	2476	575	5130	2	3234
1981	15	64	3	541	474	3946	7258	3557	10734	2530	189	50	3122
1982	963	10	135	109	2149	5073	4072	6516	6762	3274	275	53	1961
1983	49	13	41	52	633	368	1087	2859	5834	6763	225	4	2964
1984	1	2	163	1633	3652	8131	3607	1878	5664	1943	52	19	1754
1985	26	22	470	2799	1166	1353	4240	691	3475	1568	1188	38	4324
1986	2	2	10	77	406	1242	27440	2910	2592	4238	5642	244	4384
1987	12	1	466	617	2469	10325	9863	8775	4254	2687	1828	12	1860
1988	4	37	1043	1602	1288	1840	3737	1089	2416	3692	929	29	2472
1989	11	15	335	1087	2619	4410	6335	2504					1837
1990		103	531	1012	2201	3427	2729	3007	2794	731			2763
1991		117	166	928	830	3543	2789	3430	7308	5758			8105
1992		13	221	3778	13825	10150	4112	10362	15114	15373			7312
1993		38	138	2566	2008	8678	7588	16453	12323	16016			
1994		135	11666	13298									2624
1995				176	6332	1154	2279		3527	2274	161	19	
1981-1988	134	19	291	929	1530	4035	7663	3534	5216	3337	1291	56	

Table 5 Monthly abundance indices (divided by 1000) of age-1+ northern anchovy captured in the midwater trawl from 1980 to 1995. The last column is the annual index, the mean abundance from February to October. The bottom row is the average seasonal abundance from 1981 to 1988. No index was calculated for 1994.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Index
1980		19	24	26	258	541	625	339	290	157	1598	0	253
1981	<1	61	1	2125	107	1297	662	315	159	94	<1	1	535
1982	123	0	8	5	5639	4911	2191	277	384	200	0	0	1513
1983	1	9	61	14	742	674	766	1084	475	33	2	0	428
1984	0	0	3	7856	11738	10012	5984	2149	12294	4240	9	0	6030
1985	2	4	76	4101	3494	1538	2467	552	3244	3580	960	0	2117
1986	1	1	2	19	3338	1250	6582	1171	297	3603	1450	4	1807
1987	1	<1	509	226	7945	1829	2313	1146	416	11	25	1	1599
1988	2	12	529	5782	2366	1839	2023	946	293	242	8	4	1559
1989	2	2	289	1665	5732	986	3000	1190					1837
1990		491	525	1642	1291	1311	1349	832	165	22			848
1991		43	99	1246	498	1519	1162	786	2633	167			906
1992		2	135	2450	1210	3972	1014	872	696	77			1159
1993		14	231	3002	9227	10643	8259	1147	134	1635			3810
1994		47	5341	2144									
1995				2	4677	4524	3694		570	126	21	1	2265
1981-1988	16	11	148	2516	4421	2919	2874	955	2195	1500	307	1	

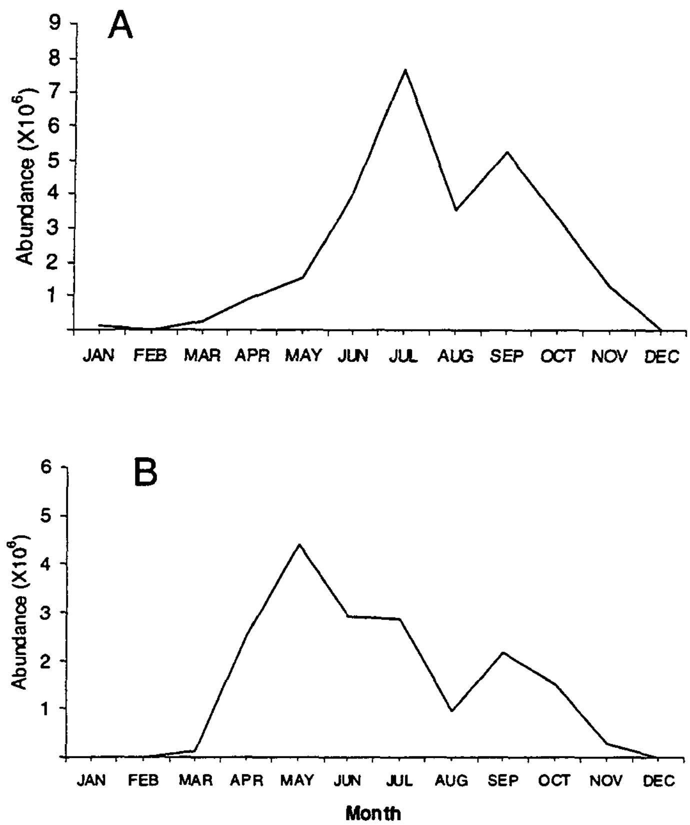

Figure 2 Seasonal abundance of northern anchovy from 1981 to 1988: (A) age 0 and (B) age 1+

Both age groups exhibited similar seasonal abundance trends, which were often bimodal with a peak in the late spring or summer, a decline in late summer and a 2nd peak in the fall (Figures 2A and 2B). Abundance was lowest in winter.

Annual Distribution

The distribution pattern of age–0 northern anchovy was typical of that of marine species; in most years the highest CPUEs were in Central Bay (Figure 3), whereas South and San Pablo bays had the next highest CPUEs. In dry years (1981, 1987–1992, and 1994), the South Bay tended to have the 2nd highest CPUE and in wet years (1980, 1982, and 1983) San Pablo Bay had the 2nd highest CPUE.

Age–1+ northern anchovy had a similar annual distribution but unlike age–0 fish, the South Bay CPUE of age–1+ fish tended to be greater than the CPUE in San Pablo Bay, especially after 1984, regardless of water year type (Figure 4).

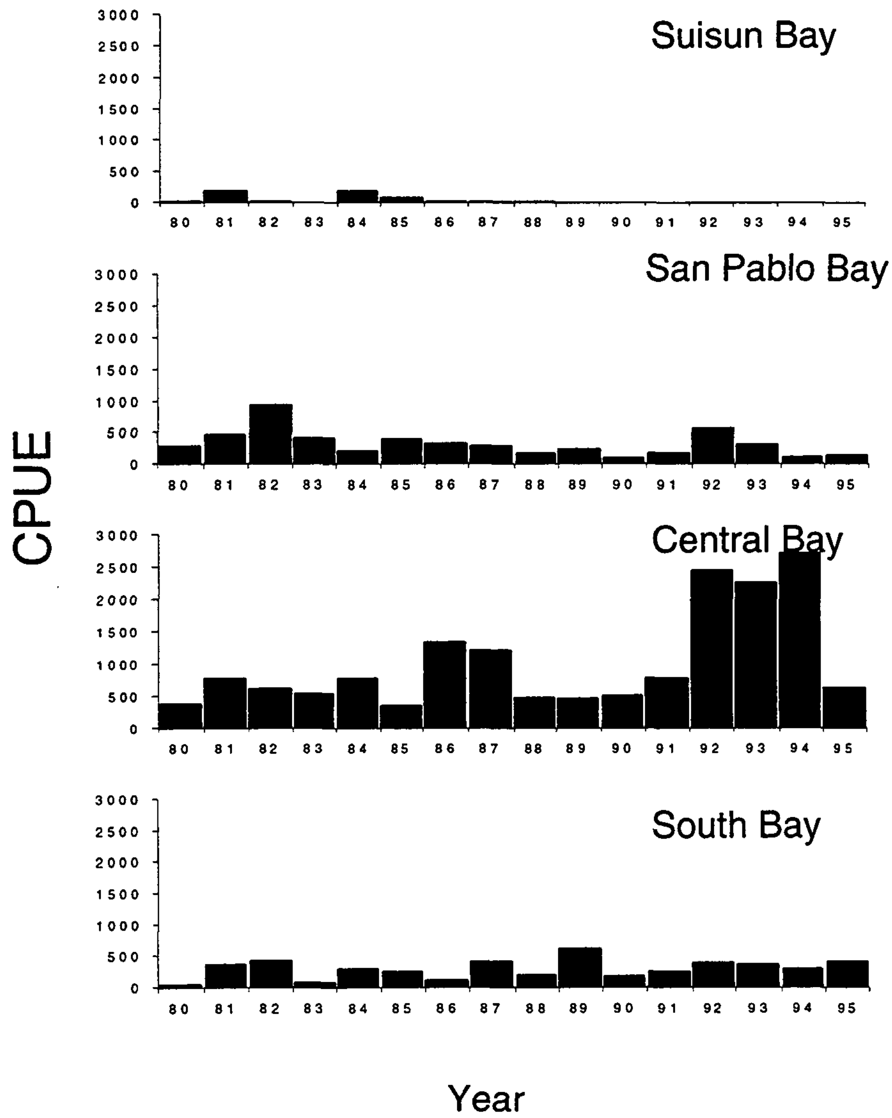

Figure 3 Annual distribution of age–0 northern anchovy by region. Values are the average CPUE for February to October.

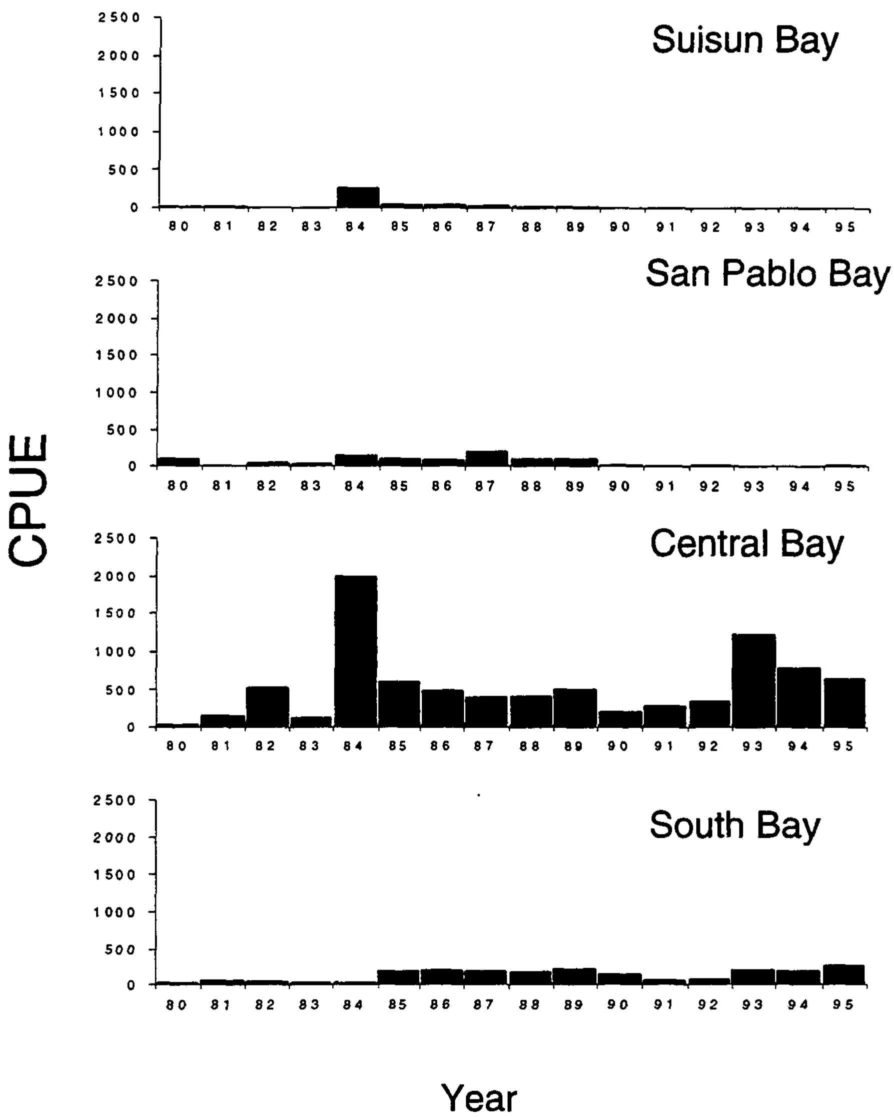

Figure 4 Annual distribution of age–1+ northern anchovy by region. Values are the average CPUE for February to October.

Seasonal Distribution

Age–0 northern anchovies had relatively low densities in winter, increasing numbers in spring, a peak in summer, and a decrease in fall (Figure 5). This pattern held for all bays except Central Bay, where a 2nd CPUE peak occurred from September to October. The greatest densities occurred in Central, San Pablo, and South bays. Only in late summer were they collected in appreciable numbers in Suisun Bay.

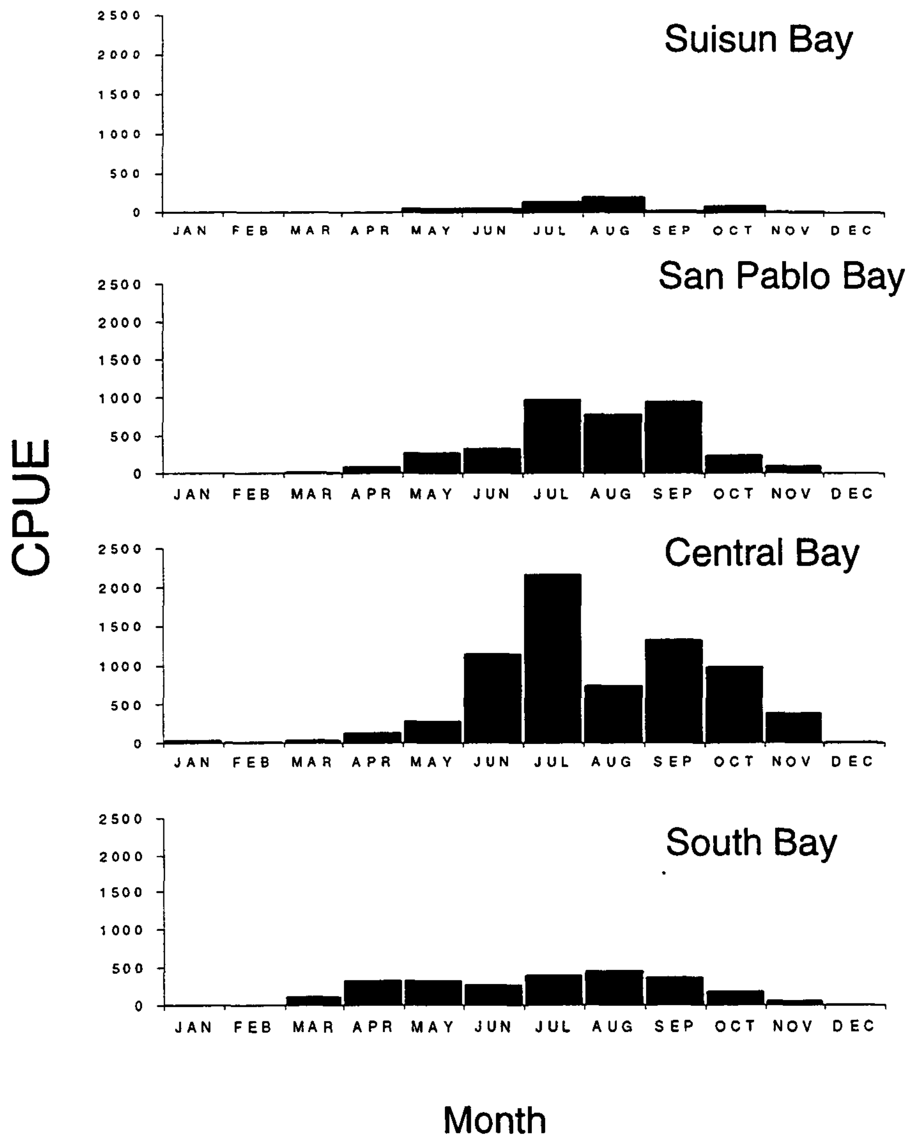

Figure 5 Seasonal distribution of age–1+ northern anchovy by region. Values are the average CPUE for 1981 to 1988.

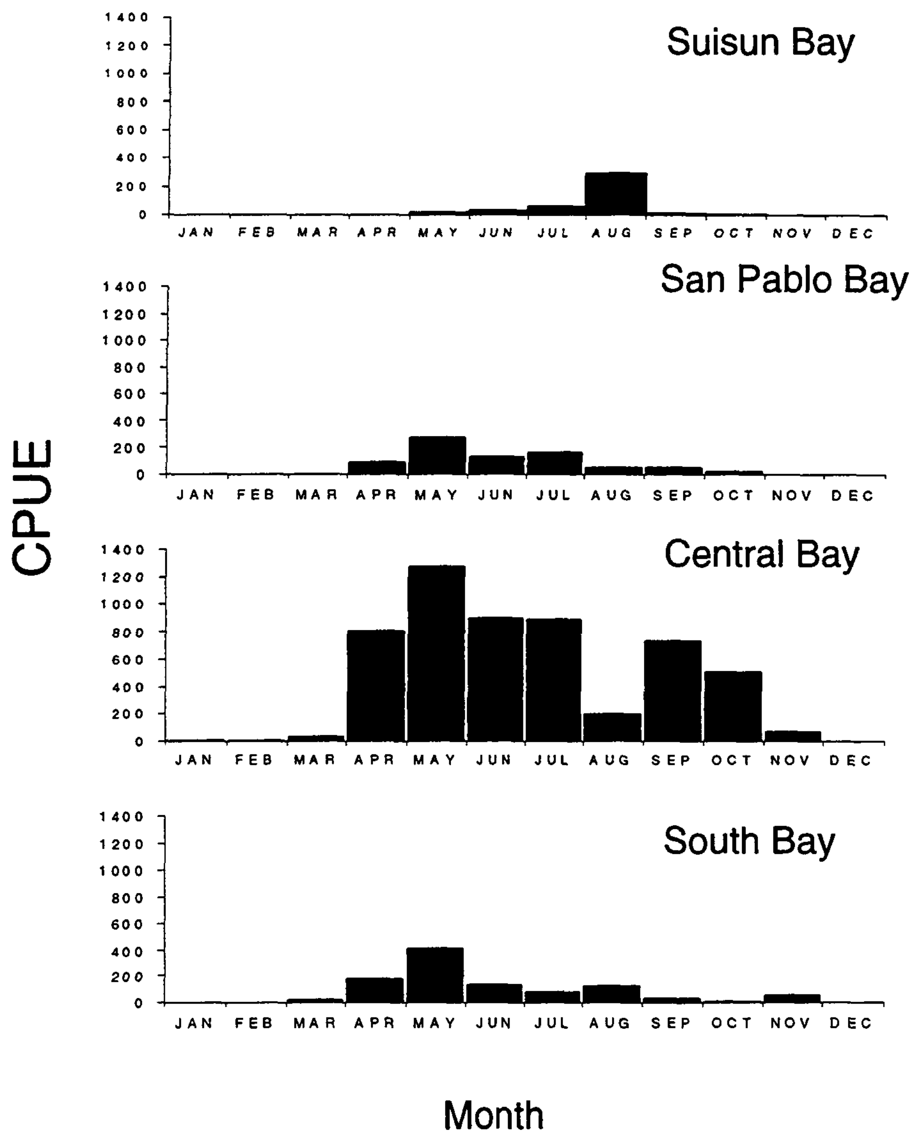

Figure 6 Seasonal distribution of age–0 northern anchovy by region. Values are the average CPUE for 1981 to 1988.

The pattern of seasonal distribution for age–1+ northern anchovies was similar to that of the age 0, but age–1+ fish were more concentrated in Central Bay than age–0 fish (Figure 6).

Temperature and Salinity

Most northern anchovies were collected between 13 and 21 °C (Figures 7A and 8A). They entered the estuary when the average temperature in Central Bay rose above about 13 °C, which typically happened in late winter, and they left in late fall, when the temperature dropped below about 13 °C. The mean temperature at which age–0 fish were found, 17.2 °C, was slightly warmer than the mean for age–1+ fish, 16.0 °C.

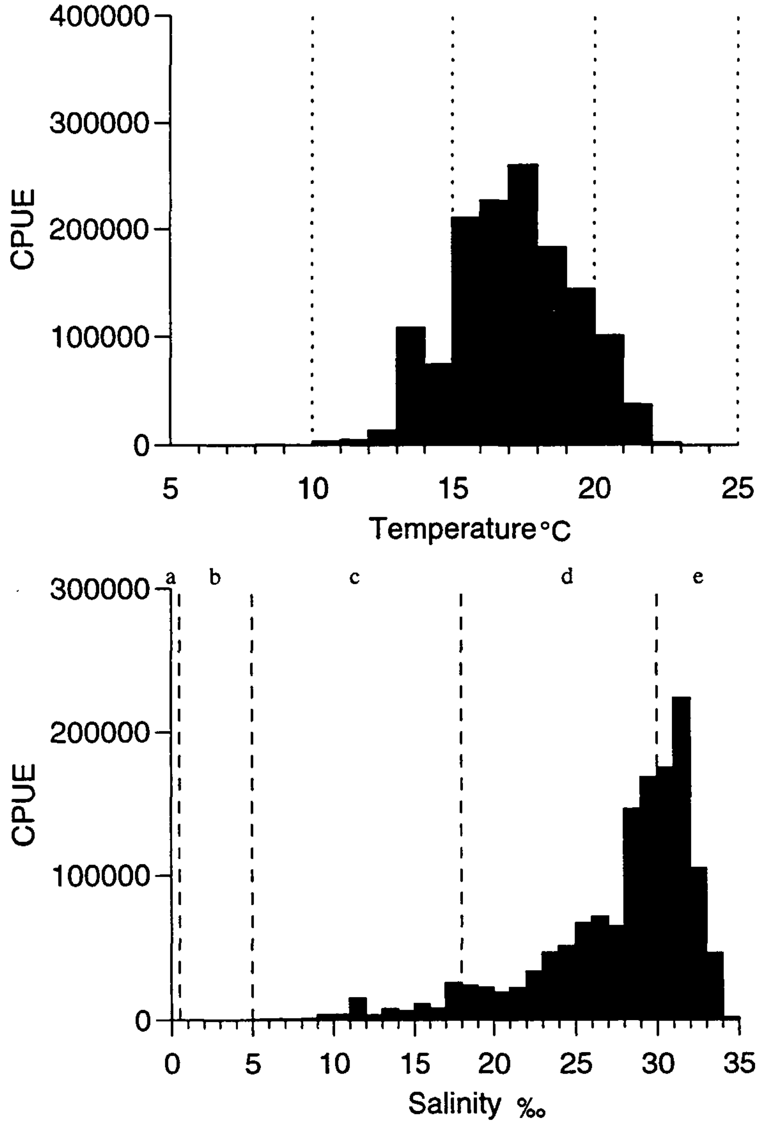

Figure 7 Temperature and salinity distributions of age–0 northern anchovy. The vertical lines on the salinity graph mark the boundaries of the Venice system ranges: (a) limnetic, (b) oligohaline, (c) mesohaline, (d) polyhaline, and (e) euhaline.

Northern anchovies were found over wide salinity ranges (Figures 7B and 8B). Both age classes were found primarily in polyhaline to euhaline ranges and the means for both were very close: 27.3‰ for age 1+ and 27.6‰ for age 0.

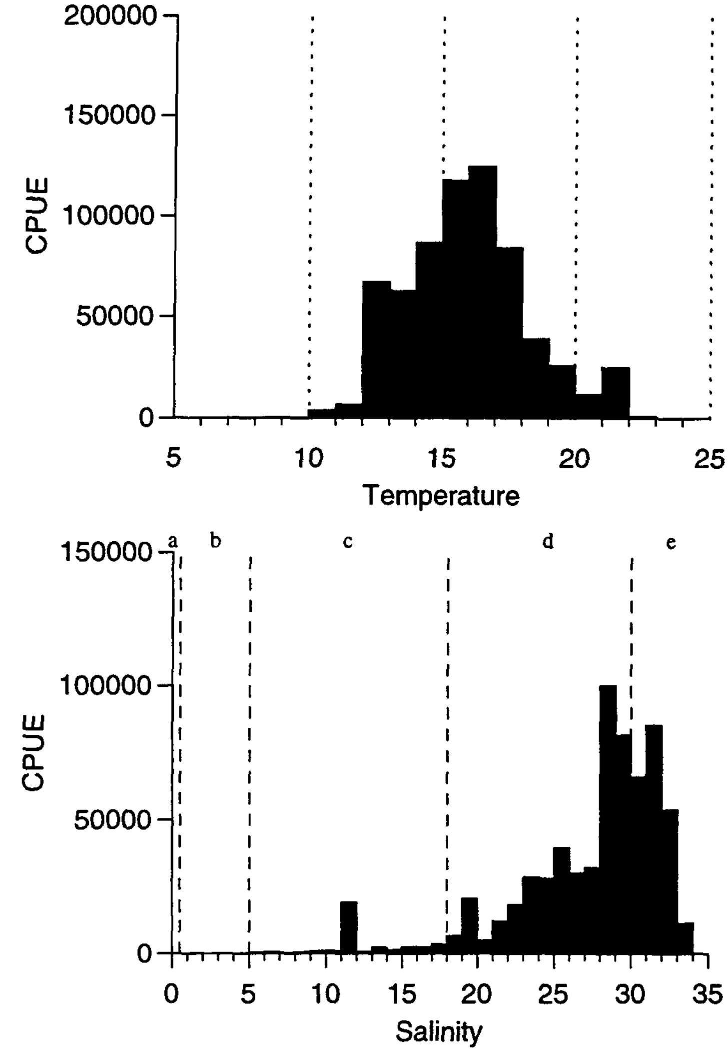

Figure 8 Temperature and salinity distributions of age–1+ northern anchovy. The vertical lines on the salinity graph mark the boundaries of the Venice system ranges: (a) limnetic, (b) oligohaline, (c) mesohaline, (d) polyhaline, and (e) euhaline.

Discussion

Northern anchovies follow a predictable pattern of seasonal abundance in the estuary. They move in from the ocean throughout the spring and summer. Peak abundance is generally in late spring but abundance is often bimodal with a 2nd peak in the fall. Abundance is lowest in winter. Despite great fluctuations in abundance, the northern anchovy is the most numerous fish species in the estuary, comprising from 74% to 98% of the total midwater trawl catch. Most northern anchovy are found in the polyhaline to euhaline waters of the estuary.

Northern anchovies in this estuary are part of the central population (Vrooman and others 1981, Haugen and others 1951). The size and proximity of the ocean schools to the estuary, and therefore, the potential for estuary use, depend upon oceanic conditions. Immigration into the estuary may be in response to the higher temperatures found in it that may allow earlier spawning opportunities than would be possible in the ocean. The timing of estuarine entry and exit corresponded with seasonal changes in the temperature of Central Bay.

Seasonal changes in the temperature differential between the ocean and Central Bay may also partly explain the 2nd peaks in CPUEs of both age classes that occurred in many years in fall. Although the estuary usually has higher temperatures than the ocean, ocean temperatures may be higher in summer and fall. The higher ocean temperature appears to correspond to the decreased CPUE in the estuary. As ocean temperatures decrease in late fall, the CPUE in the estuary increases again. The increased fall abundance can also explain the 2nd spawning mode because northern anchovy spawn all year and spawning intensity should, therefore, be a function of the number of spawners in an area.

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Osmeridae

Randall Baxter

This chapter describes trends in abundance and distribution for osmerid species collected in the San Francisco Estuary. For each species, abundance and distribution information is discussed in the context of life history. Analyses of larval abundance and distribution are presented for species with identifiable larvae collected in sufficient numbers.

Six species of Osmeridae, or true smelts, were collected from the San Francisco Estuary between 1980 and 1995 (Table 1): longfin smelt, *Spirinchus thaleichthys*; night smelt, *S. starksi*; delta smelt, *Hypomesus transpacificus*; wakasagi, *H. nipponensis*; surf smelt, *H. pretiosus*; and whitebait smelt, *Allosmerus elongatus* (Robins and others 1991, Stanley and others 1995). Night smelt, surf smelt, and whitebait smelt are marine species. The longfin smelt and delta smelt are euryhaline species, spending the early portions of their lives in freshwater and entering brackish water as late stage larvae or juveniles. Some longfin smelt migrate to marine waters during the middle of their lives. The wakasagi is the only non-native osmerid and has 2 life-history types in its native Japan, a completely freshwater type and an anadromous type (Hamada 1961, as cited in McAllister 1963). Wakasagi eggs from a reservoir in Japan were originally introduced into 6 California freshwater impoundments in 1959 (Wales 1962). It has since been introduced or spread to other waters, including the delta (Aasen and others 1998). Only 2 wakasagi have been captured, both by the midwater trawl: 107 mm at station #837 in December 1982 and 65 mm at station #431 in July 1995 (see Table 1). Other wakasagi may have been misidentified as delta smelt because of the close resemblance between the 2 species (Sweetnam 1995). No further discussion will be devoted to wakasagi. Trends in abundance and distribution for the remaining species are discussed in more detail in this section.

Table 1 Total catch by species and gear type for osmerids collected between January 1980 and December 1995. See the Methods chapter, Table 1 for duration of use for different gear types.

Species	*Plankton net larvae*	*Plankton net juveniles*	*Beach seine*	*Otter trawl*	*Midwater trawl*
Longfin smelt	130,741	6,376	215	45,548	54,459
Delta smelt	373	250	130	419	1,634
Surf smelt	2	0	498	12	93
Whitebait smelt	0	0	1	193	80
Night smelt	0	0	7	21	183
Wakasagi	0	0	0	0	2

Longfin Smelt

Introduction

The longfin smelt, *Spirinchus thaleichthys*, is a pelagic, estuarine fish which ranges from Moss Landing, Monterey Bay (R. Lea, personal communication, see "Notes") northward to Hinchinbrook Island, Prince William Sound, Alaska (McAllister 1963). In California, it is collected from San Francisco Bay, Humboldt Bay, and the Eel, Klamath, and Smith rivers (Frey 1971, Emmett and others 1991). In the early 1990s, the only California freshwater collections came from the Klamath River (M. Wallace, personal communication, see "Notes") and San Francisco Bay. The longfin smelt comprises a small portion of the "whitebait" fishery in San Francisco Bay and is not taken by sport fishers (Skinner 1962).

Maturity is reached at age 2 (Dryfoos 1965, Moulton 1974). In the late fall, maturing fish migrate from San Francisco Bay and coastal marine waters to Suisun Bay, Montezuma Slough, and the lower reaches of the Sacramento and San Joaquin rivers (Ganssle 1966, Radtke 1966, Wang 1986). Spawning probably takes place in fresh or slightly brackish water. Moyle (1976) reported that longfin smelt spawn in portions of Suisun Bay and the west delta between December and February, and Wang (1986) reported a December to June spawning period. Most appear to die after spawning, but a few females may live to spawn a 2nd time at age 3 (Dryfoos 1965, Moulton 1974, Moyle 1976). Adults reach a maximum size of about 150 mm TL (Miller and Lea 1972).

The eggs are adhesive and are probably released over a firm substrate (Moyle 1976). The larvae are pelagic and are most abundant in the upper layers of the water column (Wang 1986, Hieb and Baxter 1993). They are very common in Suisun Bay during spring (Wang 1986), but larval and juvenile distributions appear to be a function of freshwater outflow (Hieb and Baxter 1993). In April and May, juveniles are found downstream in San Pablo Bay (Ganssle 1966, Hieb and Baxter 1993). During late spring, summer, and fall, juvenile longfin smelt disperse throughout the estuary (Messersmith 1966, Aplin 1967, Hieb and Baxter 1993), and frequently venture into the Gulf of the Farallones (City of San Francisco Bureau of Water Pollution Control and CH2M Hill 1984, B. Sak, personal communication, see "Notes"). Juveniles tend to inhabit the middle and bottom strata of the water column (Moyle 1976).

The annual abundance of longfin smelt is significantly and positively correlated with the amount of freshwater flow during the spawning and larval periods (Stevens and Miller 1983, Hieb and Baxter 1993, Jassby and others 1995). Three factors were identified as potentially responsible for the high correlation: (1) a reduction in predation during high flows; (2) increased habitat availability which may improve survival by reducing intraspecific competition; and (3) an increase in nutrients stimulating the base of the food chain (Stevens and Miller 1983).

Methods

Duration of use varied by gear type and affected the annual and seasonal periods used in abundance and distribution analyses (see Methods chapter, Table 1). Although the incubation and larval periods extend from November to July (Wang 1986), most larvae appear to hatch in January or February (Hieb and Baxter 1993); therefore, larvae were assigned a January 1 birth date. Larvae were staged by the presence (yolk sac larvae or YSL) or absence of a yolk sac (post-YSL). In the plankton net, longfin smelt were classified as juveniles (that is, age 0) at ≥ 20 mm FL based upon complete fin ray development (Simonsen 1977). Catch per unit effort (CPUE) was calculated for each life stage (YSL, post-YSL, age 0). Monthly abundance was calculated as the product of mean CPUE by region and the region's weighting factor (volume) summed for all 5 regions (see Methods chapter, Tables 2 and 3). Annual abundance was calculated as the mean of January to May monthly abundance indices (YSL and post-YSL combined). To describe seasonal abundance, indices were averaged by life stage and month for 1981 to 1988 (years when sampling occurred in all 12 months) (see Methods chapter, Table 1). To describe annual distribution, total larval (YSL + post-YSL) CPUE was averaged by region for January to May. A significance of $P \leq 0.05$ was used for all analyses. To test for a relationship between freshwater outflow and larval geographic distribution, a Spearman rank correlation analysis was run on ranked average December to March Chipps Island outflow and ranked mean annual larval distribution. To calculate mean annual distribution, mean January to May CPUE by region was multiplied by region number (West Delta = 1, Suisun Bay = 2...South Bay = 5) for each region; these products were then summed and divided by the sum of the mean CPUEs for the regions.

Although the midwater and otter trawls collected longfin smelt, only otter trawl data were used to describe the abundance and distribution of the bottom-oriented, older age–0 and age–1 fish. Longfin smelt annual abundance indices for the 2 gears are well correlated: $r = 0.841$, $P < 0.001$, $n = 15$ for age–0 fish; $r = 0.984$, $P < 0.001$, $n = 15$ for age–1 fish (no midwater trawl index was calculated for either age group for 1994). To separate age classes, otter trawl length frequency data (mm FL) were tallied into 2 mm groups by month (January to December) and inspected to identify "breaks" or minima. At the minima, cutoff lengths were selected to separate fish into age–0 and age–1 classes. Cutoff lengths for separating age–0 from age–1 fish were as follows: 40, 42, 46, 52, 59, 67, 71, 75, 80, 83, 85, and 87 mm FL for January to December, respectively. Cutoff lengths for separating age–1 from age–2 fish were as follows: 90, 93, 96, 100, 105, 108, 111, 114, 117, 120, 123, and 125 mm FL for January to December, respectively.

The minimum size for inclusion into otter trawl abundance and CPUE calculations was 40 mm for longfin smelt. The CPUE was calculated for each station as the product of age specific catch divided by the tow area and 10,000, which yields catch per hectare (10,000 m^2). Monthly abundance was calculated as the product of mean CPUE by region and the region's weighting factor, then summed for all 5 regions (see Methods chapter, Tables 2 and 3). Annual abundance was calculated as the mean of monthly indices. May to October and February to October index periods were used to calculate annual abundance indices for age–0 and age–1 longfin smelt, respectively; these months represent the longest contiguous periods sampled annually (see Methods chapter, Table 1) when age–0 and age–1 longfin smelt were captured. No indices were calculated for age–2+ fish. No correction was made for missing data for September and October 1989, so the indices for age–0 and age–1 fish were probably biased high in that year. Annual distribution analyses were based on February to October monthly CPUE by region for both age–0 and age–1 fish. Seasonal abundance and distribution (geographical, salinity, and temperature) analyses were based upon data from 1981 to 1988, when all 12 months were sampled (see Methods chapter, Table 1).

Simple linear regression analyses were used to test for a relationship between outflow and age–0 longfin smelt abundance (Zar 1984). Abundance indices and outflows were log transformed to meet regression assumptions of equal variance. Seasonal salinity distribution was calculated for each age class as the monthly mean ±1 standard deviation of CPUE-weighted bottom salinity using 1981 to 1988 data. Seasonal temperature distribution was calculated similarly for salinity using CPUE-weighted bottom temperature.

Results

Catch and Length Analyses

In the plankton net, more than 130,000 larvae and 6,000 juveniles (age 0) were collected during the study period (see Table 1). Yolk sac larvae ranged in size from 4.2 to 9.6 mm TL, but 97% ranged from 5.0 to 7.9 mm TL (n = 38,302 measured). Post-yolk sac larvae ranged in size from 5.4. to 19.0 mm. Most post-yolk sac larvae were larger than 6.9 mm (95.3%; 66,690 measured). Juveniles in the plankton net ranged from 20 to 53 mm FL. In the beach seine, only 215 longfin smelt were caught, ranging in size from 24 to 101 mm FL.

The longfin smelt was the most abundant osmerid collected with either the otter or midwater trawl (see Table 1). Longfin smelt ranged in size from 17 to 154 mm FL in the midwater trawl and from 15 to 150 mm FL in the otter trawl. Cutoff lengths provided a good separation of age–0 and age–1 fish from April to June, but only an approximate separation in later months (Figure 1). Cutoff lengths provided only approximate separation of age–1 and age–2 fish due to length overlaps. In January, 2 additional year classes were also apparent: 90 to 124 (age 2) and ≥125 (age 3) (see Figure 1). Only 12 fish out of more that 45,500 captured in the otter trawl were ≥ 125 mm or age 3. Eleven of the 12 age–3 fish were captured from November to May, immediately before and during the longfin smelt spawning period.

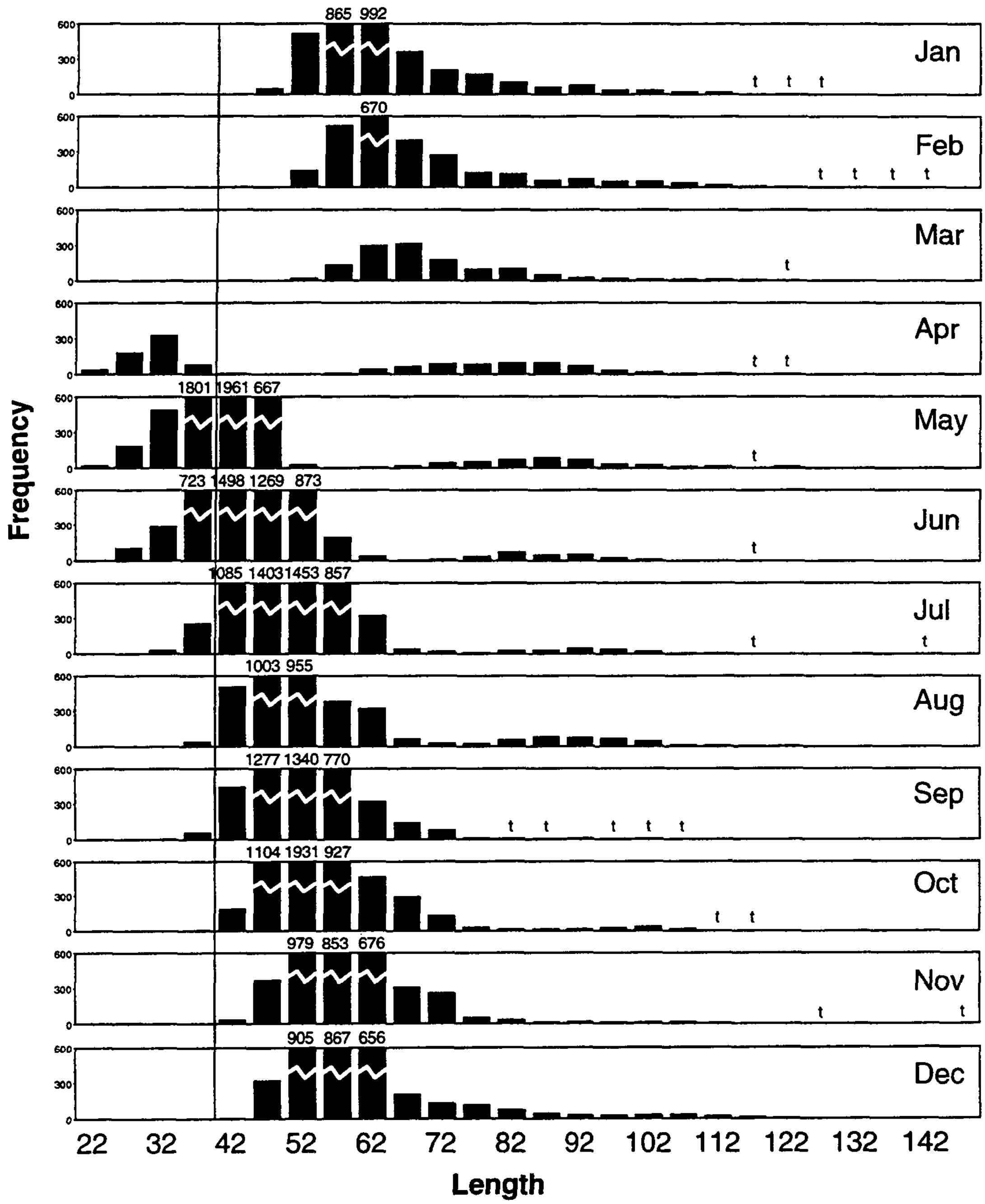

Figure 1 Length frequency (mm FL) by month of longfin smelt collected with the otter trawl from 1980 to 1995. Fish under the 40 mm (vertical line) were collected between 1980 and 1989, but were not included in index calculation. Numbers too small to show at this scale are indicated by "t" (trace).

Including fish <40 mm, examination of length-frequency modes indicates an apparent age 0 growth rate of between 5 and 10 mm per month for April to August, followed by growth at <5 mm per month for the rest of the year (see Figure 1). Most age–0 fish reached 40 mm by August. Faster growing age–0 fish attained 80 to 90 mm by December. Among age–1 fish, little growth occurred between January and March (<5 mm). After April, growth appeared to increase, but fish numbers decreased rapidly and the modes were difficult to follow.

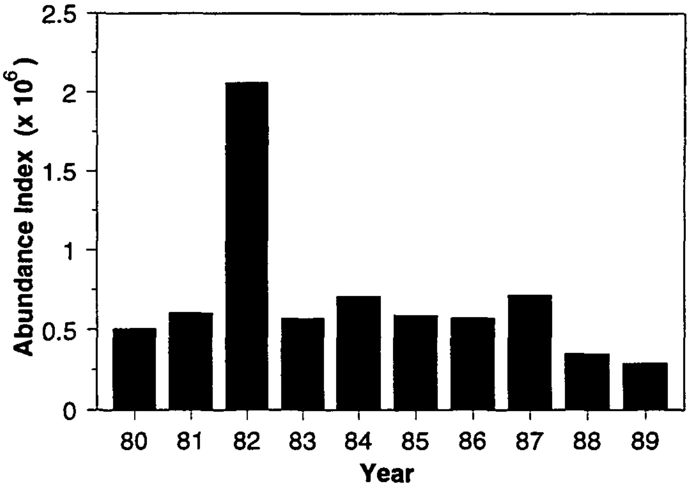

Figure 2 Annual abundance of longfin smelt larvae (YSL + post-YSL) collected with the plankton net from 1980 to 1989

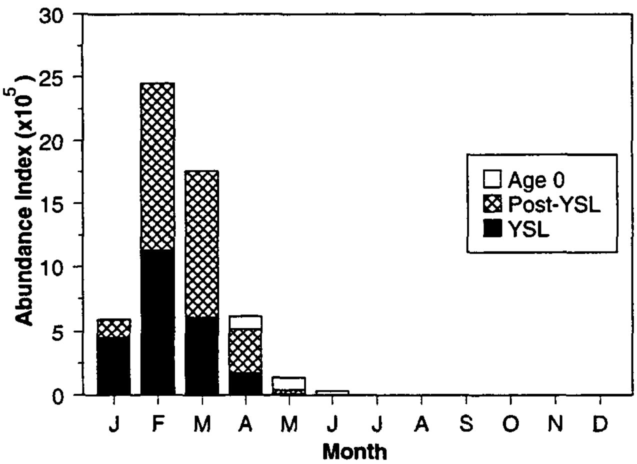

Figure 3 Seasonal abundance by life stage (YSL, post-YSL, Age 0) of longfin smelt collected with the plankton net from 1981 to 1988

Abundance and Distribution of Larvae

Except for the high abundance year 1982 and the low abundance years 1988 and 1989, larval abundance indices did not vary much annually (Figure 2). Although larval abundance peaked during the high outflow year 1982 and declined in 2 of the early years of the drought (for example, 1988 to 1989, see Figure 2), there was no relationship between December through March average monthly outflow and larval abundance ($r^2 = 0.21$, $P > 0.20$, $n = 10$). Generally, larvae were most abundant from January to April (Figure 3), but some were captured as early as November or as late as July (Table 2). Larval abundance peaked in February in 8 out of 10 years and in March in the remaining 2 years (see Table 2).

Table 2 Monthly abundance of longfin smelt larvae captured in the plankton net from 1980 to 1989. Annual abundance indices are in the far right column. Seasonal abundance indices are in the bottom row (mean 1980 to 1989 monthly abundance).

Year	*Jan*	*Feb*	*Mar*	*Apr*	*Mar*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Jan–May*
1980		1,017,999	831,472	168,224	11,925	1,758	0	0	0	0	338	0	507,405
1981	451,862	1,068,828	1,297,281	177,568	28,772	0	431	0	0	0	531	0	604,862
1982	1,089,739	5,461,695	3,061,403	605,076	91,403	413	0	0	0	0	0	4,068	2,061,863
1983	72,882	988,726	937,592	709,509	149,028	1,184	0	0	0	0	0	608	571,547
1984	602,702	1,348,685	1,159,662	414,023	1,148	0	431	0	0	0	0	7,807	705,244
1985	708,428	1,078,978	688,366	473,275	1,738	0	0	0	0	0	0	1,607	590,157
1986	191,894	2,320,317	237,865	113,748	3,496	1,714	0	0	0	0	0	23,291	573,464
1987	473,212	714,149	1,741,008	647,810	6,880	1,505	0	0	0	0	0	0	716,612
1988	242,801	1,030,047	472,529	3,893	2,149	0	0	0	0	0	0	2,790	350,284
1989	175,435	362,991	332,118	157,508	4,567								206,524
1980–1989	445,439	1,539,242	1,075,930	347,063	30,111	730	96	0	0	0	97	4,463	

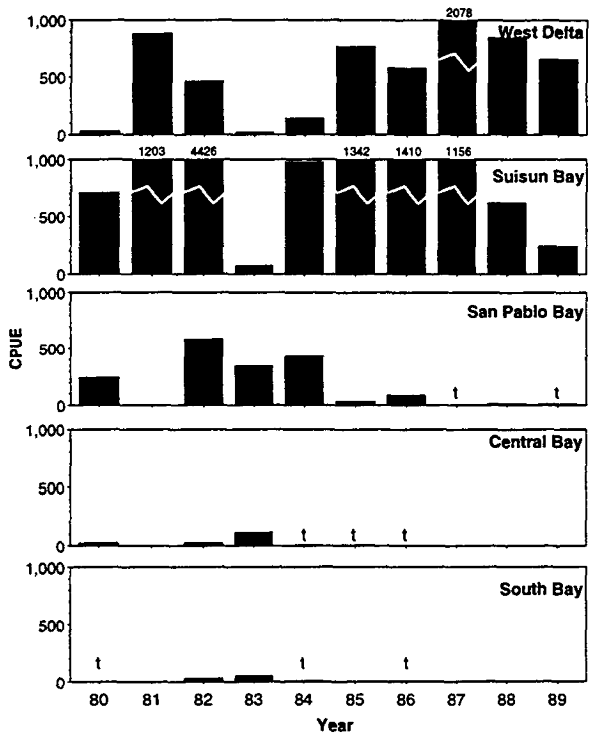

Figure 4 Annual distribution of longfin smelt larvae (YSL + post-YSL) collected in the plankton net from 1980 to 1989. Data are average January to May CPUE by region. When CPUE was too small to plot "t" was inserted in the graph. The years 1981, 1985, and 1987 to 1989 were classified as having low outflow and the remainder as having high outflow.

Larval distribution varied considerably from year to year, but larvae were always captured in the west delta and Suisun Bay, and less frequently farther downstream (Figure 4). The distribution of larvae was significantly correlated with average December to March outflow ($r_{spearman} = 0.867$, $P < 0.005$, $n = 10$).

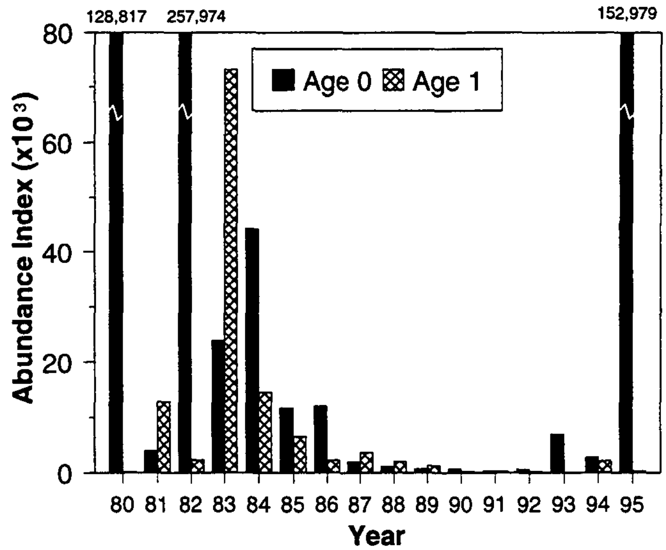

Figure 5 Annual abundance of age–0 and age–1 longfin smelt from the otter trawl from 1980 to 1995

In years with high outflows (that is, in 1980, 1982, 1983, 1984, and 1986), larvae were distributed in all regions of the estuary. They were only collected in South Bay during these high outflow years. During low outflow years, larvae were not collected in high densities outside of the west delta and Suisun Bay, though they were caught as far away as Central Bay in 1985.

Abundance and Distribution of Age–0 and Age–1 Fish

Annual Abundance

The abundance of age–0 longfin smelt varied from a high of 257,974 in 1982 to a low of 244 in 1991 (Figure 5, Table 3). From 1980 to 1987, age–0 abundance alternated between high in even years and low in odd years, and declined steadily to 1991. Beginning in 1992, age–0 abundance started to increase, but odd years were higher than even years. In 1995, abundance returned to a level comparable to that of the early 1980s.

There was a significant and positive relationship between the abundance of age–0 longfin smelt and average December to May outflow ($r^2 = 0.772$, $P < 0.05$, $n = 16$). Over the period of larval sampling (1980 to 1989), age–0 abundance was also significantly and positively related to larval abundance ($r^2 = 0.425$, $P < 0.05$, $n = 10$). This relationship was strongly driven by the 1982 abundance indices.

Age–1 abundance varied from a high of 73,222 in 1983 to a low of 24 in 1993 (see Figure 5). In general, age–1 abundance lagged age–0 abundance by 1 year. However, during the drought of 1987 to 1992, age–1 abundance did not decline as steeply as age 0. Age–1 abundance also showed signs of a slight recovery in 1994 and 1995 (see Figure 5, Table 4).

Table 3 Monthly abundance of age–0 longfin smelt captured with the otter trawl from 1980 to 1995. Annual abundance indices are in the far right column. Seasonal abundance indices are in the bottom row (mean 1981 to 1988 monthly abundance).

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*May–Oct*
1980		0	0	1078	8213	56770	258923	108942	185517	154535	118581	42046	128817
1981	0	0	0	0	173	2881	3299	8862	4435	4595	2001	4929	4041
1982	0	0	0	0	123319	170950	336405	279918	246844	390410	120106	338806	257974
1983	0	0	0	0	7036	25448	57754	30107	4415	18493	28345	27564	23876
1984	0	0	0	189	548	27686	24635	34657	14486	164097	8709	24842	44352
1985	0	0	0	0	1019	4915	4085	20164	2873	37678	42952	15052	11789
1986	0	0	0	0	30040	5640	17658	5170	5188	8940	24654	5720	12106
1987	0	0	0	0	2861	3383	819	975	2393	1560	1389	2420	1999
1988	0	0	0	0	625	2029	903	878	1802	342	766	1582	1097
1989	0	0	0	0	172	554	2621	584					983
1990		0	0	0	0	954	516	0	1455	1196			687
1991		0	0	0	250	583	0	542	0	90			244
1992		0	0	0	247	1599	1488	121	270	0			621
1993		0	0	0	3445	5338	2602	10783	14556	5352			7013
1994		0	0	0	0	514	2101	7378	5327	1738			2843
1995	0	0	0	0	263805	203328	106183		182259	9321	223910	24652	152979
1981–1988	0	0	0	24	20703	30367	55696	47591	35305	78264	28615	52614	

Table 4 Monthly abundance of age–1 longfin smelt captured in the otter trawl from 1980 to 1995. Annual abundance indices are in the far right column. Seasonal abundance indices are in the bottom row (average 1981 to 1988 monthly abundance).

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Feb–Oct*
1980		346	118	55	0	487	297	216	65	0	84	811	176
1981	39209	18305	14605	10756	3757	1309	2876	61702	352	2414	598	4738	12897
1982	4951	3804	6058	586	1818	0	216	8086	0	358	216	4136	2325
1983	433136	273635	231800	35664	30495	22944	22679	28149	1449	12185	8634	9782	73222
1984	37843	100191	12260	2859	2319	1265	1920	2396	216	7687	0	2764	14568
1985	13360	21991	7673	17102	3787	487	0	5381	1129	1287	3153	2689	6537
1986	10178	5767	789	1044	3565	939	7614	757	0	279	1642	1094	2306
1987	7735	4614	4661	13365	6131	2693	211	433	472	861	134	2183	3716
1988	19930	11562	670	2319	2753	1190	83	0	0	0	553	2041	2064
1989	1093	5251	2061	907	540	192	2496	0					1635
1990		1167	55	236	62	0	0	0	0	0			169
1991		1002	297	83	565	0	0	0	0	211			240
1992		154	446	792	379	0	216	0	0	0			221
1993		216	0	0	0	0	0	0	0	0			24
1994		6389	6461	1019	2983	1637	514	0	270	216			2165
1995	604	1139	1132	0	919	0	0		0	0	297	380	399
1981 – 1988	70793	54984	34815	10462	6828	3853	4450	13363	452	3134	1866	3678	

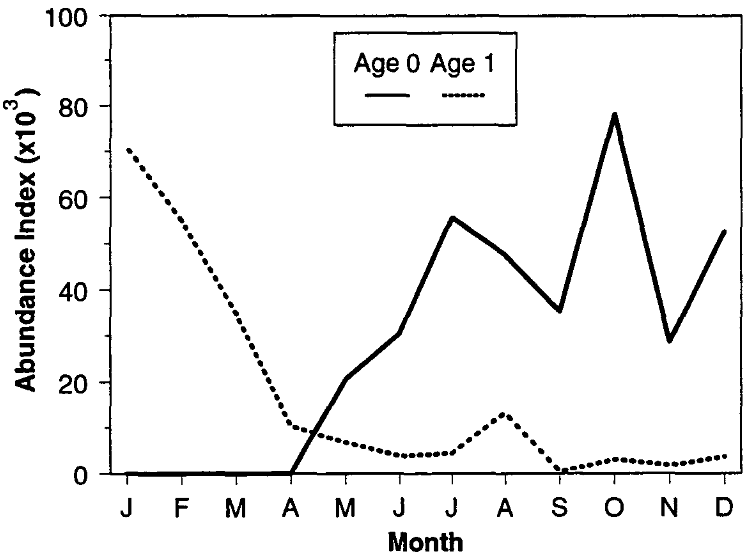

Figure 6 Seasonal abundance of age–0 and age–1 longfin smelt collected with the otter trawl. Data are monthly abundance indices averaged for 1981 to 1988.

Seasonal Abundance

Longfin smelt first reached 40 mm and began contributing to the age–0 abundance index in April (see Figure 1, Figure 6). Age–0 abundance increased in early summer as more age–0 fish reached 40 mm and then varied without trend for the rest of the year. Age–1 abundance was initially high in January, but declined rapidly through winter and early spring and less rapidly during summer, culminating in very low abundance in and after September (see Figure 6).

Annual Distribution

The annual distribution of age–0 longfin smelt was slightly broader than for larvae, extending through all regions in 10 of 16 years sampled, compared to 5 of 10 years for larvae (Table 5, compare to Figure 4). Moreover, age–0 fish were collected in Central Bay in all years and in South Bay in 13 of 16 years, indicating continued dispersal after the larval stage, particularly during low outflow years. Five of the 6 years when age–0 fish were not distributed estuary-wide were low outflow years with low abundance. Peak density of age–0 fish was in San Pablo or Central bays, except in low outflow years (1987 to 1989, and 1992, see Table 5), whereas peak density of larvae occurred in the west delta or Suisun Bay in all years except 1983 (see Figure 4).

Age–1 longfin smelt were found in all regions in 8 of 16 years (Table 6). Age–1 CPUEs were somewhat more uniform across regions than those of age–0 fish, and age–1 fish used South Bay slightly more than age–0 fish, especially in 1983 and 1984.

Table 5 Annual distribution of age–0 longfin smelt collected by the otter trawl from 1980 to 1995. Data are average February to October CPUEs by region for original stations.

Year	South Bay	Central Bay	San Pablo Bay	Suisun Bay	West Delta
1980	1	60	439	75	46
1981	<1	10	1	6	2
1982	1	206	749	264	2
1983	1	54	28	2	0
1984	<1	119	20	9	9
1985	1	29	3	14	2
1986	2	14	25	9	1
1987	<1	3	1	9	2
1988	0	2	1	1	4
1989	0	2	<1	1	4
1990	<1	1	<1	1	0
1991	0	1	<1	1	0
1992	<1	1	1	<1	2
1993	<1	15	8	2	1
1994	<1	8	<1	<1	0
1995	10	395	46	10	1
Mean	1	55	84	26	5

Table 6 Annual distribution of age–1 longfin smelt collected with the otter trawl from 1980 to 1995. Data are average February through October CPUEs by region for original stations.

Year	South Bay	Central Bay	San Pablo Bay	Suisun Bay	West Delta
1980	0	1	<1	1	<1
1981	2	37	15	25	14
1982	<1	8	2	5	<1
1983	108	90	166	8	0
1984	19	38	7	8	1
1985	3	13	10	25	3
1986	1	6	4	4	0
1987	<1	8	10	8	2
1988	1	4	4	6	2
1989	1	4	3	1	<1
1990	<1	<1	<1	<1	0
1991	1	<1	<1	1	0
1992	0	1	1	1	0
1993	0	<1	0	0	0
1994	1	7	2	1	1
1995	<1	1	1	0	1
Mean	9	13	14	6	2

Table 7 Seasonal distribution of age–0 longfin smelt collected with the otter trawl from 1981 to 1988. Data are average CPUEs by month and region for original stations.

Month	*South Bay*	*Central Bay*	*San Pablo Bay*	*Suisun Bay*	*West Delta*
January	0	0	0	0	0
February	0	0	0	0	0
March	0	0	0	0	0
April	0	0	0	0	0
May	3	22	73	71	2
June	<1	56	79	105	3
July	<1	137	155	23	1
August	0	89	181	19	3
September	1	26	177	39	1
October	1	146	263	100	15
November	1	53	57	124	21
December	25	22	257	34	5
Mean	3	46	103	43	4

Seasonal Distribution

When age–0 longfin smelt reached 40 mm in May they were present throughout the sampling area (Table 7); however, substantial use of South Bay occurred almost exclusively during high outflow years (for example, in 1980, 1982, 1983, 1986, and 1995; see Table 5). Age–0 density was usually highest in San Pablo Bay and next highest in Central and Suisun bays. A few age–0 fish were present in South Bay in summer and early fall, but the highest CPUE occurred there in December. A downstream movement in the spring and summer was indicated by increasing CPUE in Central Bay from May to July and in San Pablo Bay from May to August in conjunction with decreases in Suisun Bay and the west delta during the same period. The increased CPUE in Suisun Bay and the west delta from September to November suggests an upstream movement in fall.

Age–1 fish were present in all regions in winter (Table 8). After February or March, when CPUE was decreasing throughout the estuary, they left the west delta and then South Bay. By July, no age–1 fish were taken in South Bay or the west delta, and CPUE was much reduced in San Pablo and Suisun bays. Although CPUE in Central Bay fluctuated widely, it was usually higher there than in any other region during summer and early fall. Few age–1 fish were present in the estuary during September, but beginning in October and continuing to December, CPUE increased in all regions.

Salinity and Temperature

The distribution of age–0 longfin smelt along the salinity gradient changed seasonally. In May and June, age–0 fish were found in monthly mean salinity of 14‰ to 15‰ (Figure 7). During summer and fall, the monthly means increased to 24‰ and 28‰; in November and December, respectively, their salinity range returned to the spring levels. The upstream movement in October and November caused the downward shift in their salinity distribution. The mean temperature at which age–0 longfin smelt were found ranged from 16 to 18 °C in late spring, summer and fall, to about 11.5 °C in winter (Figure 8).

Table 8 Seasonal distribution of age–1 longfin smelt collected by the otter trawl from 1981–1988. Data are average CPUEs by month and region for original stations.

Month	*South Bay*	*Central Bay*	*San Pablo Bay*	*Suisun Bay*	*West Delta*
January	64	115	187	49	22
February	48	91	160	34	15
March	100	25	22	21	5
April	5	21	28	20	3
May	3	14	18	19	3
June	3	4	11	11	0
July	0	16	7	1	0
August	0	57	5	1	1
September	0	1	1	1	0
October	0	12	2	2	2
November	0	7	1	2	1
December	1	9	6	6	4
Mean	19	31	37	14	5

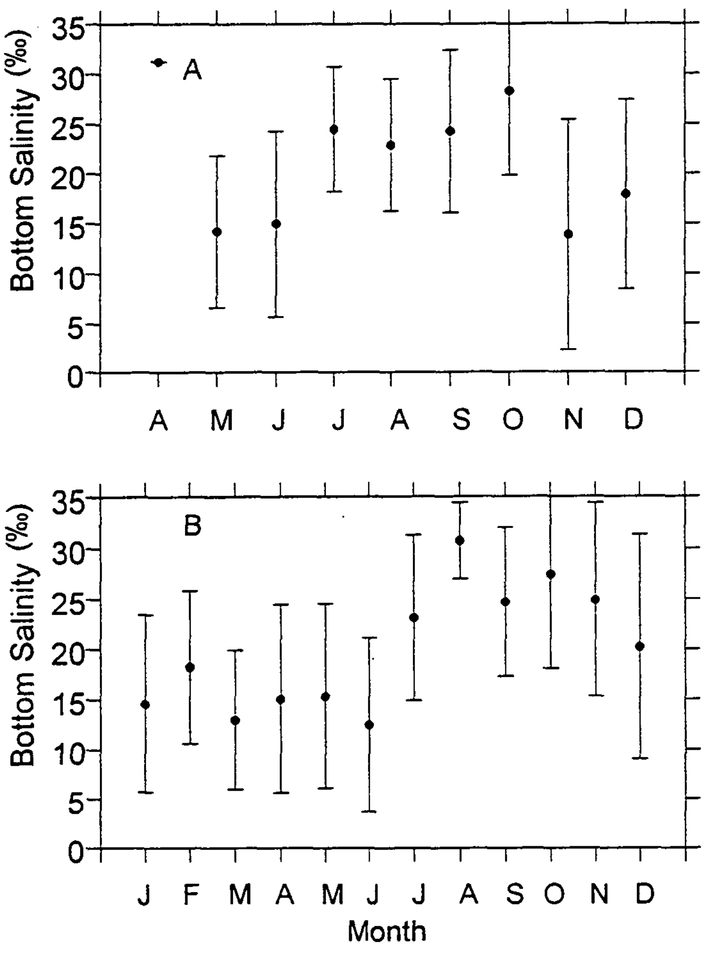

Figure 7 Salinity (‰) distributions of (A) age–0 and (B) age–1 longfin smelt collected with the otter trawl. Data are monthly mean (±1 standard deviation) CPUE-weighted bottom salinity by month and age class for 1981 to 1988.

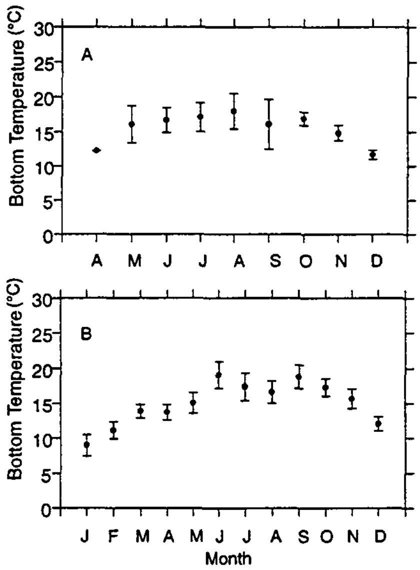

Figure 8 Temperature (°C) distributions of (A) age–0 and (B) age–1 longfin smelt collected with the otter trawl. Data are mean (±1 standard deviation) CPUE-weighted bottom salinity by month and age class for 1981 to 1988.

Age–1 longfin smelt inhabited intermediate salinities from January through June (means were 12.5‰ and 18.2‰), were found in higher salinities to a mean of 27.4‰ in October, and then at slightly reduced salinities in November and December (see Figure 7). The monthly mean temperature ranged from about 9 °C in January to about 19 °C in June (see Figure 8).

The salinity distributions of age–0 and age–1 fish were strongly influenced by the large 1982 year class during the high outflow of winter and spring 1983. There was a tendency for age–1 longfin smelt to move to euhaline waters of Central Bay during summer and early fall.

Discussion

Longfin smelt inhabit the estuary throughout their lives, though many also inhabit local coastal areas particularly during the late summer and fall (City of San Francisco Bureau of Water Pollution Control and CH2M Hill 1984; B. Sak, personal communication; S. Ralston, personal communication, see "Notes"). Longfin smelt responded to high freshwater outflow with a broader distribution of early life stages and increased abundance. The winter to early spring spawning period results in larvae hatching either during or immediately before annual peak outflows (Williams 1989, Hieb and Baxter 1993). Surface-oriented, early stage larvae are then transported downstream by winter and spring outflows (Wang 1986, Hieb and Baxter 1993, this study). These same outflows reduce salinity in Suisun, San Pablo, and occasionally Central and South bays, increasing nursery habitat for longfin smelt (Hieb and Baxter 1993, Unger 1994). Older larvae and small age–0 fish inhabit the middle and bottom strata of the water column, as evidenced by the high otter trawl catch (Wang 1986, Hieb and Baxter 1993, this study). This limits further downstream transport in spring and initially places age–0 fish in areas with bottom salinities of about 15‰ (see Figure 7). Variations in timing of spawning and in the magnitude and timing of outflows act to disperse larvae geographically.

Winter spawning and the initial salinity distribution of age–0 fish indicate that longfin smelt may avoid interspecific competition by spawning earlier in the year than most species and by inhabiting salinities mainly outside the tolerance range of potential marine and freshwater competitors. The higher the outflow, the larger the area of low and intermediate salinity habitat where longfin smelt may have a competitive advantage (Hieb and Baxter 1993, Unger 1994). Few species spawn during the winter and have planktonic larvae. Of the species with high winter larval densities, white croaker and northern anchovy larvae are distributed farther seaward in the estuary but Pacific herring larvae share the same habitats as longfin smelt larvae (CDFG 1987). The yellowfin goby is another potential competitor, yet its peak spawning is slightly later in the year. It spawns in more saline waters of Central and South bays, and its yolk sac larvae are bottom oriented before dispersing throughout the water column as post-yolk sac larvae (Wang 1986, CDFG 1987), so potential competition is delayed until late in the larval period. Of the abundant species having planktonic larvae, striped bass, prickly sculpin, shimofuri goby, arrow and cheekspot gobies, and jacksmelt spawn later in the year (Wang 1986, CDFG 1987). Thus, only Pacific herring and yellowfin goby appear to be potential competitors.

The distribution of age–1 longfin smelt appears to be influenced by high water temperatures. Age–1 longfin smelt have been collected in salinities from freshwater to sea water, but their distribution generally contracts from estuary-wide in the winter to mainly Central Bay by late summer and fall (see Table 8). Water temperatures in South Bay and the west delta generally reach their maxima between July and September and age–1 longfin smelt are rare during this period. The shift toward Central Bay during summer and reduced abundance in all regions suggests relatively high mortality, reduced catchability, or emigration to coastal habitats. Of these, emigration definitely occurs. Otter trawl sampling in the Gulf of the Farallones routinely captures longfin smelt in fall, and has captured them occasionally in spring, especially during years of high abundance (B. Sak, personal communication, see "Notes"). Size frequency information indicates that both age–0 and age–1 fish can be found in the Gulf of the Farallones, but age–1 fish are more frequently collected there. The National Marine Fisheries Service conducts a spring midwater trawl survey to assess juvenile rockfish abundance off the central California coast. In the course of 11 spring surveys (1983 to 1993), 32 longfin smelt were identified from 1 tow in June 1984 off the Marin County coast (S. Ralston, personal communication, see "Notes"). Thus, the open coast can provide some habitat for longfin smelt, but their principal habitat remains in the estuary.

Night Smelt

Introduction

The night smelt, *Spirinchus starksi*, is a pelagic marine fish which ranges from Point Arguello, California, northward to Shelikof Bay, southeast Alaska (Dryfoos 1965). It spawns at night in the surf over coarse sand from January through September (Fitch and Lavenberg 1971, Frey 1971). Eggs are demersal and adhesive, and incubation takes about 2 weeks (Fitch and Lavenberg 1971). Night smelt larvae were collected off Newport, Oregon, in June and July, and young juveniles were collected off Moolack Beach, Oregon, in October (Hearne 1983). It reaches a maximum length of 139 mm (Miller and Lea 1972) and is an important commercial and sport fish (Fitch and Lavenberg 1971). Due to overlapping preferences in spawning habitat and timing, night smelt and surf smelt are frequently caught together in the surf using A–frame dip nets. The night smelt is sold for human consumption and to oceanaria for consumption by fish, birds, and mammals (Fitch and Lavenberg 1971, Moyle 1992).

Methods

Data from the midwater trawl, otter trawl, and beach seine were combined for length frequency (mm FL). Abundance and distribution were based on total catch.

Results

Only 194 night smelt were collected in sampling between 1980 and 1995 (see Table 1). These fish ranged in size from 49 to 150 mm FL (Table 9). Of these, 159 came from 1 midwater trawl tow at station #216 in Central Bay in July 1980. Five fish from this tow were above the maximum length of 139 mm reported by Miller and Lea (1972): 3 were 140 mm and 2 were 150 mm. During all years only 2 additional night smelt were collected in July and none were taken from August to November. After the large 1980 catch, most of the other night smelt were collected in 1983 (6), 1992 (5) or 1993 (12). Excluding the large 1980 catch, 74% of the fish (*n* = 35) were collected between February and April, and abundance was highest in Central Bay: South Bay = 12, Central Bay = 15, San Pablo Bay = 8.

Table 9 Length frequency (mm FL) by month for night smelt collected with the beach seine, midwater trawl, and otter trawl from 1980 to 1995

Length	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Total*
40 - 49	1						1						2
50 - 59				2								1	3
60 - 69				5									5
70 - 79	1	2	1										4
80 - 89			1	3		1							5
90 - 99		2	1		2	1	2						8
100 - 109		1	1	1			14						17
110 - 119		1	3				25						29
120 - 129		2			1		53						56
130 - 139							61						61
140 - 149							3						3
150 - 159							2						2
Total	2	8	7	11	3	2	160	0	0	0	0	1	194

Discussion

The night smelt is an uncommon visitor to the estuary. However, it is commonly collected just outside the estuary in the Gulf of the Farallones (B. Sak, personal communication, see "Notes"). There was some question about the species identification of the extremely high catch in July 1980. The large number of fish and the collection of 5 fish larger than the known maximum size leads to speculation that these fish were misidentified longfin smelt. However, age–1 and older longfin smelt were generally not collected in high numbers in July, so the question persists.

The relative rarity of night smelt in the estuary combined with its similarity to the more abundant longfin smelt makes it probable that some night smelt were overlooked among large catches of longfin smelt. The relatively high night smelt catches in 1992 and 1993 occurred when longfin smelt abundance was low and interest in smelt was high due to a petition for listing the longfin smelt under the Endangered Species Act (USFWS 1993).

Delta Smelt

Introduction

The delta smelt is endemic to the delta, Suisun Marsh, Suisun Bay, and adjoining sloughs in the lower Sacramento and San Joaquin rivers. During periods of high freshwater outflow it occasionally ventures into San Pablo Bay (Ganssle 1966). It is presently not harvested from the estuary by sport or commercial fishers, though it once was (Moyle 1992).

Delta smelt mature at about 1 year, at 55 to 70 mm (Moyle and others 1992). In winter and spring, prespawning adults appear to concentrate in eastern Suisun Bay and the west delta (Ganssle 1966, Moyle 1976), and then disperse into dead-end sloughs and delta channels to spawn (Radtke 1966). Moyle (1976) collected ripe fish from December through April, mostly in February and March. Wang (1991) observed mature adults on Central Valley Project fish screens from late December to early April, but believed that spawning took place between mid-February to late June or early July, with the peak in late April and early May. Most delta smelt die after spawning, but the presence of a few adult fish later in the year suggests that some may live to spawn again at age 2 (Moyle 1976).

Delta smelt spawn mainly in freshwater, but some spawning may occur in slightly brackish water (Wang 1991). Eggs are demersal and adhesive, attaching singly to plants or other firm substrates (Moyle 1976). Larvae are about 5.5 to 6.0 mm TL at hatching and are planktonic (Wang 1986). Stevens and others (1990) hypothesized that, in "normal" outflow years, freshwater outflow transports larval delta smelt to the entrapment zone where growth and survival are presumably maximized because of the abundance of zooplankton (Siegfried and others 1979). Juveniles appear to move to the western delta and Suisun Bay during summer (Messersmith 1966, Radtke 1966, Wang 1991, Sweetnam and Stevens 1993). This movement may be related to the location of the entrapment zone, which moves from year to year depending on outflow (Moyle and others 1992, Sweetnam and Stevens 1993). The California Department of Water Resources and U.S. Bureau of Reclamation (1994) analyzed the salinity distribution of delta smelt and found that abundance peaks at 0.2‰ to 1.0‰, immediately upstream of the entrapment zone.

Growth is rapid; fish reach 40 mm by June (Wang 1991) and 50 to 70 mm by December (Erkkila and others 1950). The delta smelt is reported to reach a maximum size of 126 mm (Stevens and others 1990). Sampling by Radtke (1966) indicates that delta smelt are surface-oriented as juveniles and adults. Recent reviews of delta smelt biology and ecology can be found in Moyle and others (1992), Sweetnam and Stevens (1993) and in California Department of Water Resources (1994).

Methods

Delta smelt mature soon after the first of the year (Moyle 1976, Wang 1991); therefore, fish caught after 1 January were classified as adults. To separate age classes, length frequency data (mm FL) from the midwater trawl were combined into 5-mm intervals and inspected to locate numerical minima. At the minima, cutoff lengths were selected to provide the best separation of age–0 and adult fish. Cutoff lengths for separating age–0 from adult fish were as follows: 40, 50, 50, 50, 50, 55, 65, 70, 75, 80, 80, and 80 mm FL for January through December, respectively. Apparent growth rate estimates were based on monthly shifts in length modes.

Annual larval abundance was the mean CPUE (number per 1000 m^3 filtered by the plankton net) for Suisun Bay and west delta regions only, and for the months March to July. Abundance in 1989 was based upon incomplete sampling. Seasonal abundance was the mean monthly CPUE by life stage (that is, yolk sac, post-yolk sac, and age 0) for Suisun Bay and west delta stations from 1980 to 1988. Annual distribution was the mean CPUE by region for March to July. No correction was made for no sampling done in June and July 1989.

Only delta smelt ≥30 mm FL were used to calculate age–0 CPUE. For the midwater trawl, CPUE was calculated as the number of fish per 10,000 m^3 of water filtered. Annual abundance indices were based upon June to October and February to June periods for age–0 and adult fish, respectively. For age–0 fish, no indices were calculated for 1989 or 1994 due to insufficient data and the 1995 index was based upon incomplete sampling (no sampling in August, see Methods chapter, Table 1). For adults, no indices were calculated in 1994 and 1995 due to missing data. Annual distribution was calculated as the average CPUE by region for June through October and February through August for age–0 and adult fish, respectively. Seasonal abundance and distribution analyses were based upon 1981 to 1988 data when 12 months were sampled. All salinity and temperature statistics were calculated from average water column measurements and weighted by CPUE. Again, only 1981 to 1988 data were used.

Results

Length

There was little overlap in the length frequency distributions of age–0 and adult delta smelt, which allowed accurate separation of year classes (Figure 9). Few delta smelt <30 mm were caught by any gear and all were caught before September. Length mode shifts indicated that age–0 fish grew 5 to 10 mm per month from June to October. Little growth occurred from October through the next April, then growth increased to about 5 mm per month between April and July. Age–0 delta smelt grew to 50 to 78 mm FL by December. The capture of 3 delta smelt >100 mm indicated that some survived to age 2, or older in the case of the 122 mm fish (see Figure 9).

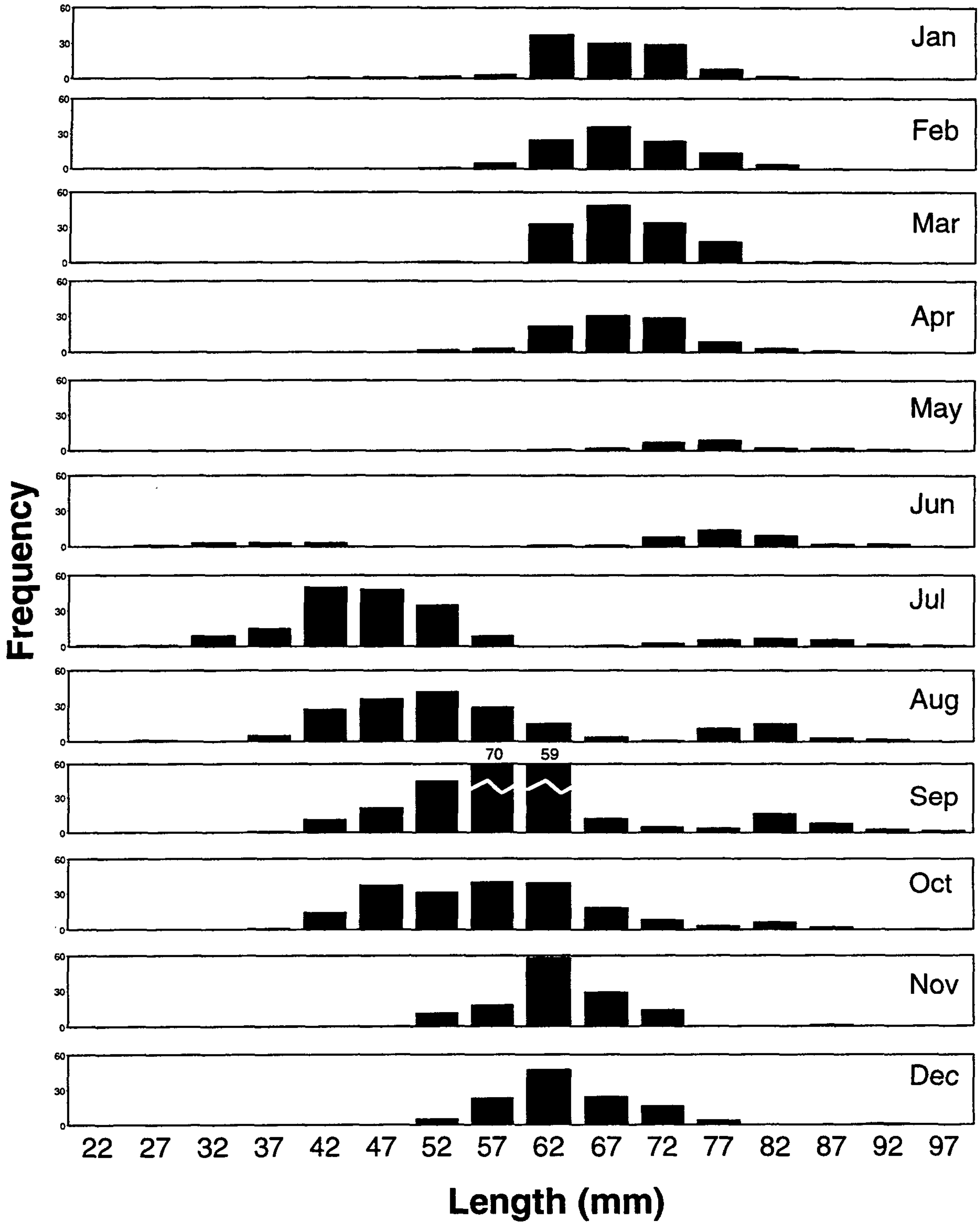

Figure 9 Length frequency (mm FL) distribution by month for delta smelt collected with the midwater trawl from 1980 to 1995. Fish under the 30 mm minimum length were collected between 1980 and 1989, but are not included in CPUE calculation. A fish 122 mm in length caught in September was not included.

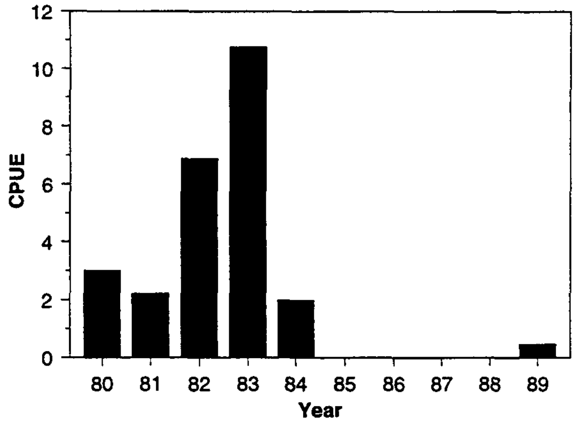

Figure 10 Annual abundance of delta smelt larvae collected with the plankton net from 1980 to 1989. Data are mean March to July CPUE for Suisun Bay and the west delta only. No correction was made for not sampling in June and July 1989.

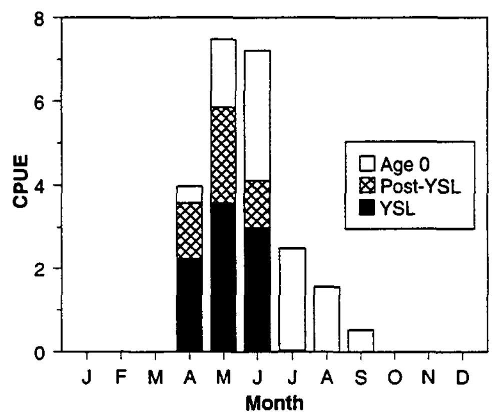

Figure 11 Seasonal abundance of delta smelt by life stage for fish collected with the plankton net from 1980 to 1988. Data are mean CPUE by month and life stage for Suisun Bay and the west delta.

The high catch in the midwater trawl compared to the otter trawl (see Table 1) indicates most delta smelt were distributed at mid-depth and surface, and not on the bottom.

Abundance and Distribution of Larvae

Delta smelt larvae were collected each year from 1980 to 1984, and again in 1989 (Figure 10). Except for 1984, when high flows occurred early and 1986 when flows were extremely high, larval abundance was greater in high rather than in low outflow years. No larvae were collected in the low outflow years 1985, 1987 and 1988, or in the extremely high outflow year 1986 (see Figure 10). Larvae were collected from April to July, with a peak in May (Figure 11). Larval delta smelt were never caught downstream of Suisun Bay and larval densities in the west delta were always as high or higher than those in Suisun Bay (Figure 12).

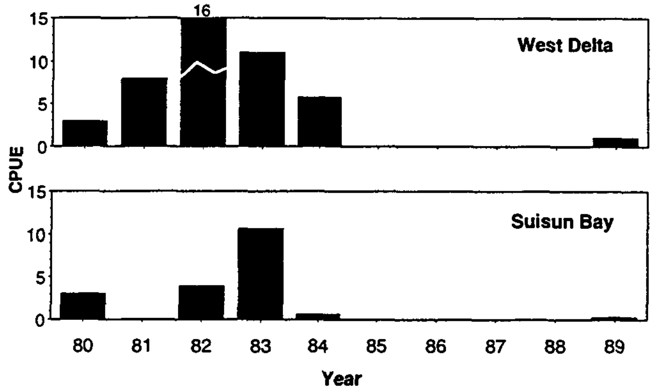

Figure 12 Annual distribution of delta smelt larvae collected with the plankton net from 1980 to 1989. Data are average March to July CPUE by region. Larvae were only collected in the west delta and Suisun Bay.

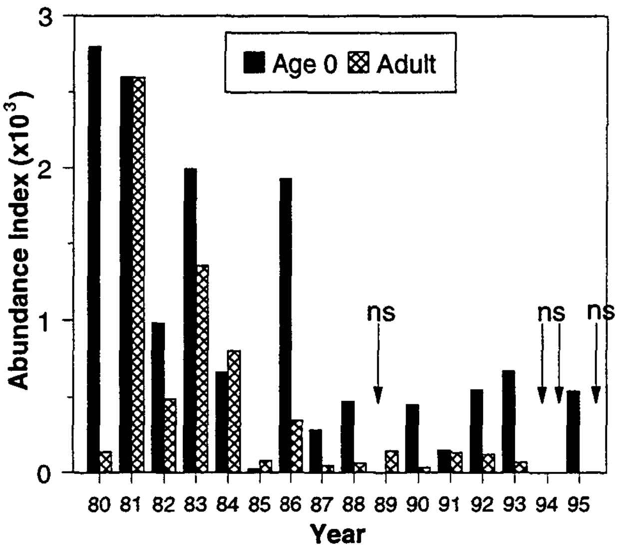

Figure 13 Annual abundance of age–0 and adult delta smelt collected with the midwater trawl from 1980 to 1995. Due to insufficient sampling, no age–0 indices were calculated for 1989 or 1994 and no adult indices were calculated for 1994 and 1995.

Abundance and Distribution of Age–0 Fish and Adults

Annual Abundance

Age–0 delta smelt abundance varied from a high of 2,799 in 1980 to a low of 24 in 1985 (Figure 13, Table 10). Abundance indices varied widely from year to year, but after 1986, they were never more than 25% of the maximum index and were generally lower than pre–1986 indices (see Figure 13). There was no indication of a relationship between abundance and freshwater outflow.

Adult abundance indices varied from a high of 2,594 in 1981 to a low of 34 in 1990 (see Figure 13, Table 11). Similar to those of age–0 fish, adult indices varied widely from year to year and abundance was generally lower after 1986 (see Figure 13). Although adult abundance was significantly correlated with the abundance of age–0 fish in the previous year ($r = 0.635$, $P < 0.05$, $n = 11$), variation in age–0 abundance explains only 40% of the variation in adult abundance.

Table 10 Monthly abundance of age–0 delta smelt captured in the midwater trawl from 1980 to 1995. Annual abundance indices are in the far right column. Seasonal abundance indices are in the bottom row (average 1981 to 1988 monthly abundance).

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Jun–Oct*
1980		0	0	0	0	0	4127	2712	4913	2245	4028	464	2799
1981	0	0	0	0	0	59	810	4198	6269	1661	825	2471	2599
1982	0	0	0	0	0	118	2535	910	625	733	531	1794	984
1983	0	0	0	0	0	0	0	413	1415	8147	1120	285	1995
1984	0	0	0	0	0	0	177	649	2158	346	633	566	666
1985	0	0	0	0	0	0	118	0	0	0	0	3467	24
1986	0	0	0	0	0	0	169	3610	3170	2689	700	1138	1928
1987	0	0	0	0	0	0	1099	0	313	0	4482	0	282
1988	0	0	0	0	0	0	0	0	1607	761	761	0	474
1989	0	0	0	0	0	0	372	59					144
1990		0	0	0	0	0	0	1064	861	338			453
1991		. 0	0	0	0	0	0	254	85	397			147
1992		0	0	0	0	423	2327	0	0	0			550
1993		0	0	0	0	0	1441	236	1035	651			673
1994		0	0	0									
1995				0	0	0	756		1192	228	1230	2679	544
1981–1988	0	0	0	0	0	22	614	1223	1945	1792	1132	1215	

Table 11 Monthly abundance of adult (age–1) delta smelt captured in the midwater trawl from 1980 to 1995. Annual abundance indices are in the far right column. Seasonal abundance indices are in the bottom row (average 1981 to 1988 monthly abundance).

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Feb–Jun*
1980		169	337	0	169	0	177	59	169	0	0	0	135
1981	2565	5361	2963	1720	321	2604	912	0	769	59	0	0	2594
1982	4301	992	707	379	261	118	202	59	85	0	0	118	491
1983	2494	933	4881	671	85	226	118	825	825	0	118	0	1359
1984	167	574	1638	1584	236	0	118	118	877	287	0	0	806
1985	592	169	169	0	0	59	144	338	169	169	0	0	79
1986	254	177	1405	0	0	169	0	0	0	0	0	0	350
1987	676	0	118	118	0	0	592	0	85	0	0	0	47
1988	0	254	59	0	0	0	0	0	85	0	0	0	63
1989	85	85	0	0	372	254	0	169					142
1990		0	169	0	0	0	0	118	0	0			34
1991		431	169	59	0	0	85	254	0	0			132
1992		144	287	0	0	169	59	287	0	0			120
1993		169	177	0	0	0	59	59	0	0			69
1994		177	438	59									
1995				59	59	0	381		169	0	0	0	
1981–1988	1381	1058	1493	559	113	397	261	168	362	64	15	15	

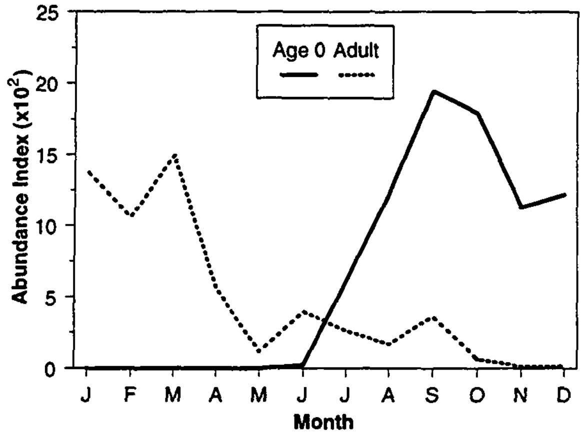

Figure 14 Seasonal abundance of age–0 and adult delta smelt collected with the midwater trawl sampling. Data are monthly abundance indices averaged from 1981 to 1988.

Seasonal Abundance

Age–0 fish first reached the 30 mm minimum length in June and continued to grow to size through September (see Figure 9). Their seasonal abundance also increased to a peak in September, then declined through the rest of the year (Figure 14). From year to year, the month of peak abundance varied from July to December (see Table 10). During several low outflow years (1985, 1987, 1988, and 1992) age–0 fish were not collected on 1 or more surveys between August and December (see Table 10).

Adult delta smelt abundance was initially high in January and remained so through March, before declining and fluctuating at a lower level from May to September (see Figure 14). After September, adult delta smelt were very rare. Adults were absent on 1 or more surveys between January and August in every year except 1982 and 1983 (see Table 11).

Annual Distribution

Age–0 delta smelt were collected from the west delta to San Pablo Bay (Table 12). They were captured in San Pablo Bay only during the high outflow years of 1983, 1993 and 1995. In several low outflow years (1987, 1988, and 1991), age–0 fish were rare or absent in the catch from Suisun Bay. Age–0 CPUE was generally higher in Suisun Bay before 1985 and in the west delta after 1985 (see Table 12).

Similar to age–0 fish, adult delta smelt were collected from the west delta to San Pablo Bay (Table 13). Adults were only collected in San Pablo Bay during the high outflow years 1982, 1983, 1984 and 1986, but were present in Suisun Bay and the west delta in all years. During the aforementioned high outflow years and 1993, adult CPUE for Suisun Bay was about equal to or higher than CPUE for the west delta, whereas during low outflow years CPUE was highest in the west delta (see Table 13).

Table 12 Annual distribution of age–0 delta smelt collected with the midwater trawl from 1980 to 1995. Data are mean June to October CPUE by region. Sampling was insufficient in 1989 to calculate an index, no sampling was conducted in 1994 and CPUE in 1995 was based upon data from 4 of 5 months (no sampling in August).

Year	*South Bay*	*Central Bay*	*San Pablo Bay*	*Suisun Bay*	*West Delta*
1980	0	0	0	5.18	1.53
1981	0	0	0	3.58	3.60
1982	0	0	0	1.80	0.53
1983	0	0	1.70	1.13	0
1984	0	0	0	1.13	0.53
1985	0	0	0	0.05	0
1986	0	0	0	1.07	5.60
1987	0	0	0	0.03	1.07
1988	0	0	0	0	1.87
1989	---	---	---	---	---
1990	0	0	0	0.35	1.13
1991	0	0	0	0.03	0.53
1992	0	0	0	0.70	0.87
1993	0	0	0.03	0.95	0.80
1994	---	---	---	---	---
1995	0	0	0.03	0.47	1.34

Table 13 Annual distribution of adult delta smelt collected with the midwater trawl from 1980 to 1995. Data are mean February through August CPUE by region. Sampling was not sufficient to allow calculation of annual distribution for 1994 and 1995.

Year	*South Bay*	*Central Bay*	*San Pablo Bay*	*Suisun Bay*	*West Delta*
1980	0	0	0	0.17	0.19
1981	0	0	0	2.15	3.67
1982	0	0	0.02	0.71	0.14
1983	0	0	0.54	1.20	0.33
1984	0	0	0.29	0.64	0.24
1985	0	0	0	0.04	0.43
1986	0	0	0.04	0.29	0.33
1987	0	0	0	0.07	0.33
1988	0	0	0	0.02	0.14
1989	0	0	0	0.04	0.43
1990	0	0	0	0.04	0.10
1991	0	0	0	0.07	0.43
1992	0	0	0	0.11	0.33
1993	0	0	0	0.09	0.10
1994	---	---	---	---	---
1995	---	---	---	---	---

Table 14 Seasonal distribution of age–0 delta smelt collected with the midwater trawl. Data are mean CPUE by month and region for 1981 to 1988.

Month	*South Bay*	*Central Bay*	*San Pablo Bay*	*Suisun Bay*	*West Delta*
January	0	0	0	0	0
February	0	0	0	0	0
March	0	0	0	0	0
April	0	0	0	0	0
May	0	0	0	0	0
June	0	0	0	0.05	0
July	0	0	0	0.88	0.79
August	0	0	0	1.36	2.29
September	0	0	0	1.86	4.21
October	0	0	1.06	1.34	0.96
November	0	0	0	0.88	2.83
December	0	0	0.02	1.20	2.50
Mean	0	0	0.09	0.63	1.13

Table 15 Seasonal distribution of adult delta smelt collected the midwater trawl. Data are mean CPUE by month and region for 1981 to 1988.

Month	*South Bay*	*Central Bay*	*San Pablo Bay*	*Suisun Bay*	*West Delta*
January	0	0	0.10	1.69	1.96
February	0	0	0.09	1.51	0.83
March	0	0	0.63	1.33	1.29
April	0	0	0.03	0.89	0.46
May	0	0	0	0.13	0.21
June	0	0	0.02	0.14	1.25
July	0	0	0	0.17	0.71
August	0	0	0	0.27	0.17
September	0	0	0	0.45	0.58
October	0	0	0	0.05	0.17
November	0	0	0	0.03	0
December	0	0	0	0.03	0
Mean	0	0	0.07	0.56	0.64

Seasonal Distribution

Age–0 delta smelt ≥30 mm were first caught in Suisun Bay in June and in the west delta in July (Table 14). They remained in Suisun Bay and the west delta throughout the year. The presence of age–0 fish in San Pablo Bay resulted from a broader distribution of fish in high outflow years, rather than from migration into the bay.

Adults were captured in Suisun Bay and the west delta from January through early fall (Table 15). By late fall, the few adults remaining were in Suisun Bay. Adults were in San Pablo Bay only during the winter and spring of high outflow years; by April, few adult delta smelt remained in San Pablo Bay.

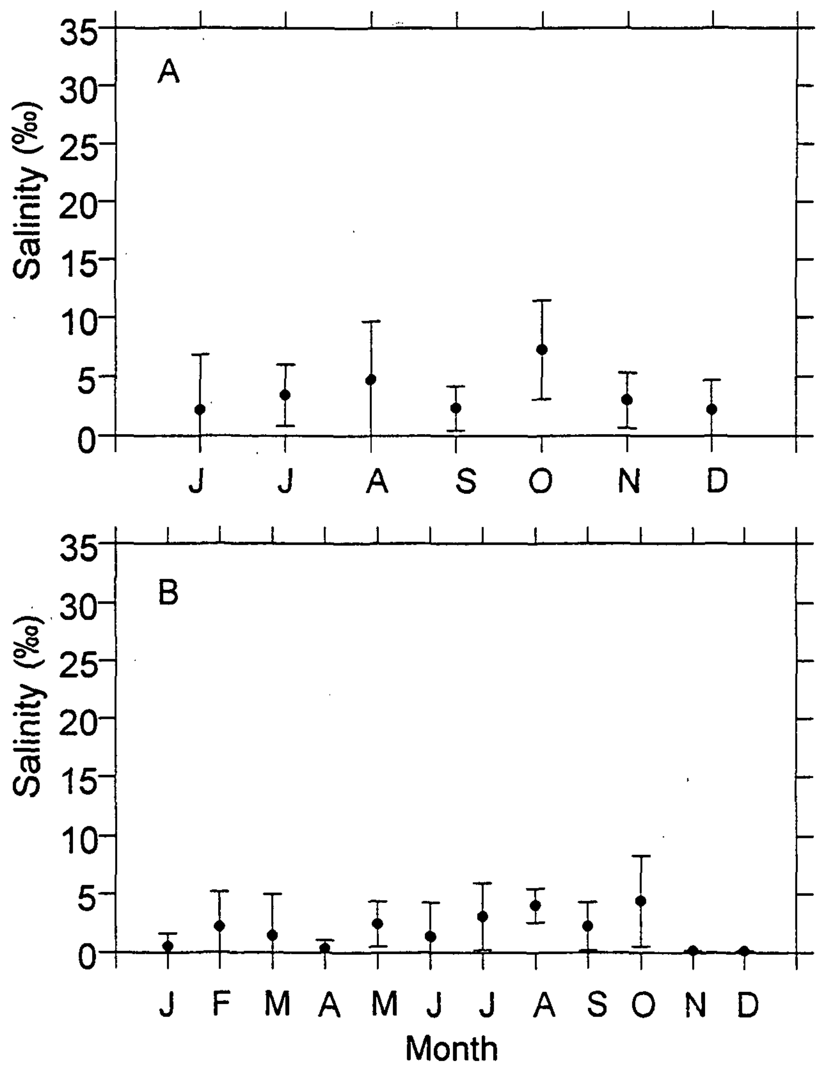

Figure 15 Salinity (‰) distributions of (A) age–0 and (B) adult delta smelt collected with the midwater trawl. Data are monthly mean ±1 standard deviation CPUE-weighted salinity by month and age class for 1981 to 1988.

The seasonal salinity distribution of age–0 delta smelt was fairly stable—the means ranged from about 2‰ to 7‰ (Figure 15). A slight increase occurred during late summer and fall. Age–0 fish were captured in salinities as high as 13.9‰. For adults the means ranged from freshwater to about 5‰. The salinity range of adults increased slightly and irregularly from January to October. Adults were captured in salinities as high as 18.4‰.

The temperature distributions of both age groups were very similar during months when both were present (Figure 16). For both age groups, July to September means ranged from about 20 to 23 °C. Maximum temperatures were 22.8 and 23.1 °C for age–0 and adult fish, respectively.

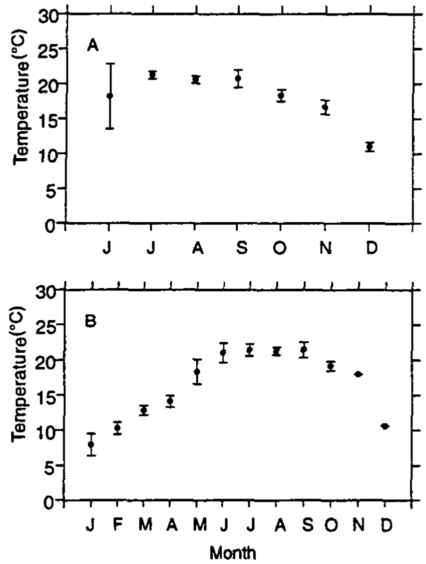

Figure 16 Temperature (°C) distributions of (A) age–0 and (B) adult delta smelt collected with the midwater trawl. Data are monthly mean ±1 standard deviation CPUE-weighted temperature by month and age class for 1981 to 1988.

Discussion

Except for a short upstream spawning migration, delta smelt spend their entire lives in tidal fresh and brackish waters of the delta, Suisun Bay, and Suisun Marsh (Moyle 1976), and appear to have mechanisms for maintaining their position. Unlike longfin smelt, delta smelt larvae do not develop an air bladder until they are relatively large, 16 to 18 mm TL (Wang 1991). The lack of a well-developed air bladder probably hinders their ability to control their position in the water column. Their buoyancy would facilitate transport downstream and larvae might be lost if high outflows pushed them into a strong, salinity-stratified area. To compensate, spawning should take place during or after high outflow events in areas where larvae might not be immediately swept away. As flows subside, "entrapment zone" circulation should act to limit the downstream transport of larvae until they are large enough to control their position (Peterson and others 1975). This hypothesis was supported by the distribution of delta smelt larvae, which was upstream of the study area in most low outflow years (Wang 1991, see Figure 10). Moderately high spring flows in the otherwise low outflow year of 1989 led to the capture of delta smelt larvae in the west delta and Suisun Bay. In comparison, early hatching and buoyant longfin smelt larvae were distributed into San Pablo Bay, occasionally farther, in almost all low outflow years (see Figure 4). The ratio of juveniles to larvae is another indication of the relative abundance of larvae in the water column and their susceptibility to downstream transport. If both life stages are pelagic, then larvae should far outnumber juveniles. This was the case for longfin smelt, but not for delta smelt: the longfin smelt juvenile to larvae ratio in the plankton net was 1:20; the delta smelt ratio was 2:3 (see Table 1). This low ratio for delta smelt suggests that most of their larvae rear in areas outside the main river channels sampled by the plankton net or upstream of the study area. Larvae rearing in dead-end sloughs or shallow water areas would be less susceptible to downstream transport that might carry them beyond suitable habitat. Another equally plausible interpretation of the low delta smelt ratio is that larval delta smelt were not accurately identified and separated from the large number of longfin smelt larvae caught. Consistent and accurate identification of longfin smelt and delta smelt larvae did not occur until about 1991 (Wang 1991).

Delta smelt abundance indices may have been biased in low outflow years because a larger part of the population was upstream from the sampling area. An upstream shift in spawning in dry years could have been responsible for the absence of larvae in plankton samples after 1984 (with the exception of 1986, a wet year). Adults spawned upstream from the study area during the drought based on the distribution of larvae in other studies (Wang 1991). The upstream distribution shift for age–0 and adult fish during the 1987–1992 drought (see Tables 12 and 13) also was detected by the CDFG fall midwater trawl survey (Sweetnam and Stevens 1993).

Delta smelt appear suited for life in tidal fresh and brackish water. Their recently observed "stroke and glide" preferred swimming motion is very energy efficient (Swanson and others 1997) and suited to a fish that follows the tide to remain in a preferred salinity range (Sweetnam and Stevens 1993). In the laboratory, delta smelt tolerated temperatures from 7 to 8 °C above acclimation temperature to a maximum of 28.9 °C and chronic exposure (12 h) to salinities from 0‰ to 19‰ (Swanson and Cech 1995). These tolerances were beyond the salinity and temperature maxima observed by the Bay Study.

Surf Smelt

Introduction

The surf smelt, or day smelt, ranges from Long Beach, California, northward to Prince William Sound, Alaska (Miller and Lea 1972). It is a minor component of both the sport and commercial marine fishery catch in the San Francisco Bay area (Oliphant and others 1990), but from central California northward, surf smelt are taken by recreational fishers in greater numbers than any other species, and have even ranked among the top species (Frey 1971).

Although surf smelt are not commonly collected in San Francisco Bay (see Table 1), estuaries provide an important habitat elsewhere within their range (Emmett and others 1991) and San Francisco Bay may be an important habitat for the local population. Surf smelt are more common north of the Bay area (Frey 1971, Moyle 1992).

Spawning in California takes place between March and October with occasional spawns at other times (McAllister 1963, Hearne 1983, Moyle 1992); however, Wang (1986) reported that spawning appeared limited to fall and winter months in the San Francisco Bay area. In Puget Sound, Penttila (1978) observed different local stocks spawning at different times and that females were capable of spawning more than once per season; thus, some spawning occurred all year.

Eggs are demersal and adhesive and attach to sand grains, shell or rock (Hart and McHugh 1944, Penttila 1978). Hatching occurs in 2 to 4 weeks depending upon temperature and wave action (Penttila 1978, Moyle 1992). Newly hatched larvae are about 3 mm long. Little is known of their life history between hatching and maturity. Surf smelt reach maturity between age 1 and 3; males predominate among 1-year-old spawners (Penttila 1978). Few individuals appear to live beyond age 3 (Penttila 1978). They reach a maximum size of about 305 mm in California, but only 222 mm in British Columbia (Hart 1973). Such large individuals are probably 3- to 5-year-old females, as females are larger than males (Penttila 1978).

Methods

Length data (mm FL) from the beach seine, otter trawl, and midwater trawl catches were combined into 10 mm groups to determine which age groups used the estuary and when they were present. Spawning was assumed to occur about 3 months prior to the capture of 30 to 40 mm fish. May, the 1st month of assumed spawning, was selected as the birth month of all fish. Age–0 fish were classified as age–1 after April 30. Cutoff lengths for separating age–0 from age–1+ fish were as follows: 50, 60, 65, 70, 75, 80, 85, 90, 100, 110, 120, and 130 for June through May, respectively. Length data also were separated by gear type to investigate the use of inshore areas (beach seine) and offshore areas (otter and midwater trawls). Annual abundance and distribution were based upon beach seine catch by station and year. No corrections were made for varying effort between regions or years. Effort was very similar from year to year, but between regions effort varied by the number of stations present (see Figure 2 in the Methods chapter).

Results

Only 2 larvae were identified from plankton samples and both were captured in Central Bay, 1 in November 1980 and the other in March 1986. Surf smelt caught in the estuary ranged from 15 to 235 mm FL, but most were between 30 and 100 mm (Table 16). Small age–0 fish (<40 mm) were collected from August to March (see Table 16). Age–0 fish appeared to grow rapidly from November to May, most reaching 70 to 90 mm FL before they dropped out of the catch between May and July as age–1 fish. From July to January, very few age–1 fish (>80 mm, assuming a May hatch date) were collected (see Table 16). Beginning in January or February and extending through June, a few age–1 fish were caught. Again, these fish disappeared from the catch by July.

Table 16 Length frequency (mm FL) by month for surf smelt collected with the beach seine, midwater trawl, and otter trawl from 1980 to 1995. A single fish at 235 mm in May is not included.

Length	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Total*
10 - 19											1		1
20 - 29	1	1						1		1			4
30 - 39	7		1					17	7	19	25	28	104
40 - 49	33	5	9	3				5	1	23	23	117	219
50 - 59	5	6	15	6		1					2	10	45
60 - 69	1	4	8	14	4						2	3	36
70 - 79	1	2	8	17	19	5					1		53
80 - 89	1		7	18	23	9		1					59
90 - 99		1	3	8	6	1	1						20
100 - 109				5	1								6
110 - 119				4					2			2	8
120 - 129				1	1							1	3
130 - 139			1										1
140 - 149		2		2			1				1		6
150 - 159			1	3	2							1	7
160 - 169	1	1	1		2	2							7
170 - 179						1							1
Total	50	22	54	81	59	19	2	24	10	43	55	162	581

Table 17 Length frequency distribution of surf smelt collected with the midwater trawl, otter trawl, and beach seine from 1980 to 1995. One 235 mm fish from the midwater trawl catch is not included.

Length	*Midwater*	*Otter*	*Beach Seine*	*Total*
10 - 19			1	1
20 - 29			4	4
30 - 39			104	104
40 - 49		1	218	219
50 - 59		1	44	45
60 - 69	9	1	26	36
70 - 79	13		40	53
80 - 89	10	2	47	59
90 - 99	8	3	9	20
100 - 109	2	1	3	6
110 - 119	6	1	1	8
120 - 129	2		1	3
130 - 139	1			1
140 - 149	6			6
150 - 159	6	1		7
160 - 169	7			7
170 - 179	1			1
Total	72	11	498	581

Most of the total catch was collected with the beach seine and was composed of age–0 fish (Table 17). A few larger age–0 fish and virtually all the age–1 and older fish were collected in the midwater trawl.

Age–0 surf smelt were most abundant in 1982 (Table 18). Annual catch was moderate in the remaining years from 1981 to 1985, and low in 1980 and 1986. From 1981 through 1986, the annual catch was composed primarily of age–0 fish collected from January to June (that is, spawned in the previous year). In 1980, beach seining was only conducted from August to December, so no 1979 year class fish were collected.

Table 18 Surf smelt abundance (annual catch) by region and station for fish collected with the beach seine from August 1980 through December 1986. Station #274 in Central Bay was not sampled after 1981.

Region	*Station #*	*1980*	*1981*	*1982*	*1983*	*1984*	*1985*	*1986*	*Station Total*	*Region Total*
South	169		2	1	1				4	39
	170		1	13				1	15	
	171	3		3					6	
	172		1	1					2	
	178			1	1				2	
	179		1	6	1			2	10	
Central	173		2	48		2	33		85	402
	177		1		2				3	
	251		5	25	4	2	17		53	
	262		22				2		24	
	263		1	4	3	29	1		38	
	264		3	4	1		3		11	
	265			4	2	2	3		11	
	266			1					1	
	274		2						2	
	275		4	3	1			5	13	
	276			37	4	1		2	44	
	352		22	88	2	1	3	1	117	
San Pablo/ Carquinez Strait	353		10		4		2	1	17	57
	354			8	6	1	1		16	
	367		1	1	4				6	
	368	1	5	3	6		1	1	17	
	456						1		1	
Total		4	83	251	42	38	67	13	498	

Otter and midwater trawl sampling was not done during many fall and winter months from 1989 through 1994 (otter trawling in all months was reinstated in 1995, but caught few surf smelt), making it impossible to provide a reliable index of abundance from these gear types. Nevertheless, no surf smelt were caught in either trawl from 1993 through 1995. The combined annual catch from the midwater and otter trawls ranged from 1 to 29 fish from 1980 through 1992.

In the beach seine, most surf smelt were caught in Central Bay, but sizeable numbers were also collected in both South and San Pablo bays (see Table 18). One individual was collected as far upstream as Carquinez Strait, and in trawling gear, 3 were collected in Suisun Bay.

Discussion

Surf smelt appear to use beaches within the estuary as an extension of their juvenile foraging area. The collection of fish <60 mm almost exclusively in the beach seine indicates that shallow, protected water may be important habitat for juvenile surf smelt. The lack of surf smelt catch during the summer and limited catch during early fall months indicates that the estuary may not be suitable habitat during these periods, possibly because of high temperatures. Bays and estuaries provide habitat for surf smelt throughout their range, but residence times appear to increase farther north. In Yaquina Bay, juvenile surf smelt (37 to 87 mm TL) ranked 4th in abundance in intertidal areas, and as in San Francisco Bay, they were collected primarily between November and May (Bayer 1981). Farther north in the Columbia and Squamish estuaries, surf smelt are residents all year (Levy and Levings 1978, Bottom and others 1984). In the Columbia Estuary, surf smelt are most abundant during the summer (Bottom and others 1984), opposite of the winter-spring high abundance period found in the San Francisco Estuary (see Table 16), again suggesting temperature is controlling distribution.

The relative lack of larvae and small juveniles (<30 mm) suggests that little or no spawning takes place in the estuary. This conclusion is supported by the relative lack of reproductive-sized fish (>120 mm) at any time (see Table 16). Penttila (1978) believed that moderate temperatures and wave action were necessary for successful hatching, and that prolonged direct exposure to sunlight led to desiccation and heat mortality. Therefore, reduced solar radiation (cloudy weather or direct shading) and cooling through wave action or water seepage through the substrate were important survival factors for eggs deposited during summer and fall. Of these factors, fog in particular, is more prevalent on the coast than in the estuary and several important spawning areas are known to exist on San Mateo County and Sonoma County coastal beaches (Frey 1971).

Whitebait Smelt

Introduction

The whitebait smelt ranges from San Francisco Bay, California, northward to the Strait of Juan de Fuca, Washington (Hart 1973, Hearne 1983). Little is known of its life history. It is believed to spawn subtidally over a sandy bottom (Moyle 1992). Hubbs (1925) observed that the young remained translucent (postlarval) until they reached "about 3 inches" (about 76 mm) in length. They live 1 to 3 years (Moyle 1992) and reach a maximum of approximately 229 mm (Hart 1973). Although catch records for the true smelts are lumped into the category "whitebait smelt," it is unlikely that many true whitebait smelt are caught commercially (Moyle 1992).

Methods

Whitebait smelt were considered post-larvae until they reached 75 mm FL, based upon Hubbs (1925) and field observations. Length data were tallied into 5 mm intervals and grouped by month and year. Total catch for all gear types was summed for each year to provide an annual index. Data for all stations were used for Table 1, but only data from original 35 stations were otherwise used.

Results

Whitebait smelt collected in the estuary ranged from 43 to 122 mm FL; most (74%) fell into the post-larval size range (<75 mm; Table 19). The smallest individuals (45 to 50 mm FL) were collected between August and December.

Table 19 Length frequency (mm FL) distribution of whitebait smelt collected with all gear types from 1980 to 1995

Length	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Total*
45 - 49								1	1	2		1	5
50 - 54	9	3						1		1			14
55 - 59	17	1							2			12	32
60 - 64	52	3		1							1	35	92
65 - 69	17	3	2							1	2	14	39
70 - 74	3	2	3									4	12
75 - 79	3	1	3	1		1							9
80 - 84		1	1	7									9
85 - 89				11	1	1							13
90 - 94				7									7
95 - 99		2		4	1				1				8
100 - 104		1			2								3
105 - 109		3			1								4
110 - 114	1	4			2							2	9
115 - 119		3											3
120 - 124		2											2
Total	102	29	9	31	7	3	0	2	4	4	3	68	261

No whitebait smelt were collected in 1980, 1981, or 1991 to 1995 (Table 20). Five even-year year classes (1982, 1984, 1986, 1988, and 1990) accounted for 97% of the total catch of 261 fish. All whitebait smelt caught from 1982 through 1984 were from the 1982 year class. The 1982 year class comprised 87% of the 194 post-larval fish (<75 mm) and 72% of the total catch. There was no evidence of a 1983 year class. The 1984 year class made up all the fish collected in 1985 (Table 20). The 1985 year class was made up of the single large fish (85 to 89 mm) collected in 1986. The 1986 year class was comprised of the 4 smallest fish in 1986, the 4 largest in 1987, and 2 of the 3 largest in 1988. Five fish from a 1987 year class were captured in 1987 and 1988. The 1988 year class was composed of the 2 smallest fish in 1988 and all 3 fish in 1989. The 1990 year class was composed of the entire 1990 catch. Sixty percent (n = 10) of the fish caught from August through October were taken in 1990.

Table 20 Annual length frequency (mm FL) distribution for whitebait smelt collected with the beach seine, midwater trawl, and otter trawl from 1980 to 1995. No fish were collected in 1980, 1981, or 1991 to 1995.

Length	1982	1983	1984	1985	1986	1987	1988	1989	1990	Total
45 - 49	1						1		3	5
50 - 54		12							2	14
55 - 59	12	18			2					32
60 - 64	33	51		3	1	2	2			92
65 - 69	15	18		1	1	2	1		1	39
70 - 74	4	2		4				2		12
75 - 79		2		4		1	1	1		9
80 - 84		1		8						9
85 - 89				12	1					13
90 - 94				7						7
95 - 99			2	4			2			8
100 - 104			1	2						3
105 - 109			3	1						4
110 - 114		2	6				1			9
115 - 119			3							3
120 - 124			2							2
Total	65	106	17	46	5	5	8	3	6	261

Table 21 Annual catch of whitebait smelt by region collected with the beach seine, midwater trawl, and otter trawl from 1980 to 1995. No fish were collected in 1980, 1981, or 1991 to 1995. No correction was made for unequal sampling effort in different years.

Region	1982	1983	1984	1985	1986	1987	1988	1989	1990	Total
San Pablo	7		1	11	1	2	2	1	1	26
Central	44	95	14	32	3	2	6	2	4	202
South	14	11	2	3	1	1			1	33
Total	65	106	17	46	5	5	8	4	6	261

During the study period, 77% of the whitebait smelt were collected in Central Bay, and 13% and 10% were taken in South and San Pablo bays, respectively (Table 21). Their distribution outside of Central Bay shifted into South Bay during the high outflow years 1982 and 1983, then into San Pablo Bay during the low outflow years 1985, 1987, and 1988 (see Table 21).

Discussion

The whitebait smelt is rarely caught in the estuary (see Table 1), or in local coastal waters (Moyle 1992). The lack of small post-larvae (<40 mm) in the catch makes it unlikely that any spawning takes place in the estuary. The estuary appears to be an extension of their coastal nursery and foraging habitat. They entered the estuary sporadically, primarily during winter and spring, but once in the estuary they remained for 2 to 5 months. Some of the 1982 and 1986 year class fish even re-entered the Bay to spend a second winter and spring. Like other marine smelt, they remained primarily in Central Bay. The succession of even-year cohorts suggests a 2-year maturity schedule.

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Atherinidae

Suzanne DeLeón

Introduction

The silverside family, Atherinidae, occurs worldwide in tropical and temperate coastal areas. Many species are marine or estuarine but some live in freshwater. The marine and estuarine species are pelagic surface schoolers. They generally occur at depths <30 m and are most common at depths of <15 m.

On the west coast of the United States, there are 3 marine species of Atherinidae and 1 introduced freshwater species. The topsmelt, *Atherinops affinis*; the jacksmelt, *Atherinopsis californiensis*; and the grunion, *Leuresthes tenuis*, are marine species, and the inland silverside, *Menidia beryllina*, occurs in freshwater habitats. Only the topsmelt, jacksmelt, and inland silverside were collected in the San Francisco Estuary and are discussed here (Tables 1, 2, and 3).

Table 1 Catch of all atherinids collected with the midwater trawl at the original 35 stations

Year	*Topsmelt*	*Jacksmelt*	*Inland Silverside*	*Total*
1980	126	217		343
1981	68	1046	1	1115
1982	120	491		611
1983	384	505		889
1984	61	1107	2	1170
1985	1689	2747		4436
1986	89	706		795
1987	1688	673		2361
1988	149	468		617
1989	11	454		465
1990	17	415		432
1991	12	487		499
1992	4	250		254
1993	62	230		292
1994	11	94		105
1995	355	228		583
Total	4846	10118	3	15346

Table 2 Catch of all atherinids collected with the otter trawl at the original 35 stations

Year	*Topsmelt*	*Jacksmelt*	*Inland Silverside*	*Total*
1980	8	5		13
1981		7	1	8
1982	17	7		24
1983	12	5		17
1984		2	1	3
1985	2	8		10
1986	1	7		8
1987	4	4		8
1988	14	3		17
1989	2	23		25
1990	1	6		7
1991		4		4
1992		1		1
1993		2		2
1995	1	22		23
Total	62	106	2	171

Table 3 Catch of all atherinids collected with the beach seine from 1980 to 1986

Year	*Topsmelt*	*Jacksmelt*	*Inland Silverside*	*Total*
1980	5149	87	216	5452
1981	2785	347	644	3776
1982	4013	1200	262	5475
1983	7293	6056	315	13664
1984	10922	3802	2526	17250
1985	12702	1557	540	14799
1986	7850	10107	467	18424
Total	50918	23191	4975	79084

Atherinids are oviparous and fertilization is external. Eggs are deposited on vegetation in shallow nearshore habitats. The coastal species usually lay eggs on eelgrass in nearshore estuarine and bay habitats. The larvae school near the surface.

Atherinids are omnivorous and feed on diatoms, algae, mysids, copepods, and ostracods (Ruagh 1976). In turn, they are prey for many piscivorous birds such as pelicans, gulls, and the least tern, and piscivorous fish including yellowtail and kelp bass (Feder and others 1974).

The atherinids are not important commercially in California but are important to the recreational fishery. The marine species are one of the most common fishes taken by pier and shore anglers (Gregory 1992).

Topsmelt

Introduction

The topsmelt, *Atherinops affinis*, ranges from the Gulf of California to Vancouver Island, British Columbia (Miller and Lea 1972) and is one of the most abundant fishes in many Pacific coast estuaries (Frey 1971). It is found in estuaries and along the coast over sandy beaches, rocky reefs, mudflats, around piers, and in interspaces of kelp beds (Hart 1973, Feder and others 1974). The topsmelt forms schools of similar-sized fish at the surface in shallow water. It is found from the surface to 9.1 m but usually occurs at 1.2 m (Feder and others 1974). The larvae are planktonic but also school near the surface in shallow water.

Topsmelt are euryhaline and can withstand high salinity (Gregory 1992). In San Francisco Bay, the young-of-the-year (YOY) are common in mesohaline and oligohaline salinities (Wang 1986). In laboratory studies juveniles tolerated salinities from 2‰ to 80‰ although growth was severely impeded in hypersaline water (Middaugh and Shenker 1988). Spawning adults and YOY were found in southern California from 35‰ to 63‰ (Carpelan 1955) and in salt ponds in San Francisco Bay from 40‰ to 53‰. Juveniles and adults are eurythermal. The lower lethal temperature for juveniles is 10.4 °C and the upper lethal temperature is 31.7 °C (Doudoroff 1945, as cited in Frey 1971).

Adults move to shallow sloughs and mudflats from late spring to summer to spawn. Females mature and spawn at age 3 with some large females spawning in their 2nd year (Fronk 1969). Males usually mature at 2 years but the larger ones can mature at 1 year. Females may spawn more than once from April to October at 10 to 25 °C in San Francisco Bay (Schultz 1933 and Wang 1986). Fecundity is positively correlated with female parental size. Females are followed by several males when spawning (Feder and others 1974). The large demersal eggs are laid on blades of aquatic vegetation, usually eelgrass, and fertilized externally. Hatching time varies with temperature. The eggs hatch from 35 days at 13 °C to less than 9 days at 27 °C (Hubbs 1965).

Larvae are 4.3 to 4.9 mm long and juvenile characteristics are formed at 18.5 mm (Wang 1986). They grow fastest in their 1st year, becoming half the adult size. Topsmelt reach a maximum size of 366 mm TL (Miller and Lea 1972) and live to 7 to 8 years (Gregory 1992).

In the ocean, topsmelt are planktonic feeders and prey on crustaceans including amphipods and copepods. They clean barnacles and whale lice off grey whales (Swartz 1981). In the estuary, they feed on the bottom and consume plant material, algae, diatoms, and small crustacea (Fronk 1969). Topsmelt are preyed upon by yellowtail, halibut, croaker, sand bass, and piscivorous birds. They have little economic value but are among the most abundant fish available to pier and shore anglers (Gregory 1992).

Methods

The midwater trawl data from 1980 to 1988, and 1995, and the beach seine data from 1981 to 1986 were analyzed for annual abundance and distribution, and temperature and salinity distribution. The midwater trawl data from 1981 to 1988 and the beach seine data from 1981 to 1986 were used for seasonal abundance and distribution. The midwater trawl data from 1989 to 1994 were not used because sampling did not occur in November and December when topsmelt were abundant in the estuary. In 1995, we did not sample with the midwater trawl in August. The egg and larval data were used to show seasonal distribution.

Two age groups were separated by visual inspection of length frequencies. All fish <100 mm FL were classified as age 0 and those >100 mm FL were classified as age 1+. The index period for age–0 fish was July to December in both the midwater trawl and beach seine. The index period for age–1+ fish was July to December in the midwater trawl and January to September in the beach seine.

Results

Abundance in the Midwater Trawl

Age–0 topsmelt were most abundant in 1985 and 2nd most abundant in 1987 (Figure 1A, Table 4). Although 1995 was the 3rd most abundant year, the lack of August data probably biased the index high because August was typically a low index month. No age–0 fish were collected from March through October 1992.

The age–0 topsmelt abundance was low from January through July (Figure 2A, Table 4). They were usually collected beginning in August and were most abundant from late fall through December. Abundance decreased in late winter and they disappeared from our collections in May and June.

The age–1+ topsmelt abundance index was highest in 1983 and next highest in 1985 (Figure 1B, Table 5). Abundance trends are difficult to determine due to the lack of winter data from 1989 to 1994.

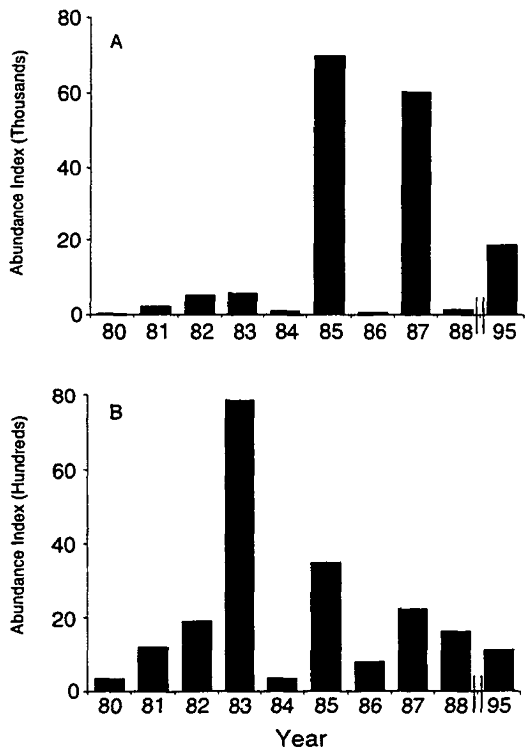

Figure 1 Annual abundance indices of topsmelt collected with the midwater trawl from 1980 to 1988 and 1995: (A) age 0, the index period was July to December; (B) age 1+, the index period was July to December

Table 4 Age–0 topsmelt monthly abundance indices collected with the midwater trawl from 1980 to 1995. The index period was July to December. "NI" indicates no index calculated due to incomplete sampling.

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Index*
1980		35019	6398	376	0	0	0	0	903	430	0	0	222
1981	915	0	0	215	0	0	7521	0	941	0	188	4595	2208
1982	546	0	0	0	0	0	108	4612	1317	2766	19736	2502	5174
1983	753	0	0	0	0	0	0	0	188	0	7151	26532	5645
1984	0	0	0	0	0	376	0	0	511	466	1317	3575	978
1985	565	188	0	0	0	0	1317	2070	109510	221995	77074	7903	69978
1986	0	8871	1882	4334	0	0	0	376	565	1694	753	296	614
1987	8516	376	565	565	0	0	0	888	338519	4247	4892	12419	60161
1988	5081	9409	923	1505	0	0	0	188	4122	188	1129	2823	1408
1989	376	1317	0	0	0	0	0	0					NI
1990		1505	358	0	0	0	0	0	376	565			NI
1991		0	0	0	0	0	0	0	0	2769			NI
1992		904	0	0	0	0	0	0	0	0			NI
1993		0	188	0	0	0	0	0	753	7151			NI
1994		0	1694	0									NI
1995				7151	0	0	0		0	13844	77957	1129	18586
1981–1988	2047	2356	421	827	0	47	1118	1017	56959	28920	14030	7581	

Age–1+ fish were collected throughout the year but catches were highly variable between years (Figure 2B, Table 5). Age–1+ abundance was bimodal; there was a small peak in June and July and a larger peak in November and December. Abundance was lowest in April and May, and high from October to December.

Abundance in the Beach Seine

In the beach seine, the age–0 topsmelt annual abundance index was highest in 1985 (Figure 3A). This corresponds to the highest midwater trawl index. The lowest index was in 1981, but the indices did not vary much over the years. Age–0 fish were collected in every month except June 1981 and abundance peaked from July to October (Figure 4A and Table 6).

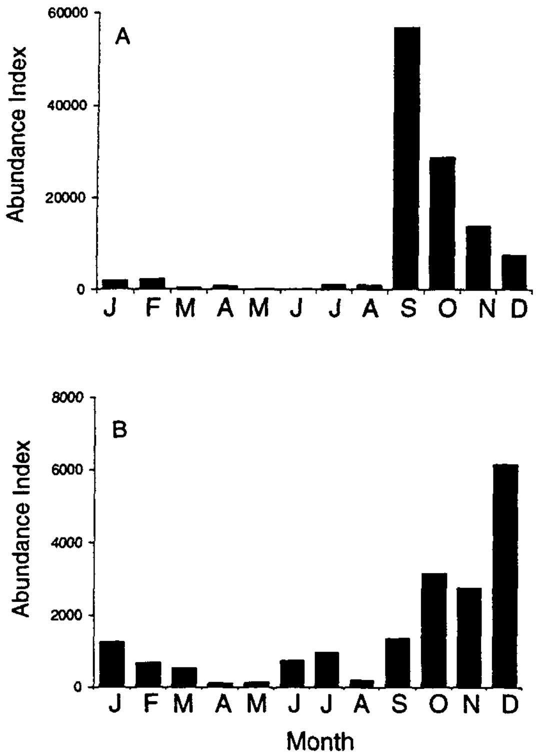

Figure 2 Seasonal abundance of topsmelt collected with the midwater trawl from 1981 to 1988: (A) age 0 and (B) age 1+

Table 5 Monthly abundance indices of age–1+ topsmelt collected with the midwater trawl from 1980 to 1995. The index period was July to December. Values are CPUE x 100. "NI" indicates no index calculated due to incomplete sampling.

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Index*
1980		5208	1129	215	0	0	430	0	0	0	0	1637	345
1981	546	3053	0	215	753	0	2786	592	376	0	0	3475	1205
1982	1111	0	0	188	0	0	484	0	0	108	9414	1425	1905
1983	0	0	0	0	376	0	0	296	188	188	7381	39049	7850
1984	716	0	0	0	0	4704	0	376	646	0	188	941	359
1985	565	215	753	0	0	188	188	431	0	16936	2072	1317	3491
1986	0	565	0	0	0	376	2446	0	0	1694	108	619	811
1987	6196	188	2222	0	0	753	188	0	8541	941	2258	1505	2239
1988	941	1505	1433	565	0	0	1694	0	1129	5463	565	904	1626
1989	0	546	0	0	0	0	0	376					NI
1990		188	0	0	0	0	0	0	0	1370			NI
1991		0	0	0	0	0	0	0	0	0			NI
1992		716	0	0	0	0	0	0	108	0			NI
1993		0	188	0	0	0	188	0	0	7715			NI
1994		0	565	1263									NI
1995				565	0	0	1093		0	753	3816	0	1132
1981–1988	1259	691	551	121	141	753	973	212	1360	3166	2748	6154	

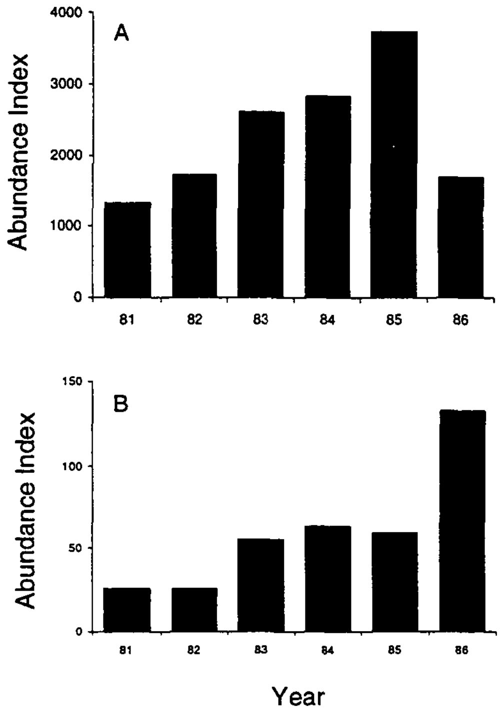

Figure 3 Annual abundance indices of topsmelt collected with the beach seine from 1981 to 1986: (A) age 0, the index period was July to December; (B) age 1+, the index period was January to September

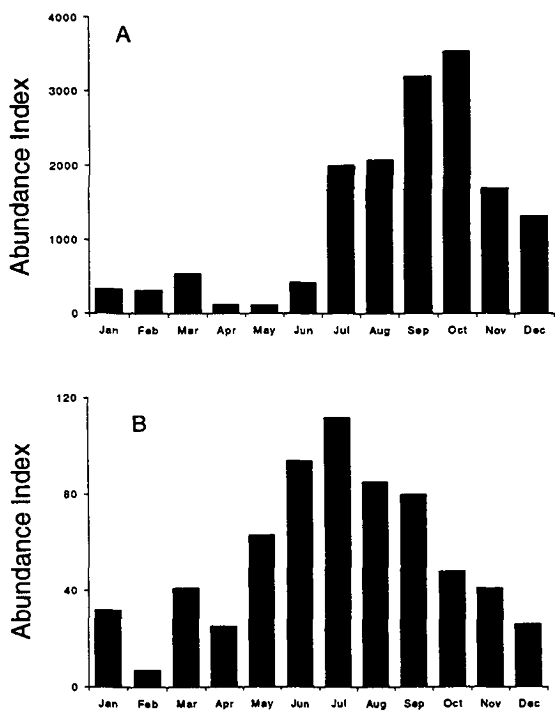

Figure 4 Seasonal abundance of topsmelt collected with the beach seine from 1981 to 1986: (A) age–0 fish and (B) age–1+ fish

Table 6 Monthly abundance indices of age–0 topsmelt collected with the beach seine from 1980 to 1986. The index period was July to December.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Index
1980								4043	1519	1838	1422	3274	
1981	910	1252	260	66	33	0	3284	114	1278	1285	1266	783	1328
1982	71	68	106	35	3	660	3855	2082	1654	1709	33	543	1731
1983	87	126	451	25	46	825	619	2743	5379	5685	784	113	2626
1984	10	142	815	111	171	676	1588	3175	3801	5211	2582	663	2839
1985	306	84	1031	64	276	233	1682	3816	3103	5107	3597	5429	3760
1986	600	209	573	431	140	69	988	558	4000	2271	1986	426	1705
1981–1986	331	314	539	122	112	411	2003	2081	3203	3545	1708	1326	

Table 7 Monthly abundance indices of age–1+ topsmelt collected with the beach seine from 1980 to 1986. The index period was January to September.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Index
1980								55	47	10	39	34	
1981	38	27	27	0	25	0	22	9	82	68	147	18	26
1982	4	3	53	14	46	13	43	5	48	29	5	11	26
1983	0	1	53	2	14	6	190	70	148	68	19	3	56
1984	2	4	30	29	165	154	147	14	17	73	22	21	64
1985	96	1	73	8	27	267	0	0	63	30	33	29	60
1986	43	10	5	94	94	103	254	437	152	57	45	65	133
1981–1986	31	8	40	25	62	91	109	89	85	54	45	25	61

In the beach seine, age–1+ topsmelt were most abundant in 1986, which follows the highest age–0 abundance by 1 year (Figure 3B). On average, abundance peaked from May to October (Figure 4B), but peak monthly abundance varied yearly. In some years abundance peaked in late summer and early fall and in other years, in spring and summer (Table 7). Age–1+ fish were collected in almost every month, but in 1981, none were collected in April and June, and in 1985 none were collected in July and August (see Table 7).

Distribution

Topsmelt larvae were collected from April to September from South to San Pablo bays (Figure 5). The highest CPUE was in South Bay in all months except April when they were collected only in San Pablo Bay.

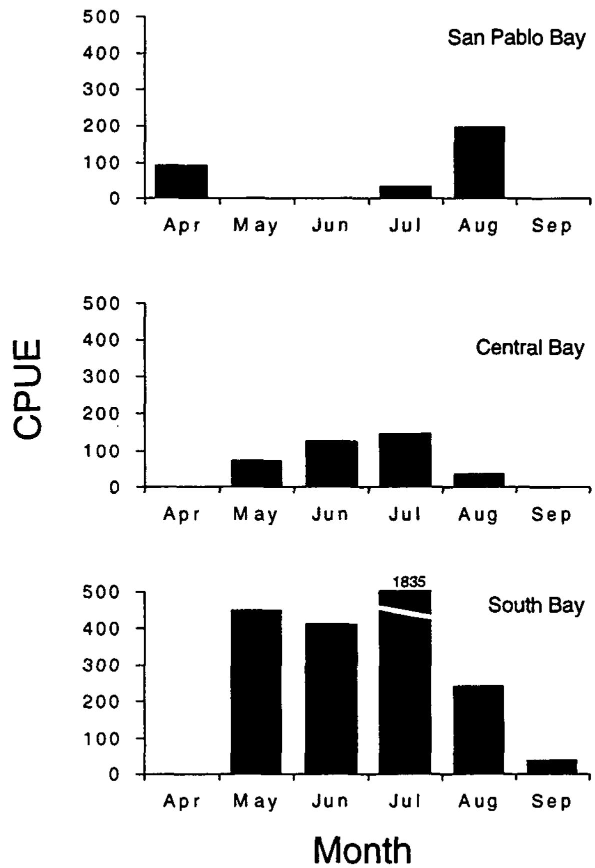

Figure 5 Seasonal distribution by region of larval topsmelt collected from 1980 to 1989

Age–0 topsmelt ranged from South to San Pablo bays but their distribution was centered in South Bay (Figure 6). In 1985 and 1987, when they were most abundant, they ranged to San Pablo Bay, but in very low abundance. In every year, the CPUE was highest in South Bay, except in 1982 when age–0 fish were equally distributed between South and Central bays.

Seasonally, the center of distribution of age–0 topsmelt was in South Bay from January to April. They disappeared from the estuary (or at least from our sampling area) in May and June (Figure 7). In July, they reappeared in Central and South bays and in September and October, the CPUE was highest in South Bay. In November, they were distributed equally in South and Central bays. They were present but rare in San Pablo Bay from September to January.

Age–1+ topsmelt usually ranged from South Bay to San Pablo Bay but in 1980 they were also collected in Suisun Bay (Figure 8). The highest CPUE was in South Bay, except in 1980 and 1988, when they were equally distributed between South and Central bays, in 1982, when the highest CPUE was in Central Bay, and in 1987, when the highest CPUE was in San Pablo Bay.

The age–1+ topsmelt CPUE was usually highest in South Bay but in January and February, it was equal in South and Central bays (Figure 9). In August and September their center of distribution shifted to San Pablo Bay and they returned to South Bay in late fall and winter.

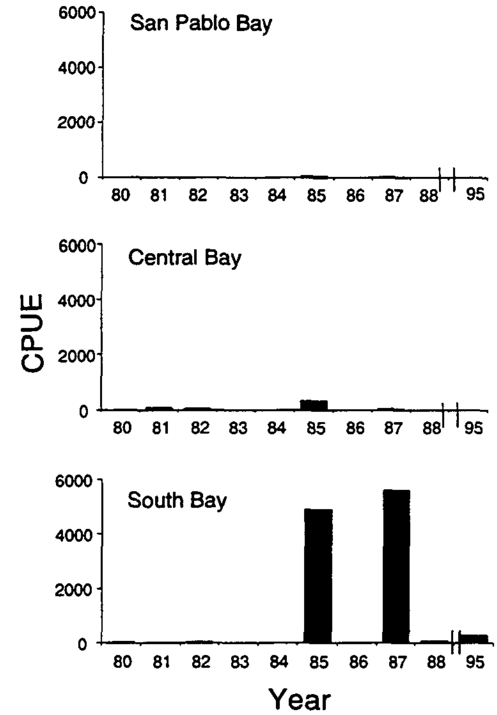

Figure 6 Annual distribution of age–0 topsmelt collected with the midwater trawl from 1980 to 1988 and 1995. Values are average CPUE × 100 from July to December.

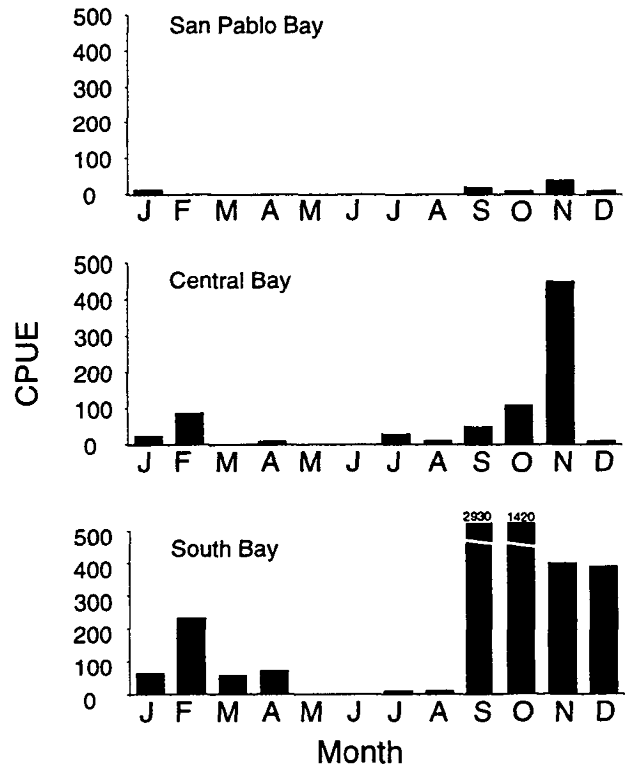

Figure 7 Seasonal distribution of age–0 topsmelt collected with the midwater trawl from 1980 to 1988 and 1995. Values are CPUE × 100.

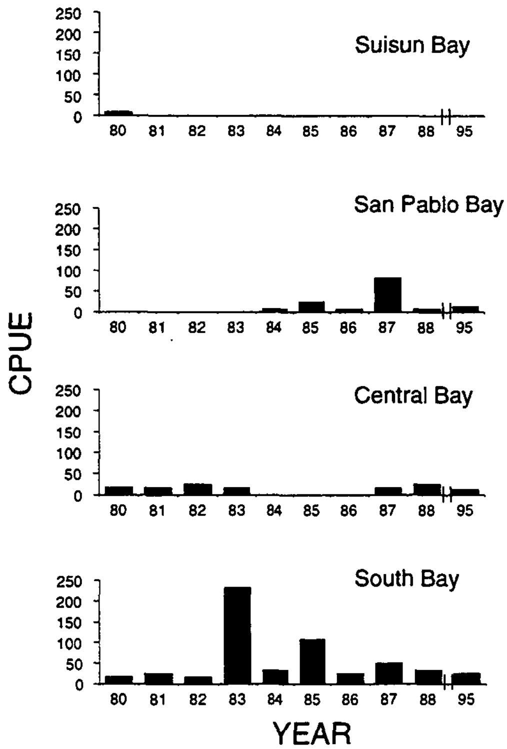

Figure 8 Annual distribution of age–1+ topsmelt collected with the midwater trawl from 1980 to 1988 and 1995. Values are CPUE x 100 from July to December.

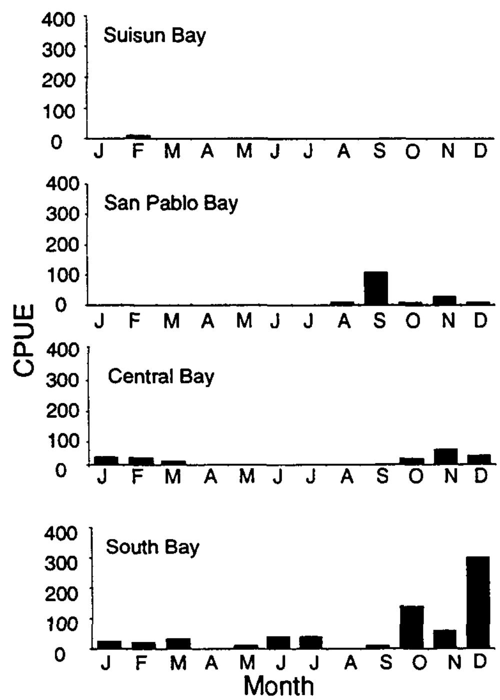

Figure 9 Seasonal distribution of age–1+ topsmelt collected with the midwater trawl from 1980 to 1988 and 1995. Values are CPUE x 100.

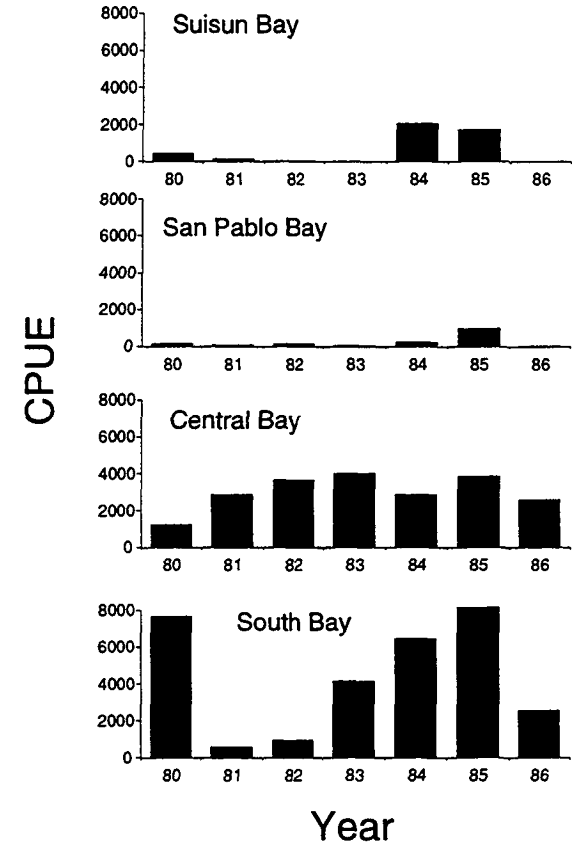

Figure 10 Annual distribution of age–0 topsmelt collected with the beach seine from 1980 to 1986. Index period was July to December.

Distribution in the Beach Seine

Age–0 topsmelt were collected in the beach seine from South to Suisun bays, except in 1983 and 1986 when none were collected in Suisun Bay (Figure 10). Their distribution was centered in South and Central bays in all years. In most years, the Suisun Bay CPUE was higher than the San Pablo Bay CPUE and in 1984 and 1985 it was almost as high as the Central Bay CPUE.

From January through April, the highest age–0 topsmelt CPUE was in South Bay and it shifted to Central Bay from May through July (Figure 11). In fall and winter the CPUE was highest in either South or Central bays and higher in Suisun Bay than San Pablo Bay.

The highest age–1+ topsmelt CPUE was in South Bay except in 1984 and 1985 when CPUE was highest in Central Bay (Figure 12). They ranged from South to Suisun bays in 1982, 1984, and 1985, and in 1986 they were collected only in South and Central bays.

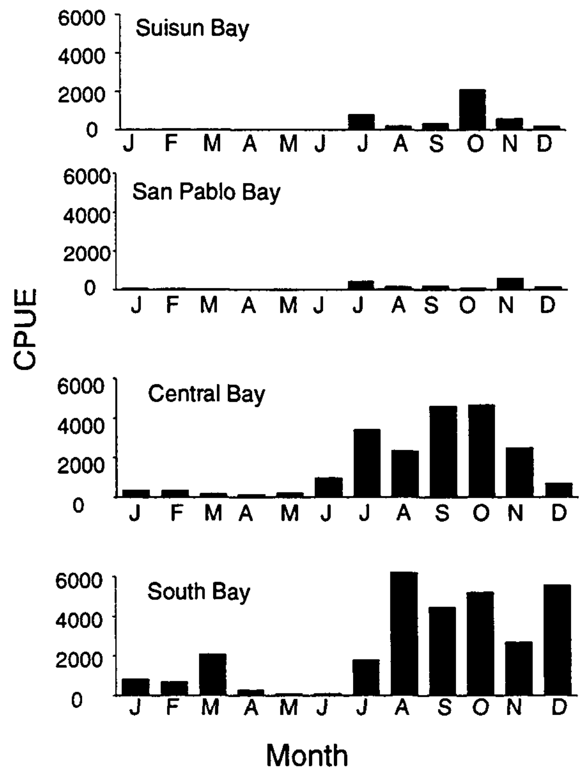

Figure 11 Seasonal distribution of age–0 topsmelt collected with the beach seine from 1981 to 1986

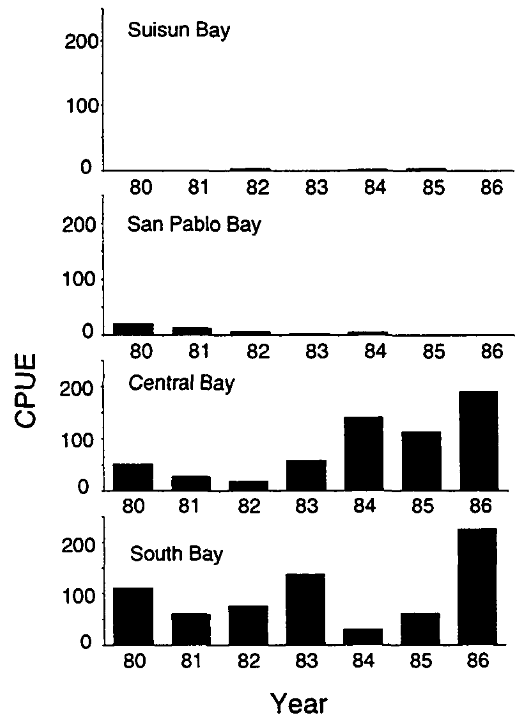

Figure 12 Annual distribution by region of age–1+ topsmelt collected with the beach seine from 1980 to 1986. Index period was January to September.

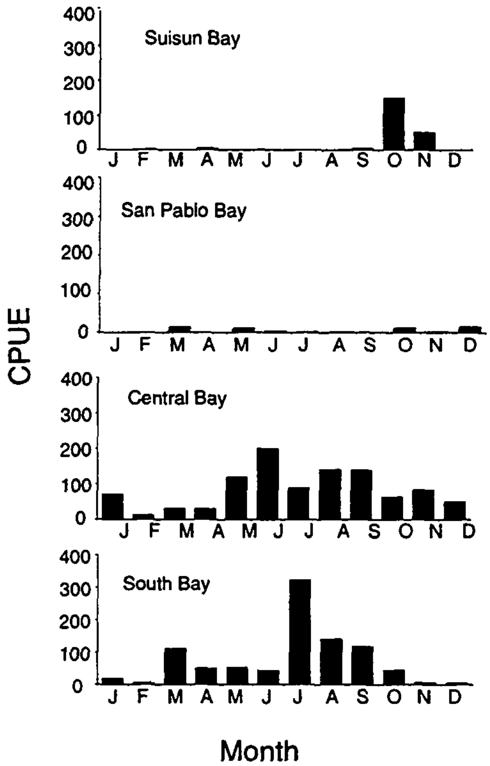

Figure 13 Seasonal distribution of age–1+ topsmelt collected with the beach seine from 1981 to 1986

The center of age–1+ topsmelt distribution shifted between South and Central bays in spring and early summer (Figure 13). From August to December, they were concentrated in Central Bay except for October, when the CPUE was highest in Suisun Bay.

Temperature and Salinity

In the beach seine, age–0 fish were found in a wider range of temperatures than age–1+ fish but at similar salinities (Figures 14 and 15). For age–0 fish, temperatures ranged from 5.9 to 33.8 °C, $\bar{\chi}$ = 18.7 °C (see Figure 14). Age–1+ fish were collected from 7.6 to 28.2 °C, $\bar{\chi}$ = 20.5 °C (see Figure 15).

Both age groups were collected in similar salinities. Age–0 fish were caught from 0.25‰ to 34.3‰, $\bar{\chi}$ = 26.0‰ (see Figure 14); age–1+ fish from 0.1‰ to 33.3‰, $\bar{\chi}$ = 26.1‰ (see Figure 15).

In the midwater trawl, age–0 fish were collected in similar temperatures and at slightly higher salinities than age–1+ fish (Figures 16 and 17). Age–0 fish were collected at 8.3 to 22.3 °C, $\bar{\chi}$ = 17.0 °C (see Figure 16). Age–1+ fish were found in 8.4 to 21.8 °C, $\bar{\chi}$ = 15.5 °C (see Figure 17).

Age–0 and age–1+ fish were taken at slightly different salinities. Age–0 fish were collected from 10.7‰ to 34.0‰, $\bar{\chi}$ = 29.0‰ (see Figure 16). Age–1+ fish were collected in salinities from 6.9‰ to 34.02‰, $\bar{\chi}$ = 25.7‰ (see Figure 17).

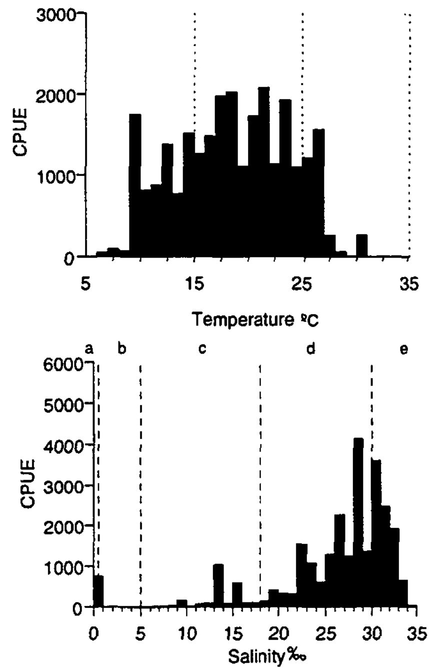

Figure 14 Temperature and salinity distribution of age–0 topsmelt collected with the beach seine from 1980 to 1986. The vertical lines on the salinity graph mark the boundaries of the Venice system ranges: (a) limnetic, (b) oligohaline, (c) mesohaline, (d) polyhaline, and (e) euhaline.

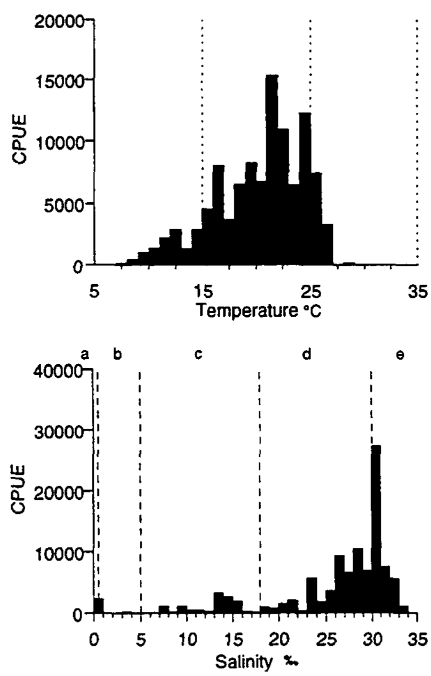

Figure 15 Temperature and salinity distribution of age–1+ topsmelt collected with the beach seine from 1980 to 1986. The vertical lines on the salinity graph mark the boundaries of the Venice system ranges: (a) limnetic, (b) oligohaline, (c) mesohaline, (d) polyhaline, and (e) euhaline.

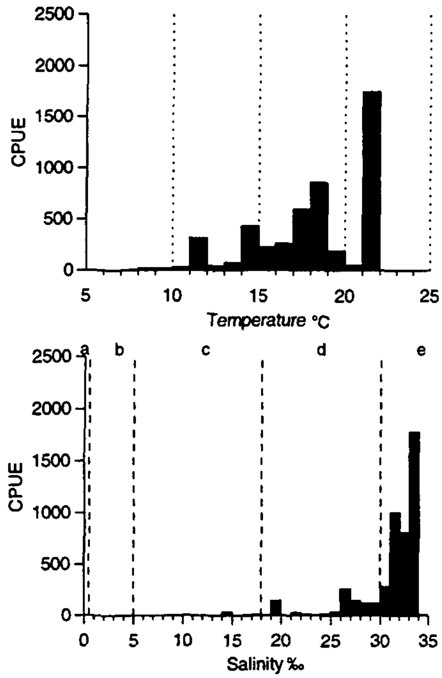

Figure 16 Temperature and salinity distribution of age–0 topsmelt collected with the midwater trawl from 1980 to 1988 and 1995. The vertical lines on the salinity graph mark the boundaries of the Venice system ranges: (a) limnetic, (b) oligohaline, (c) mesohaline, (d) polyhaline, and (e) euhaline.

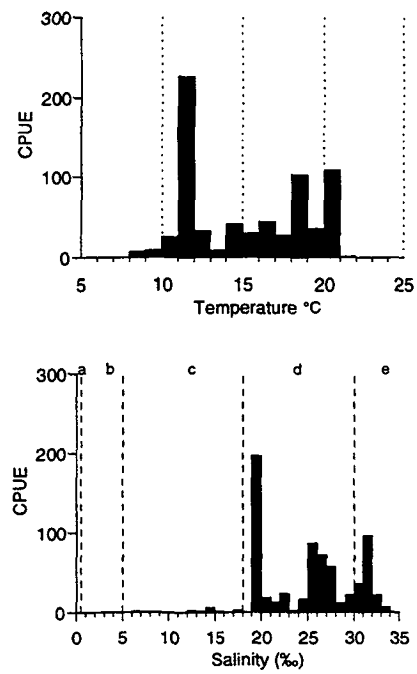

Figure 17 Temperature and salinity distribution of age–1+ topsmelt collected with the midwater trawl from 1980 to 1988 and 1995. The vertical lines on the salinity graph mark the boundaries of the Venice system ranges: (a) limnetic, (b) oligohaline, (c) mesohaline, (d) polyhaline, and (e) euhaline.

Discussion

Topsmelt use the estuary as a nursery and a spawning ground. Some age–1+ fish appear to be resident in the estuary but some emigrate out of it. They are resident in shallow water as shown by the year-long catch in the beach seine. In late fall and winter, the increased midwater trawl catch shows that they move to deeper areas. In Coos Bay, Oregon, topsmelt move to the open ocean in August and September but in Newport Bay, California, they remain in the bay all year (Fronk 1969 and Frey 1971). The midwater trawl data shows movement of fish from shallows to channels but is not reliable for abundance trends because so few age–1+ fish were collected in it.

Age–1+ fish disappeared from the midwater trawl from April through June but were still found in the beach seine. They moved into the shallows to spawn in March and April as shown by appearance of larval fish in April and May and the appearance of large numbers of age–0 fish in the beach seine in June. Spawning took place as early as April and continued until September. Age–0 topsmelt remained in the shallows through late fall and migrated to deeper areas in winter. Catches were very low throughout winter and spring, indicating they emigrated to the ocean.

Age–0 topsmelt were most abundant in the low outflow years, 1985 and 1987, but not in 1981, another low outflow year. It is difficult to determine what controls abundance, because no data was collected in winter during low outflow years and the beach seine data were limited to 1980 to 1986.

Age–0 topsmelt were collected in slightly higher salinities and warmer temperatures than age–1+ fish. This may be a reflection of seasonality of catches rather than actual environmental preferences because age–0 fish were collected primarily in summer when temperatures and salinities are high, whereas age–1+ fish were collected all year.

In this estuary, age–0 topsmelt reside in polyhaline to euhaline water. This disagrees with Wang (1986) who found age–0 fish in mesohaline and oligohaline water in San Francisco Bay.

To determine overall abundance trends of topsmelt in the estuary, we need to collect more data in winter and in shallow habitats to determine how salinity, temperature, and possibly outflow govern abundance and distribution.

Jacksmelt

Introduction

The jacksmelt, *Atherinops californiensis*, ranges from Santa Maria Bay, Baja California to Yaquina Bay, Oregon (Miller and Lea 1972, Eschmeyer and others 1983). It is a pelagic, schooling, marine species found within a few miles of shore. It prefers turbid water and is found in estuaries, bays, kelp canopy, and sandy beaches (Gregory 1992). During summer, large schools of juveniles reside in estuaries and bays; in fall, they migrate to coastal waters (Frey 1971). Juveniles and adults are found to 29 m but are usually concentrated at 1.5 to 15 m. The larvae also school near the surface and are pelagic. Temperature and salinity tolerances for the jacksmelt are unknown. Optimal growth is from 10‰ to 20‰ and the optimal salinity for survival is 15‰ (Middaugh and others 1990).

Jacksmelt are batch spawners. Adults move into bays and estuaries to spawn during late winter and early spring; however, in southern California they spawn all year with a peak in winter. Peak reproductive activity is from January to March in northern California (Middaugh and others 1990). In San Francisco Bay, spawning occurs from October through August and in San Pablo Bay, from September to April (Ganssle 1966). Spawning occurs more than once during the breeding season (Clark 1929). All jacksmelt are mature in their 3rd year and the larger individuals may mature at the end of their 2nd year. Eggs are adhesive and are laid on vegetation in shallow estuaries and bays (Frey 1971). Eggs may hatch in salinities as low as 5‰ and hatch within 7 days at 10 to 12 °C (Wang 1986).

The larval size range is 7.5 to 8.6 mm TL. Juvenile characteristics are formed at 25 mm (Clark 1929). They grow to 110 to 120 mm TL during their 1st year and 180 to 190 mm TL by the end of their 2nd year (Clark 1929). They live as long as 11 years and reach 445 mm TL (Miller and Lea 1972).

Jacksmelt are omnivorous. Larvae prey on copepods, diatoms, and bivalve veligers in southern California (Watson and Davis 1989). The adults prey on algae, benthic diatoms, mysids, copepods, and smelt eggs. In turn they are eaten by yellowtail, kelp bass, sharks, brown pelicans, and gulls. They have little commercial value but are part of an important recreational fishery on piers and jetties (Frey 1971).

Methods

The midwater trawl data from 1980 to 1995 (except for 1989 and 1994), and the beach seine data from 1981 to 1986 were analyzed for annual abundance and distribution, and temperature and salinity distributions. The 1981 to 1988 midwater trawl data and the 1981 to 1986 beach seine data were analyzed for seasonal abundance and distribution. The egg and larval data were used for supporting seasonal distribution.

Two age groups of jacksmelt were identified by visual inspection of length frequencies. Fish <110 mm FL were classified as age 0 and fish >110 mm were classified as age 1+. The index period for age–0 fish in the midwater trawl was July to October. The index period for age–0 fish collected in the beach seine was April to December.

The midwater trawl index period for age–1+ jacksmelt was February to June. All years except 1994 and 1995 were analyzed for annual abundance, temperature and salinity distributions. The 1981 to 1988 midwater trawl data were used for seasonal abundance and distribution analyses. Not enough age–1+ fish were collected in the beach seine for analyses.

Results

Abundance

In the midwater trawl, age–0 jacksmelt were most abundant in 1981, and 2nd most abundant in 1984 (Figure 18A, Table 8). They were most abundant from July to November and peaked in September in all years (Figure 19A). In most years age–0 fish were present in low numbers from late winter to early spring, but in 1981, 1985, and 1988 they were collected during these months (see Table 8).

Age–0 jacksmelt in the beach seine were most abundant in 1983 and 1986 (Figure 20A, Table 9). In all other years abundance was 10 times lower. They were collected throughout the year but were most abundant from April to July (Figure 20B). Abundance usually peaked in May or June except in 1986 when the peak was in April (see Table 9).

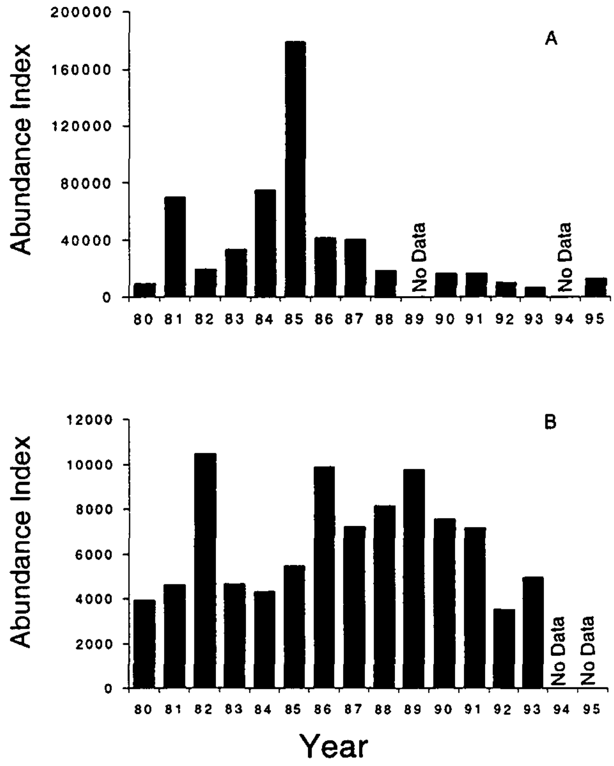

Figure 18 Annual abundance indices of jacksmelt collected with the midwater trawl from 1980 to 1995: (A) age 0, index period is July to October; (B) age 1+, index period was February to July

Table 8 Monthly abundance of age–0 jacksmelt collected with the midwater trawl from 1980 to 1995. Abundance index was July to October. "NI" indicates no index due to insufficient data.

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Index*
1980		0	0	0	0	215	358	2529	27218	9707	6799	6958	9953
1981	0	2149	1228	645	188	10282	86675	45276	114491	33812	11145	0	70064
1982	1281	188	0	188	0	565	1388	27876	24493	24377	1195	3199	19534
1983	0	0	0	0	0	0	4298	5615	111860	10511	20667	2930	33071
1984	0	0	0	0	0	376	31739	105614	137833	25067	129729	860	75063
1985	0	358	188	188	2886	1156	8513	175241	230424	302178	187723	0	179089
1986	0	0	0	0	188	188	60446	68836	30114	6682	7818	2008	41520
1987	654	0	2507	188	1505	1373	62843	68841	20808	7794	1793	0	40072
1988	188	753	3581	1882	188	1452	5390	24838	11205	33567	1074	188	18750
1989	0	0	188	188	376	0	34733	49210					NI
1990		0	0	0	188	3727	17480	17216	27955	3055			16427
1991		0	0	0	0	188	1542	44471	14309	5179			16375
1992		0	0	0	188	0	4595	35352	1809	0			10439
1993		188	0	188	0	1093	6119	6086	10289	4451			6736
1994		1639	0	3539									NI
1995				3557	0	1505	25258		5840	7983	0	1299	13027
1981-1988	265	431	938	386	619	1924	32662	65267	85154	55499	45143	1148	

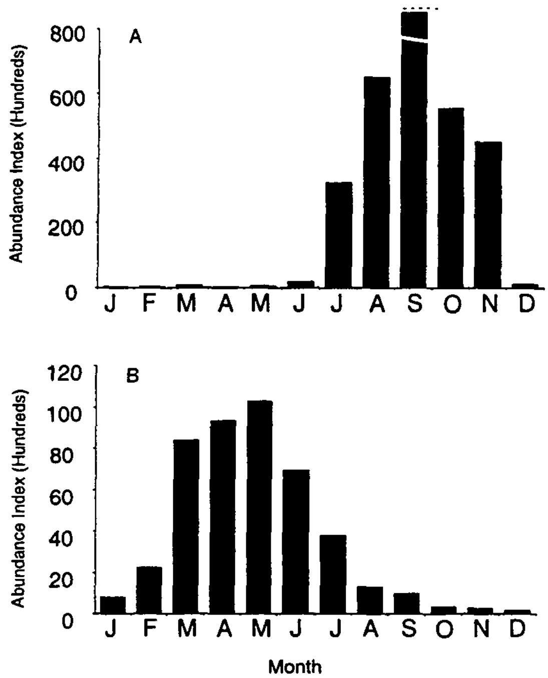

Figure 19 Seasonal abundance of jacksmelt collected with the midwater trawl from 1981 to 1988: (A) age 0 and (B) age 1+

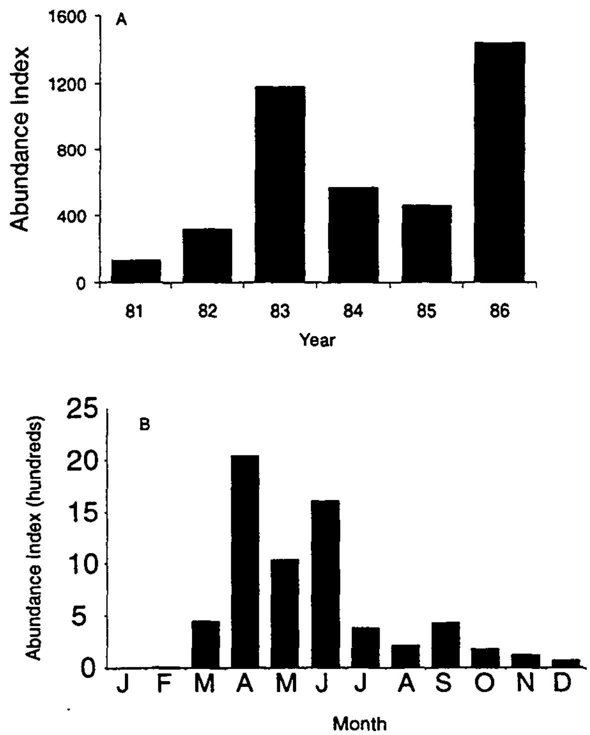

Figure 20 (A) Annual abundance indices of age–0 jacksmelt collected with the beach seine from 1980 to 1986. The index period was April to December. (B) Seasonal abundance of age–0 jacksmelt in the beach seine from 1981 to 1986.

Age–1+ jacksmelt were most abundant in the midwater trawl in 1982, 1986, and 1989 (see Figure 18B, Table 10). They were most abundant from March to July and peaked in April or May in all years (see Figure 19B, Table 10). They were collected throughout the year, except from October to December in some years (see Table 10).

Table 9 Monthly abundance indices of age–0 jacksmelt in the beach seine from 1980 to 1986. Abundance index was from April to December. No sampling from January to July 1980.

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Index*
1980								43	99	2	13	0	
1981	0	24	0	265	104	547	7	2	64	67	95	77	136
1982	4	4	20	75	418	1473	165	78	542	36	13	0	311
1983	3	28	0	15	825	6482	425	650	1613	263	35	3	1146
1984	0	1	29	933	2692	488	144	140	81	319	95	267	573
1985	5	1	0	254	1375	339	972	314	290	44	484	22	455
1986	5	0	2651	10708	836	315	585	91	22	350	15	50	1441
1981–1986	3	10	450	2042	1042	1607	383	213	435	180	123	70	

Table 10 Monthly abundance of age–1+ jacksmelt collected with the midwater trawl from 1980 to 1995. The abundance index period is February to July. "NI" indicates no index calculated due to insufficient data.

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Index*
1980		753	2508	6720	5926	4805	2797	1290	323	0	376	0	3918
1981	1290	3367	5175	6520	4224	6900	1492	1506	431	0	376	376	4613
1982	188	2478	11079	10544	28335	7150	3137	807	654	0	0	0	10454
1983	0	376	5321	8463	8181	3952	1613	376	2257	716	1425	0	4651
1984	1791	1093	6959	5053	6349	3100	3335	2126	108	431	188	0	4315
1985	376	904	7060	5863	7027	6262	5693	1828	1120	215	0	215	5468
1986	1317	3027	14999	6996	11280	15563	7500	404	888	923	0	546	9894
1987	1237	2786	6334	14221	10294	6195	3280	2707	1944	215	108	188	7185
1988	296	4050	10261	17258	6656	6308	4272	716	484	296	188	0	8134
1989	188	716	5230	32061	10756	6640	3173	646					9763
1990		3459	12786	8507	13632	4758	2161	592	1827	323			7551
1991		2033	4569	6444	10055	11104	8786	1157	1604	108			7165
1992		4254	3540	3362	4706	3881	1299	672	1290	2293			3507
1993		3619	6118	4543	11514	1936	2017	995	2552	1049			4958
1994		3933	4445	12025									NI
1995				9173	1703	4973	1138		2205	1765	0	1621	NI
1981-1988	812	2260	8399	9365	10293	6929	3790	1309	986	350	286	166	

Distribution

Jacksmelt larvae ranged from South to Suisun bays (Figure 21). They were collected in all months but were most abundant from October to April. In all months, the highest CPUE was in Central Bay. From May to September larval jacksmelt were not collected in Suisun Bay.

In the midwater trawl, age–0 jacksmelt ranged from South Bay to San Pablo Bay (Figure 22). The CPUE was highest in Central Bay in most years, except in 1981 when it was slightly higher in San Pablo Bay, and in 1986, 1991, 1992, and 1995 when it was highest in South Bay. In 1982, jacksmelt were almost equally distributed in Central and South bays. In 1993, the CPUE was highest in Central Bay but about equal in South and San Pablo bays.

CPUE of age–0 jacksmelt was highest in South Bay in late spring and summer and the center of distribution shifted to Central Bay from midsummer to winter (Figure 23). They extended their distribution into San Pablo Bay in summer but were not present there from January to April.

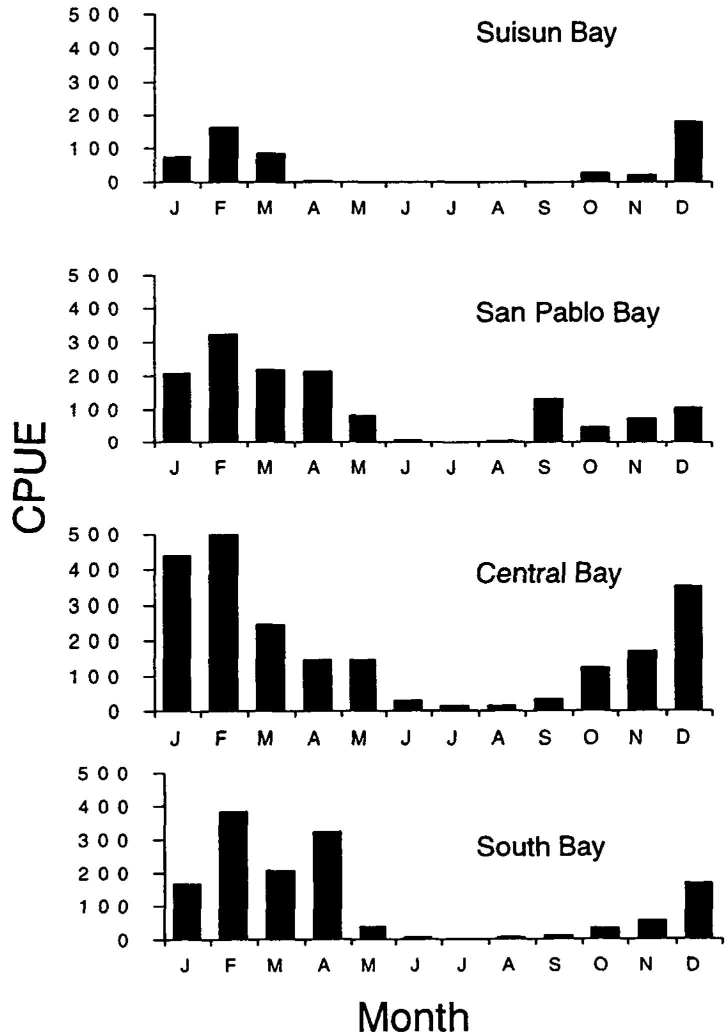

Figure 21 Seasonal distribution by region of larval jacksmelt from 1980 to 1989

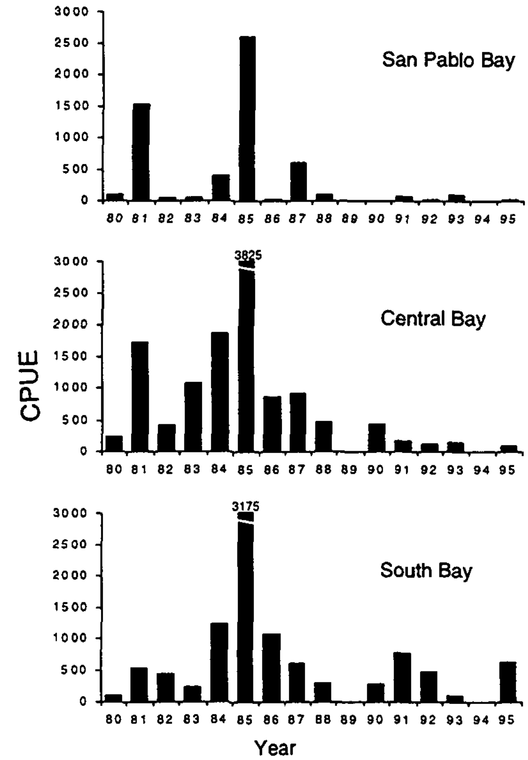

Figure 22 Annual distribution by region of age–0 jacksmelt collected with the midwater trawl from 1980 to 1995. Abundance index was July to October.

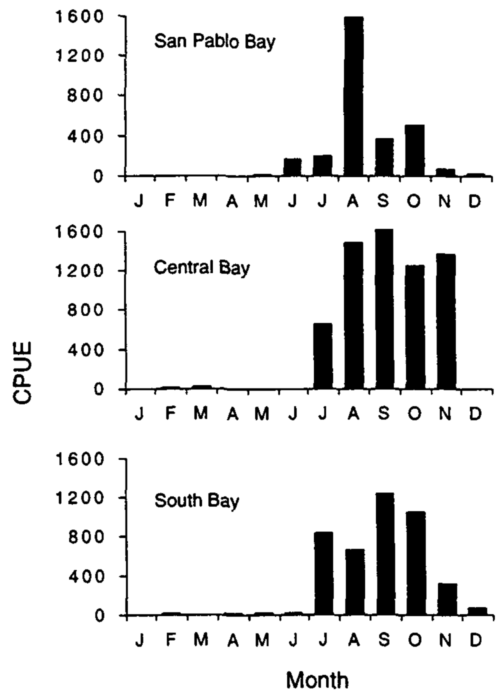

Figure 23 Seasonal distribution by region of age–0 jacksmelt collected with the midwater trawl from 1981 to 1988

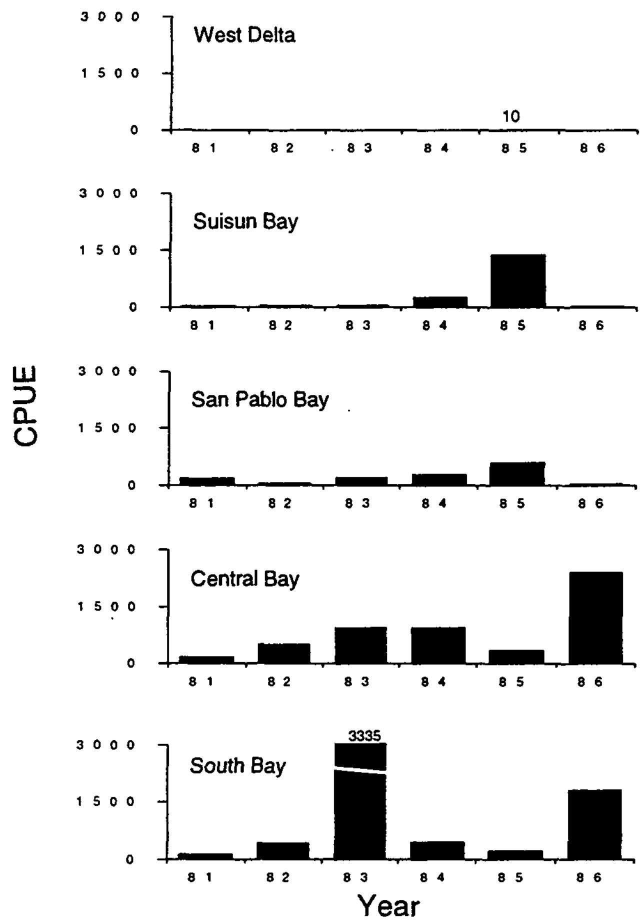

Figure 24 Annual distribution by region of age–0 jacksmelt collected with the beach seine from 1981 to 1986. Index period was April to December.

In the beach seine, age–0 fish ranged from South to Suisun bays except in 1985, when a single collection at station 857 was made in the west delta (Figure 24). The distribution varied greatly from year to year. They were concentrated in Central Bay, except in 1981 when highest concentrations were in Central and San Pablo bays, and in 1983 and 1985 when the age–0 fish moved to South Bay and Suisun Bay.

In the beach seine, age–0 fish were collected from South to Suisun bays in every month, except from January to March when none were collected in San Pablo and Suisun bays (Figure 25). Age–0 fish were collected in the west delta only in November. They were concentrated in Central Bay from March to May and CPUE was highest in either South Bay or Central Bay the rest of the year. In November and July, their distribution shifted to Suisun Bay, but this high CPUE was due to large catches at only a few stations in 1985.

Age–1+ jacksmelt ranged from South to San Pablo bays but CPUE was usually highest in South Bay and next highest in San Pablo Bay (Figure 26). In 1980, they were equally distributed in South and San Pablo bays and in 1985 and 1992 the highest CPUE was in San Pablo Bay. In 1994 and 1995, there was insufficient data for the index period to show the annual distribution.

Seasonally, CPUE was highest in spring in South and Central bays and highest in summer in San Pablo Bay (Figure 27). Age–1+ jacksmelt left San Pablo Bay in August and Central Bay in October but were still present in South Bay in December.

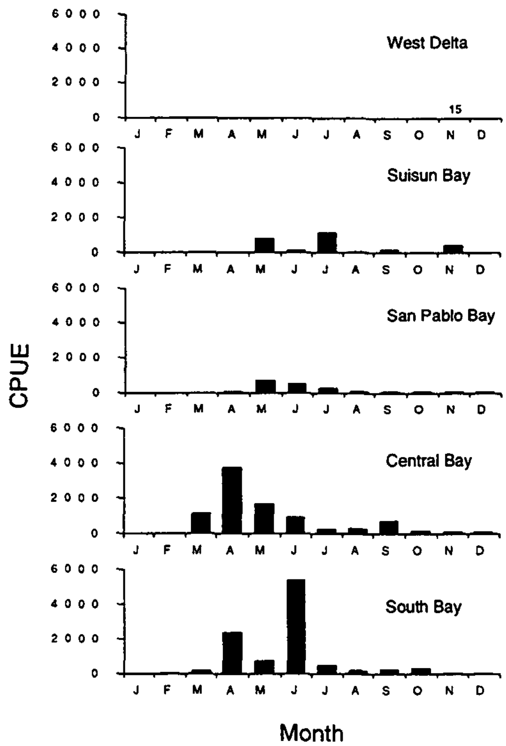

Figure 25 Seasonal distribution by region of age–0 jacksmelt collected with the beach seine from 1981 to 1986

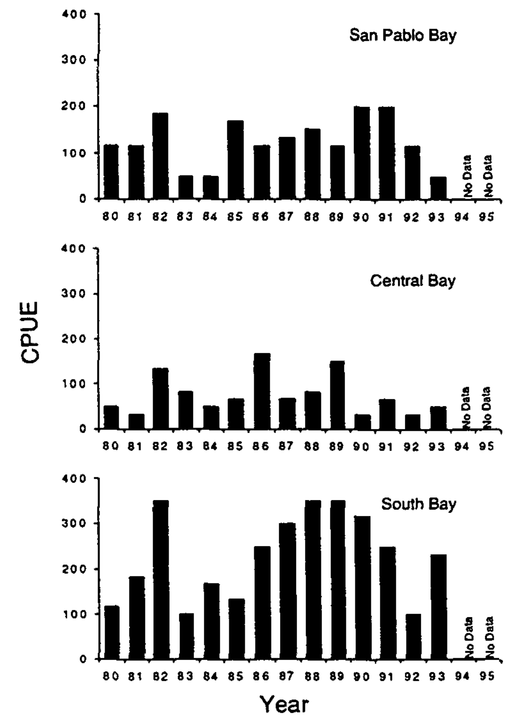

Figure 26 Annual distribution by region of age–1+ jacksmelt collected with the midwater trawl from 1980 to 1993. The index period was February to July.

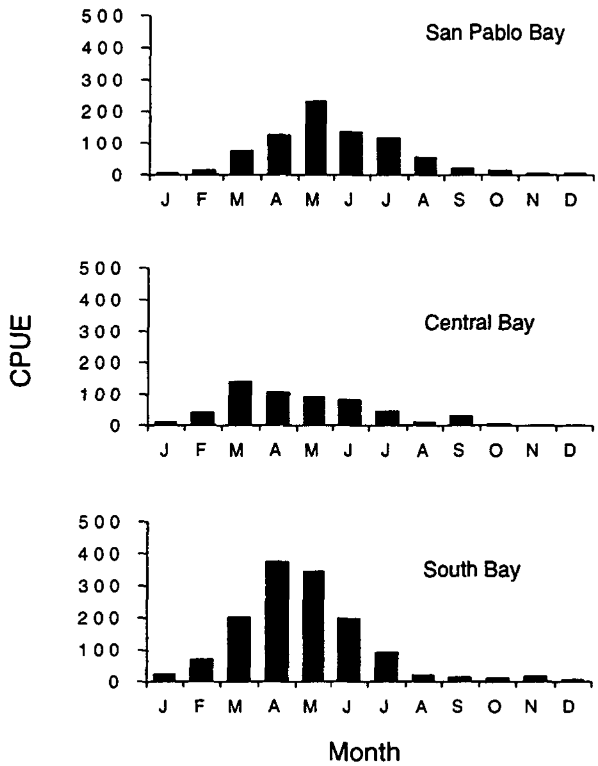

Figure 27 Seasonal distribution by region of age–1+ jacksmelt collected with the midwater trawl from 1981 to 1988

Temperature and Salinity

Collection temperatures for age–0 jacksmelt differed between the midwater trawl and beach seine (Figures 28A and 29A). In the beach seine, they were collected from 6.6 to 30.5 °C, $\bar{\chi}$ = 20.6 °C and in the midwater trawl, from 8.8 to 22.2 °C, $\bar{\chi}$ = 18.0 °C.

In the midwater trawl, age–0 fish were collected at higher salinities than in the beach seine (Figures 28B and 29B). Salinity ranged from 7.2‰ to 34.3‰, $\bar{\chi}$ = 29.3‰ in the midwater trawl, and from 0.2‰ to 34.3‰, $\bar{\chi}$ = 21.8‰ in the beach seine.

In the midwater trawl, age–1+ fish were collected from cooler temperatures and lower salinities than age–0 fish (Figure 30A): 8.2 to 21.6 °C, $\bar{\chi}$ = 15.9 °C and 3.5‰ to 33.5‰, $\bar{\chi}$ = 24.0‰.

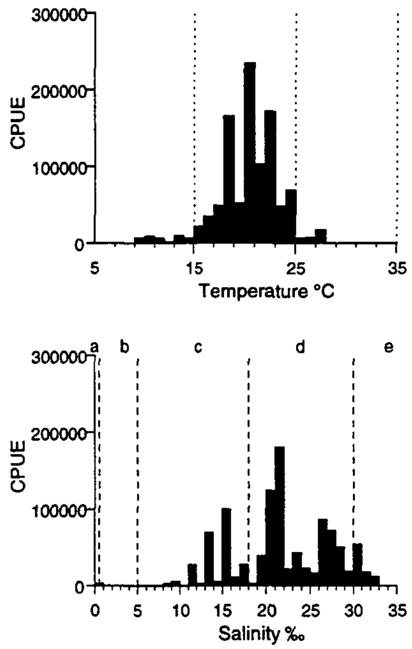

Figure 28 Temperature and salinity distributions of age-0 jacksmelt in the beach seine. The vertical lines on the salinity graph mark the boundaries of the Venice system ranges: (a) limnetic, (b) oligohaline, (c) mesohaline, (d) polyhaline, and (e) euhaline.

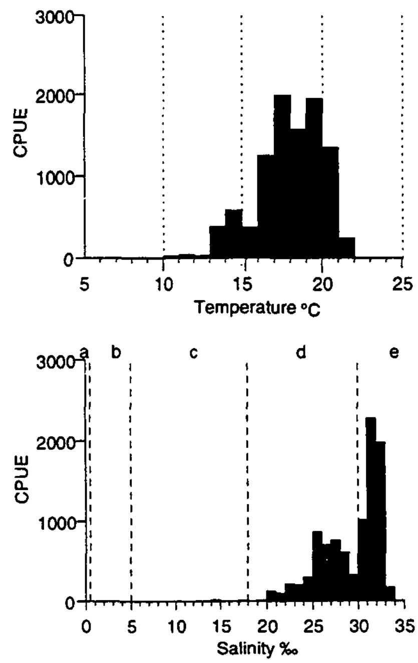

Figure 29 Temperature and salinity distributions of age–0 jacksmelt collected with the midwater trawl. The vertical lines on the salinity graph mark the boundaries of the Venice system ranges: (a) limnetic, (b) oligohaline, (c) mesohaline, (d) polyhaline, and (e) euhaline.

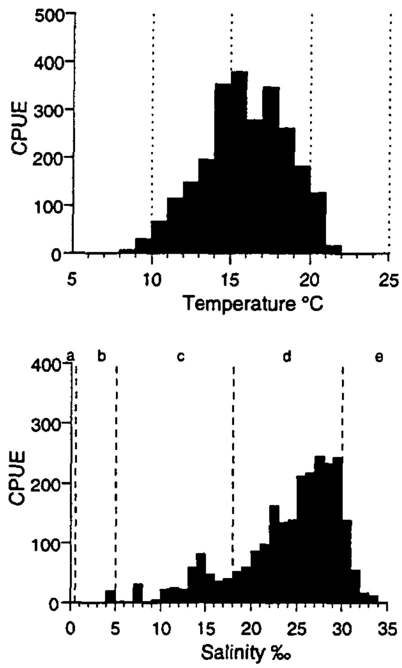

Figure 30 Temperature and salinity distributions of age–1+ jacksmelt collected with the midwater trawl. The vertical lines on the salinity graph mark the boundaries of the Venice system ranges: (a) limnetic, (b) oligohaline, (c) mesohaline, (d) polyhaline, and (e) euhaline.

Discussion

Jacksmelt use the estuary primarily as a spawning and nursery area but some remain there all year. The low winter catch may be due to movement into the shallows or out of the estuary to the coast. Our gear is ineffective in catching age–1+ fish in the shallows as shown by the low beach seine catches. However, Baxter (1980) found that jacksmelt juveniles and adults reside in the estuary in summer and move to coastal water in fall.

Jacksmelt adults move to shallows to spawn. Larvae were present throughout the year and age–0 fish were collected in all months in the beach seine, demonstrating that spawning may occur all year. The larvae were most abundant from December to April, and age–0 fish were most abundant from April through July. Reproductive activity appeared to peak in January and February. Catch of age–0 fish decreased after June and a 2nd peak occurred in September, indicating that spawning may take place more than once in a season. These results agree with the findings of other studies that report different spawning seasons: January to March (Middaugh and others 1990) and September to April (Ganssle 1966).

Age–0 fish seemed to expand their distribution to San Pablo Bay in the low outflow years 1981, 1985, and 1987, but not in 1988. From August to October, they used San Pablo Bay when the salinities there were at annual maxima, but were not quite as high as the salinities in South and Central bays. In general, salinity was <28‰ in San Pablo Bay and >30‰ in South and Central bays during these months.

The age–0 beach seine and midwater trawl geographical distributions differed. It is unclear what governed the distribution pattern of age–0 fish and the adult spawning area as the distribution varied from year to year. Low midwater trawl gear efficiency may affect the catches of age–0 and age–1+ jacksmelt. For example, age–0 fish were collected in the beach seine in Suisun Bay and the west delta but no age–0 or age–1+ fish were collected there with the midwater trawl.

Age–0 fish caught in the beach seine were in less saline water and were found over a wider salinity range than those taken in the midwater trawl. This is due to the wider geographical distribution of fish caught in the beach seine and the limitation of beach seining from 1980 to 1986, when wet years predominated.

Age–1+ fish were collected in lower salinities than age–0 fish but it is not clear what governed their abundance and distribution. The lack of data during the drought years makes it difficult to determine if outflow affected distribution. However, age–1+ abundance remained relatively constant during the drought, whereas age–0 abundance declined during the drought and remained relatively low after it.

Inland Silverside

The inland silverside, *Menidia beryllina*, is native from the Gulf of Mexico to the Mississippi River basin to Oklahoma and Tennessee. It is also found along the Atlantic Coast from Massachusetts to Vera Cruz, Mexico (Moyle 1976, Middaugh and Hemmer 1992). It was introduced into the Blue Lakes and Clear Lake, California in 1967 (Cook and Moore 1970), and small lakes in Alameda and Santa Clara counties in 1968. It has since moved into the Sacramento–San Joaquin Delta and San Francisco Bay.

It is most abundant in the littoral zone of warm water lakes and reservoirs. It schools by size on the surface and occurs in the top 2 meters of the water column. It prefers protected areas over sand or gravel. The inland silverside feeds primarily on zooplankton including cladocerans, instars of chironomid midges and gnats during the day, and amphipods and insect larvae at night (Bachen and Elston as cited in Moyle 1976).

The inland silverside is short-lived and grows quickly, reaching half of its total length in its 1st year. It reaches a maximum of 150 to 160 mm TL. Females grow faster than males and most spawn and die in their second summer. Like the topsmelt and jacksmelt, spawning occurs over beds of aquatic plants or among emergent vegetation. The reproductive season varies according to latitude, and fecundity is positively related to maternal size (Middaugh and Hemmer 1992).

Inland silversides were collected primarily in the beach seine in the San Francisco Estuary (see Tables 1, 2, and 3). Only 4 were collected in the otter trawl and 3 in the midwater trawl compared to 4,982 in the beach seine. They were collected in and upstream of Carquinez Strait and were most abundant from July to October. Sizes ranged from 16.0 to 104 mm. They were collected in salinities ranging from 0.1‰ to 33.1‰, but only 150 fish were found in salinities >20‰. The temperature range for inland silverside was 5 to 25 °C.

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Cottidae

Randall Baxter

This section describes the abundance and distribution trends for species of the family Cottidae commonly collected in the San Francisco Estuary. In some cases, factors are identified that affect the abundance and distribution of a species. The description of how each species uses the estuary is then compared to what is known of its life history from investigations of other coastal habitats. For uncommonly collected species, brief summaries of size at capture, and dates and locations of capture are combined in a single section at the end.

The family Cottidae is composed of primarily small, bottom dwelling, nearshore, marine species. Most species have large heads, mouths, and pectoral fins, followed by a tapered body, a slim caudal peduncle and moderately-sized tail. Cryptic coloration and lack of a swim bladder make them well suited to a demersal existence. In general, cottids spawn adhesive eggs on hard substrates that hatch into planktonic or semi-planktonic larvae and develop into demersal juveniles and adults (Wang 1986).

Nine species of cottids were collected from the San Francisco Estuary between 1980 and 1995 (Table 1): Pacific staghorn sculpin, *Leptocottus armatus*; prickly sculpin, *Cottus asper*; bonehead sculpin, *Artedius notospilotus*; brown Irish lord, *Hemilepidotus spinosus*; red Irish lord, *Hemilepidotus hemilepidotus*; scalyhead sculpin, *Artedius harringtoni*; cabezon, *Scorpaenichthys marmoratus*; fluffy sculpin, *Oligocottus snyderi*; and tidepool sculpin, *Oligocottus maculosus* (Robins and others 1991). All are native to the eastern Pacific Ocean or to streams draining into it. All are marine species, except for the Pacific staghorn sculpin and the prickly sculpin, which are euhaline and freshwater species, respectively, although larvae of prickly sculpin are tolerant of salt water (Wang 1986).

Table 1 Total catch by species for cottids collected between January 1980 and December 1995. See Methods chapter, Table 1 for duration of use for each gear type.

Species	*Plankton Net Larvae*	*Plankton Net Juveniles*	*Beach Seine*	*Otter Trawl*	*Midwater Trawl*
Pacific staghorn sculpin	5,576	1	5,143	13,015	468
Prickly sculpin	9,985	21	3	66	1
Bonehead sculpin	34	0	0	79	1
Brown Irish lord	9	0	0	3	0
Red Irish lord	0	0	0	1	0
Scalyhead sculpin	0	0	0	1	0
Cabezon	131	0	2	0	0
Fluffy sculpin	0	0	1	0	0
Tidepool sculpin	4	0	0	0	0

Pacific Staghorn Sculpin

Introduction

The Pacific staghorn sculpin, *Leptocottus armatus*, ranges from San Quintin Bay, Baja California, to Chignik, Alaska (Miller and Lea 1972). It inhabits waters from the intertidal zone to a depth of 91 m (Miller and Lea 1972) and is common in brackish water and occasionally in freshwater (Jones 1962, Pearcy and Myers 1974, Moyle 1976). It is one of the most commonly caught species by pier and dock anglers, and it is likely to be the 1st fish caught by many young coastal anglers, particularly in the San Francisco region (Frey 1971, Karpov and others 1995). It has commercial value only as a baitfish.

Spawning occurs from October through April and peaks in January and February (Jones 1962, Wang 1986). The staghorn sculpin spawns both in estuaries and on the open coast (Wang 1986). Eggs are demersal, temporarily adhesive, and are deposited in clusters on a variety of substrates (Jones 1962, Wang 1986). In laboratory experiments, eggs hatched 9 to 14 days after fertilization at 15 °C. A salinity of 26‰ produced the best hatch of normal, healthy larvae (Jones 1962). At hatching, larvae measure 3.8 to 4.9 mm (Jones 1962). They are planktonic and can tolerate lower salinities better than the eggs can (Jones 1962, Wang 1986). Wang (1986) found few juveniles >10–15 mm TL in plankton samples and believed staghorn become demersal at this size. Larval and juvenile staghorn sculpins are common in bays and estuaries. They use shallow marine, brackish, and fresh water as nursery areas (Jones 1962, Eldridge and Bryan 1972, Pearcy and Myers 1974, Nybakken and others 1977, Greer and others 1980, Horn 1980, Bottom and others 1984, Bayer 1985, Wang 1986).

As the fish grow, they move to deeper water (Jones 1962). Sexual maturity is reached toward the end of or soon after their 1st year (Jones 1962, Tasto 1975). After spawning, adults leave the shallow spawning grounds for deeper, offshore areas (Tasto 1975). Adults reach a maximum size of about 305 mm TL (Miller and Lea 1972).

The staghorn sculpin is one of the most abundant demersal fish in the San Francisco Estuary as well as in other west coast estuaries (Levy and Levings 1978, Horn 1980, Bayer 1981, Bottom and others 1984), and because of its numbers and feeding behavior, it may be one of the most important predators of estuarine invertebrates (Tasto 1975, Karl 1979, Posey 1986, Armstrong and others 1995). In turn, staghorn sculpin provide food for a variety of wading and diving birds (Tasto 1975, Bayer, 1985). Thus, the staghorn sculpin is an important link in the estuarine food chain.

Methods

Staghorn sculpin were categorized as larvae, age 0, and adults for analyses. Fish collected in the plankton net were classified as larvae unless they possessed a full complement of dorsal fin rays. Fish 10 to 20 mm caught in the beach seine and otter trawl were assumed to have settled from the plankton and to be fully developed; hence, they were classified as age 0. Since staghorn sculpin mature in September at or near the end of their first year (Jones 1962, Tasto 1975), fish older than age 0 are classified as adults. An October 1 hatching date was assumed for all fish. Separation of age–0 and adult fish was accomplished by visual inspection of beach seine and otter trawl length-frequency data (mm TL). Cutoff lengths used to separate age classes for each month from October to September were as follows: 50, 60, 70, 80, 90, 100, 112, 127, 146, 166, 172, and 178 mm TL. Fish hatched in the fall were identified as part of next calendar year's year class; thus, fish hatched from October 1 to December 31, 1994 were part of the 1995 year class.

Annual abundance indices for larvae were calculated from plankton net data based upon an October to September index period. For both age–0 and adult fish, annual abundance indices were calculated from otter trawl data using February to September index periods (we did not sample from November through January in many years). Annual distribution (mean CPUE by region) analyses were based upon the same time period for each age group. Seasonal abundance indices were calculated as monthly means by age group for 1981 to 1988. Seasonal distribution was calculated as mean CPUE by age group, region, and month for 1981 to 1988. The depth distribution of each staghorn sculpin age group was the average monthly CPUE in the beach seine (intertidal areas) and in the otter trawl shoal stations (subtidal areas) and channel stations (deep areas) for 1981 to 1988. The depth cutoff between shoal and channel stations is about 6 m. Seasonal salinity and temperature distributions were calculated as the mean ±1 standard deviation of CPUE-weighted bottom salinity and bottom temperatures by month and age group for 1981 to 1988.

Results

Catch and Length Analyses

All gear types collected staghorn sculpin in substantial numbers (see Table 1). Larvae caught with the plankton net ranged from 3.0 to 14.3 mm TL but almost all were 4.0 to 10.3 mm TL. Of the 3,302 measured, only 7 larvae were <4.0 mm and only 31 were >10.3 mm. Fish collected with the beach seine ranged from 9 to 297 mm TL and those in the otter trawl from 19 to 272 mm TL (Figure 1). Age–0 fish in the 10 to 20 mm size range were first captured in November and were last caught in May. Based upon increases in modal length, age–0 fish grew at about 13.6 mm per month from February to September. The largest age–0 fish reached 180 to 190 mm by September. There was some overlap in length between age–0 fish and adults from March to September. Adult fish appeared to be primarily age 1. They grew slowly, averaging about 4.2 mm per month from October to April. Few fish >210 mm were captured.

Abundance and Distribution of Larvae, Juveniles, and Adults

Annual Abundance

Larval abundance was moderate in 1981, declined slowly to a minimum of 24,739 in 1983, increased slightly in 1984, then increased sharply to a maximum of 132,317 in 1985 (see Figure 2, Table 2). Larval abundance declined again from 1985 to 1988, then increased slightly in 1989.

Between 1980 and 1988, abundance of age–0 staghorn sculpin was higher in even than in odd years, except for 1985 (Figure 2, Table 3). From 1989 to 1995, abundance was higher in odd years. Maximum abundance was reached in 1986 and the minimum in 1981. Adult abundance was highest in 1986, lowest in 1991, and consistently low from 1988 to 1995 (see Figure 2, Table 4).

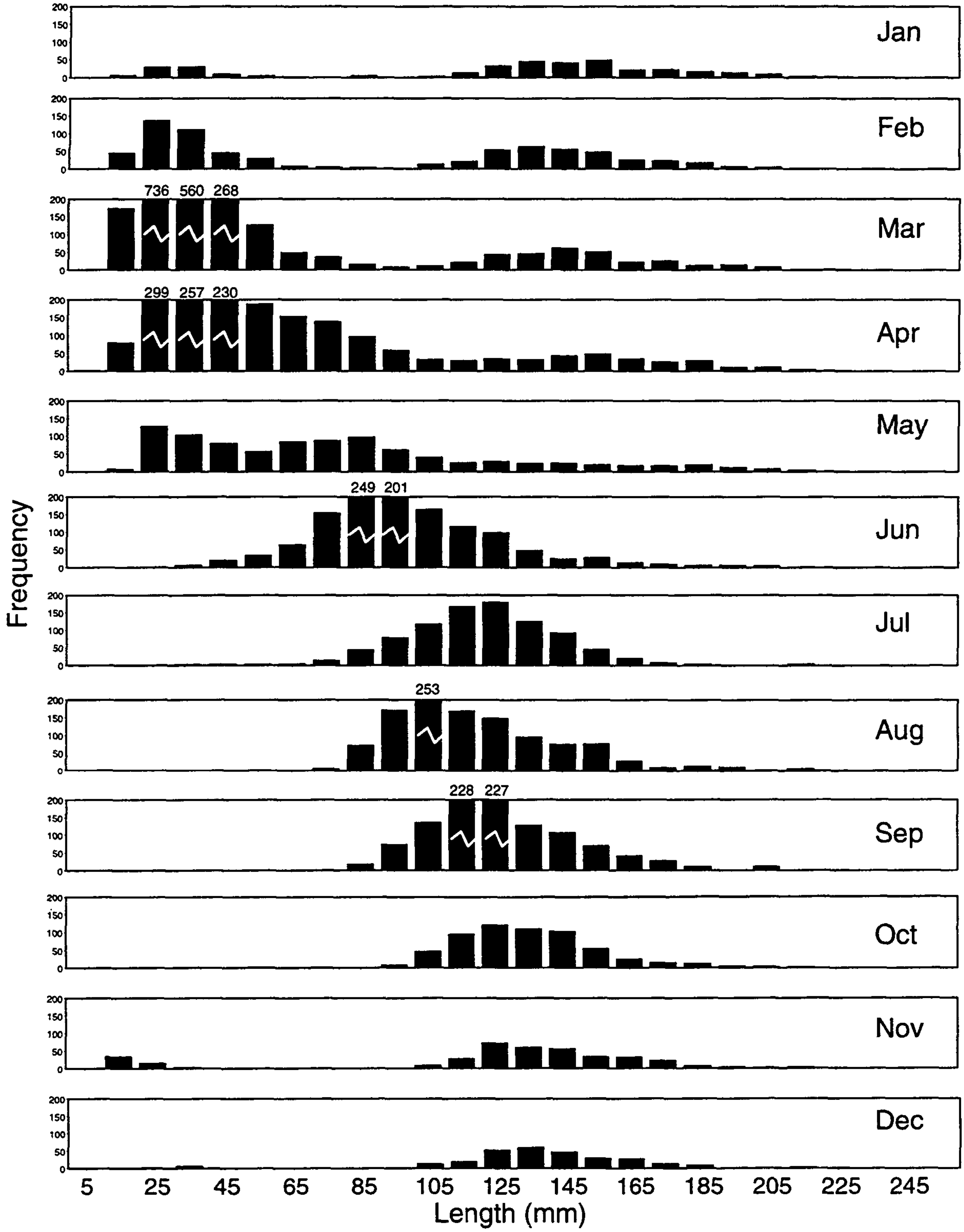

Figure 1 Length frequency (mm TL) of Pacific staghorn sculpin collected with the beach seine (1981 to 1986) and otter trawl (1981 to 1988)

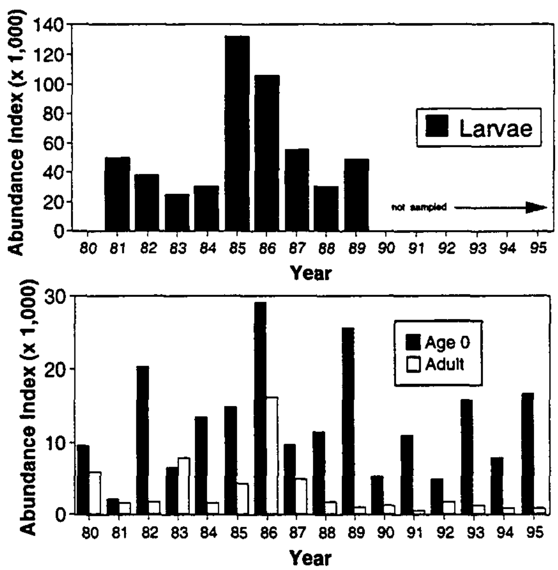

Figure 2 Annual abundance of Pacific staghorn sculpin larvae collected with the plankton net (top), and age–0 and adult fish collected with the otter trawl (bottom). In 1980, plankton sampling was insufficient to calculate an index for larvae.

Table 2 Monthly abundance of larval Pacific staghorn sculpin captured in the plankton net from 1980 to 1989. Annual abundance indices are in the far right column. Monthly abundance indices are in the bottom row (mean 1981 to 1989 monthly abundance).

Year	*Oct*	*Nov*	*Dec*	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct–May*
1980					126574	43947	15000	5591	0	0	0	0	
1981	0	1910	26271	190556	99837	67245	12435	0	565	0	0	0	49782
1982	1129	2222	8055	36970	183628	56581	20805	0	0	0	0	0	38674
1983	7157	2285	25252	76938	75223	8116	1469	1469	0	0	0	0	24739
1984	0	1827	5322	48688	153813	32293	3332	0	0	0	0	0	30659
1985	0	23821	87549	346660	400070	171077	27570	1791	0	0	0	0	132317
1986	0	1074	47735	522580	159401	80842	33883	0	0	0	0	0	105689
1987	0	2865	86158	92634	193995	63425	5733	0	0	0	0	0	55601
1988	753	1433	11748	77068	103738	41816	6841	0	1074	0	0	0	30425
1989	0	1074	15828	116872	131334	123576	0	0					48586
1981–1989	1130	4680	37261	174012	171213	65174	14009	408	205	0	0	0	

Table 3 Monthly abundance of age-0 Pacific staghorn sculpin captured in the otter trawl from 1980 to 1995. Annual abundance indices are in the far right column. Monthly abundance indices are in the bottom row (mean 1981 to 1989 monthly abundance).

Year	*Oct*	*Nov*	*Dec*	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Feb–Sep*
1980					668	775	2662	3242	12494	30844	16212	9458	9544
1981	189	0	111	219	0	959	4443	2417	1261	2377	2885	2852	2149
1982	0	0	0	0	0	0	2697	16421	45096	9060	45294	45091	20457
1983	0	0	0	156	0	1017	1368	1506	15397	20392	11606	1090	6547
1984	0	0	0	0	0	0	3284	2251	34811	53731	5062	8680	13477
1985	48	0	0	0	0	622	492	1702	29953	18177	36918	30756	14828
1986	134	0	0	0	281	3511	10913	11929	25333	49658	81408	50400	29179
1987	0	0	188	76	313	0	0	844	7028	20212	19433	30010	9730
1988	0	243	62	0	0	414	3507	11803	33780	30075	4276	7601	11432
1989	0	0	0	0	250	404	4899	26127	32023	25007	90903		25659
1990					0	542	1200	3955	6224	12352	14410	3912	5324
1991	0				0	2312	2741	6564	19832	28757	14504	12717	10928
1992	0				0	1733	4990	11022	11305	2769	2494	5772	5011
1993	352				0	0	5366	37625	16982	37477	23969	4470	15736
1994	0				97	657	919	1904	16148	6948	29197	7330	7900
1995	0			0	0	6293	7559	16825	29504	34730		21129	16577
1996	0	0	0										
1981–1989	41	27	40	50	94	770	3511	8333	24965	25410	33087	22060	

Table 4 Monthly abundance of adult Pacific staghorn sculpin captured in the otter trawl from 1980 to 1995. Annual abundance indices are in the far right column. Monthly abundance indices are in the bottom row (mean 1981 to 1989 monthly abundance).

Year	*Oct*	*Nov*	*Dec*	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Feb–Sep*
1980					23662	16283	1158	2614	1664	857	864	189	5911
1981	7584	14775	2112	2998	2571	1565	5241	2380	326	216	1161	162	1703
1982	3865	2440	1292	16048	1317	752	1769	7038	1729	211	1370	230	1802
1983	16761	9864	3746	14139	9571	21150	20080	5206	3385	1286	2308	55	7880
1984	5530	5054	4983	460	974	3286	3264	3042	1336	1212	0	216	1666
1985	19523	4057	5895	7427	17956	3970	6352	2819	2540	0	487	243	4296
1986	31453	23957	28926	19870	47146	37556	25237	5906	5535	1367	2662	3213	16078
1987	7193	4627	7442	8010	17279	8916	2787	2874	1952	2391	1974	1163	4917
1988	11229	4583	12444	6106	2978	2541	6255	2881	192	0	0	0	1856
1989	807	541	501	299	1287	2153	1937	597	659	0	403		1005
1990					5909	2272	612	1947	0	0	0	0	1343
1991	2574				1619	435	307	591	406	688	0	0	506
1992	6731				4419	2723	2712	4411	622	0	0	0	1861
1993	1940				2336	3292	1298	2036	1263	0	297	0	1315
1994	1959				2190	2194	568	817	730	270	297	0	883
1995	567			1541	703	2245	0	1290	1584	0		865	955
1996	1556	4841	4772										
1981–1989	11549	7766	7482	8373	11231	9099	8102	3638	1962	743	1152	660	

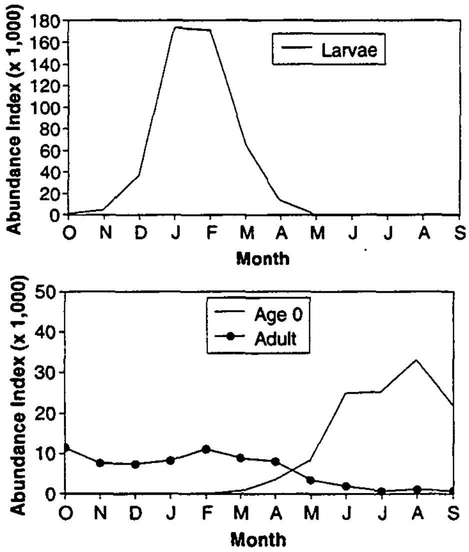

Figure 3 Seasonal abundance of Pacific staghorn sculpin larvae collected with the plankton net (top), and age–0 and adult fish collected with the otter trawl (bottom). Data are mean abundance indices by month for 1981 to 1988.

Seasonal Abundance

Larval staghorn sculpin were initially collected in October and abundance rapidly increased to a maximum in January (Figure 3, see Table 2). Abundance remained high through February, then declined sharply to very low levels in May and June. None were collected after June.

A few age–0 staghorn sculpins were collected from October through February when their abundance began a rapid increase to June (see Figure 3, see Table 3). Peak age–0 abundance occurred in August, followed in September by a sharp decline as the spawning period approached.

Throughout the November to April spawning period, adult abundance remained stable except for a slight increase in February (see Figure 3, Table 4). After February, abundance declined steadily to a minimum in July and remained low until October.

Annual Distribution

Larval staghorn sculpins were collected from South Bay to the west delta, but were rare in the west delta (Figure 4). Few larvae were collected in Suisun Bay, and none were collected there during the high outflow years 1982 and 1983. In most years with low outflow during the spawning period (1981, 1987 to 1989), larval CPUE was highest in San Pablo Bay. In the low outflow year 1985, larval CPUE was highest in South Bay, a distribution pattern found in most high outflow years (for example, 1982, 1983, 1986). Thus, larval CPUE tended to be higher in San Pablo Bay during dry years and in South Bay during wet years.

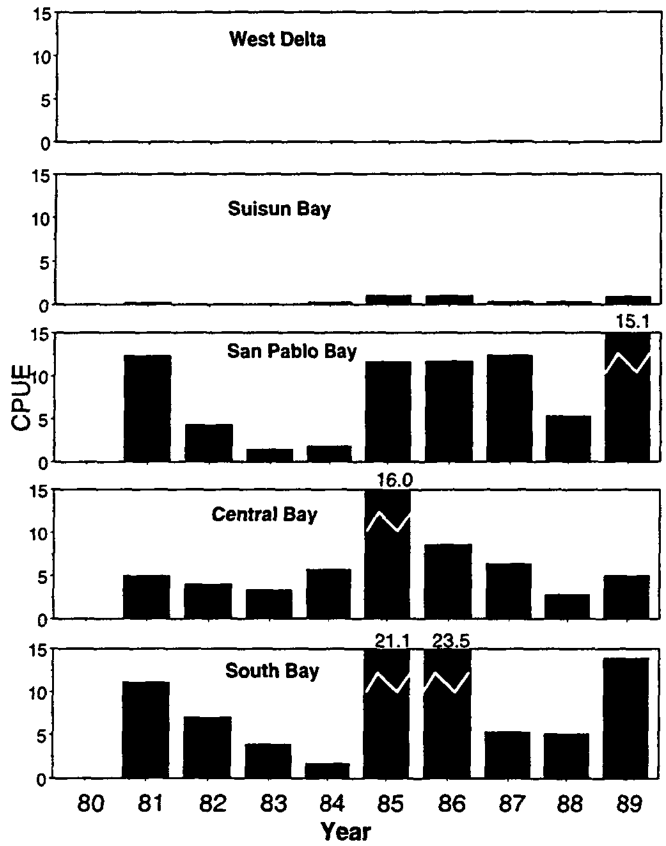

Figure 4 Annual distribution of Pacific staghorn sculpin larvae collected with the plankton net. Data are mean CPUE by region for October to September.

By the time age–0 staghorn sculpins were captured by the otter trawl, they had moved upstream relative to larvae. Age–0 staghorn were collected from South Bay to the west delta in all years except 1982 and 1983, when none were captured in the west delta (Figure 5). From 1980 through 1988, age–0 CPUE was highest in San Pablo Bay in every year except 1985 and 1987, when it was highest in Central Bay. After 1988, maximum CPUE shifted between Central Bay, San Pablo Bay and Suisun Bay (see Figure 5). Other indications for the upstream movement of age–0 fish relative to larvae were the higher CPUE in Suisun Bay compared to South Bay, and the substantial use of the west delta during most low outflow years (for example, 1981, 1985, 1988, and 1990 to 1992).

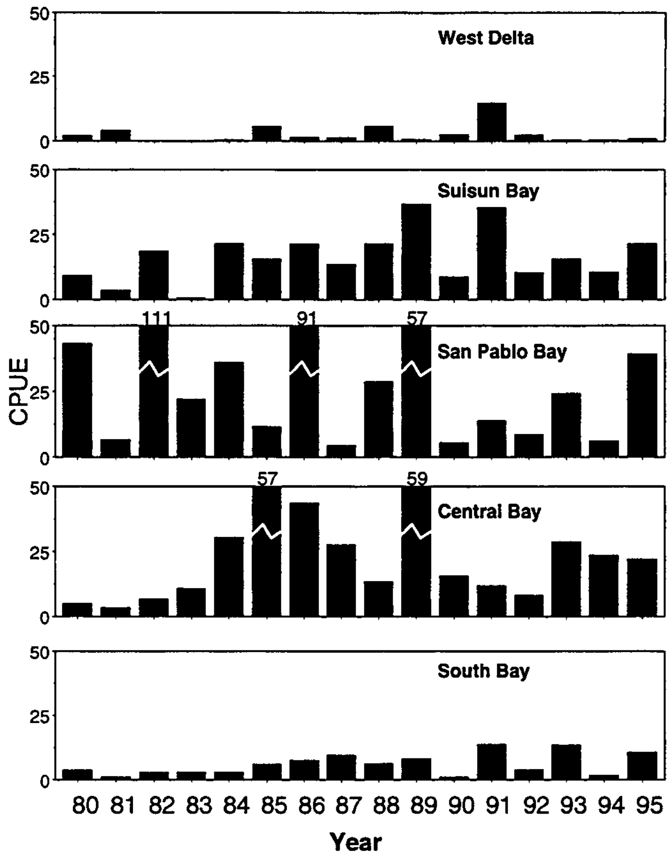

Figure 5 Annual distribution of age–0 Pacific staghorn sculpin collected with the otter trawl. Data are mean CPUE by region for February to September.

Although adult staghorn sculpins were collected from all regions during the study period, they were uncommon in Suisun Bay and were only collected in the west delta in 1986 (Figure 6). South Bay CPUE increased substantially during the high outflow years 1983 and 1986, but not in other high outflow years. Maximum adult CPUE was found in Central Bay except for the low outflow years 1981 and 1988 to 1991, when it was in San Pablo Bay. Adult staghorn were most broadly distributed during 1986, their year of maximum abundance (see Figure 2).

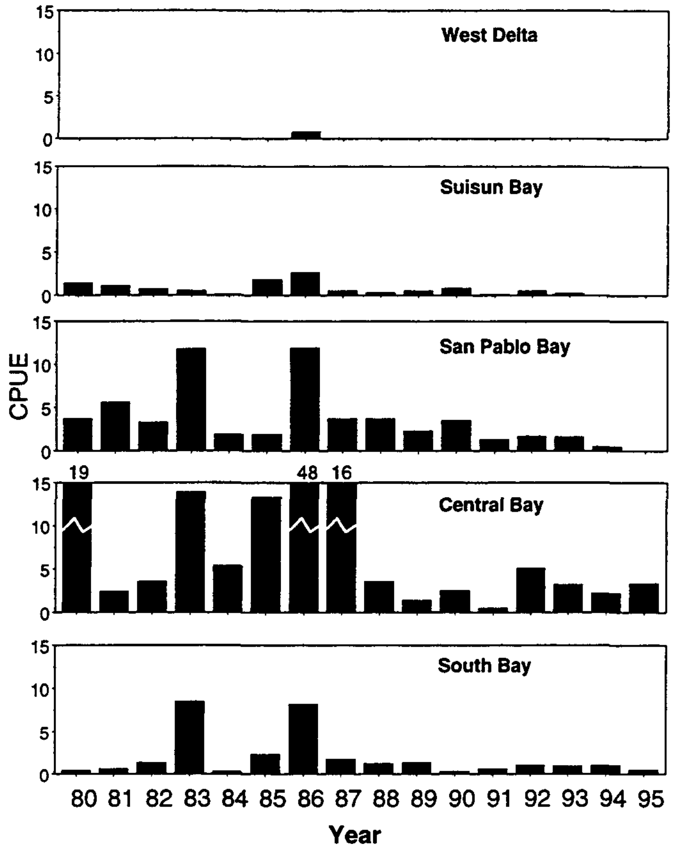

Figure 6 Annual distribution of adult Pacific staghorn sculpin collected with the otter trawl. Data are mean CPUE by region for February to September.

Seasonal Distribution

In October, staghorn sculpin larvae were evenly distributed from South Bay to San Pablo Bay (Figure 7). In December, as larval densities increased, the first collections of larvae occurred in Suisun Bay. Larval density reached a maximum in South and San Pablo bays in January and in Central and Suisun bays in February. February was the only month when staghorn larvae were collected in the west delta. In March, CPUE declined in all regions except Suisun Bay. Between March and June, CPUE declined to zero from the west delta downstream to San Pablo Bay in successive months. In June, the last few larvae were collected in South and Central bays.

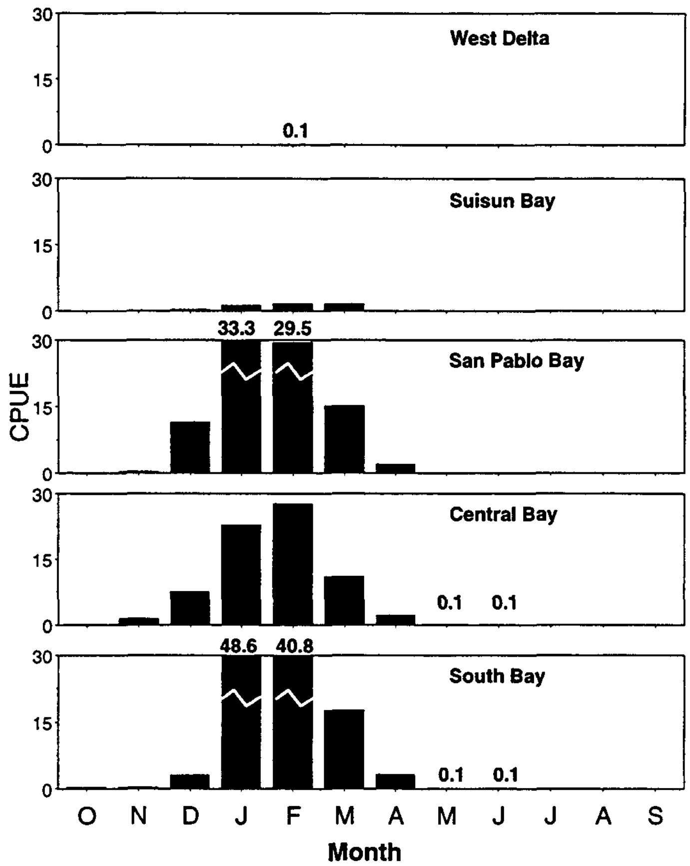

Figure 7 Seasonal distribution of Pacific staghorn sculpin larvae collected with the plankton net. Data are mean CPUE by region for 1981 to 1988.

Age–0 staghorn sculpins recruited to the otter trawl sporadically from October to February (Figure 8). Beginning in March or April, recruitment increased in all regions. Age–0 fish used Suisun Bay and the west delta more often than larvae (see Figures 7 and 8). After June, numbers of age–0 fish declined in South Bay and remained at much lower levels through September. However, in Central Bay, CPUE remained high through September after peaking in July. Age–0 fish density peaked in San Pablo Bay in June at a level higher than any other region and remained high through September. In Suisun Bay, CPUE increased through September. After June, CPUE in the west delta declined to low levels in July and August, but increased sharply to its highest level in September.

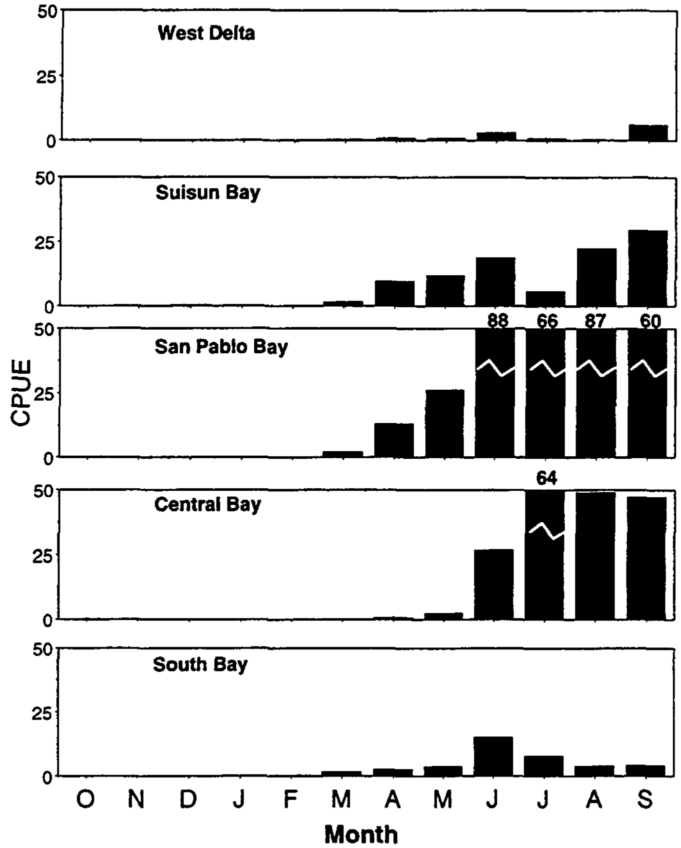

Figure 8 Seasonal distribution of age–0 Pacific staghorn sculpin collected with the otter trawl. Data are mean CPUE by region for 1981 to 1988.

From October to December, adult staghorn sculpins were found in all regions (Figure 9). Their numbers decreased in all regions in November and continued to decline in the west delta and Suisun Bay through March and April. From November to February, CPUE in San Pablo Bay remained stable, whereas it increased in Central and South bays. Beginning in March and continuing through the summer, CPUE declined in South, Central, and San Pablo bays.

Age–0 staghorn sculpins were taken almost exclusively in the intertidal zone from October to February (Figure 10). Density in the intertidal zone increased exponentially from December to March, yet very few were caught on shoals or in channels during this period. From March to July, many age–0 fish moved to deeper water, first to shoals, then to channels. By September, density in channels was higher than in shoals for the first time, and few fish remained in intertidal areas.

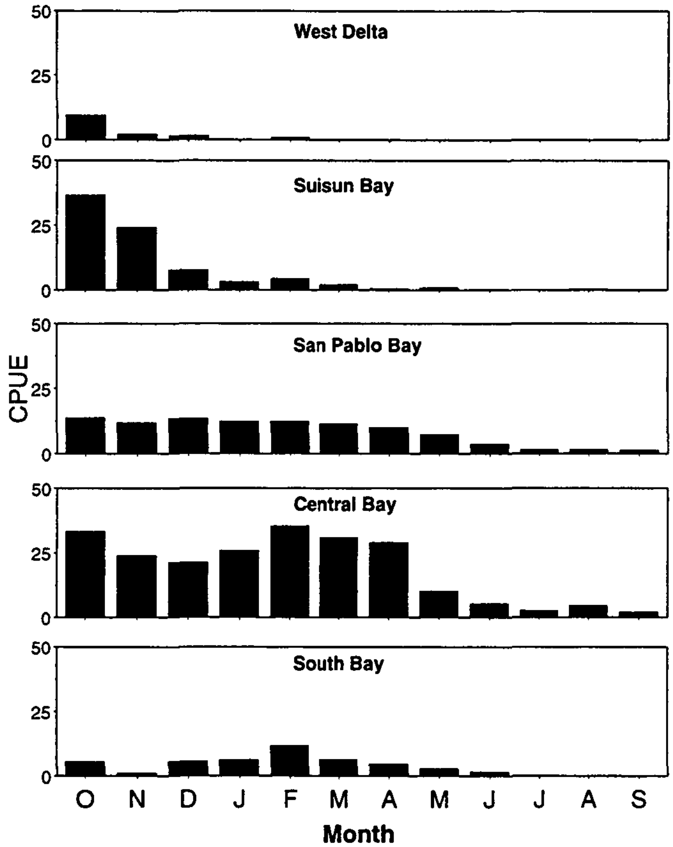

Figure 9 Seasonal distribution of adult Pacific staghorn sculpin collected with the otter trawl. Data are mean CPUE by region for 1981 to 1988.

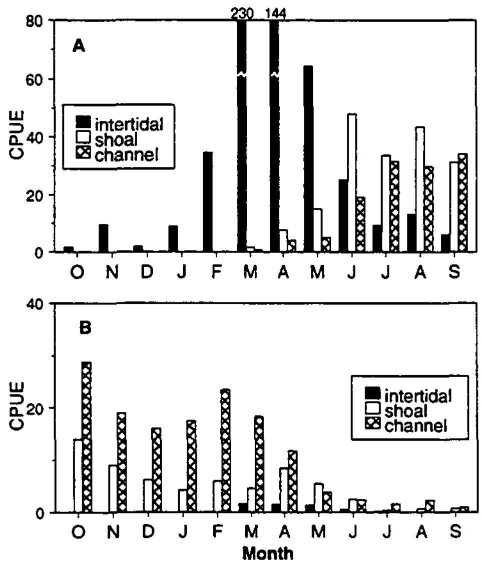

Figure 10 Depth distribution by month of (A) age–0 and (B) adult Pacific staghorn sculpin collected with the beach seine (intertidal) and the otter trawl (shoal and channel). Data are mean CPUE by month and age group for 1981 to 1986 for the beach seine and for 1981 to 1988 for the otter trawl.

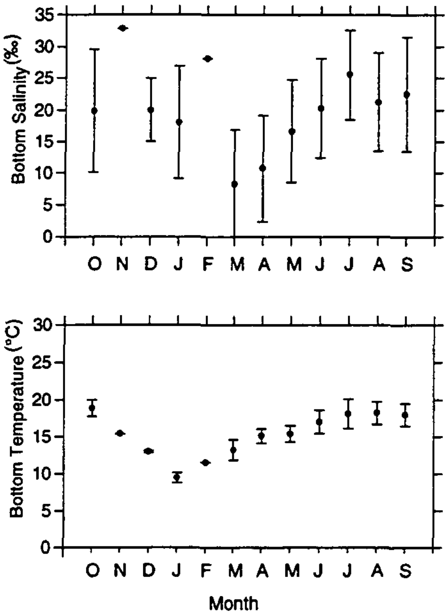

Figure 11 Salinity and temperature distributions of age–0 Pacific staghorn sculpin collected with the otter trawl. Data are mean ±1 standard deviation CPUE-weighted bottom salinity and bottom temperature by month for 1981 to 1988.

The trend toward increased use of channels rather than shoal and intertidal areas seen for age–0 staghorn sculpin in September continued for adult fish in October and reached a peak in February (see Figure 10). Adult fish were collected in intertidal areas from March to July only. During these months, shoal use increased in April, then CPUE declined in both channels and shoals. In May and June, shoal CPUE was equal to or higher than that of channels, but the reverse was true for all other months (see Figure 10).

Salinity and Temperature

Age–0 staghorn sculpins were captured throughout the salinity range found in the estuary, <0.1‰ to >34‰. The few fish collected by the otter trawl from October to February came from water with a mean salinity of about 19‰ to 20‰ or higher (Figure 11). From March through July, as numbers increased in the otter trawl and as estuarine salinities increased, age–0 fish were found in steadily increasing salinities. Starting at a mean of 8.3‰ in March, the salinity increased to of 25.6‰ in July, before declining to 21‰ and 22.5‰ in August and September.

Age–0 staghorn sculpins were in water with a mean temperature of 9.5 °C in January (see Figure 11). Temperatures at which they were found rose steadily to about 18 °C in July, stabilized until September, and reached a high point of about 19 °C in October.

The movement of adult fish out of the west delta and Suisun Bay from October to December was reflected in the increased mean salinity in December to 26.5‰ (Figure 12). After the December peak, declining estuarine salinities caused by high outflow were responsible for most of the downward shift in salinity to a minimum of 15.2‰ in March. Otherwise, the continued emigration from the less saline west delta and Suisun Bay during this period should have increased their salinity range. After March, adult fish were collected from increasingly saline waters through summer (see Figure 12). This increase was due partly to increasing estuarine salinities and partly to a continued downstream movement (see Figure 9). Even when their salinity range reached a maximum in July, adult fish were still collected at salinities as low as 9.5‰.

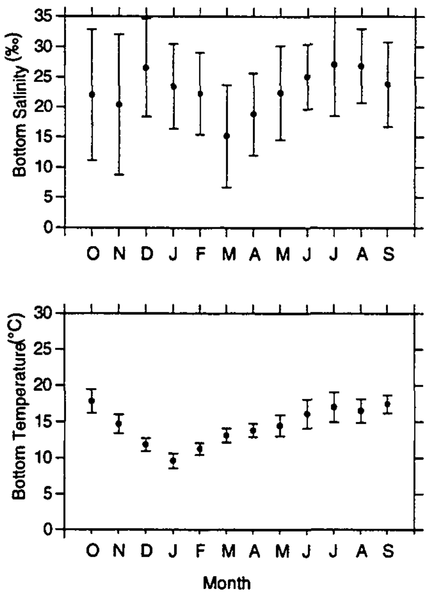

Figure 12 Salinity and temperature distributions of adult Pacific staghorn sculpin from the otter trawl. Data are mean ±1 standard deviation CPUE-weighted bottom salinity and bottom temperature by month for 1981 to 1988.

Adult staghorn sculpins were found at temperatures ranging from 6.6 °C in January to 22.1 °C in September. Monthly mean temperatures ranged from 9.6 °C in January to 17.8 °C in October (see Figure 12). Their temperature distribution was fairly stable during summer at means of 16.1 to 17.8 °C from June to October, then decreased rapidly in winter. Although the salinity and temperature distributions of age–0 and adult fish overlapped, age–0 fish were usually found in fresher, warmer water than adults.

Discussion

The Pacific staghorn sculpin completes its entire life cycle within the estuary, but length frequency data suggest adult fish emigrate or die before their 2nd spawning cycle: there were few fish ≥180 mm present between November and April (see Figure 1). Adults (primarily age 1) appeared to migrate to the open coast after their 1st spawning (City of San Francisco, Bureau of Water Pollution Control, unpublished data). Adult distribution shifted toward Central Bay from February to July as their abundance declined after spawning, suggesting emigration to the coast. In June 1983, when abundance of age–1 fish was low in the estuary, otter trawl sampling in the Gulf of the Farallones collected 201 age–1 fish (1982 year class) and 6 age–2 fish (1981 year class based upon length frequency) in 7 tows (City of San Francisco, Bureau of Water Pollution Control, unpublished data). Similarly, in June 1984, another smaller group of age–1 fish was caught in the Gulf of the Farallones. Very few age–0 fish were collected in the Gulf of the Farallones (<10 in 35 trawls from October 1982 to June 1984), indicating that most reared in the estuary; therefore, age–1 fish must have migrated to the coast after spawning and remained there through their next spawning cycle. In Anaheim Bay, a similar spring-summer decline in abundance of age–1 fish was also observed and was attributed to mortality and emigration to the open coast of surviving post-spawning fish, although no coastal sampling was conducted to confirm the emigration (Tasto 1975). In other trawl studies, staghorn sculpin age classes were combined, so no shifts in geographical distribution could be detected (Haertel and Osterberg 1967, Fierstine and others 1973, Bottom and others 1984). By contrast, Jones (1962) used otoliths to age 146 adult staghorn from the shrimp fishery in San Francisco Bay and found substantial numbers of age–2 and age–3 fish present. Moreover, the size range (125 to 189 mm TL) of age–2 fish completely overlaps that of fish identified as age 1 by this study during November to April (see Figure 1). This suggests little or no growth in length from age 1 to age 2, as length frequency data clearly indicates that fish can grow to 125 to 189 mm by December to February, only a couple months past their 1st birthday. The length range of age–3 fish (165 to 239 mm) also conflicted with the no-growth hypothesis, as these fish were distinctly larger than the age–2 fish, indicating strong growth between these age groups. Regardless of the accuracy of aging, the shrimp trawl data indicate that older age groups were present in the estuary (Jones 1962).

Based on the collection of larvae, staghorn sculpin spawned throughout the estuary, but spawning in Suisun Bay and the west delta occurred only in low outflow years. In October and November, adult fish moved out of Suisun Bay and the west delta, possibly to spawn. This occurred before or coincident with salinity reductions in these regions. In the laboratory, eggs successfully hatched in salinities from 10.2‰ to 34.3‰, but hatching success was best at intermediate salinities of 17.6‰ and 26.4‰ (Jones 1962). Salinities >10.0‰ did not occur in Suisun Bay and the west delta during winter except in low outflow years. Thus, spawning would usually have to take place downstream from Suisun Bay to be successful.

Age–0 fish moved inshore and toward freshwater soon after settlement, dispersing to all regions of the estuary. This movement occurred from February to May when salinities were at or near annual lows. Similar movements of juveniles into brackish water were observed in Walker Creek, a tributary to Tomales Bay, California, (Jones 1962), and in the Squamish River Estuary, British Columbia (Levy and Levings 1978). Even in the absence of reduced salinities an inshore movement of juveniles occurs in central and southern California bays (Karl 1979, Horn 1980, Yoklavich and others 1991); this movement is apparently enhanced by a slight reduction in salinity (Fierstine and others 1973). In conjunction with the downstream shift of maturing and mature fish, this represents an ontogenic shift in salinity distribution.

Prickly Sculpin

Introduction

The prickly sculpin, *Cottus asper*, is common in coastal streams from the Kenai Peninsula, Alaska to the Ventura River, southern California, and is widespread in the low elevation streams of California's Central Valley (Moyle 1976). Its larvae and juveniles are tolerant of a wide range of water conditions and are commonly found in brackish water (Pearcy and Myers 1974, Moyle 1976, Bottom and others 1984, Jones and Bottom 1984, Wang 1986). It is characterized over most of its range by visible prickles over most of its body; however, in California's Central Valley the smooth-skinned form is typical (Moyle 1976).

Spawning occurs from late February through June, but primarily in March and April in California (Krejsa 1965). Males move to fresh or brackish water spawning areas and prepare nests by digging small hollows under rocks or other solid objects; females follow when ripe (Krejsa 1965, 1967). Eggs are laid in clusters on the ceiling of the nest and are guarded by the male (Krejsa 1967, Moyle 1976). Males may spawn with more than 1 female. At 10 to 12 °C in the laboratory, eggs hatch 19 to 20 days after fertilization (Mason and Machidori 1976). Larvae begin swimming soon after hatching and are swept downstream to slower water where they remain planktonic for 3 to 5 weeks (Krejsa 1967, Mason and Machidori 1976, Moyle 1976). They metamorphose and settle to the bottom at about 12 mm TL (Krejsa 1967, Mason and Machidori 1976). Juveniles hatched from eggs spawned in or near an estuary eventually migrate upstream into tributaries (McLarney 1968). They may begin migrating soon after settling (Moyle 1976) or may remain in the estuarine zone until the summer of the following year before migrating (Mason and Machidori 1976).

As prickly sculpin grow they select pool habitats with progressively deeper and slower water, and better cover (Mason and Machidori 1976). Fish mature during their 2nd, 3rd or 4th year of life depending upon their stock (Patten 1971) at 40 to 70 mm SL (Moyle 1976). They reach a maximum length of about 300 mm TL, but are usually <130 mm (Eschmeyer and others 1983).

Methods

In the plankton net, fish <11 mm were classified as larvae and were measured to the nearest mm TL. Due to the low number of juvenile and adult fish caught, no separation of age groups was made for abundance and distribution analyses. Abundance and distribution analyses for larvae were based upon the plankton net catch and for juveniles and adults combined, the otter trawl catch was used for analysis.

Results

Catch and Length Analyses

Prickly sculpin collected with the plankton net ranged from 4.5 to 50 mm TL, but most were between 5.0 and 7.4 mm TL (Table 5). Prickly sculpin caught with the otter trawl, the beach seine, and midwater trawl ranged from 27 to 137 mm, collectively (Table 6). Since prickly sculpin mature at lengths of 40 to 70 mm SL (Moyle 1976), both juvenile and adult fish were caught (see Table 6). Length modes at 30 to 39, 70 to 79 and 110 to 119 mm, suggest at least 3 age groups were caught.

Abundance and Distribution of Larvae, Juveniles, and Adults

Annual Abundance

Annual, larval prickly sculpin abundance was highest from 1982 to 1984 and next highest in 1986 (Table 7). Abundance was lowest from 1988 to 1989. Larval catch was higher in high outflow years than in low outflow years.

Juvenile and adult prickly sculpin were collected in only half the years sampled, and except for 2 fish collected in 1992, all were collected during high outflow years (Table 8). The peak catch of 23 occurred in 1983.

Seasonal Abundance

Larvae were collected from January to May in all years, and to September in 1983 (see Table 7). Larval abundance usually peaked in March, but peaked in May in 1982. Few larvae were collected after May.

Although juvenile and adult fish were collected in almost every month of the year, most were collected from May to July (see Table 8). A few fish were collected during the high outflows in the falls of 1982 and 1983, and in the winters of 1984 and 1986.

Annual Distribution

Larvae were collected in all regions but catch was highest in Suisun Bay and lowest in South Bay (Table 9). In the low outflow years, 1985 and 1988, larval catch was highest in the west delta. Larvae were present in South Bay only in the high outflow years, 1980, 1982, 1983, and 1986.

Juveniles and adults were only collected in Suisun Bay and the west delta: 56 in Suisun Bay and 10 in the west delta. Fish were collected in Suisun Bay during all high outflow years. One or 2 fish were collected in the west delta in all high outflow years, except 1980 when none were caught.

Table 5 Length frequency of prickly sculpin collected with the plankton net from 1980 to 1988. Eighteen fish ranging from 14.3 to 50 mm were not included.

Length	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Total*
4.5–4.9			4	5	2				1				12
5.0–5.4	4	21	83	161	127	4	5	1					406
5.5–5.9	22	126	345	599	330	8							1430
6.0–6.4	60	384	919	581	258	5	3						2210
6.5–6.9	17	107	243	72	33								472
7.0–7.4	8	81	101	30	15								235
7.5–7.9	1	8	22	7	11								49
8.0–8.4		8	15	7	11								41
8.5–8.9	1	2	4	6	9								22
9.0–9.4			13	5	10								28
9.5–9.9			7	2	7								16
10.0–10.4			5	5	2								12
10.5–10.9			6	3	3								12
11.0–11.4	1												1
11.5–11.9													0
12.0–12.4					1								1
12.5–12.9				1									1
Total	115	737	1767	1501	820	17	8	1	1	0	0	0	4967

Table 6 Length frequency of prickly sculpin collected with the otter trawl from 1980 to 1995

Length	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Total*
20–29					2	1	2						5
30–39					6	5	3						14
40–49				1	1	2	1						5
50–59					1	7	1						9
60–69	1					1	3				1		6
70–79				2	1	3	2		1			1	10
80–89				1							1		2
90–99					1	1	1				1		4
100–109		1			1	1	1						4
110–119						2	2			1			5
120–129													
130–139										1	1		2
Total	1	1	0	4	13	23	16	0	1	2	4	1	66

Table 7 Annual and seasonal abundance (total catch) of prickly sculpin larvae collected with the plankton net. No plankton sampling occurred in January 1980 or after May 1989.

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Abundance*
1980		148	370	146	70								735
1981	88	130	192	120	15								545
1982	18	184	596	481	702	32							2013
1983	3	101	1158	718	1135	10	8	1	1				3134
1984	5	180	456	412	85								1138
1985	1	34	194	184	14	1							428
1986	7	112	372	422	130	4							1047
1987	21	55	229	202	7	1							515
1988	4	35	85	21	9								154
1989	2	32	28	205	9								276
Total	149	1011	3680	2911	2176	48	8	1	1	0	0	0	9985

Table 8 Annual and seasonal abundance (catch) of prickly sculpin from the otter trawl. See the Methods chapter, Table 1 for the months of sampling missed with this gear.

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Total*
1980				1	1								2
1981													0
1982						4	2				1	1	8
1983					1	8	10		1	1	2		23
1984	1			3	1	2				1			8
1985													0
1986		1			4	3							8
1987													0
1988													0
1989													0
1990													0
1991													0
1992					2								2
1993					3	2	2						7
1994													0
1995					1	4	2				1		8
Total	1	1	0	4	13	23	16	0	1	2	4	1	66

Table 9 Annual distribution of larval prickly sculpin collected with the plankton net. Data are total annual catch by region.

Year	*South Bay*	*Central Bay*	*San Pablo Bay*	*Suisun Bay*	*West Delta*
1980	3	9	190	437	96
1981		3	10	308	224
1982	1	39	297	1327	349
1983	14	139	764	1992	225
1984		4	92	681	361
1985			6	173	249
1986	8	44	343	454	198
1987			6	305	204
1988				74	80
1989			6	169	101
Total	26	238	1714	5920	2087

Discussion

The prickly sculpin was primarily collected seasonally in the study area, returning to freshwater soon after larval settlement or when salinities increased during summer. This was similar to migration patterns observed elsewhere, in which settled juveniles left brackish water and migrated into freshwater during summer (Shapavolv and Taft 1954, Krejsa 1965, 1967).

The catch of all age groups of prickly sculpin in the study area increased during periods of high freshwater outflow. Meng and Moyle (1994) also found this to be true in Suisun Marsh. As a winter-spring spawner with planktonic larvae, the prickly sculpin uses river outflow to disperse its larvae, the higher the outflow the broader the dispersal downstream. In addition, higher outflows create more freshwater habitat and may have led to better recruitment, as was the case for longfin smelt, another winter-spawning species with planktonic larvae (CDFG 1992). This larval dispersal and juvenile tolerance of brackish water enables prickly sculpin in coastal drainages to periodically exchange genetic material through the exchange of individuals. Prickly sculpin are found in tributaries in every region of the estuary (Leidy 1984).

We could not determine whether adults made a downstream migration in preparation for spawning as was observed elsewhere (Shapavolv and Taft 1954, Krejsa 1967, Mason and Machidori 1976). The few adult-sized fish were caught primarily in the late spring and early summer, after the spawning period. These fish may represent weakened post-spawning individuals washed into the study area.

Bonehead Sculpin

Introduction

The bonehead sculpin, *Artedius notospilotus*, is an uncommon cottid ranging from Point San Telmo, Baja California, to Puget Sound, Washington (Miller and Lea 1972). It inhabits intertidal areas to waters roughly 46 m deep (Miller and Lea 1972). It is taken incidentally in both sport and commercial fisheries, but is not used.

Little is known of bonehead sculpin ecology; it has a sparse distribution and few taxonomic characters to identify larvae of this genus. It grows to a maximum size of about 250 mm TL (Miller and Lea 1972).

Methods

Due to low numbers of larvae and older individuals, our analyses was limited to length frequency (mm TL), and abundance and distribution based upon total catch. All data were used with no corrections made for months not sampled.

Results

Catch and Length Analyses

Larvae of the genus *Artedius* could not be keyed to species, but the numeric dominance of juvenile and adult bonehead sculpin relative to other *Artedius* species in the estuary (that is, scalyhead sculpin, *A. harringtoni*; padded sculpin, *A. fenestralis*; and smoothhead sculpin, *A. lateralis*), led to the classification of *Artedius* larvae as bonehead (Aplin 1967, Wang 1986, Pearson 1989, this study). Thirty-four putative bonehead sculpin larvae were collected and 25 were measured (Tables 1 and 10). These larvae ranged from 2.6 to 7.4 mm TL and about half were 3.0 to 4.5 mm TL (see Table 10). Only 1 unmeasured bonehead sculpin was captured in the midwater trawl. In the otter trawl, 79 fish ranging from 49 to 157 mm TL were caught, but only 1 fish was larger than 129 mm (Table 11). Length data were not sufficient to separate age groups.

Table 10 Length frequency (mm TL) of bonehead sculpin larvae collected with the plankton net from 1980 to 1988

Length	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Total*
2.5 - 2.9				1	1								2
3.0 - 3.4			4	1									5
3.5 - 3.9			5										5
4.0 - 4.4		1	1		2								4
4.5 - 4.9		2			1								3
5.0 - 5.4				1									1
5.5 - 5.9		2				1			1				4
6.0 - 6.4													
6.5 - 6.9													
7.0 - 7.4			1										1
Total	0	5	11	3	4	1	0	0	1	0	0	0	25

Table 11 Length frequency (mm TL) of bonehead sculpin collected with the otter trawl from 1980 to 1995

Length	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Total*
45 - 49										1			1
50 - 54			1										1
55 - 59			1						1		1		3
60 - 64		1	1						2				4
65 - 69		2						1	1				4
70 - 74		2	1									2	5
75 - 79									1				1
80 - 84	1	2	2			1				1	2		9
85 - 89			3			1						1	5
90 - 94	1	1		1					1			1	5
95 - 99		4	2	1		1							8
100 - 104	2	2	1		4	2							11
105 - 109			3			1	1						5
110 - 114		1		1	1		1	1					5
115 - 119					1	3							4
120 - 124			1		1								2
125 - 129		1	2				1	1					5
130 - 134													
135 - 139													
140 - 144													
145 - 149													
150 - 154													
155 - 159				1									1
Total	4	16	18	4	7	9	3	3	6	2	3	4	79

Abundance and Distribution

Bonehead sculpin larvae were collected during only 6 of the 10 years sampled: 1980, 1981, 1982, 1984, 1985 and 1989. Twenty-seven of the 34 larvae were caught in 1980 and 1981 (15 and 12 larvae respectively), 4 were caught in 1982 and 1 each in the remaining years. Most were collected from February to June (see Table 10). Two larvae were not measured in March and 8 were not measured in May. Eighty-five percent of the total catch (n = 34) came from South Bay, 12% from Central Bay, and 3% from San Pablo Bay.

Juvenile and adult bonehead sculpin were caught in every year except 1980, 1988 and 1989 (Table 12). The peak catch was 15 in 1993. They were most abundant in Central Bay, followed by South Bay, and were only rarely caught in San Pablo Bay or upstream; none were collected in the west delta (see Table 12). Bonehead sculpin were collected throughout the year, but catches were highest in February and March (see Table 11) when larval numbers were also highest (see Table 10).

Table 12 Annual abundance and distribution (catch) of bonehead sculpin by region collected with the otter trawl

Year	*South Bay*	*Central Bay*	*San Pablo Bay*	*Suisun Bay*	*Total*
1980					0
1981	2	1	3		6
1982	1				1
1983	2	2			4
1984		8			8
1985		1			1
1986	2	1			3
1987	1		1		2
1988					0
1989					0
1990	2	6			8
1991		9			9
1992	1	6		1	8
1993	3	12			15
1994	2	5			7
1995		7			7
Total	16	58	4	1	79

Discussion

The bonehead sculpin appears to be an uncommonly collected resident species, confined primarily to the polyhaline and euhaline regions of the estuary. This species may inhabit rocky substrates as other cottids do, and other sampling data suggests it may be nocturnal. Thus, it may be more abundant in the estuary than the catches indicate due to limited sampling of rocky substrates and after dark. In March 1990, 32 one-meter beam trawl samples were taken in San Pablo Bay over 2 complete tidal cycles, 16 during the day and 16 at night (CDFG, unpublished data). Eight bonehead sculpin (68 to 110 mm TL) were collected, all at night. Although darkness may have reduced net avoidance, Secchi disc depths of ≤45 cm suggest visibility was poor throughout sampling and probably not an important factor.

The bonehead sculpin was not abundant in the estuary based on historic otter trawl sampling (Aplin 1967, Kinnetic Labs and Larry Walker Associates 1987, Pearson 1989). Aplin (1967) collected 20 bonehead sculpin from Central (19) and South bays (1) in 6 monthly otter trawl samples from January 1963 to December 1966. Kinnetic Labs and Larry Walker Associates (1987), trawled in the southern part of South Bay and captured 32 bonehead sculpin in monthly sampling at 5 locations between December 1981 and November 1986. Pearson (1989) collected 265 bonehead sculpin from 2,561 otter trawl samples taken in South Bay from February 1973 through June 1982. Both Aplin and Pearson obtained slightly higher catches from February through June.

If our assignment of *Artedius* larvae to *A. notospilotus* is correct, then spawning occurs from January through May. This assumes a 2 to 4 week incubation period that would shift the start of spawning back 1 month from the beginning of the larval catch (see Table 10). Movement of individuals seeking mates may have been responsible for the increased catch in the otter trawl in February and March.

Cabezon

Introduction

The cabezon, *Scorpaenichthys marmoratus*, is the largest species of the cottid family, attaining a maximum length of about 100 cm (Miller and Lea 1972). It is a common marine cottid, found from Point Abreojos, Baja California, to Sitka, Alaska, at depths from the intertidal zone to 76 m (Miller and Lea 1972). Historically, the cabezon was not targeted directly by a commercial fishery, but was taken regularly in set-line fisheries directed toward rockfish (O'Connell 1953, Frey 1971). Presently, it is an important component of the live fish catch (Bob Lea, personal communication, see "Notes").

The cabezon spawns in the subtidal and intertidal regions of the open coast between October and April from California south (O'Connell 1953, Wang 1986) and between late November and early September in Puget Sound, Washington (Lauth 1988). Eggs are demersal, temporarily adhesive and are laid on hard surfaces. Both sexes probably spawn more than once per season (O'Connell 1953, Lauth 1988). After spawning, males remain with the nest and guard it, even though the roe is poisonous (Hubbs and Wick 1951, O'Connell 1953, Wilson–Vandenberg 1992).

In 2 to 3 weeks after fertilization, eggs hatch into pelagic, surface oriented larvae that are found primarily nearshore (O'Connell 1953, Richardson and Pearcy 1977, Richardson and Washington 1980). Settlement occurs 3 to 4 months after hatching at about 38 to 40 mm TL (O'Connell 1953). Soon after settlement, juveniles move inshore to rocky, vegetated habitats, particularly tidepools (O'Connell 1953, Feder and others 1974). They move to deeper water with growth (O'Connell 1953). Male cabezon mature between ages 2 and 3, whereas, females mature between ages 3 and 5 (O'Connell 1953).

Methods

Due to low numbers of larvae and older individuals, analyses were limited to length frequency (mm TL), and abundance and distribution based upon total catch. All data were used with no corrections made for months not sampled. Annual larval catches were based on an October to September period and designated by the year beginning January 1 within the period.

Results

Between February 1980 and May 1989, 131 larval cabezon were collected, of which 108 were measured (Table 13). These larvae ranged from 4.0 to 6.7 mm TL. Larvae were collected from October through June, but most were caught from December to March. The annual larval catch ranged from 4 in 1983 and 1988 to 31 in 1985 (Table 14). There were 2 abundance modes, 1 from 1981 to 1982 and 1 from 1985 to 1986. Although larvae were collected from South Bay to San Pablo Bay, almost all were taken in Central Bay (see Table 14).

Only 2 juvenile cabezons were captured: 1 at 130 mm TL in August 1980 and 1 at 65 mm TL in May 1983. Both were caught in the beach seine at station #263 (north side of the Golden Gate) over a rock and sand substrate.

Table 13 Length frequency (mm TL) of cabezon larvae collected with the plankton net from 1980 to 1988

Length	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Total*
4.0 - 4.1	1												1
4.2 - 4.3													0
4.4 - 4.5		1				1							2
4.6 - 4.7		1											1
4.8 - 4.9		1	1										2
5.0 - 5.1		4	1	1	1	1					1	5	14
5.2 - 5.3		2	1	1	1						1	2	8
5.4 - 5.5	5	5	3	1							1	5	20
5.6 - 5.7	3	1									1	2	7
5.8 - 5.9	2	5	2							1	2	4	16
6.0 - 6.1	4	8	8	1								3	24
6.2 - 6.3	3	2	2	2								1	10
6.4 - 6.5	1	1											2
6.6 - 6.7		1											1
Total	19	32	18	6	2	2	0	0	0	1	6	22	108

Table 14 Annual abundance (total catch from October to September) and distribution of cabezon larvae from the plankton net. None were collected in Suisun Bay or the west delta. No correction was made for incomplete sampling in 1980 or 1989.

Year	*South Bay*	*Central Bay*	*San Pablo Bay*	*Total*
1980		4	2	6
1981		27	1	28
1982	1	19	1	21
1983		4		4
1984	1	5		6
1985	2	28	1	31
1986		11	2	13
1987		9		9
1988		4		4
1989		9		9
Total	4	120	7	131

Discussion

Based upon the few larvae collected and their distribution, it is unlikely that cabezon spawn within the estuary. The larval cabezon taken in Central Bay could easily have been spawned on the coast and transported into the estuary via tidal exchange. Older life stages are strongly associated with rocks and vegetation (O'Connell 1953, Miller and Geibel 1973), so they may be present in the estuary without being detected by our sampling. In other estuaries cabezon are present in low numbers and are associated with vegetation (Bayer 1981, Bottom and others 1984). In Elkhorn Slough, cabezon are caught on rocky bottoms and around pier pilings (Nybakken and others 1977, Yoklavich and others 1991).

Rarely Captured Species

The fluffy sculpin, *Oligocottus snyderi*, ranges from Baja California to Sitka, Alaska (Miller and Lea 1972). It is a common cottid in coastal areas attaining a maximum length of 83 mm TL and inhabiting intertidal and subtidal areas (Miller and Lea 1972). One 66 mm TL fish was collected with the beach seine at station #264 in northwestern Central Bay in October 1982.

The brown Irish lord, *Hemilepidotus spinosus*, attains a maximum length of 250 mm TL and ranges from Santa Barbara Island and Ventura, California, to Puffin Bay, Alaska (Miller and Lea 1972). It is considered uncommon and is known to inhabit depths from the intertidal zone to roughly 77 m (Miller and Lea 1972). Two larvae (expanded to 9 based upon subsampling) and 4 juveniles were collected. Both larvae were collected in February 1980 from South Bay (stations #106 and #108) and measured 6 mm TL. Three of the juveniles were captured at station #213 near Alcatraz Island: 2 in September 1985 (72 and 80 mm TL) and the 3rd in April 1989 (28 mm TL). The last (71 mm TL) was collected at station #323 in western San Pablo Bay in November 1985.

The red Irish lord, *Hemilepidotus hemilepidotus*, is a common cottid ranging from southern Monterey Bay, California, to the Sea of Okhotsk, Russia (Miller and Lea 1972). It inhabits depths from the intertidal to approximately 48 m and reaches lengths to 500 mm, but rarely grows larger than 300 mm (Miller and Lea 1972). One fish (136 mm TL) was collected at station #213, Alcatraz Island, in December 1985.

The scalyhead sculpin, *Artedius harringtoni*, is an uncommon cottid that ranges from San Miguel Island, Baja California, to Kodiak Island, Alaska (Miller and Lea 1972). It is found from the intertidal to 21 m and reaches a maximum length of 100 mm TL (Miller and Lea 1972). One scalyhead sculpin (126 mm TL) was collected at station #215 near Angel Island in June 1980.

The tidepool sculpin, *Oligocottus maculosus*, is a common cottid and ranges from White Point and Portuguese Bend, Los Angeles County, California, to the Sea of Okhotsk, USSR (Miller and Lea 1972). It is primarily found in shallow, rocky, intertidal areas where it reaches a maximum length of 89 mm TL (Miller and Lea 1972). Only 4 tidepool sculpin were collected—all larvae—from February through April. Three larvae were collected in Central Bay (2 at station #212 and 1 at #214); the 4th was collected in San Pablo Bay at station #318.

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Many of the data summaries for Pacific staghorn sculpin expand upon those first developed by Patrick Coulston, California Department of Fish and Game, for the State Water Resources Control Board 1987 Water Quality/Water Rights proceedings.

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Notes

Bob Lea (California Department of Fish and Game, Marine Resources, Monterey Field Office). Telephone call to author, March 1994.

White Croaker

Kevin Fleming

Introduction

The family Sciaenidae includes croakers, drums, kingfish, and seatrout. It is a cosmopolitan family that inhabits warm, shallow, nearshore ocean waters, estuaries, and rivers. The family consists of about 250 species (Eschmeyer and others 1983), 10 of which occur in California waters (Miller and Lea 1972) and 2 in the San Francisco Estuary: the white croaker, *Genyonemus lineatus*, and the queenfish, *Seriphus politus*. San Francisco Bay represents the northern boundary of the queenfish range (Skogsberg 1939) and we have taken only a few in it. The white croaker, on the other hand, is quite abundant.

The white croaker is found in small schools (Skogsberg 1939) and ranges from Magdalena Bay, Baja California, to Mayne Bay, Vancouver Island, British Columbia (Miller and Lea 1976, Baxter 1980, Hart 1973). It is primarily a shallow water fish, but has been found as deep as 183 m (Love and others 1984). White croaker supports both commercial and sports fisheries.

White croakers spawn throughout the year in bays and estuaries (Wang 1986) but most spawning occurs in early spring (Baxter 1980). In San Francisco Bay, spawning is most intense from September through May (Wang 1986). Females probably spawn more than once a year (Baxter 1980) and larger females have longer spawning seasons (Love and others 1984). The eggs and newly hatched larvae are pelagic (Watson 1982, Wang 1986). As they grow, the larvae move shoreward and become more epibenthic (Watson 1982). White croakers grow to 391 mm and live 15 years or more (Baxter 1980). Half mature by the end of the 1st year of life and all mature in 3 to 4 years (Love and others 1984).

Methods

The plankton net catches were used to determine the spawning time of adult white croakers and the seasonal distribution of the yolk sac and post-yolk sac larvae. Fish <20 mm were considered larvae. White croakers taken in the otter trawl were divided into age–0 and age–1+ classes by visual inspection of monthly length frequencies. The monthly cutoff lengths for the separation of age–0 and age–1+ fish were 40, 45, 50, 75, 85, 100, 115, 125, 125, 135, 150, and 150 mm FL for January to December, respectively. Abundance indices were calculated using otter trawl data. Annual abundance indices for both the age–0 and age–1+ fish were calculated for February to October.

Results

Length Frequency

The consistent winter recruitment of the smallest white croaker and their apparent near constant growth rate provided for clear distinctions between age–0 and age–1+ fish (Figure 1).

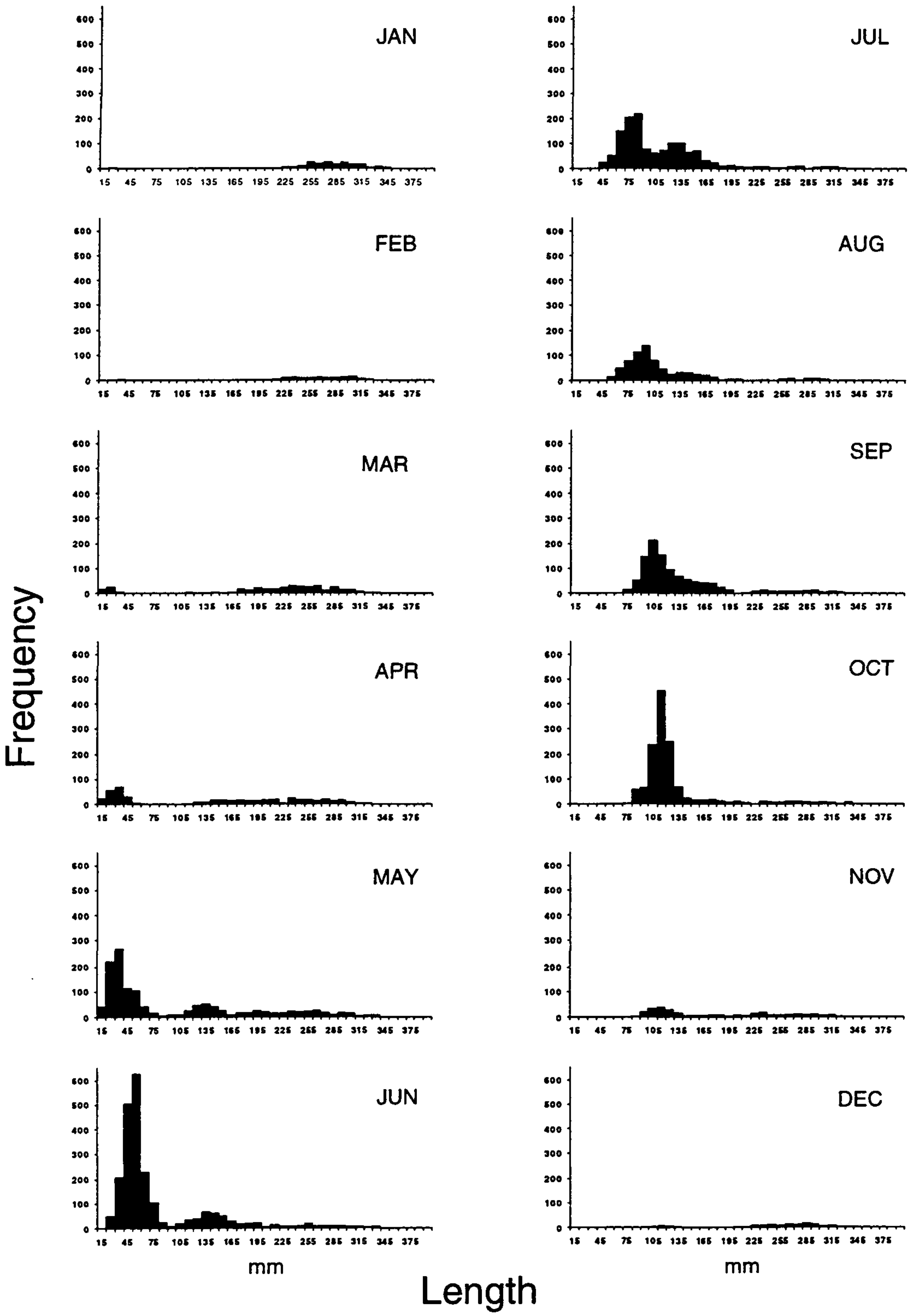

Figure 1 Length distribution of white croakers by month. Values are the sum of the catch by length (mm FL) for 1981 to 1988.

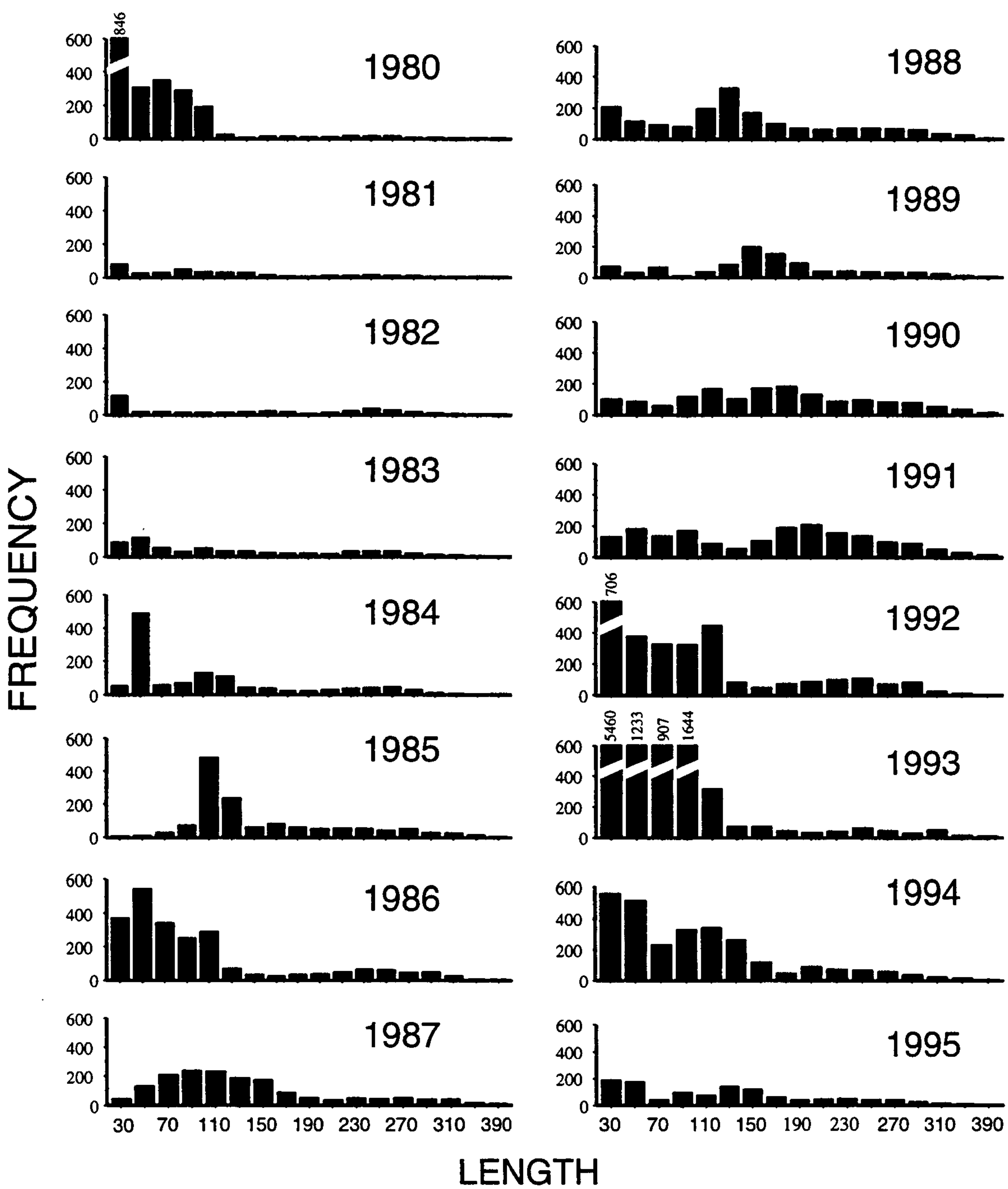

Figure 2 Annual white croaker size distribution. Values are the sum catch by length (mm FL) for each year.

The age structure of white croakers changed from year to year (Figure 2). Fish from a few strong year classes (1980, 1986, and 1993) dominated the catch in subsequent years. The 1986 year class comprised a large proportion of the subsequent annual catches until 1992. However, a strong year class was no guarantee of future abundance. The 1993 year class, which was approximately 5 times the size of the 1986 year class, did not contribute proportionally to the 1994 catch of age–1+ fish.

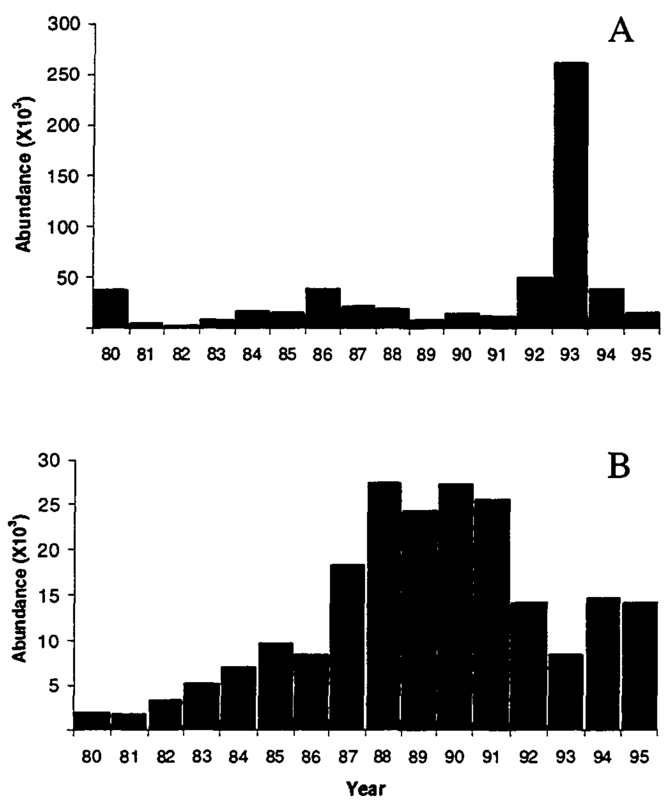

Figure 3 Annual abundance of white croaker: (A) age 0 and (B) age 1+

Abundance

The abundance of age–0 white croaker fluctuated greatly between 1980 and 1995. The annual abundance index was highest in 1993 and lowest in 1982 (Figure 3A, Table 1). The 1993 index was 5 times greater than the 1992 index and 100 times greater than the 1982 index. Age–1+ indices were low in the early 1980s, but began a sustained increase in 1982, which peaked in 1988 and remained steady through 1991 (Figure 3B, Table 2). The indices then declined through 1993 and rebounded somewhat in 1994 and 1995. The lowest age–1+ indexes were in 1980 and 1981.

Distribution

White croakers were seasonally distributed within the estuary. In early winter, most of the larvae were in Central Bay (Figure 4). As winter progressed, the larvae spread into San Pablo and South bays. The larval catch in spring declined as larvae grew into the juvenile stage. Age–0 fish were first collected in the otter trawl between February and April (Figure 5). They were collected throughout the year, and were found primarily downstream of Suisun Bay. The catch of age–0 fish peaked in spring in both South Bay and San Pablo Bay. By summer, the age–0 fish catch declined in these bays and began increasing in Central Bay. By the end of fall, all the age–0 fish along with most of the age–1+ fish had left the estuary.

Table 1 Monthly abundance indices of age–0 white croaker captured in the otter trawl from 1980 to 1995. The last column is the annual index, the mean abundance from February to October. The bottom row is the average seasonal abundance from 1981 to 1988.

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Index*
1980		834	284	2630	145017	34847	83910	53716	9127	13245	20335	961	38179
1981	0	463	61	1848	20016	1113	4181	4926	6658	10579	7068	194	5538
1982	0	287	235	1218	2955	12867	1274	2691	889	839	1870	222	2584
1983	0	0	271	1015	12725	32163	12544	5100	2901	10039	3712	225	8529
1984	225	0	0	3508	12636	78014	23734	4426	3084	33827	1006	0	17692
1985	0	0	425	0	113	3010	5518	8202	7479	115669	11867	843	15602
1986	119	388	4170	9038	48557	133606	45054	48092	54658	15092	8855	3305	39851
1987	610	284	664	3760	30159	49129	23240	23161	33189	32855	3935	1598	21827
1988	648	816	5225	17305	46410	31373	28342	19415	18549	3355	839	934	18977
1989	0	1269	847	2890	13678	13977	20699	6250					8516
1990		1156	1731	12929	24245	15187	9881	16728	22885	25944			14521
1991		728	1433	5544	10621	28699	30871	9376	11122	16956			12817
1992		189	564	16260	164560	61426	61203	39373	68673	33448			49522
1993		138	235	1447533	146011	154238	156865	168532	159150	120895			261511
1994		711	1166	8354	89044	69001	32487	57353	72690	18104			38768
1995	0	0	308	2342	20655	66276	6043		27461	1105	840	1695	15524
1981–1988	200	280	1381	4712	21696	42659	17986	14501	15926	27782	4894	915	

Table 2 Monthly abundance indices of age–1+ white croaker captured in the otter trawl from 1980 to 1995. The last column is the annual index, the mean abundance from February to October. The bottom row is the average seasonal abundance from 1981 to 1988.

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Index*
1980		637	1889	7104	1175	745	1220	2976	2010	186	742	212	1994
1981	2094	284	186	1049	2637	2618	5291	3080	768	1286	668	694	1911
1982	4820	4344	775	1948	6777	9367	1084	2855	1513	1653	3320	1983	3368
1983	474	765	3319	6577	4893	7374	10111	5038	5245	3029	4270	2773	5150
1984	2695	7021	12278	9801	9445	10466	5628	3191	4617	1650	2146	6519	7122
1985	4223	1298	18012	22855	7143	5442	2164	1319	15285	14652	9909	2962	9797
1986	9156	2631	4350	6254	21912	7448	15345	4707	4517	8171	5528	4997	8370
1987	7747	1760	3216	6542	41203	43526	15954	11096	28730	12910	5100	3197	18326
1988	13971	8878	23802	7393	21587	49122	73129	21420	35472	6180	11962	9047	27443
1989	8877	7731	7714	34843	13706	31549	41567	33799					24416
1990		14551	20602	31761	23191	24810	52944	34760	25931	16929			27275
1991		19921	33716	22438	14902	51213	46630	25603	7868	8747			25671
1992		24602	17362	27047	33758	8032	534	1360	9635	5219			14172
1993		3673	8426	6621	9382	7344	12736	16767	4239	6642			8425
1994		5512	8685	6246	13789	19199	11457	28697	30885	7722			14688
1995	9122	3791	3826	6332	12072	10911	40388		27765	8879	414	18611	14246
1981-1988	5648	3373	8242	7802	14450	16920	16088	6588	12018	6192	5363	4022	

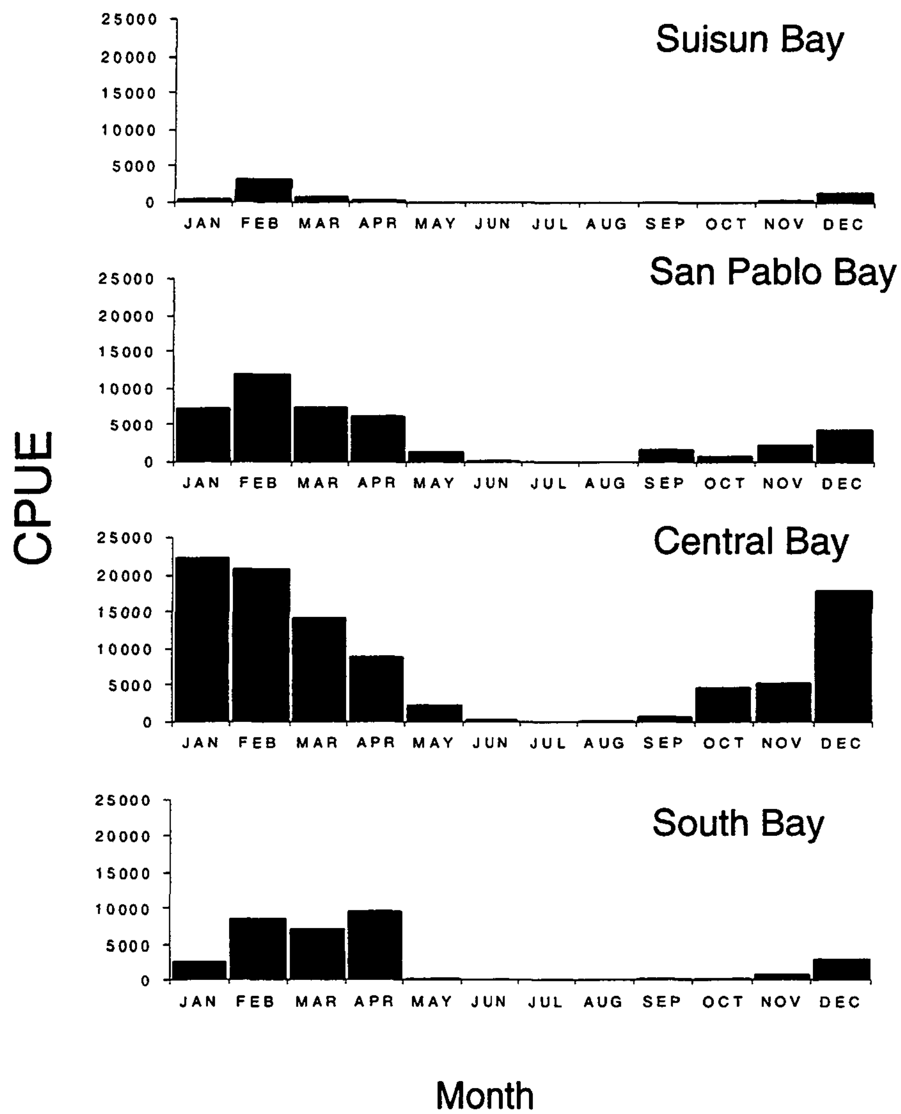

Figure 4 Seasonal distribution of white croaker larvae by region. Values are the average CPUE for 1981 to 1988.

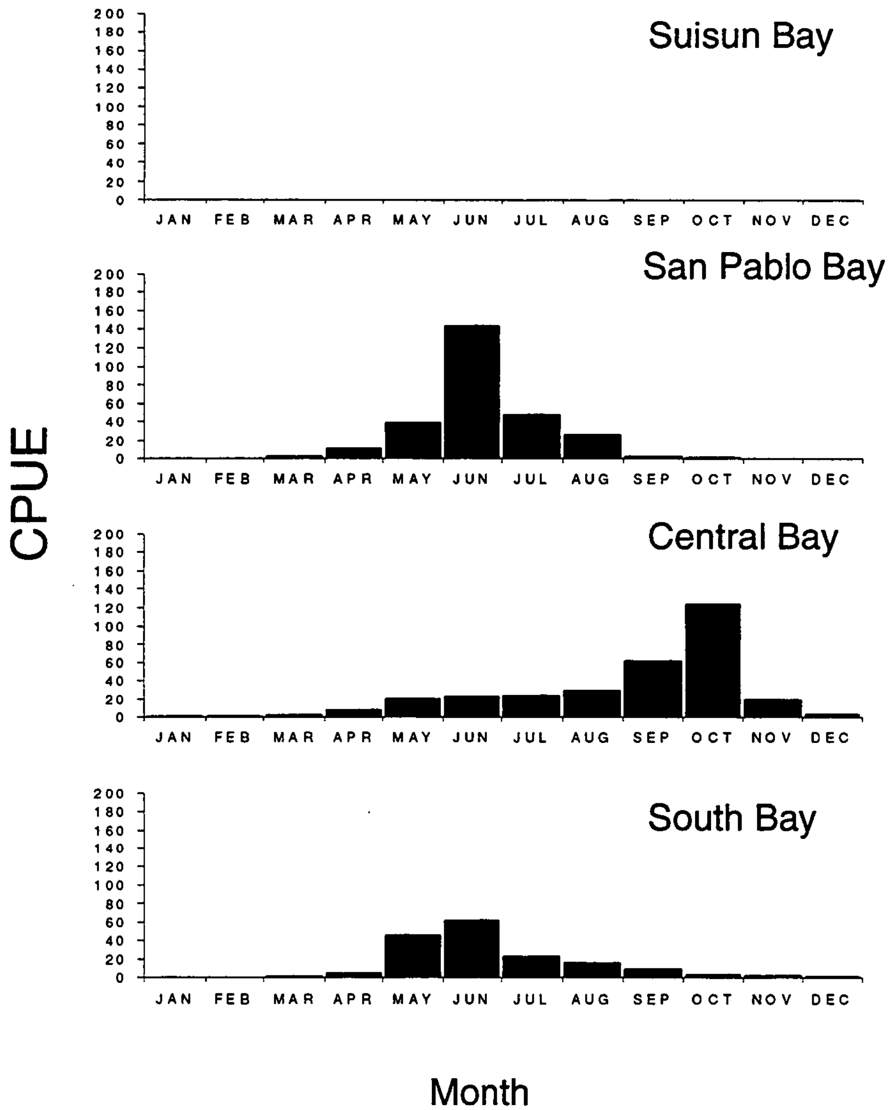

Figure 5 Seasonal distribution of age–0 white croaker by region. Values are the average CPUE for 1981 to 1988.

Age–1+ white croakers were found in Central Bay throughout the year (Figure 6). Their distribution expanded and their numbers increased to a mid-summer peak in South, Central, and San Pablo bays. In late fall and early winter, the catch of age–1+ fish decreased, first in San Pablo and South bays and then in Central Bay, as age–1+ fish moved into the ocean. The emigration was comprised primarily of fish <200 mm FL. Larger fish showed a slight increase in numbers during winter, but not enough to compensate for the decline in the smaller fish.

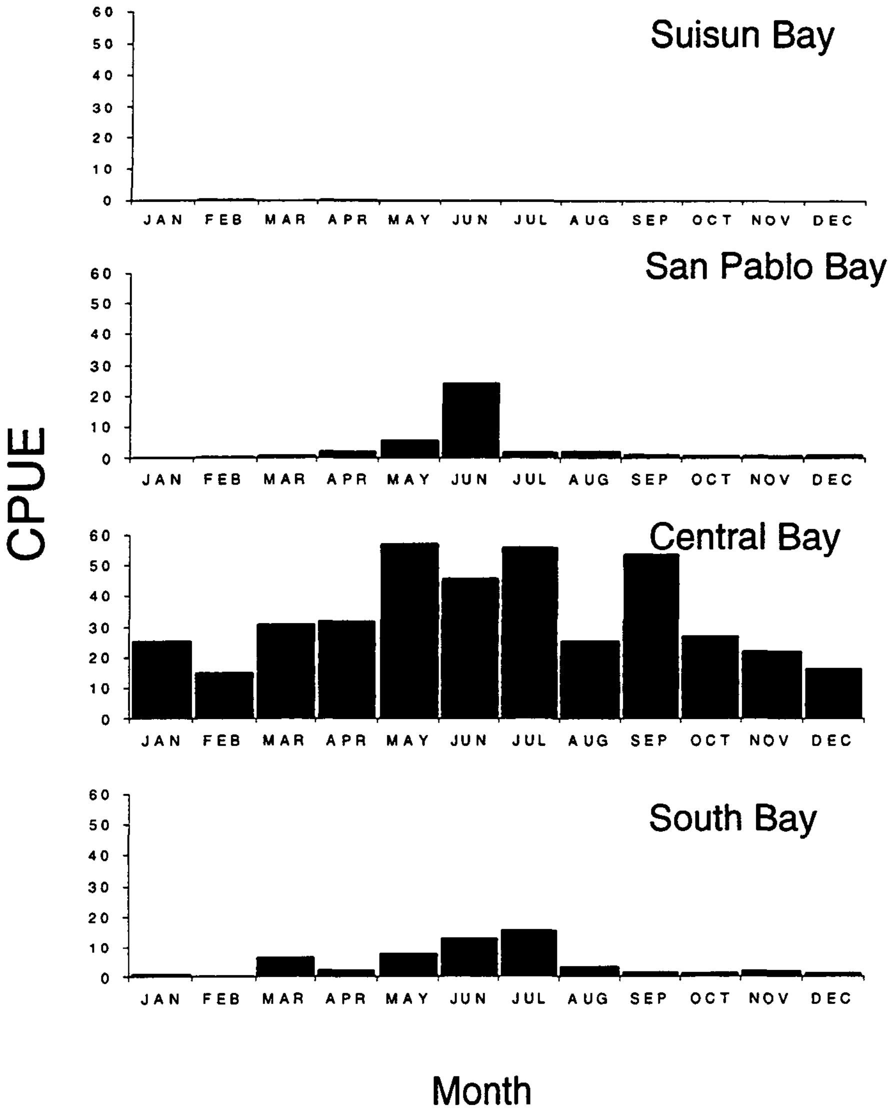

Figure 6 Seasonal distribution of age–1+ white croaker by region. Values are the average CPUE for 1981 to 1988.

The annual distribution pattern of age–0 white croaker varied with outflow (Figure 7). In most years with high winter outflows (1980, 1982, 1984, and 1986) relatively more age–0 fish were caught in San Pablo Bay than in Central or South bays. In years with low outflow, age–0 CPUE was similar in Central and South bays. The annual distributions of age–1+ fish did not vary as much as for age–0 fish. Age–1+ fish were primarily restricted to Central Bay but expanded their range to South and San Pablo bays during low outflow periods when the salinity in those bays increased (Figure 8).

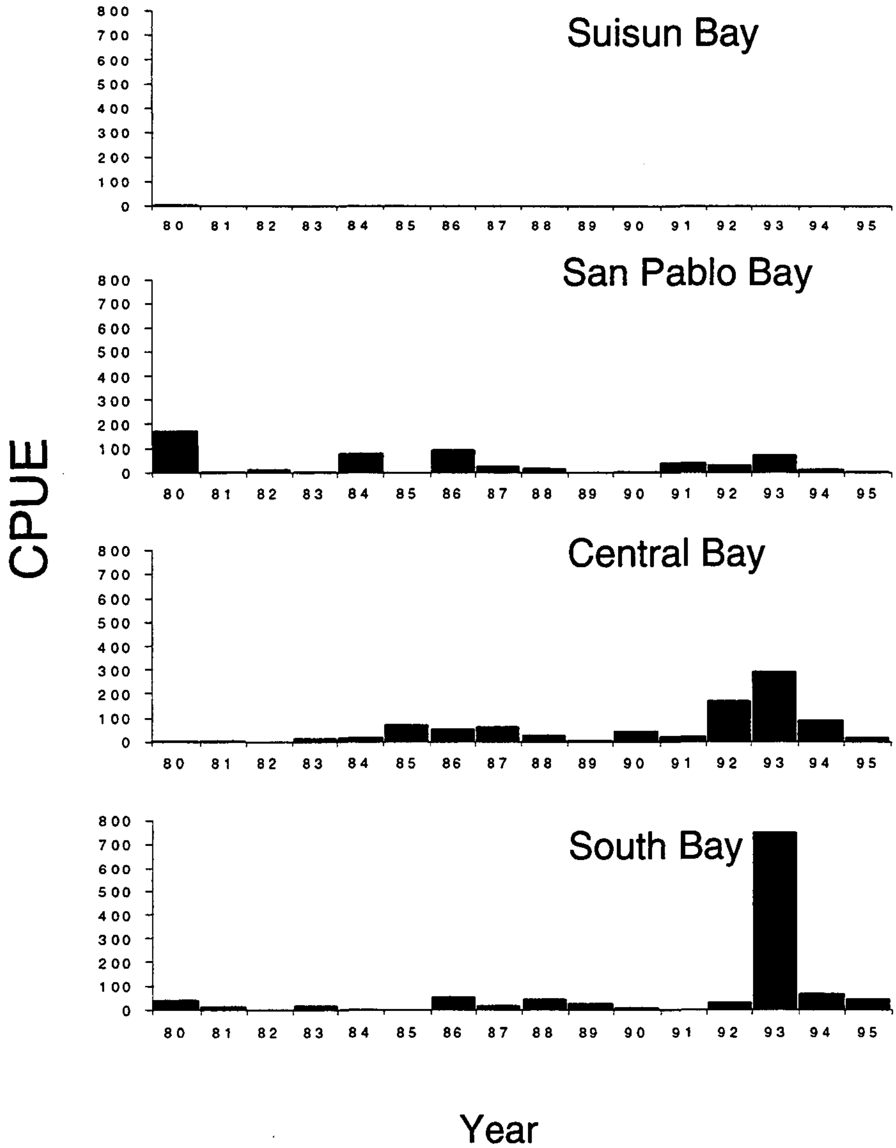

Figure 7 Annual distribution of age–0 white croaker by region. Values are the average CPUE for February to October.

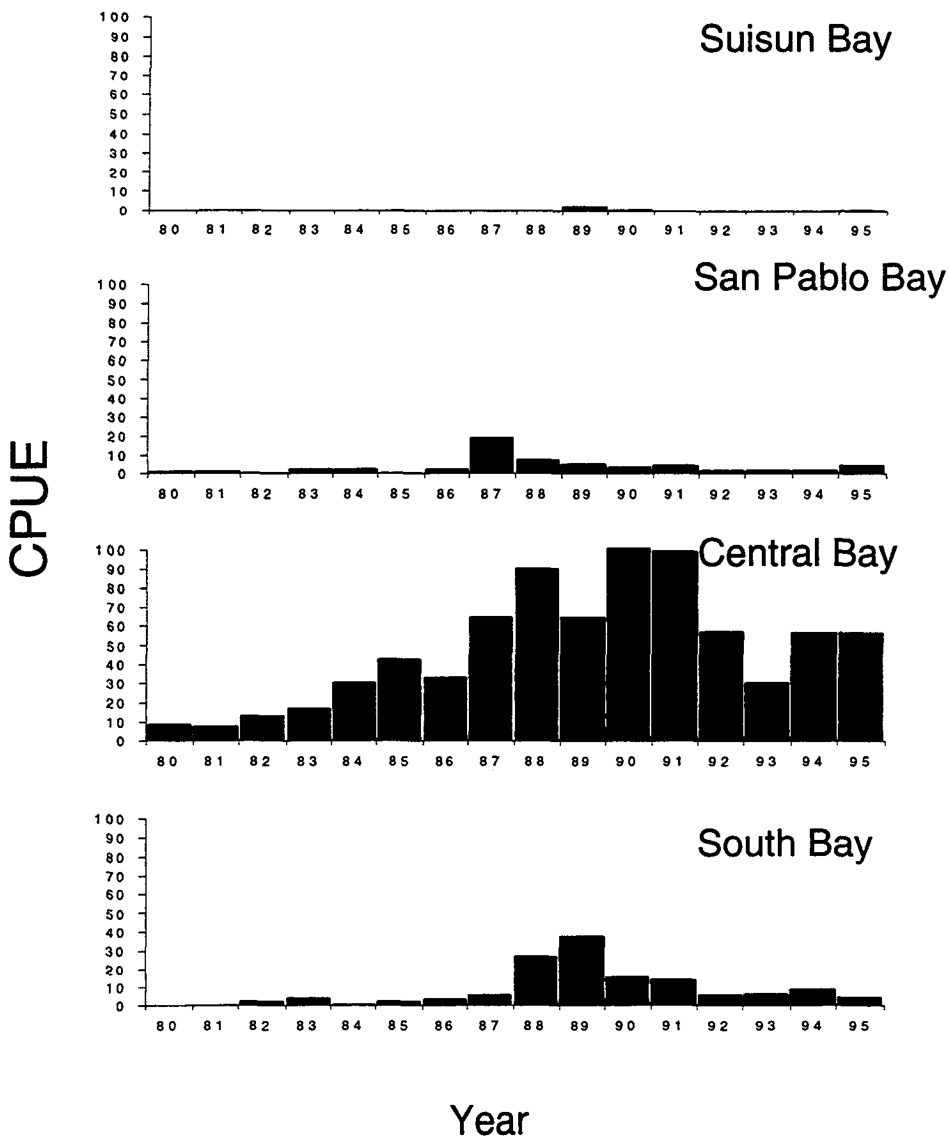

Figure 8 Annual distribution of age–1+ white croaker by region. Values are the average CPUE for February to October.

Salinity and Temperature

Both the salinity and temperature at which white croaker were found changed with size. Both age groups ranged between polyhaline and euhaline salinities but age–0 fish were found in fresher and warmer waters than older ones (Figure 9). The salinity and temperature ranges of age–1+ fish varied little.

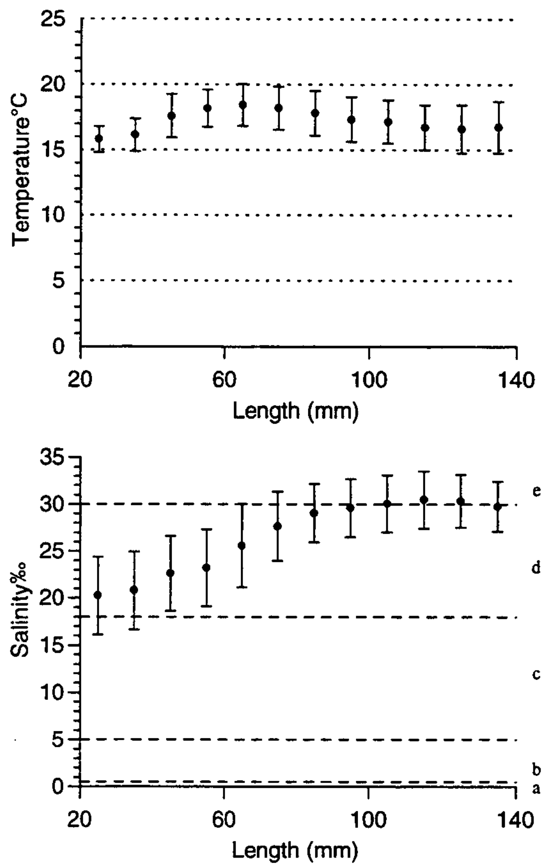

Figure 9 Temperature and salinity distributions of white croakers by length. The dots are the means and the bars are 1 standard deviation. The horizontal lines on the salinity graph mark the boundaries of the Venice system ranges: (a) limnetic, (b) oligohaline, (c) mesohaline, (d) polyhaline, and (e) euhaline.

Discussion

The white croaker is a coastal marine species that is confined mainly to the polyhaline and euhaline environments of San Pablo, Central, and South bays. It has a fairly predictable seasonal pattern of movement. Tidal transport of the young and salinity control their distribution in the estuary and their emigration to the ocean.

During winter, mature fish move shoreward to spawn and some enter the estuary. Eggs and larvae are pelagic and are most abundant in Central Bay. As the young develop, they become increasingly epibenthic and are transported by tidal currents to the polyhaline environments of San Pablo and South bays. Because of this passive transport age–0 fish are found over a greater range of salinity and have a broader distribution than age–1+ fish.

Age–1+ white croakers remain in the higher salinity areas of the estuary. An upstream expansion of the age–1+ distribution occurred during the drought when the salinity of San Pablo and South bays increased to the euhaline and upper polyhaline levels. During normal water years, high winter outflow reduced the salinity in San Pablo Bay to the lower mesohaline and upper oligohaline ranges and restricted the distribution of age–1+ fish to Central and South bays.

The seasonal movements of age–0 and age–1+ fish reflected their preferences for euhaline water. The timing of the seasonal movements corresponds with the seasonal changes in salinity that occur in each bay. From spring to midsummer the highest densities of age–0 fish were in San Pablo and South bays. As the summer progressed, the age–0 fish migrated toward the higher salinities of Central Bay. By winter they, along with the immature age–1+ fish, emigrated out of the estuary into the ocean.

The size of a year class was not an indicator of future abundance. The 1986 year class, though comparable in size to the 1980 year class and 1/4th the size of the 1993 year class, contributed to the greatest increases in age–1+ abundance. White croaker from the 1980 year class failed to make a large contribution to age–1+ abundance until the mid-1980s. Fish from the 1993 year class, the largest of record, did contribute to the 1994 and 1995 age–1+ indices, but in numbers far less than might have been expected from its size.

The drought increased the suitability of the estuary for the white croaker by increasing the salinity. The 1986 year class made greater use of the estuary during the drought. These fish still moved seasonally in and out of the estuary, but during the drought years, many more of these fish entered Central Bay from the ocean. The increased salinity however, did not appear to influence reproductive success. Although large numbers of spawners should have been produced by the maturation of the large 1986 year class in 1987 and 1989, spawning in these years did not appear to be high, judging from the small numbers of age–0 fish.

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Embiotocidae

Suzanne DeLeón

Introduction

The surfperch family (Embiotocidae) ranges along the Pacific coast from southern Alaska to central Baja California; there are also 2 species in the Sea of Japan and 1 species in freshwater in California's Central Valley (Tarp 1952, Miller and Lea 1972). Surfperches use a variety of habitats: rocky or sandy surf areas, kelp forests, ocean reefs, and areas around structures such as pilings and piers (Karpov and others 1995). Habitat use often changes during mating and parturition. Surfperches are usually found in shallow water, although silver surfperch and shiner perch have been caught as deep as 110 and 146 m, respectively (Miller and Lea 1984).

Life history strategies vary by species and include differences in fecundity, in age at first reproduction, in longevity, and in size of young at birth (Wiebe 1968, Wilson and Millemann 1969, Shaw 1971). All surfperches are viviparous; small species reproduce at age 1 and large species after age 1 (Baltz 1984). They mate in winter, except for shiner perch and black surfperch, which mate in spring and summer. Sperm is stored for 3 to 9 months before fertilization takes place, except for rainbow seaperch, barred surfperch, and walleye surfperch, which do not store sperm (Carlisle and others 1960, Anderson and Bryan 1970). Gestation lasts 3 to 6 months and the young are born fully developed. Young of all species are born in coastal bays, except those of pink seaperch, which are born in deeper waters. Longevity ranges from 2 to 10 years and growth is indeterminate (Baltz 1984).

Surfperches feed on molluscs, polychaetes, amphipods, copepods, gastropods, crabs, shrimp, and algae (Chu 1989, Holbrook and Schmitt 1986). In turn, they are prey for larger fish such as kelp bass, halibut, sculpins, sturgeon, salmon, barred sand bass, and in San Francisco Bay, striped bass and harbor seals (Thomas 1967, Feder and others 1974).

Many of the larger species of surfperches are commercially important, although some may no longer be targeted due to declines in abundance. All species are important in the sport fishery except dwarf perch, which are too small.

Fourteen species of Embiotocidae were collected in the San Francisco Estuary between 1980 and 1995 (Tables 1, 2, and 3). Length, abundance, and distribution analyses were focused on the commonly caught species: dwarf perch, pile perch, shiner perch, walleye surfperch, and white seaperch. Only life histories and size information were described for the uncommon species. Although, the tule perch is included in the catch tables, it is not described here. Our sampling includes only a small portion of its geographical range.

Table 1 Total catches of surfperches collected at the original stations collected with the midwater trawl from 1980 to 1995

	Year																
Species	*80*	*81*	*82*	*83*	*84*	*85*	*86*	*87*	*88*	*89*	*90*	*91*	*92*	*93*	*94*	*95*	*Total*
Barred surfperch	1	1										1	1				4
Black surfperch						1											1
Calico surfperch														1			1
Dwarf perch			1														1
Pile perch	2	6	5	2	1	4	4	1	1			1					27
Redtail surfperch																1	1
Rubberlip seaperch								4									4
Shiner surfperch	395	1148	790	302	320	826	731	635	665	333	262	211	142	357	29	31	7177
Silver surfperch	1				1												2
Tule perch	1												1	1		1	4
Walleye surfperch	41	207	72	22	78	40	29	67	35	36	26	15	15	21		11	715
White seaperch	9	23	3	3	1	1	1	13	5	5	1		1				66
Totals	450	1385	871	329	401	872	765	720	706	374	289	228	160	380	29	44	8003

Table 2 Total catches of surfperches collected at the original stations in the otter trawl from 1980 to 1995

	Year																
Species	*80*	*81*	*82*	*83*	*84*	*85*	*86*	*87*	*88*	*89*	*90*	*91*	*92*	*93*	*94*	*95*	*Total*
Barred surfperch	18	29	16	48	19	6		7	3	4	4	3	1	1	2	4	165
Black perch		13	3	4	12	4	1	1	3	3	2	1	4	4	3	2	60
Dwarf perch	14	31	50	48	5		3	1	18	5	1	1			2	1	180
Pile perch	35	34	38	35	9	19	19	1	16	3	1						210
Rainbow seaperch				1													1
Rubberlip seaperch	2	3	2		2				1	1						1	12
Shiner perch	1546	1929	3167	1667	1015	1803	2730	1375	1402	433	649	412	283	259	204	413	19287
Silver surfperch	2							2									4
Spotfin surfperch					1												1
Tule perch	10	2	3	1	1	6		1	5	2	1	18	13	21	4	6	94
Walleye surfperch	26	184	91	37	22	16	39	26	24	5	7	7	5	3	2		494
White seaperch	16	35	12	10	24	5	9	7	4	1	4						127
Total	1669	2260	3382	1851	1110	1859	2801	1421	1476	457	669	442	306	288	217	427	20635

Table 3 Total catches of surfperches collected with the beach seine from 1980 to 1986

Species	*1980*	*1981*	*1982*	*1983*	*1984*	*1985*	*1986*	*Total*
Barred surfperch	7	7	1	14	3	17	24	73
Black perch	2	8	1		4		2	17
Calico surfperch				1			1	2
Dwarf perch	467	524	190	135	161	142	317	1936
Pile Perch	3	4		6	7	7	3	30
Rubberlip seaperch	4	1					7	12
Shiner perch	618	529	181	482	248	403	686	3147
Silver surfperch						1	1	2
Tule perch	2	29	1	2	1	14	2	51
Walleye surfperch	67	49	15	166	18	32	122	469
White seaperch	1	7				2	1	11
Total	1171	1158	389	806	442	618	1166	5750

Shiner Perch

Introduction

The shiner perch, *Cymatogaster aggregata,* has the broadest distribution of the Embiotocidae, ranging from Baja California north to Port Wrangell, Alaska (Roedel 1953, Miller and Lea 1972). The shiner perch is most abundant in bays in eelgrass beds and around the pilings of wharfs and piers (Bayer 1981, Baxter 1980), but it can also be found in deeper water in winter (Bane and Bane 1971). It occurs over sandy and muddy bottoms and has been caught from the surface to 146 m (Miller and Lea 1972. The shiner perch is reported to be eurythermal and is caught from 4 to 21 °C. But in Anaheim Bay, California, the catch decreased at 18.5 °C (Odenweller 1975). It is relatively euryhaline, tolerating salinities as low as 1 to 3‰ but is most often found in polyhaline and euhaline salinities.

In California, mating occurs in late spring and summer. Sperm is stored for 5 to 6 months and fertilization takes place in winter. Gestation takes approximately 6 months and the females migrate to shallow water to give birth from June to August. However, in Anaheim Bay, shiner perch bear young as early as May (Odenweller 1975). This earlier birth date may be attributed to a faster gestation rate resulting from warmer water temperatures and a more productive environment.

At birth, the young are fully developed and both the males and females may be mature, although sexual maturity in females may be size-dependent (Wilson and Millemann 1969). Shiner perch may produce a brood at age 1 except under circumstances that result in a slow growth rate (Gordon 1965). Average fecundity is 8 young, and fecundity and embryo size are positively correlated with female parental size (Wiebe 1968, Wilson and Milleman 1968). The young grow rapidly in the 1st year of life, especially females, which grow faster and have a longer life span than males (Anderson and Bryan 1970). Although the shiner perch can live for 8 years, most studies report it to be shorter lived, from 2.5 to 5 years (Gordon 1965, Odenweller 1975, Baxter 1980). Adults may reach a maximum length of 203 mm TL (Miller and Lea 1972). Because of its small size, it is not commercially important, although it is an important sport fish and may be used as bait (Frey 1971).

In the San Francisco Estuary, shiner perch consume primarily epibenthic invertebrates including crustaceans, amphipods, bivalves, and polychaetes (Boothe 1967). Food items differ with sex, age, and season (Gordon 1965). Juveniles feed mainly on copepods and switch to mussels, algae, and barnacles as they grow. Hobson and others (1981) found 2 feeding modes in southern California based on size. Shiner perch <65 mm standard length (SL) were primarily diurnal feeders preying on crustaceans in the water column. Fish > 65 mm fed during the day but also fed on benthic organisms at night. In turn, shiner perch are prey for larger marine fishes including sturgeon, salmon, barred sand bass, and in San Francisco Estuary, striped bass and harbor seals (Thomas 1967, Feder and others 1974). In Yaquina Bay, Oregon, they are also eaten by great blue herons (Bayer 1981).

Methods

Beach seine (1981 to 1986) and otter trawl (1980 to 1995) data were used for the analyses. Beach seine data were analyzed for seasonal distribution and abundance and the otter trawl data were used for seasonal and annual abundance and distribution analyses. Data from both gear types were used for salinity and temperature distributions.

Fish were classified into 2 age groups: age 0 and age 1+ by visual inspection of length frequencies. A January 1 birth date was assumed, but this corresponds to the date of fertilization, not the actual birth date. Cutoff lengths for the separation of age 0 and age 1+ were as follows: 55 mm FL for January through May, 70 mm for June, 85 mm for July, 95 mm for August, 100 mm for September and October, and 105 mm for November and December.

The age–0 annual abundance index period was May to October for the beach seine and the otter trawl. The age–1+ annual abundance index was February to June in the otter trawl and March to July in the beach seine. We did not sample with the otter trawl in January from 1990 to 1994, and therefore, this month is not included in the age–1+ index period.

Results

Length Analyses

In the otter trawl, the minimum length of shiner perch was 25 mm FL, although fish <30 mm were rare (Figure 1). The maximum length was 235 mm, which is larger than the reported maximum length of 203 mm TL (Miller and Lea 1972). Very few fish >145 mm were collected in the otter trawl. Modal length from January to March was 80 to 90 mm; these are age–1+ fish. In April, the mode increased to 90 to 100 mm. In summer, when parturition occurred, smaller fish were collected and 2 modes appeared in June and July. There were very few fish >2 years old (110 mm) entering the estuary for parturition. This agrees with other studies which report shiner perch to be short-lived (Gordon 1965, Odenweller 1975).

In the beach seine, fish ranged from 31 to 150 mm, although very few fish >80 mm were collected (Figure 2). From February to April, mostly larger fish ranging from 95 to 135 mm were found. In May and June, during parturition, the modal length was 35 to 45 mm and the fish grew quickly to 55 and 65 mm during summer. A few small fish remained in the shallows in winter and the larger fish disappeared in August and September.

Abundance

In the otter trawl, age–0 shiner perch were most abundant in 1982, followed closely by 1981 (Figure 3A, Table 4). Abundance was low from 1988 to 1995; the lowest indices were in 1991 and 1994.

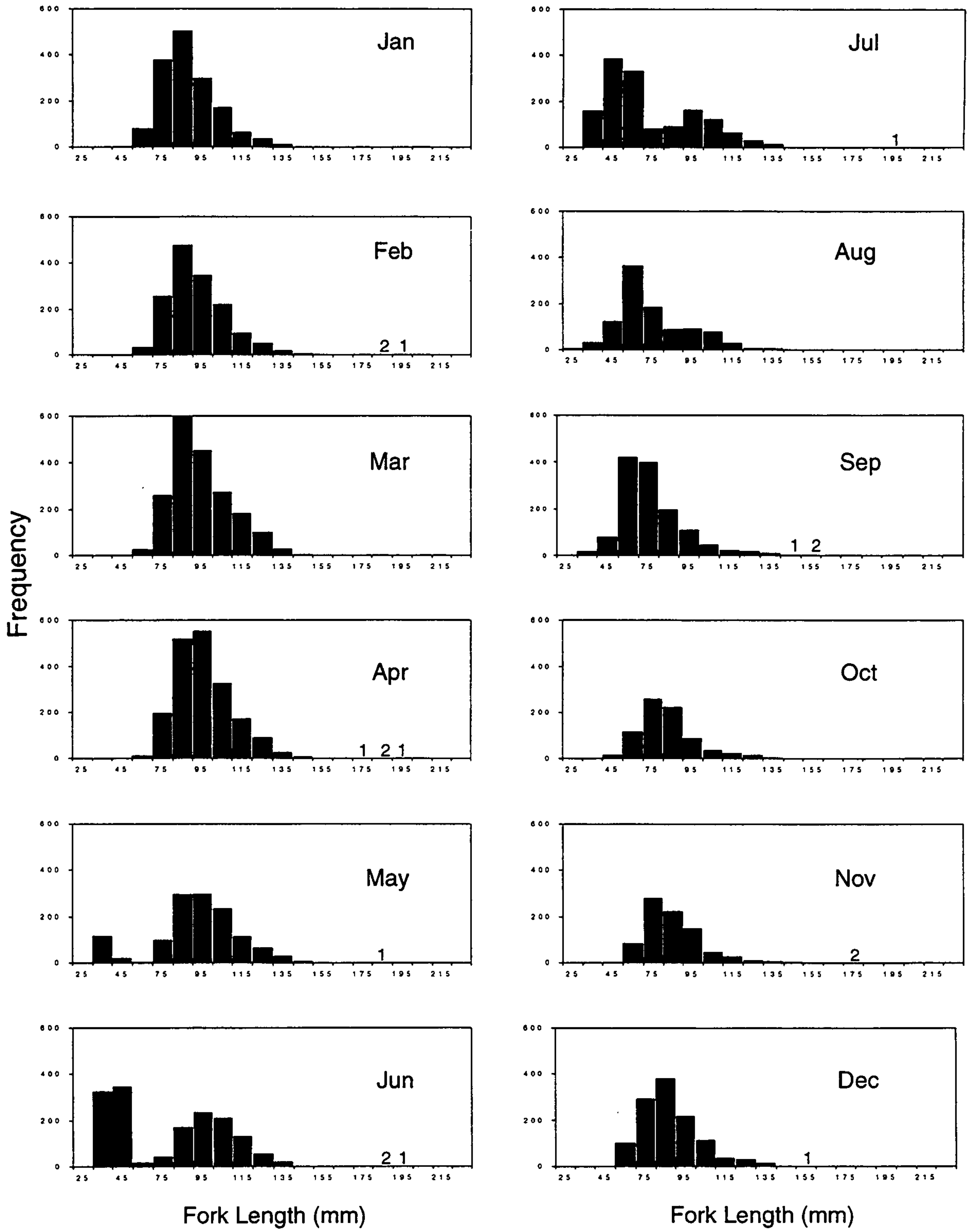

Figure 1 Monthly length frequencies of shiner perch collected with the otter trawl from 1980 to 1995. Numbers on x-axis are lower class limits.

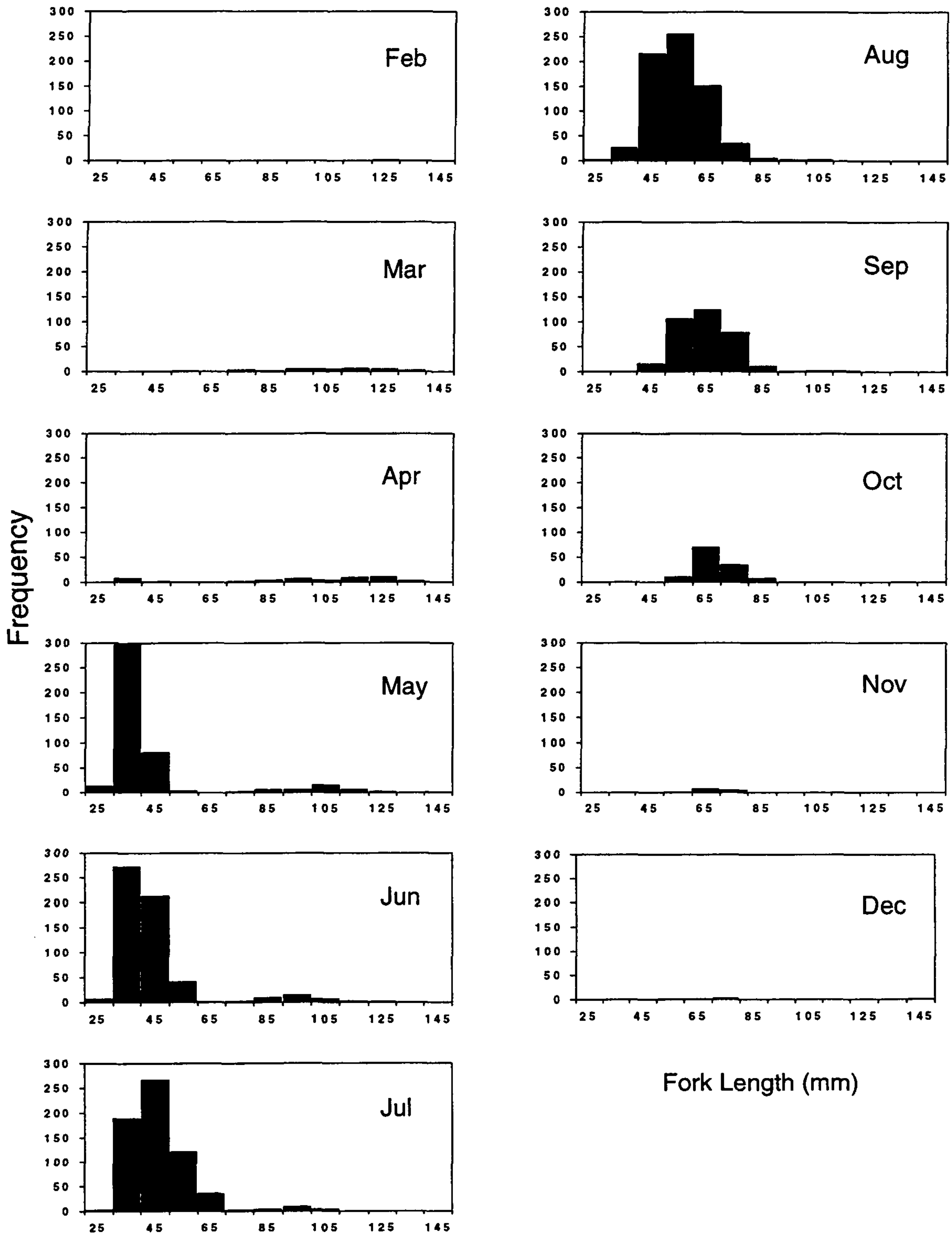

Figure 2 Monthly length frequencies of shiner perch collected with the beach seine from 1980 to 1986. No shiner perch were collected in January. Numbers on the x-axis are lower class limits.

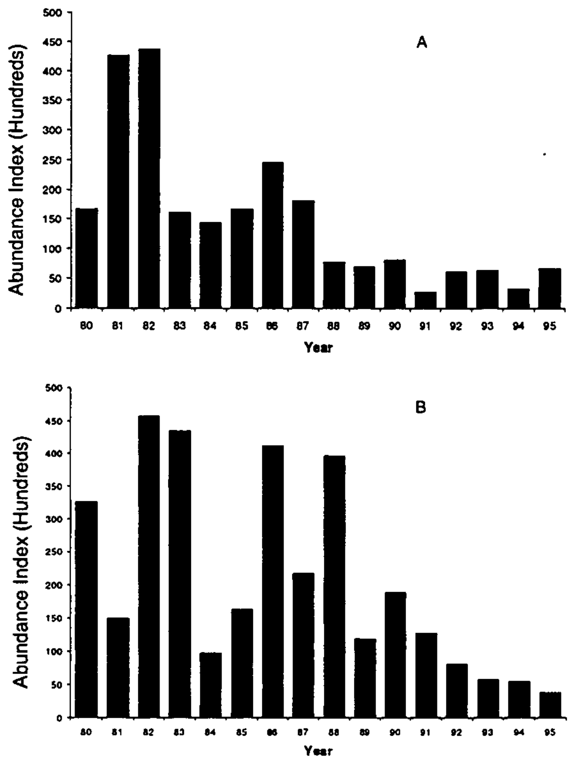

Figure 3 Annual abundance indices of shiner perch collected with the otter trawl from 1980 to 1995: (A) age 0, index period was May to October; (B) age 1+, index period was February to June

Table 4 Monthly abundance indices (in hundreds) of age–0 shiner perch collected with the otter trawl from 1980 to 1995. The annual index period was May to October. In 1989 the annual index period was May to August.

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Annual Index*
1980		0	0	0	5	11	194	431	259	101	193	46	167
1981	0	0	0	0	126	144	1143	825	215	107	311	177	426
1982	0	0	5	0	10	1191	390	369	480	182	244	354	437
1983	0	0	0	0	5	538	122	47	88	169	76	36	161
1984	0	0	0	0	0	54	251	272	164	122	248	257	144
1985	0	0	4	0	0	104	403	82	201	208	321	869	166
1986	0	0	0	0	0	47	157	406	769	96	129	396	246
1987	0	0	0	0	0	54	113	242	522	152	191	204	181
1988	0	0	0	0	34	74	181	102	72	2	84	63	77
1989	0	0	0	0	5	46	100	127					70
1990		0	0	0	9	82	169	36	53	142			82
1991		0	0	0	0	7	46	33	72	7			27
1992		0	0	0	56	228	31	15	23	15			61
1993		0	0	0	14	215	124	17	9	2			63
1994		0	0	0	7	87	37	27	21	16			32
1995	0	0	0	0	0	0	251		61	22	128	148	67
1981–1988	0	0	1	0	22	276	345	293	314	130	200	294	

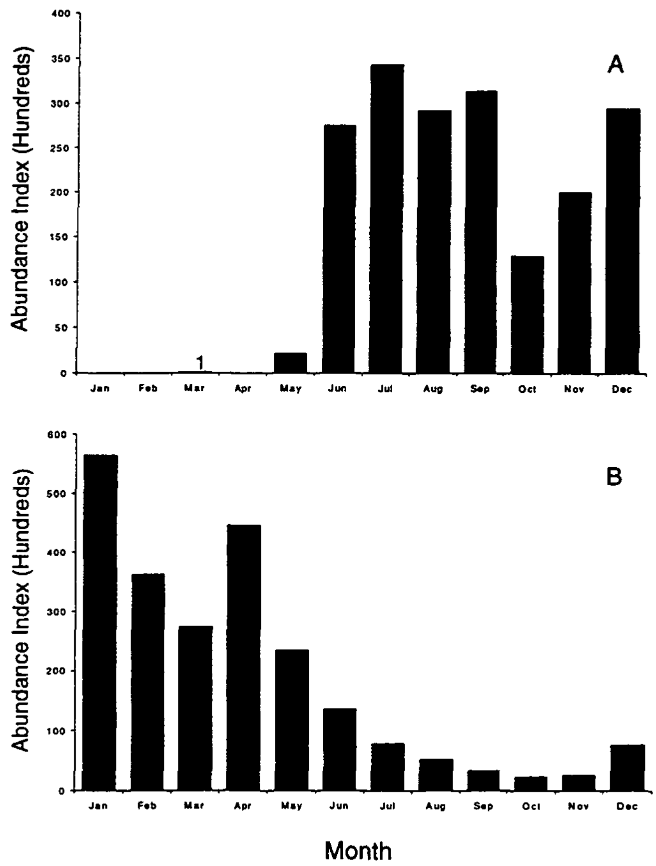

Figure 4 Seasonal abundance of shiner perch collected with the otter trawl from 1981 to 1988: (A) age 0 and (B) age 1+

Table 5 Monthly abundance indices of age–0 shiner perch collected with the beach seine from 1981 to 1986. The annual index period was May to October.

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Annual Index*
1981	0	0	0	3	122	432	458	395	140	34	11	9	264
1982	0	0	0	0	36	82	248	117	2	3	0	0	81
1983	0	0	0	0	321	88	212	48	95	33	0	0	133
1984	0	0	0	0	11	208	159	58	43	1	0	0	80
1985	0	0	0	3	551	84	121	52	47	3	0	0	143
1986	0	0	0	10	20	356	464	116	47	70	9	0	179
1981–1986	0	0	0	3	177	208	277	131	62	24	3	2	

In the otter trawl, age–0 fish were first collected in May and June, except in 1995 when they were not collected until July (Figure 4A, see Table 4). Monthly abundance of age–0 fish peaked from June to September, and in many years there was a 2nd and smaller peak in winter. But in 1985, the winter peak was higher than the summer peak (see Table 4). In the beach seine, age–0 fish were first collected as early as April but did not become abundant until May (Figure 5A, Table 5). Abundance peaked in July and declined sharply in August to lows in November and December.

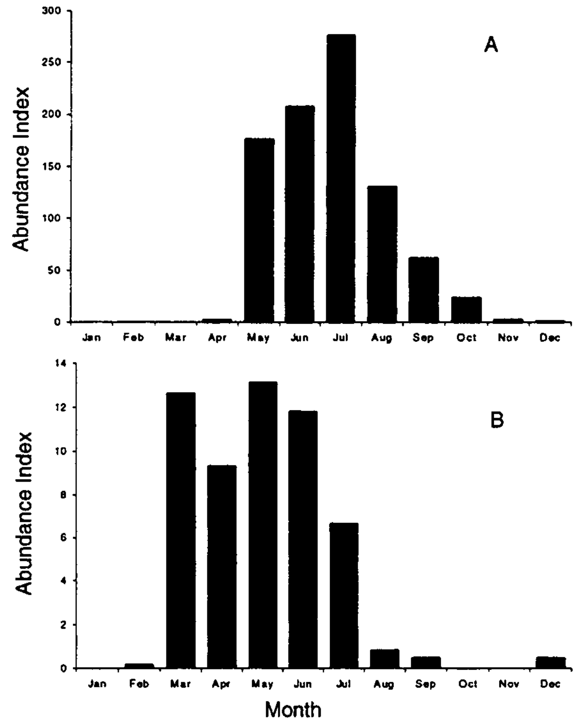

Figure 5 Seasonal abundance of shiner perch collected with the beach seine from 1981 to 1986: (A) age 0 and (B) age 1+

Table 6 Monthly abundance indices (in hundreds) of age–1+ shiner perch collected with the otter trawl from 1980 to 1995. The annual index period was February to June.

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Index*
1980		632	284	374	266	74	82	35	28	12	5	4	326
1981	275	110	220	336	52	38	146	46	33	45	32	38	151
1982	1703	533	256	1061	242	194	84	101	66	12	37	111	457
1983	526	326	491	961	264	139	56	15	5	24	15	14	436
1984	112	225	136	44	44	39	39	13	24	8	11	78	98
1985	303	219	289	151	60	97	37	9	26	15	81	301	163
1986	971	689	214	626	326	206	122	79	19	7	12	7	412
1987	276	590	250	46	66	133	62	124	88	73	20	59	217
1988	360	215	342	349	829	245	87	30	8	0	0	13	396
1989	182	140	95	90	56	215	38	18					119
1990		271	225	156	131	163	54	12	8	35			189
1991		232	175	79	141	14	129	6	6	4			128
1992		173	50	97	44	40	9	0	3	0			81
1993		29	171	15	47	28	27	3	2	0			58
1994		42	78	38	31	87	10	14	3	4			55
1995	114	25	117	41	7	5	12		3	2	51	51	39
1981–1988	566	364	275	447	235	136	79	52	34	23	26	78	

In the otter trawl, the highest annual abundance indices of age–1+ shiner perch were in 1982 and 1983 (Figure 3B, Table 6). These lagged the highest age–0 indices by 1 year. Abundance indices declined from 1990 to 1995, and the lowest indices were from 1992 to 1995.

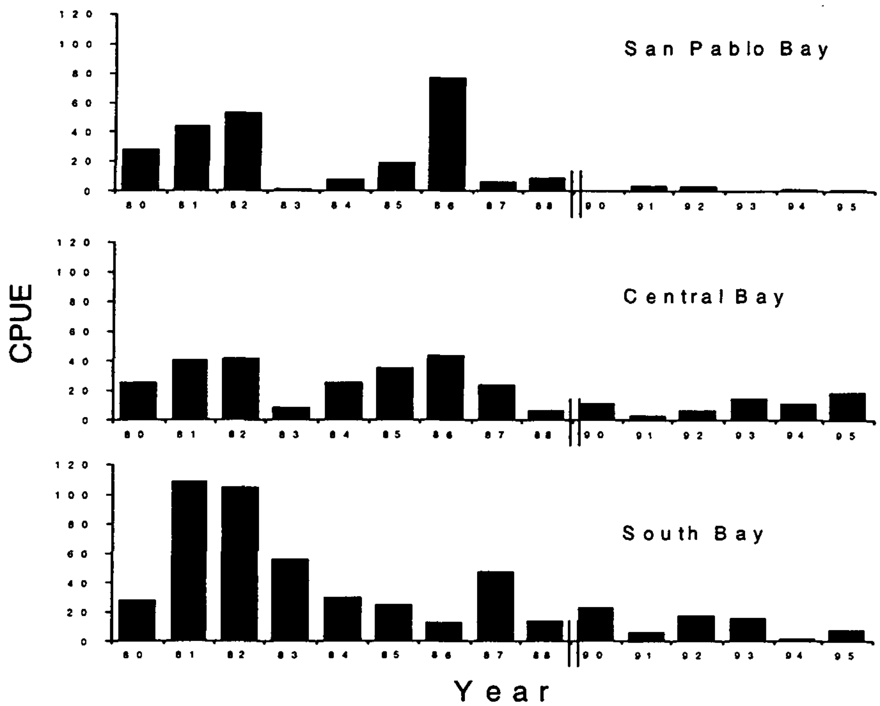

Figure 6 Annual distribution of age–0 shiner perch collected with the otter trawl from 1980 to 1988 and 1990 to 1995. Annual CPUE was calculated from May to October. CPUE was <1 in Suisun Bay and no shiner perch were collected in the west delta.

In the otter trawl, age–1+ shiner perch were collected in all months (Figure 4B, see Table 6). Abundance was low in summer and fall, rose to a peak in winter, usually in January, then declined and often rose to a 2nd mode in April. Since a January 1 birth date was assumed, the winter mode was probably composed of overwintering juveniles. During the winter mode from January to March, young fish ranging from 75 to 105 mm fish were abundant. In the beach seine, age–1+ fish were present from February to September and were most abundant from March through June (Figure 5B). This contrasts with the otter trawl, in which age–1+ shiner perch were also abundant in winter (see Figure 4B).

Distribution

In the otter trawl, age–0 shiner perch ranged from South to Suisun bays (Figure 6). In most years, CPUE was usually highest in South Bay, although in 1985, 1994, and 1995 it was highest in Central Bay, and in 1986 in San Pablo Bay. In 1980, CPUE was equal in South, Central, and San Pablo bays. Very few age–0 shiner perch were collected in Suisun Bay.

In the otter trawl, age–0 CPUE was highest in South Bay in June and July and in San Pablo Bay in August and September (Figure 7). CPUE decreased in South and San Pablo bays in October and increased in Central Bay from October to December. This suggests a movement of age–1+ fish to Central Bay where they may remain in the estuary or emigrate to the ocean. In the beach seine, age–0 fish ranged from South to Suisun bays (Figure 8). The CPUE was highest in South and Central bays. It decreased significantly in South Bay in October, Central Bay in November and San Pablo Bay in August. This contrasted with the otter trawl, in which the CPUE remained relatively high in winter.

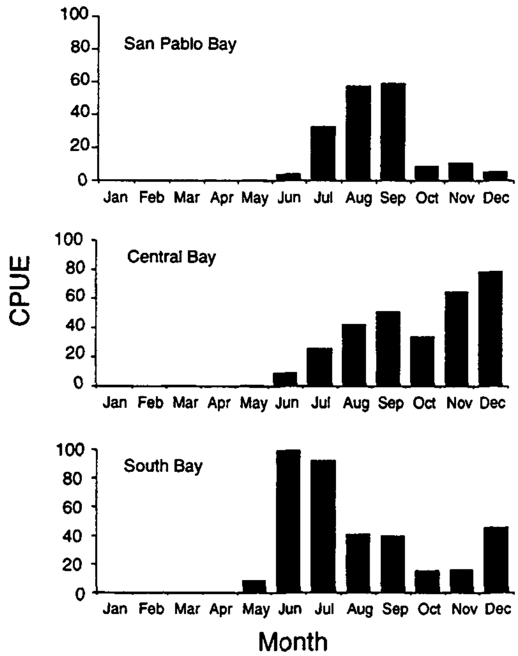

Figure 7 Seasonal distribution by bay of age–0 shiner perch collected with the otter trawl from 1981 to 1988. Values are CPUE x 10. CPUE was <1 in August and November in Suisun Bay. No shiner perch were collected in the west delta.

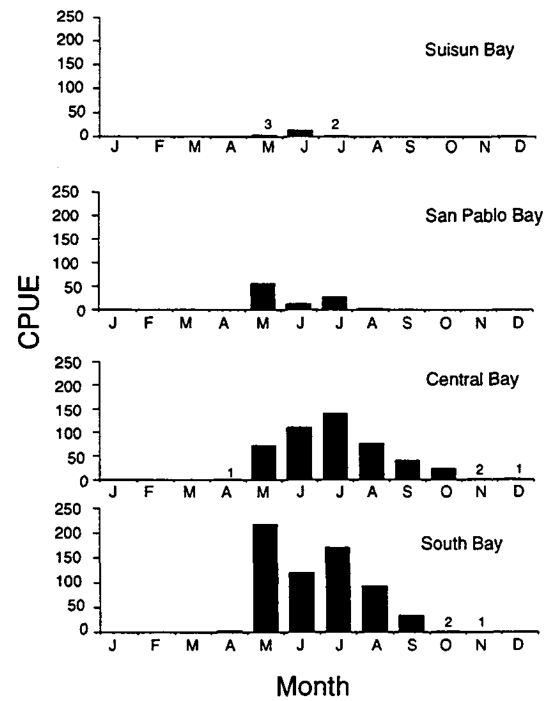

Figure 8 Seasonal distribution of age–0 shiner perch collected with the beach seine from 1981 to 1986

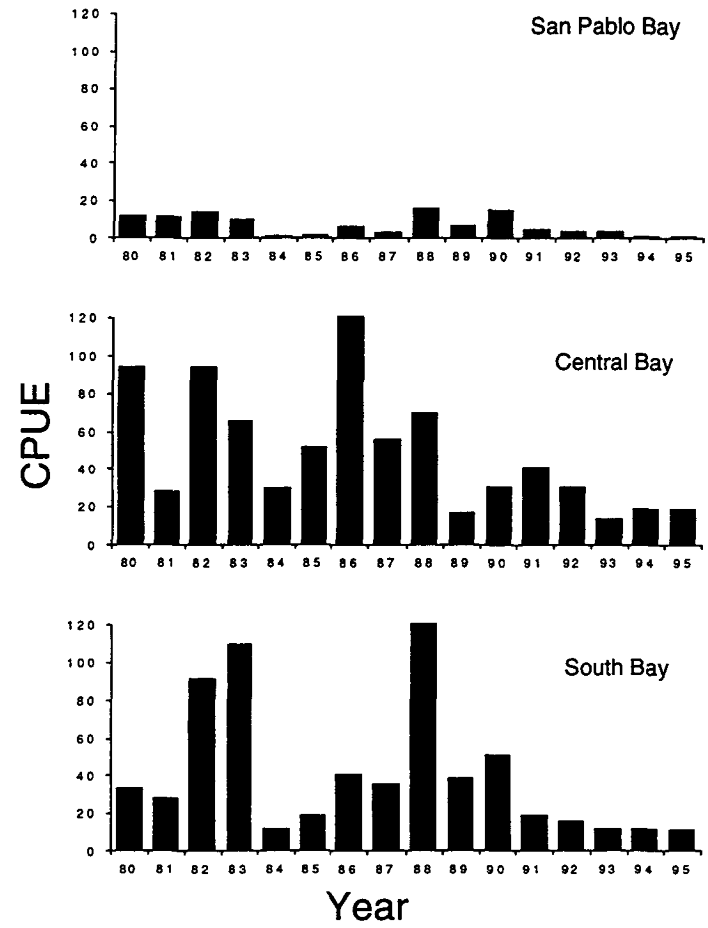

Figure 9 Annual distribution of age–1+ shiner perch collected with the otter trawl from 1980 to 1995. Values are annual CPUE from February to June. No shiner perch were collected in Suisun Bay and the west delta.

Age–1+ fish were collected from South to San Pablo bays in all years with the otter trawl (Figure 9). The highest CPUE usually occurred in Central Bay except in 1983 and 1988 to 1990 when CPUE was highest in South Bay. In 1981 and 1993, CPUE was equal in South and Central bays.

In the otter trawl, age–1+ shiner perch were collected from South to San Pablo bays from January to September and from South and Central bays from October to December. The CPUE was highest in Central Bay in January and February. From March to May, CPUE increased in South Bay and the distribution expanded to San Pablo Bay. They moved back to Central Bay in summer and remained there for the rest of the year (Figure 10). In the beach seine, age–1+ shiner perch were also collected from South to San Pablo bays (Figure 11). They were collected from February to September and in December, but were most abundant from March to July. The CPUE was usually highest in South Bay except in May and August when it was highest in Central Bay. The CPUE decreased in June in San Pablo Bay, July in Central Bay, and August in South Bay.

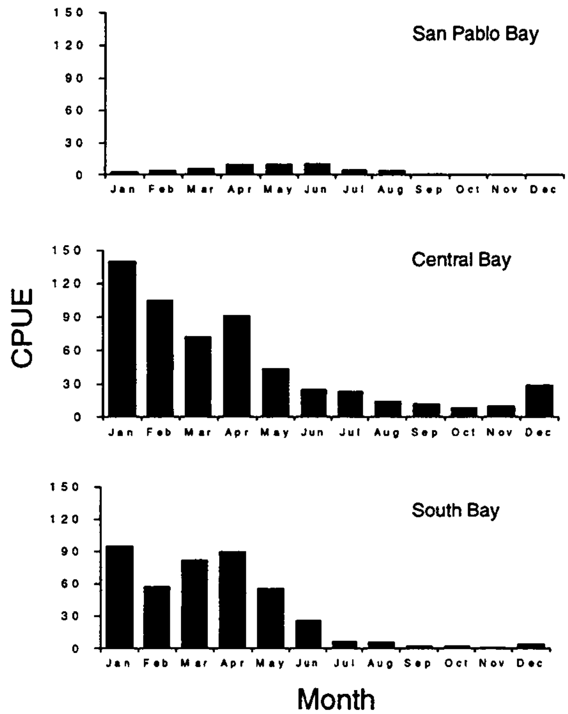

Figure 10 Seasonal distribution by bay of age–1+ shiner perch collected with the otter trawl from 1981 to 1988. No shiner perch were collected in Suisun Bay and the west delta.

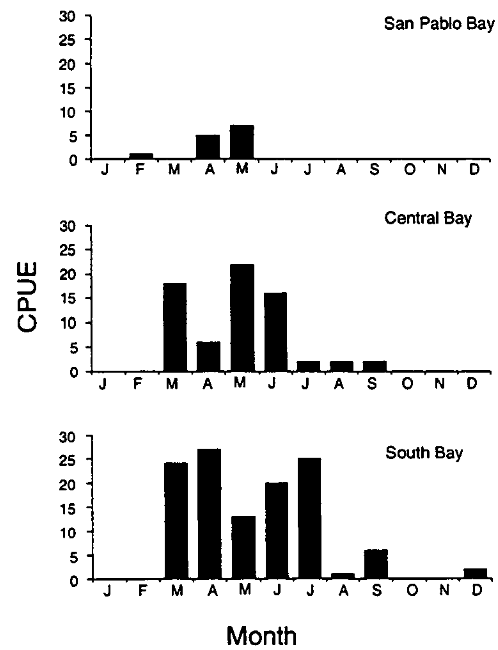

Figure 11 Seasonal distribution of age–1+ shiner perch collected with the beach seine from 1981 to 1986. None were collected in Suisun Bay or the west delta.

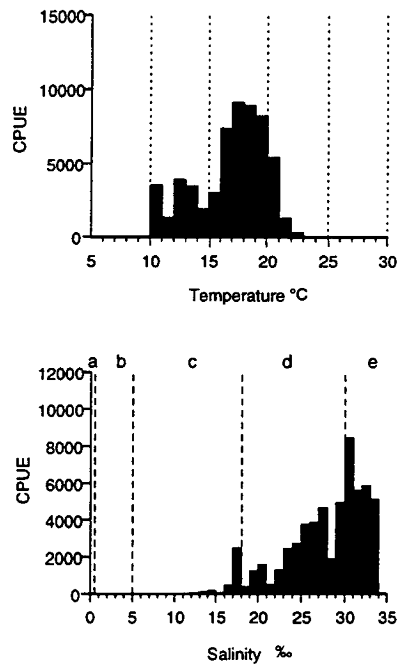

Figure 12 Temperature and salinity distributions for age–0 shiner perch collected with the otter trawl. The vertical lines on the salinity graph mark the boundaries of the Venice system ranges: (a) limnetic, (b) oligohaline, (c) mesohaline, (d) polyhaline, and (e) euhaline.

Temperature and Salinity

In the otter trawl the temperature range for age–0 shiner perch was 10.4 to 22.5 °C, $\bar{\chi}$ = 16.6 °C (Figure 12), and 12.4 to 25.5 °C, $\bar{\chi}$ = 19.6 °C in the beach seine (Figure 13). Age–1+ fish were collected at lower temperatures than age–0 fish in the otter trawl: 7.5 to 22.6 °C, $\bar{\chi}$ = 13.3 °C (Figure 14). In the beach seine, temperatures ranged from 12.0 to 25.7 °C, $\bar{\chi}$ = 18.6 °C for age–1+ fish (Figure 15). In both the otter trawl and beach seine, temperature ranges decreased with increased size of fish (Figures 16 and 17).

In the otter trawl, age–0 shiner perch were collected at salinities from 8.4 to 34.4‰, $\bar{\chi}$ = 27.9‰ (see Figure 12). Beach seine salinities for age–0 fish were similar: range 9.1‰ to 33.3‰, $\bar{\chi}$ = 27.4‰ (see Figure 13).

A higher percentage of age–1+ fish were at lower salinities than age–0 fish. The salinity range for age–1+ fish was 0.1 to 34.3‰, $\bar{\chi}$ = 25.0‰ in the otter trawl (see Figure 14). Only 23 fish were collected at <5.0‰. In the beach seine, age–1+ fish were found at 0.6 to 33.3‰, $\bar{\chi}$ = 23.1‰ (see Figure 15).

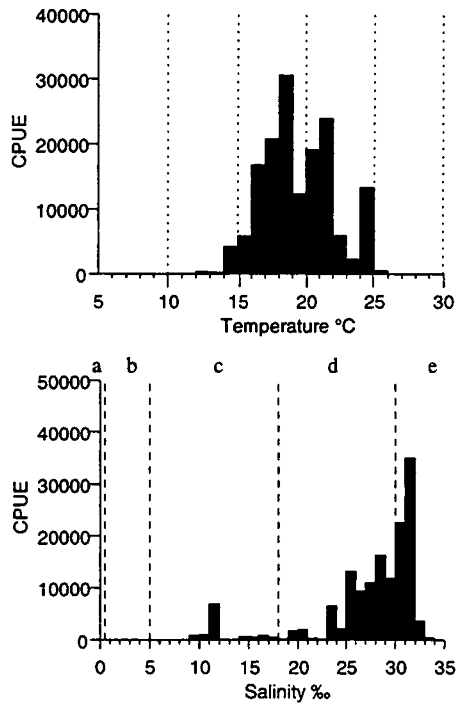

Figure 13 Temperature and salinity distributions for age–0 shiner perch collected with the beach seine. The vertical lines on the salinity graph mark the boundaries of the Venice system ranges: (a) limnetic, (b) oligohaline, (c) mesohaline, (d) polyhaline, and (e) euhaline.

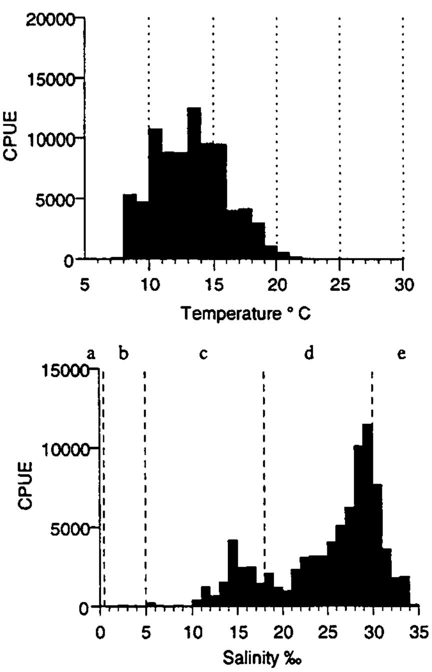

Figure 14 Temperature and salinity distributions for age–1+ shiner perch collected with the otter trawl. The vertical lines on the salinity graph mark the boundaries of the Venice system ranges: (a) limnetic, (b) oligohaline, (c) mesohaline, (d) polyhaline, and (e) euhaline.

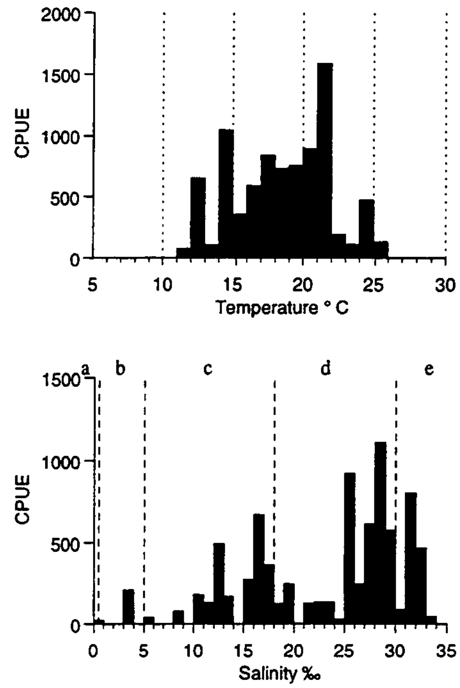

Figure 15 Temperature and salinity distributions for age-1+ shiner perch collected with the beach seine. The vertical lines on the salinity graph mark the boundaries of the Venice system ranges: (a) limnetic, (b) oligohaline, (c) mesohaline, (d) polyhaline, and (e) euhaline.

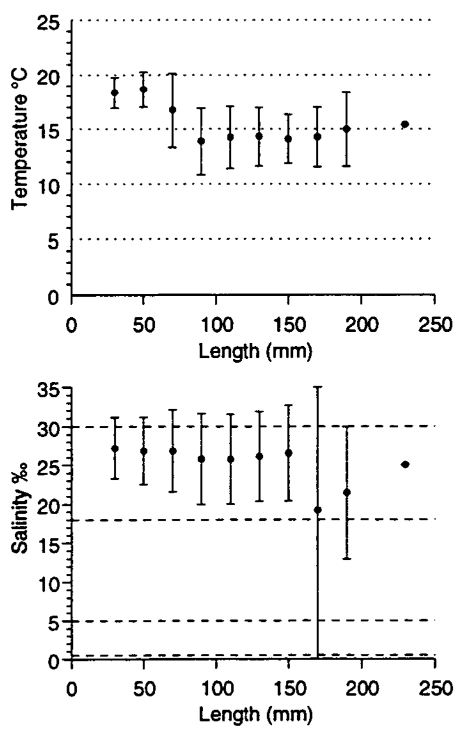

Figure 16 Temperature and salinity by length of shiner perch collected with the otter trawl from 1980 to 1995. Values are mean ±1 standard deviation.

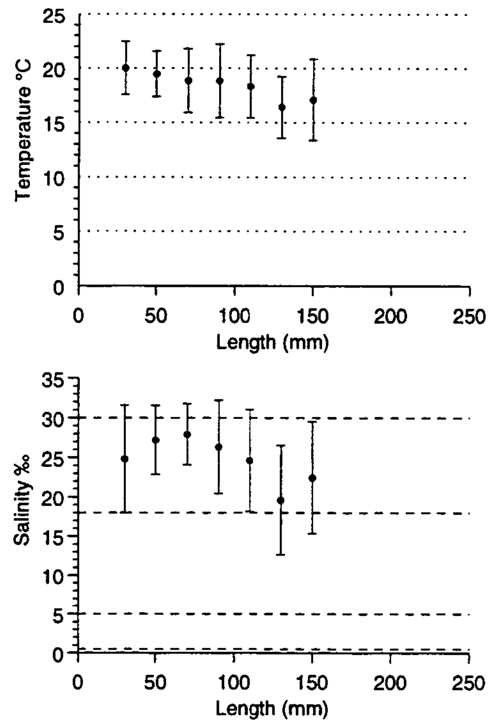

Figure 17 Temperature and salinity by length of shiner perch collected with the beach seine from 1980 to 1986. Values are the mean ±1 standard deviation.

Discussion

Shiner perch were found in the estuary throughout the year and used it primarily for parturition and as a nursery area. Both age groups migrated in the estuary and emigrated to the ocean. Our data and other research indicate that complex migrations occur relative to season, sex, and age of fish. Age–0 fish first appeared in the estuary in May and were most abundant in June, indicating that parturition occurred during or just prior to these months. Abundance decreased in late fall and early winter in the beach seine but remained relatively high in the otter trawl. This suggests the young shiner perch moved from shallow to deeper waters in fall, but did not leave the estuary. This seems to be true in other areas also. In Newport Bay, Oregon, juveniles do not emigrate until after their 1st year (Bane and Robinson 1970).

Age–1+ shiner perch were collected in the beach seine mostly from March to July, and in the otter trawl were most abundant from late winter through June. This indicates that some age–1+ fish move into shallow water throughout summer. Age–1+ fish are known to move to shallow, protected areas for parturition, but this movement may also be due to higher temperatures and better feeding conditions in the shallows, which could help shorten the development time of the young. However, Gordon (1965) found that the depth distribution of shiner perch in British Columbia may be related to light intensity rather than feeding habits. In winter, shiner perch move into deeper water. This has also been reported in other areas. Adults leave Anaheim Bay in August and migrate to the deeper water in the nearshore ocean during winter (Odenweller 1975).

Age–1+ shiner perch were found primarily in deeper areas of Central Bay in winter and moved to the shallows of South and Central bays from March to June, when parturition occurred, and then returned to Central Bay from late summer to winter. The monthly length frequency data shows this movement to the shallows is comprised of age–1+ fish migrating from the ocean to Central Bay, and juveniles which over-wintered in the estuary. Both age groups then return to Central Bay in late summer and either remain there through the winter or emigrate to the ocean. In Bodega Bay, males enter birthing areas and 1 week later the females arrive to give birth. They are immediately inseminated after parturition and both sexes of adults then leave the area (Shaw and others 1974).

Age–1+ shiner perch were collected at lower salinities and temperatures than age–0 fish. This contradicts laboratory studies which found that juveniles preferred colder temperatures than adults and age–0 fish preferred the coldest temperatures of any age group (Shrode and others 1983). In the field, juveniles are observed in warm shallow waters, although they are not restricted to this habitat. The temperature preferences of both age classes may be affected by other factors such as timing of parturition, habitat selection, and food availability. For example, age–0 fish may not be in warm water because they preferentially migrated to it, rather they were born there and have not dispersed. They may then remain in protected areas with greater food availability. McCauley and Huggins (1979) found no consistent pattern of seasonal differences in temperature preference of shiner perch.

Abundance of age–0 fish has declined since 1987 and abundance of age 1+ since 1988. Although these declines were concurrent with the drought, abundance remained low through 1995.

Factors which may have contributed to the shiner perch decline include degradation of nursery habitat, low fecundity, and overharvest. Urbanization, flood control, ports, marinas, and water development projects have caused a decline in nearshore habitat in the San Francisco Estuary (SFEP 1991). Shiner perch may be affected by loss of this habitat, which they use as nursery and rearing areas. They are also vulnerable to overharvest by angling because there are no bag, possession, or size limits on them, and they can be taken any time of the year. Their low fecundity exacerbates the effects of heavy angling pressure.

Walleye Surfperch

Introduction

The walleye surfperch, *Hyperprosopon argenteum*, ranges from Vancouver Island, British Columbia to Point Santa Rosarita, central Baja California, including Guadalupe Island (Miller and Lea 1972). It can be found from the surface to 18 m but is most abundant from 1.5 to 6.7 m (Feder and others 1974). It is common along sandy beaches (Roedell 1953), over flat rocks, in the surf, around piers and jetties (Bane and Bane 1971, Baxter 1980), and in kelp beds (Baltz 1984). The walleye surfperch congregates in dense schools composed of several hundred to several thousand fish when not breeding. Its temperature range is primarily from 7 to 21 °C (Tarp 1952).

During mating, large schools break up into isolated pairs or schools of 4 to 10 females attended by 1 male (Rechnitzer and Limbaugh 1952). Mating takes place from October to December (Rechnitzer and Limbaugh 1952). Like all surfperch, the walleye surfperch is viviparous. It is 1 of 3 species of embiotocids that does not store sperm; therefore, fertilization occurs when mating. Gestation lasts 5 to 6 months and the young are born from April through June. The average fecundity is 5 to 12 young and the number and size of young are correlated with maternal weight and age (DeMartini and others 1983, Rechnitzer and Limbaugh 1952).

Mean size at birth is 40 mm SL (Rechnitzer and Limbaugh 1952). The walleye surfperch grows fastest in its 1st year of life (Anderson and Bryan 1970). Most males mature 4 to 6 months after birth at 65 to 95 mm

SL, and most females mature about 7 months after birth at 100 to 110 mm SL (DeMartini and others 1983). Slow growing males and females may mature in their 2nd year. Geographic factors may influence these differences in age, growth, and sexual maturation patterns (DeMartini and others 1983). Northern populations live longer and have delayed maturity and greater fecundity (Baltz 1984). Maximum age of walleye surfperch is reported as 6 years. Eckmayer (1979) reported that males and females have similar life spans, but according to DeMartini and others (1983) females may live longer than males. Maximum size is 305 mm TL (Miller and Lea 1972).

The walleye surfperch is a benthic or near bottom feeder (Morning 1984) and preys on squid eggs and crustaceans including isopods and amphipods (Bane and Bane 1971, Feder and others 1974). Kelp bass, sculpin, and halibut prey on walleye surfperch. It was formerly the most commonly caught surfperch in California's commercial and sport fisheries. Sport anglers catch walleye surfperch from shores, jetties, and piers (Fritzsche and others 1992).

Methods

Fish were classified as age 0 or age 1+ by visual inspection of length frequencies. The cutoff lengths for this separation were as follows: 115 mm FL from January through July, 120 mm for August and September, and 125 mm from October through December. The midwater trawl index period was May through August for age–0 fish, and March through October for age–1+ fish. The beach seine age–0 index period was May through October.

The 1980 to 1995 midwater trawl data were used for annual abundance and distribution analyses of age–0 and age–1+ fish. For seasonal abundance and distribution analyses, the 1981 to 1988 midwater trawl data were used. The 1981 to 1986 beach seine data were also used for seasonal distribution of age–0 fish. No age–1+ fish were collected in the beach seine. Data from both gear types were used for salinity and temperature distributions.

Results

Length Analyses

In the midwater trawl, walleye surfperch ranged from 42 to 285 mm FL (Figure 18). At least 2 year classes were collected in the estuary. The first length mode was 50 to 80 mm FL, and a second smaller mode was >130 mm FL. Year classes older than 1 were difficult to distinguish as catches of fish >200 mm were sporadic. Age–0 fish grew quickly in spring and summer after parturition. Modal length in May was 50 to 70 mm, in June 60 to 80 mm, in July 70 to 90 mm, and in August 90 to 100 mm.

Only very young fish ranging from 47 to 110 mm were usually collected with the beach seine (Figure 19).

Abundance

In the midwater trawl, annual age–0 walleye surfperch abundance indices varied from a high of 11,600 in 1981 to <100 in 1991 (Figure 20A, Table 7). Abundance declined dramatically in 1982 and 1983, then increased slightly in 1984. A steady decline occurred from 1990 to 1995. In 1994, midwater trawl sampling ended in April and there was no index due to insufficient data. In 1995, no age–0 fish were collected during the index period.

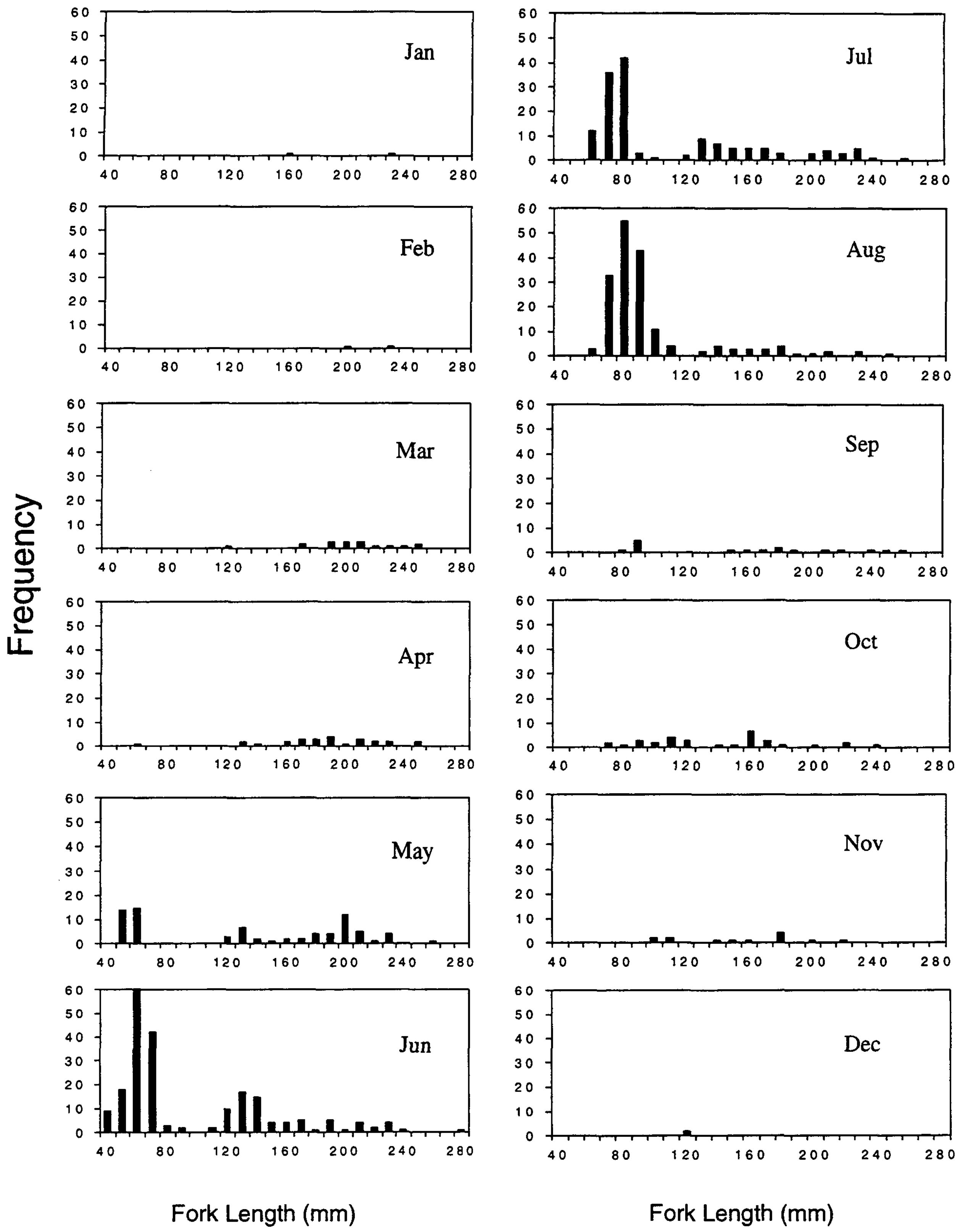

Figure 18 Monthly length frequencies of walleye surfperch collected with the midwater trawl from 1980 to 1995. Values on x-axis are lower class limits.

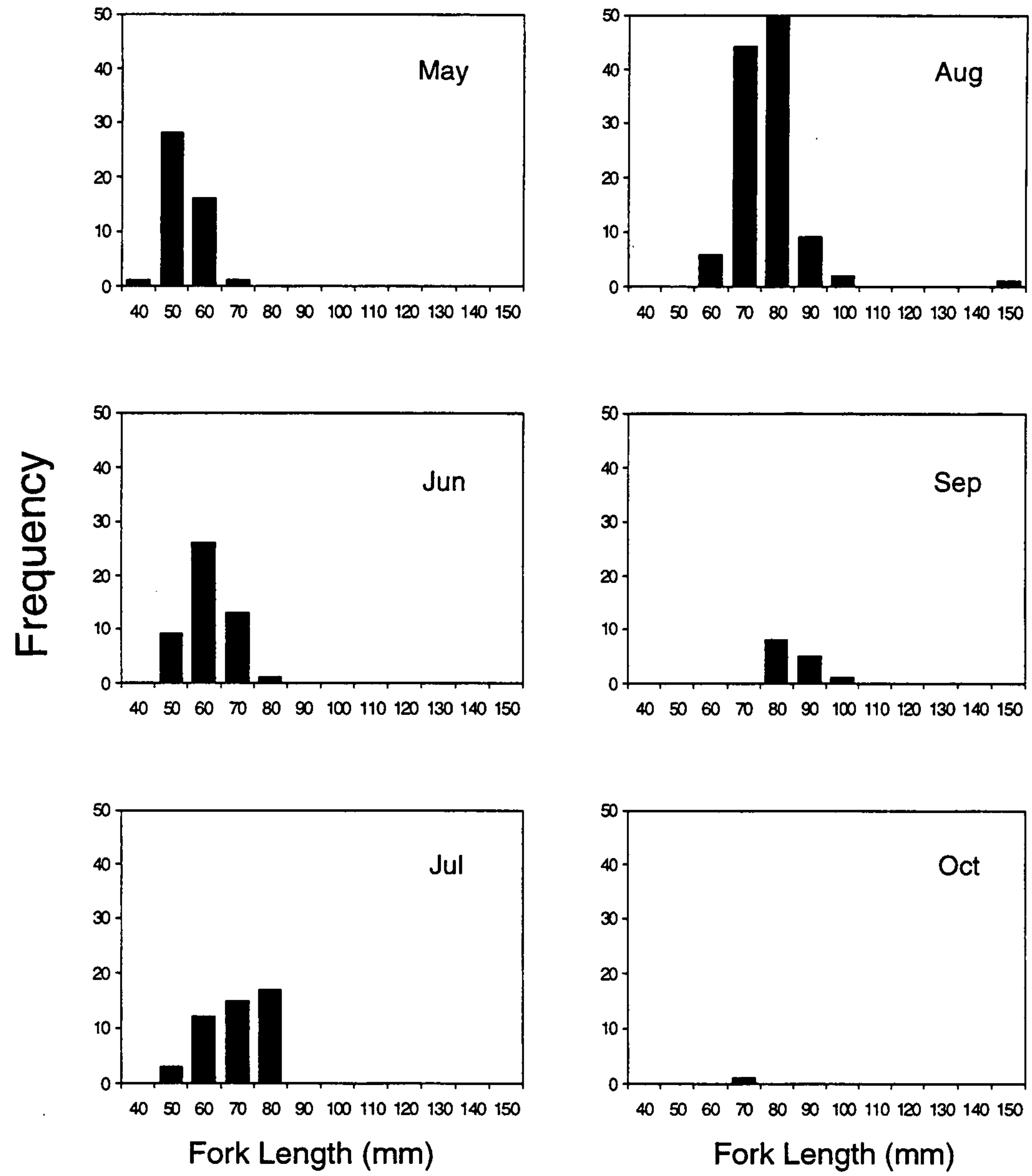

Figure 19 Monthly length frequencies of walleye surfperch collected with the beach seine from 1980 to 1986. Values on x-axis are lower class limits. No walleye surfperch were collected from January to April or in November and December.

Abundance of age–0 walleye surfperch collected with the midwater trawl peaked from June to August, then decreased dramatically in fall, and none were collected from December to March (Figure 21A, see Table 7). Age–0 fish were usually present from May to October with exceptions in 1982, 1993, and 1995 (see Table 7).

Age 1+ walleye surfperch were most abundant in 1981 and 1987 in the midwater trawl catches (Figure 20B, Table 8). The abundance index was very low in 1983, increased to a peak in 1987 and then declined from 1988 to 1995. In 1994, there was no index due to insufficient data. Age 1+ fish were collected in all months except December (Figure 21B, see Table 8). Abundance peaked from May to July and was low in fall and winter.

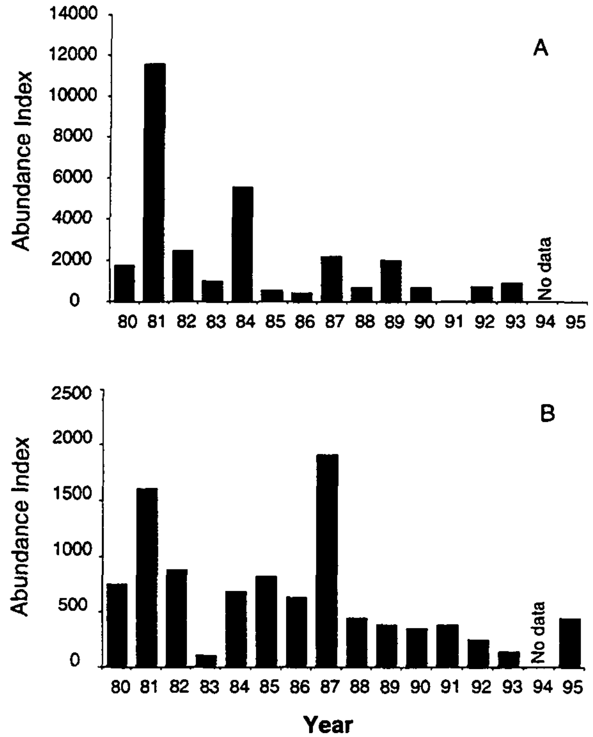

Figure 20 Annual abundance indices of walleye surfperch collected with the midwater trawl from 1980 to 1995: (A) age 0, index period was May to August; (B) age 1+, index period was March to October

Table 7 Monthly abundance indices of age–0 walleye surfperch collected with the midwater trawl. The annual index period was May to August.

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Annual Index*
1980		0	0	0	0	0	215	6923	358	430	0	0	1785
1981	0	0	0	0	6022	19488	10119	10769	188	1505	0	0	11600
1982	0	0	0	0	565	5358	2616	1344	0	0	1745	0	2471
1983	0	0	0	0	0	565	1049	2446	0	0	0	0	1015
1984	0	0	0	0	0	5748	2446	14156	0	716	0	0	5588
1985	0	0	0	0	0	1694	376	188	0	0	0	0	565
1986	0	0	0	0	0	188	904	646	108	0	0	0	435
1987	0	0	0	0	0	2167	6125	466	0	0	0	0	2190
1988	0	0	0	0	188	565	484	1505	108	0	0	0	686
1989	0	0	0	0	0	4979	923	2141					2011
1990		0	0	0	323	1809	716	0	358	0			712
1991		0	0	0	0	0	0	108	0	0			27
1992		0	0	0	0	2275	699	0	0	0			744
1993		0	0	358	0	842	0	2858	0	0			925
1994		0	0	0									
1995				0	0	0	0		0	716	0	0	0
1981–1988	0	0	0	0	847	4472	3015	3940	51	278	218	0	

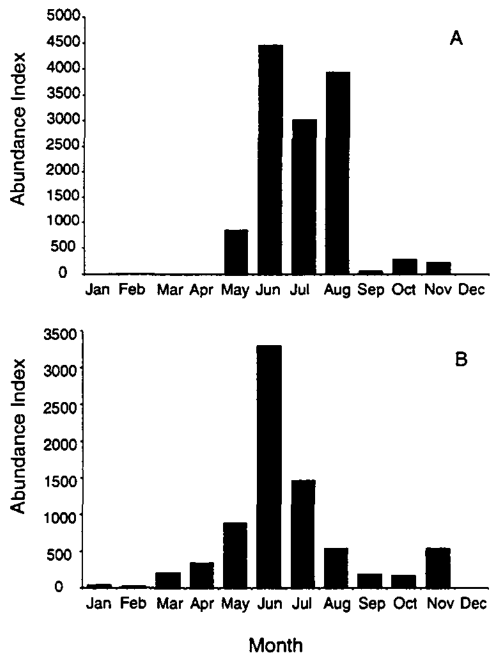

Figure 21 Seasonal abundance of walleye surfperch collected in the midwater trawl from 1981 to 1988: (A) age 0 and (B) age 1+

Table 8 Monthly abundance indices of age–1+ walleye surfperch collected with the midwater trawl. The annual index period was March to October. NI indicates no index calculated.

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Annual Index*
1980		0	1487	753	0	215	2006	1074	466	0	0	0	750
1981	0	0	0	2366	0	8954	358	431	0	753	3940	0	1608
1982	358	0	753	0	1505	3600	923	0	0	215	0	0	875
1983	0	0	0	0	0	0	376	466	0	0	0	0	105
1984	0	0	0	0	2258	734	0	2149	0	358	0	0	687
1985	0	0	565	0	0	4445	1540	0	0	0	0	0	819
1986	0	188	0	0	296	546	3877	358	0	0	0	0	635
1987	0	0	0	0	2410	7521	4656	358	358	0	358	0	1913
1988	0	0	323	376	619	546	0	546	1112	0	0	0	440
1989	716	0	0	565	546	358	358	466					382
1990		358	753	108	897	0	108	0	358	573			350
1991		0	0	0	0	1433	1587	0	0	0			378
1992		0	0	0	0	1523	0	466	0	0			249
1993		0	296	0	358	0	0	431	0	0			136
1994		0	0	0									NI
1995				0	0	0	0		0	2615	0	546	436
1981–1988	45	24	205	343	886	3293	1466	539	184	166	537	0	

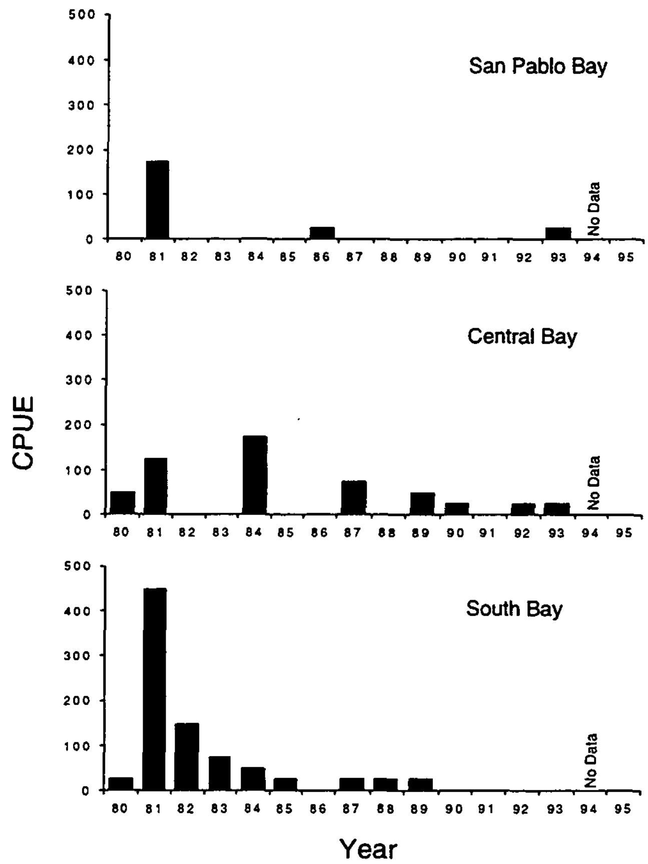

Figure 22 Annual distribution by bay of age–0 walleye surfperch collected with the midwater trawl from 1980 to 1995. Annual CPUE was May to August. Values are CPUE x 100.

Distribution

Age–0 walleye surfperch ranged from South to San Pablo bays in the midwater trawl catches (Figure 22). Annual CPUE was usually highest in either South or Central bays. Only in 1981, 1986, and 1993 did they enter San Pablo Bay in large numbers and then only in August (Figure 23). No walleye surfperch were collected in Suisun Bay or the west delta. Age–0 CPUE was highest in South Bay from May to July. In August, the CPUE was highest in San Pablo Bay due to fish collected in 1981, 1986, and 1993. In October they were collected only in South Bay and in November only in Central Bay.

Age–0 walleye surfperch also ranged from South to San Pablo bays in the beach seine (Figure 24). The CPUE was highest in Central Bay in all months. In the beach seine, the seasonal distribution was restricted to May to September compared to May to November in the midwater trawl.

Age–1+ walleye surfperch had the same range as age–0 fish in the midwater trawl from South to San Pablo bays (Figure 25). From 1980 to 1987, the CPUE was highest in either South or Central bays but, during the drought years 1988 to 1992, the CPUE was usually highest in San Pablo Bay. In 1995 they were found only in Central Bay. The CPUE was highest in South Bay in spring, in Central Bay in summer, and in San Pablo Bay in late summer and early fall (Figure 26).

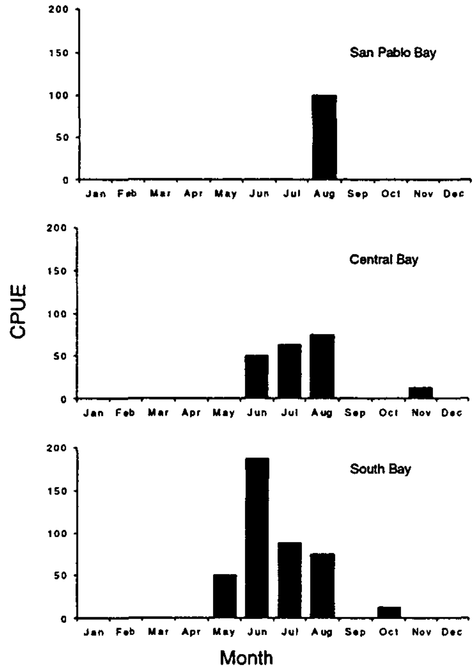

Figure 23 Seasonal distribution by bay of age–0 walleye surfperch collected with the midwater trawl from 1981 to 1988. No walleye surfperch were collected in Suisun Bay and the west delta. Values are CPUE x 100.

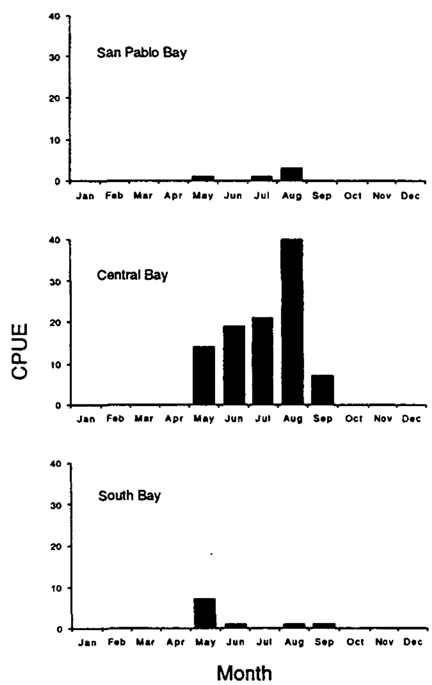

Figure 24 Seasonal distribution by bay of age–0 walleye surfperch collected with the beach seine from 1981 to 1986. No walleye surfperch were collected in Suisun Bay and the west delta. Values are CPUE x 100.

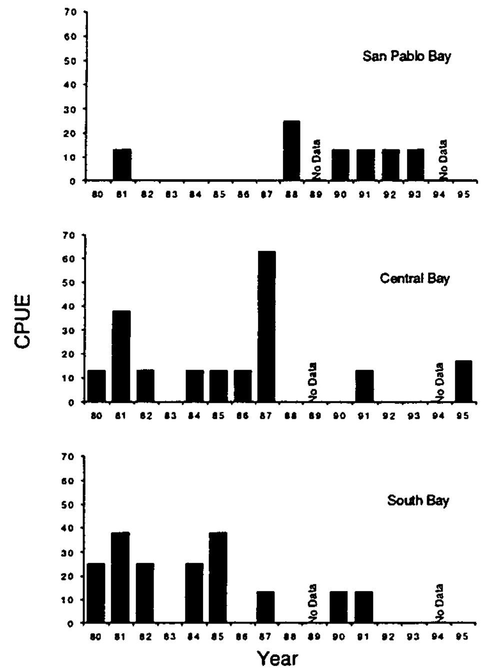

Figure 25 Annual distribution by bay of age–1+ walleye surfperch collected with the midwater trawl. Annual CPUE was March to October. No walleye surfperch were collected in Suisun Bay or the west delta. Values are CPUE × 100.

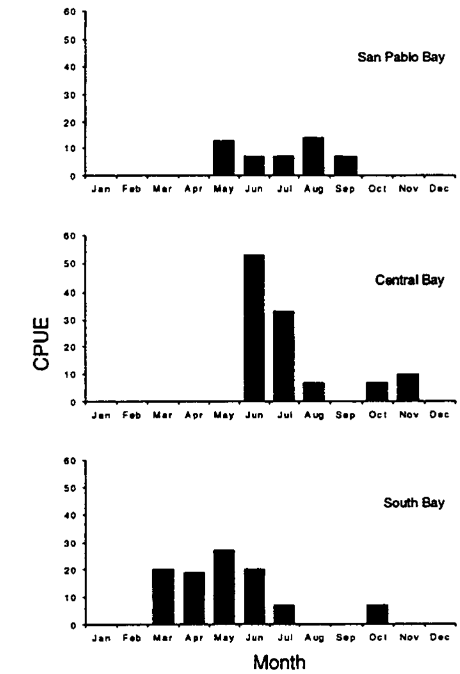

Figure 26 Seasonal distribution by bay of age–1+ walleye surfperch collected with the midwater trawl from 1981 to 1988. No walleye surfperch were collected in Suisun Bay and the west delta. Values are CPUE × 100.

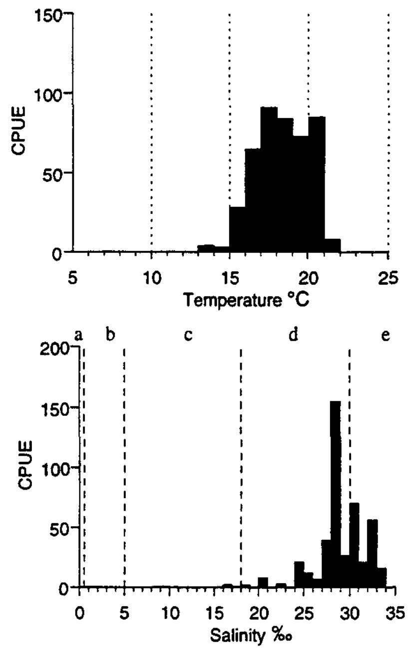

Figure 27 Temperature and salinity distributions for age–0 walleye surfperch collected with the midwater trawl. The vertical lines on the salinity graph mark the boundaries of the Venice system ranges: (a) limnetic, (b) oligohaline, (c) mesohaline, (d) polyhaline, and (e) euhaline.

Temperature and Salinity

Age–0 fish were collected with the midwater trawl at slightly lower average temperatures and over a narrower temperature range than age–1+ fish (Figures 27 and 28). The range for age–0 fish was 13.3 to 21.7 °C, $\bar{\chi}$ = 14.0 °C. The range for age–1+ fish was 8.6 to 21.7 °C, $\bar{\chi}$ = 17.0 °C.

Both age groups were collected in polyhaline and euhaline salinities (see Figures 27 and 28). Age–0 fish were collected at slightly higher salinities than age 1+: from 9.3 to 33.6‰, $\bar{\chi}$ = 27.9‰ for age–0 fish compared to 7.2 to 32.8‰, $\bar{\chi}$ = 27.7‰ for age–1+ fish.

Age–0 fish were collected with the beach seine at higher temperatures but lower salinities than in the midwater trawl (see Figure 27, Figure 29). The temperature range was 14.3 °C to 22.0°C, $\bar{\chi}$ = 16.7 °C, and the salinity range was 0.8‰ to 32.6‰, $\bar{\chi}$ = 26.0‰.

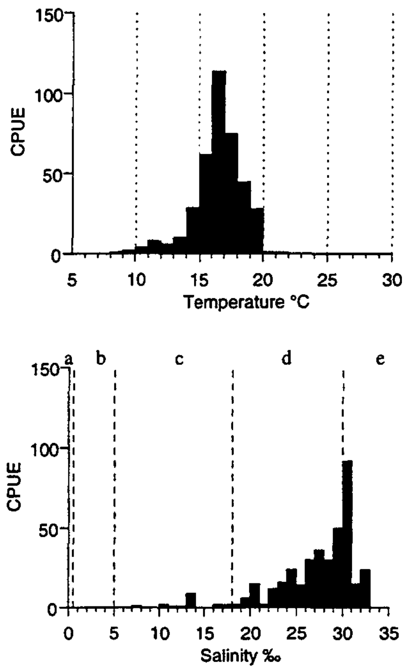

Figure 28 Temperature and salinity distributions for age–1+ walleye surfperch collected with the midwater trawl. The vertical lines on the salinity graph mark the boundaries of the Venice system ranges: (a) limnetic, (b) oligohaline, (c) mesohaline, (d) polyhaline, and (e) euhaline.

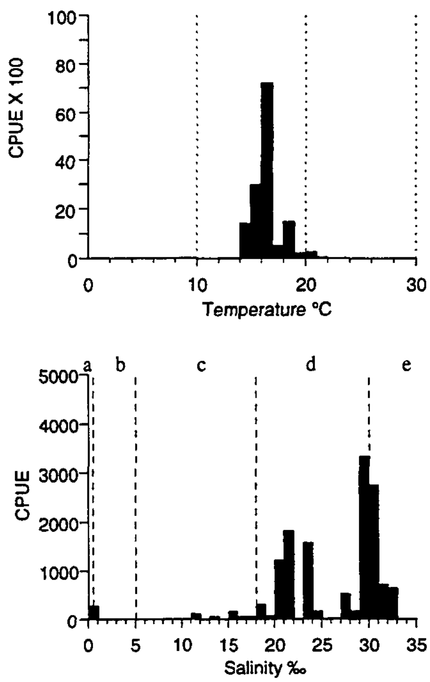

Figure 29 Temperature and salinity distributions for age–0 walleye surfperch collected with the beach seine. The vertical lines on the salinity graph mark the boundaries of the Venice system ranges: (a) limnetic, (b) oligohaline, (c) mesohaline, (d) polyhaline, and (e) euhaline.

Discussion

Walleye surfperch used the estuary primarily as a birthing area and secondarily as a nursery area. Age–1+ fish entered the estuary in spring and summer to give birth. Their abundance decreased in September and most emigrated from the estuary in fall and winter. The length frequency data show that the fish still present in January and February were older fish, either migrating into the estuary early or overwintering in the estuary.

Age–0 walleye surfperch were collected in the shallows from May to August. They moved to the deeper areas of the estuary from June to August and then migrated out of the estuary in fall and winter as shown by the decrease in the midwater trawl catch in September. Walleye surfperch are reported to use bays and estuaries less than other surfperch species and our data suggests that they did not remain in the estuary as long as the more frequently collected surfperch species, which include shiner perch, pile perch, and dwarf perch.

Both age groups were collected in polyhaline and euhaline salinities. The differences in age–0 and age–1+ regional and seasonal distributions accounted for the slightly higher salinity and temperature ranges of age–0 fish. For example, age–0 fish primarily used South and Central bays, whereas age–1+ fish used South, Central, and San Pablo bays. Also, during dry years when outflow was low and salinity high, age–1+ fish moved to the lower salinity of San Pablo Bay. Age–0 fish were collected in South Bay in summer, whereas age–1+ fish were found in South Bay in spring and in Central and San Pablo bays in summer. South Bay was usually warmer than Central and San Pablo bays in summer.

Similar to other surfperch species, walleye surfperch abundance has declined: age–0 abundance since 1984 and age–1+ abundance since 1987. There has also been a long-term decline of walleye surfperch along the coast. Between 1980 and 1986, the annual number of walleye surfperch sampled from the marine recreational fishery decreased by 72% (Karpov and others 1995). Although the walleye surfperch is considered a coastal species, its occurrence in bays and estuaries may contribute to its decline as it migrates to shallow areas where it may be vulnerable to overfishing. There are no size or take regulations for the species.

Pile Perch

Introduction

The pile perch, *Rhacochilus vacca*, ranges from Guadalupe Island, Baja California to Port Wrangell, Alaska (Tarp 1952, Miller and Lea 1972). It is common in bays and estuaries along sandy and rocky shores and around pilings (Roedel 1953) but has also been observed in open water (Baltz 1984), and in close association with dense kelp (Alevizon 1975). Pile perch may school in midwater when not foraging (Baltz 1984). It is eurythermal (Tarp 1952) and found in polyhaline to euhaline salinities (Wang 1986). It is common from the surface to 46 m and temperature may control its depth distribution. In southern California, subadults were observed at 8.5 to 10.4 m in fall and <7.5 m in winter and spring (Terry and Stephens 1976).

The pile perch is viviparous, as are all surfperch. Mating takes place in fall, sperm is stored for at least 2.5 months, and fertilization occurs from December to April. The gestation period lasts 6 months and parturition occurs from June to October (Wares 1968). In the San Francisco Estuary, parturition occurs from late spring to early summer (Wang 1986). In the southern regions of the pile perch range, reproduction occurs earlier in the year. For example, in La Jolla, pile perch give birth in April (Wares 1968).

Most males mature at ages 3 and 4 but a small proportion matures as early as age 2 (Wares 1968). Females are usually mature at ages 3 or 4, the year they mate or give birth, and may delay reproduction for 1 to 4 years. The mean fecundity is 12 young for the 1st reproduction and 60 young for older fish (Baltz 1984, Fritzsche and others 1992). Fecundity is positively correlated with maternal size, but there is no evidence that size at birth depends on maternal size or age. Size at birth has been reported as 76.0 to 85.7 mm TL (Wares 1968) or 70 to 80 mm TL (Wang 1986). Pile perch can live to 9 or 10 years and females live longer than males (Wares 1971). They reach a maximum size of 441 mm TL (Miller and Lea 1972).

Because of its highly developed pharyngeal teeth, the pile perch can crush hard-shelled invertebrates. Food preferences differ by season, location, and age of fish (Wares 1971). Juveniles feed on mussels, clams, and snails (Wares 1971). Adults feed on barnacles, shrimp, mussels, clams, crabs, and amphipods (Haldorson and Moser 1979, Ebeling and Laur 1986).

The pile perch is an important sport fish along the California coast and in estuaries and supports a small commercial fishery in southern California and Baja California (Hart 1973, Fritzsche and others 1992). It is taken by anglers from shore, piers, jetties, and skiffs. (Feder and others 1974). In northern California it is caught mostly from piers, and from Santa Cruz to San Luis Obispo, it is taken primarily by spear fishermen (Karpov and others 1995).

Methods

Otter trawl data from 1980 to 1995 were used for seasonal and annual abundance, seasonal distribution, and temperature and salinity analyses. The otter trawl data is incomplete for 1989 and the trawl was not used from November to January 1990 to 1994. Because only 210 pile perch were collected in the otter trawl no annual distribution data is presented.

Based on length frequencies, fish were classified into 2 age groups: age 0 and age 1+. The cutoff lengths for this separation were as follows: 105 mm FL from January through June, 110 mm FL for July, 130 mm FL for August, 135 mm FL for September, 140 mm FL for October, 155 mm FL for November and 160 mm FL for December. A January 1 birth date was assumed. This corresponds to the date of fertilization, not the date of parturition. The index period for age–0 pile perch was June to October, and February to October for age–1+ pile perch.

Results

Length Analyses

Pile perch collected with the otter trawl ranged from 42 to 322 mm FL, although fish >220 were uncommon (Figure 30). Using Wares (1971) size criteria, at least 3 age classes were collected in most months. Ages 1 and 2 (<200 mm) were the most common in all months. From December to March, and in June and July, modes were present for ages 1 and 2 and ages 3 and 4 (200 to 260 mm). In March, 1 age–5 fish (322 mm) was collected.

Abundance

Age–0 pile perch were most abundant in 1981 and next most abundant in 1980 (Figure 31A). Abundance declined after 1983 and no age–0 fish were collected in 1987, 1988, and 1990 to 1995. They were most abundant from July to October (Figure 32A). In 1981, they were also collected in November and December, and in 1982 and 1983, in May and December (Table 9).

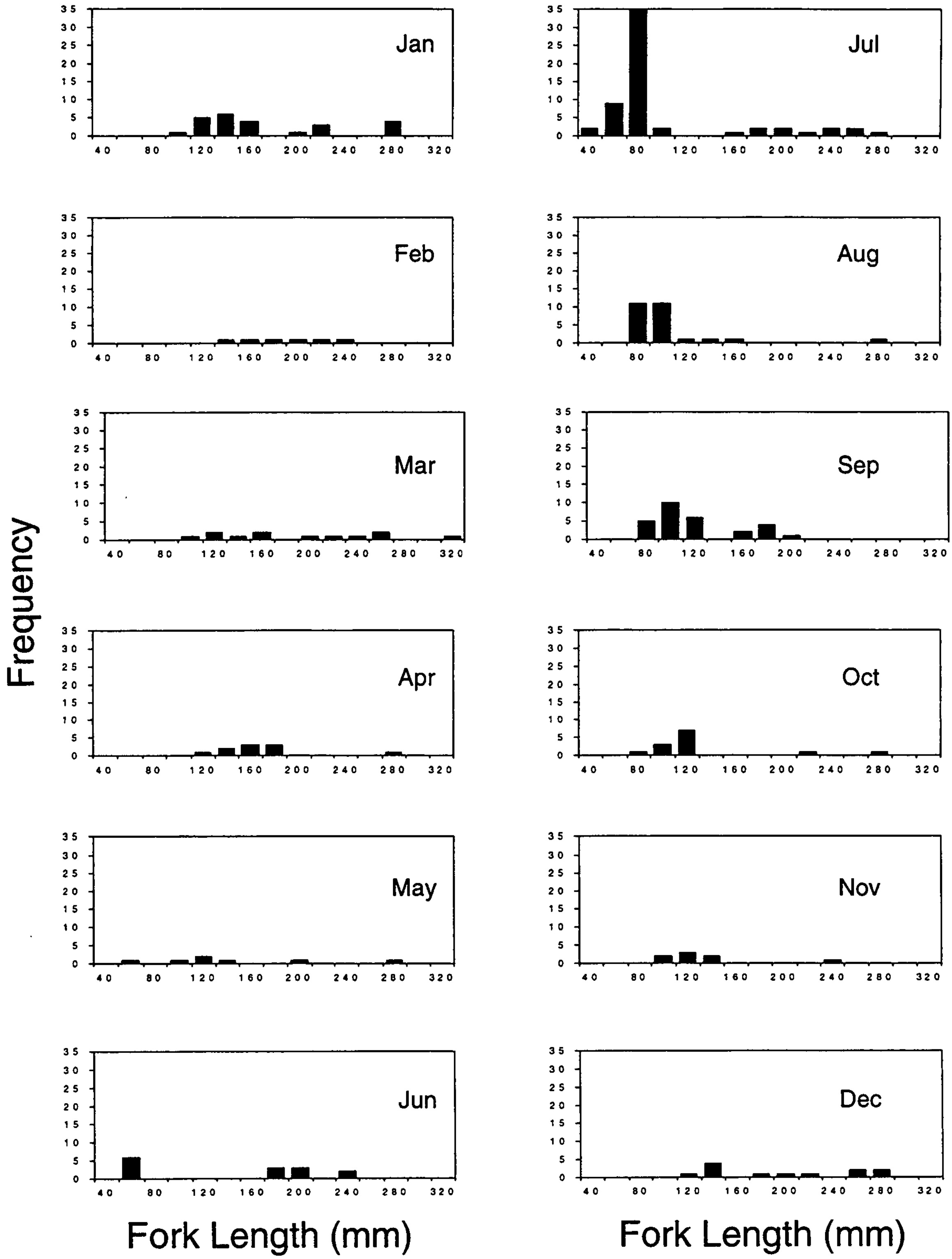

Figure 30 Monthly length frequencies of pile perch collected with the otter trawl from 1980 to 1995. Values on x-axis are lower class limits.

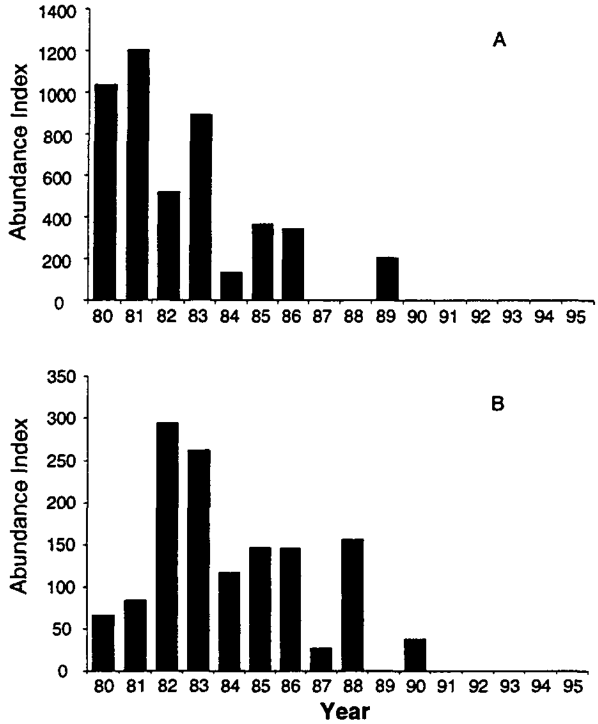

Figure 31 Annual abundance indices of pile perch collected with the otter trawl from 1980 to 1995: (A) age 0, index period was June to October; (B) age 1+, index period is February to October. Values are index × 100.

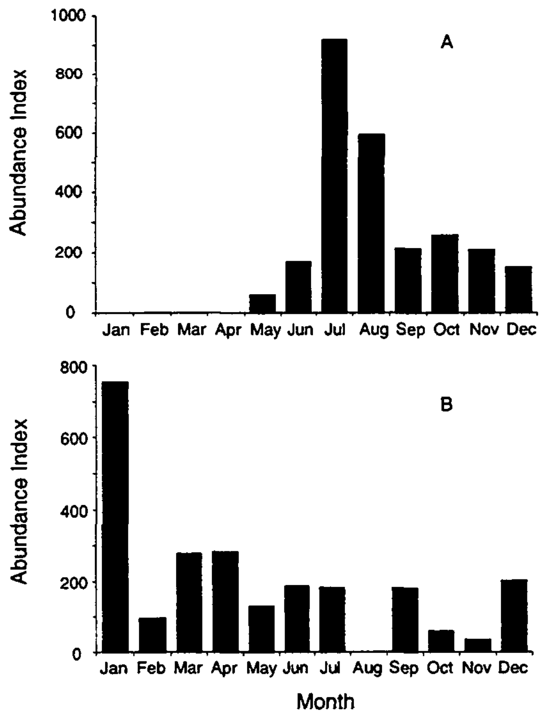

Figure 32 Seasonal abundance of pile perch collected with the otter trawl from 1981 to 1988: (A) age 0 and (B) age 1+

Table 9 Monthly abundance indices (in hundreds) of age–0 pile perch collected with the otter trawl, 1980 to 1995. The annual index period was June to October.

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Index*
1980		0	0	0	0	0	1819	787	2380	189	0	0	1035
1981	0	0	0	0	0	250	1126	3777	532	322	1697	250	1201
1982	0	0	0	0	250	0	970	974	464	188	0	469	519
1983	0	0	0	0	219	688	2032	0	162	1563	0	500	889
1984	0	0	0	0	0	216	460	0	0	0	0	0	135
1985	0	0	0	0	0	0	1601	0	219	0	0	0	364
1986	0	0	0	0	0	188	1170	0	352	0	0	0	342
1987	0	0	0	0	0	0	0	0	0	0	0	0	0
1988	0	0	0	0	0	0	0	0	0	0	0	0	0
1989	0	0	0	0	0	0	365	250					205
1990		0	0	0	0	0	0	0	0	0			0
1991		0	0	0	0	0	0	0	0	0			0
1992		0	0	0	0	0	0	0	0	0			0
1993		0	0	0	0	0	0	0	0	0			0
1994		0	0	0	0	0	0	0	0	0			0
1995	0	0	0	0	0	0	0		0	0	0	0	0
1981-1988	0	0	0	0	59	168	920	594	216	259	212	152	

Table 10 Monthly abundance indices (in hundreds) of age–1+ pile perch collected with the otter trawl from 1980 to 1995. The annual index period was February to October.

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Index*
1980		0	189	189	0	0	0	219	0	0	0	0	66
1981	0	281	250	0	0	0	230	0	0	0	281	216	85
1982	1921	0	219	250	346	435	710	0	688	0	0	673	294
1983	497	0	250	946	412	0	0	0	750	0	0	466	262
1984	216	0	0	0	0	1055	0	0	0	0	0	0	117
1985	0	0	594	0	0	0	513	0	0	216	0	0	147
1986	909	243	619	454	0	0	0	0	0	0	0	0	146
1987	0	243	0	0	0	0	0	0	0	0	0	0	27
1988	2470	0	281	594	281	0	0	0	0	250	0	250	156
1989	0	0	0	0	0	0	0	0					0
1990		0	344	0	0	0	0	0	0	0			38
1991		0	0	0	0	0	0	0	0	0			0
1992		0	0	0	0	0	0	0	0	0			0
1993		0	0	0	0	0	0	0	0	0			0
1994		0	0	0	0	0	0	0	0	0			0
1995	0	0	0	0	0	0	0		0	0	0	0	0
1981–1988	752	96	277	281	130	186	182	0	180	58	35	201	

Abundance indices of 1+ pile perch were highest in 1982 and 1983, lagging behind the highest age–0 abundance indices by 1 year (Figure 31B). No fish were collected in 1989 and from 1991 to 1995. Age–1+ fish were collected in every month except August and were most abundant in January (Figure 32B). In most years no age–1+ pile perch were collected from June to November (Table 10).

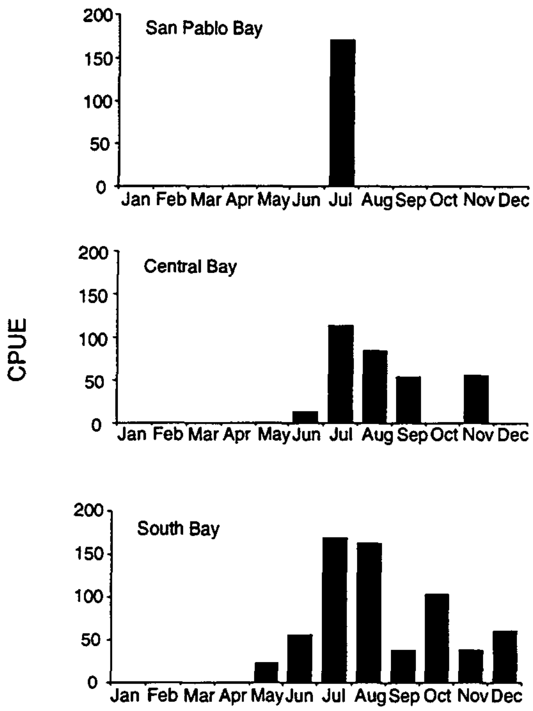

Figure 33 Seasonal distribution by bay of age–0 pile perch collected with the otter trawl from 1981 to 1988. No pile perch were collected in Suisun Bay or the west delta. Values are CPUE x 100.

Seasonal Distribution

Age–0 pile perch ranged from South to San Pablo bays but the highest CPUEs occurred in South and Central bays (Figure 33). They were first collected in May in South Bay and extended their distribution to Central Bay in June and to San Pablo Bay in July. The increase in CPUE in San Pablo Bay in July may not be an actual distribution expansion because it is based on only 14 age–0 fish caught in southern San Pablo Bay in 1980, 1982, and 1985. Likewise, the CPUE variations in South Bay and Central Bay in August, September, and November may be an artifact of low catches.

Age–1+ pile perch also ranged from South to San Pablo bays but had no strong seasonal distribution pattern (Figure 34). The CPUE was highest in South Bay in all months except February, June, and July. In February and June the CPUE was highest in Central Bay and in July in San Pablo Bay. However, the CPUE increase in San Pablo Bay in July was based on collections of only 4 fish in 1982 and 1 fish in 1985.

Temperature and Salinity

Age–0 pile perch were collected at higher temperatures than age–1+ fish. Age–0 fish were collected at 10.9 to 20.6 °C, $\bar{\chi}$ = 17.7 °C (Figure 35). Age–1+ fish were collected between 7.9 and 21.2 °C, $\bar{\chi}$ = 13.9 °C (Figure 36).

Both age groups were primarily collected in euhaline and polyhaline salinities, but age–0 fish were collected at higher salinities than age–1+ fish. The salinity for age–0 fish ranged from 14.2 to 33.6‰, $\bar{\chi}$ = 28.0‰ (Figure 35). Age–1+ fish were collected at 5.1 to 32.4‰, $\bar{\chi}$ = 24.5‰ (Figure 36).

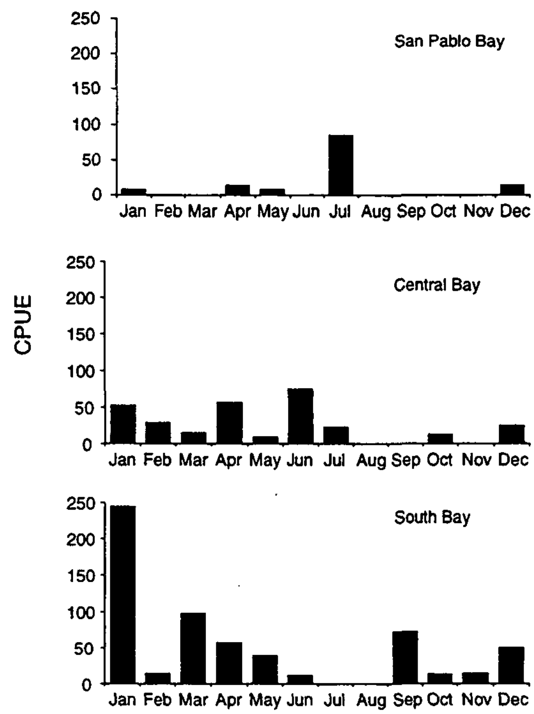

Figure 34 Seasonal distribution by bay of age–1+ pile perch collected with the otter trawl from 1981 to 1988. No pile perch were collected in Suisun Bay or the west delta. Values are CPUE x 100.

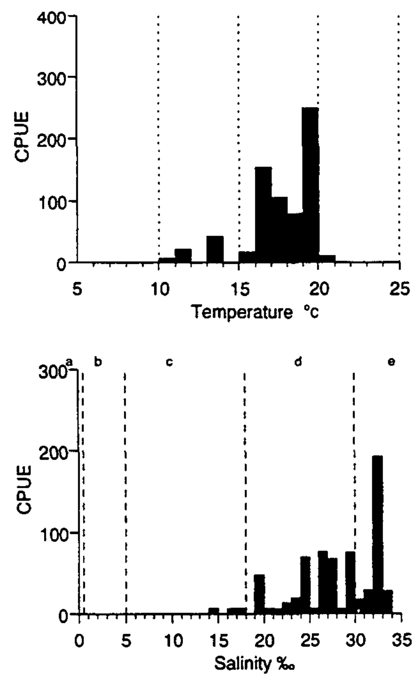

Figure 35 Temperature and salinity distributions of age–0 pile perch collected with the otter trawl. The vertical lines on the salinity graph mark the boundaries of the Venice system ranges: (a) limnetic, (b) oligohaline, (c) mesohaline, (d) polyhaline, and (e) euhaline.

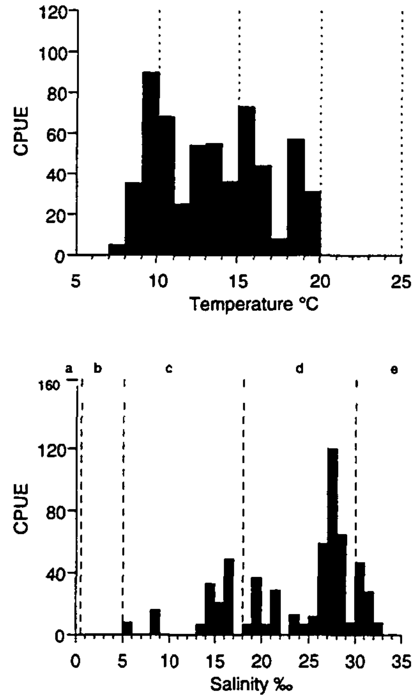

***Figure 36 Temperature and salinity distributions for age–1+ pile perch collected with the otter trawl* from 1980 to 1995.** The vertical lines on the salinity graph mark the boundaries of the Venice system ranges: (a) limnetic, (b) oligohaline, (c) mesohaline, (d) polyhaline, and (e) euhaline.

Discussion

The pile perch is found all year in the San Francisco Estuary. It uses the estuary as a birthing and nursery area and is found mostly in Central and South bays. Age–0 fish are present in late spring and early summer, when parturition occurs. In winter the low catch of age–0 fish may represent emigration out of the estuary or to areas where the otter trawl does not sample effectively. Young fish leave Yaquina Bay, Oregon, during their first winter (Wares 1971), but in the San Francisco Estuary, the catch of age 1+ fish increased in January. The length frequency data show that most of these fish are overwintering juveniles (age 2) rather than adults entering the estuary. Age 1+ abundance peaked in March and April, just before parturition, then decreased from summer through November. This decrease has also been reported in other studies (Wares 1968). In southern California, the fall decrease reportedly represents emigration in response to warmer temperatures (Terry and Stephens 1976).

The migratory patterns of both age groups of pile perch in the estuary are hard to define. Otter trawl catches were low in all years—only 210 were collected from 1980 to 1995. Even fewer (30) were collected with the beach seine, too few to determine residence time of age–0 fish, movement from the shallows to deep areas within the estuary, and response to temperature and salinity. Our gear is probably ineffective in catching pile perch due to their preferred habitats around pilings, wharfs and rocky outcroppings. Other studies using sport fishing gear and spears have been more effective in sampling pile perch (Karpov and others 1995).

Age–0 pile perch were captured at higher salinities and temperatures than age–1+ fish. In southern California, adults were rarely present at >16 °C but subadults were collected at these temperatures (Terry and

Stephens 1976). Our data show that age–1+ fish were found in temperatures >16 °C but most were collected between 9 and 14 °C. Very few age–0 fish were collected in <16 °C.

Both age groups were collected primarily in polyhaline and euhaline salinities as Wang (1986) also found. The collection of age–0 pile perch at higher salinities than age–1+ may be an artifact of the large number of age–1+ fish collected in January when salinities were lower. Most age–0 fish were collected in summer.

Similar to other surfperch species in the San Francisco Estuary, pile perch abundance has declined. Age–0 abundance decreased after 1987 and age–1+ abundance after 1988. No age–0 fish were collected from 1990 to 1995, and age–1+ fish were absent from 1991 to 1995. This agrees with a long-term decline in pile perch populations along the coast (Karpov and others 1995). Factors which may have contributed to the pile perch decline may include a reduction in estuarine habitat, low fecundity, and overharvest. The dredging of channels and filling in of shallows have caused significant alterations to estuarine habitats in the San Francisco Estuary (SFEP 1991). Pile perch may be affected by this as they use the shallows for nursery and rearing areas. Pile perch use shallow habitats during critical times in their life cycles, which also makes them vulnerable to overfishing. There are no bag, possession, or size limits, and no closed season for this species.

Dwarf Perch

Introduction

The dwarf perch, *Micrometrus minimus,* ranges from Cedros Island, Baja California to Bodega Bay (Miller and Lea 1972). It is restricted to shallow inshore, marine and estuarine habitats (Terry and Stevens 1976) primarily in shallow eelgrass beds, on rock reefs, and around jetties (Feder and others 1974). It is common from the surface to 9 m but is concentrated from 0.9 to 6 m (Feder and others 1974, Tarp 1952). In southern California the dwarf perch is found at mean depths of 1.5 m throughout the year (Shrode and others 1982). The dwarf perch prefers temperatures of 11 to 21 °C, and at 23 °C was found to move to deeper waters (Shrode and others 1982). It is found throughout the year in bays and estuaries and is resident in the San Francisco Estuary (Hubbs 1921).

The dwarf perch mates in summer and parturition occurs from June to August (Hubbs 1921) or April to May in southern California (Feder and others 1974). Males are mature at birth and females mature at 1 year. Males inseminate the females a few weeks after birth and the females store sperm for 6 to 9 months (Schultz 1993). Gestation lasts 6 months. The brood size of 2 to 50 young is moderately large for the surfperch family (Baltz 1984). Fecundity is positively correlated with maternal age (Hubbs 1921). Males live 1 year and females 2 or 3 years. Length at birth is 25 to 35 mm TL and the maximum size is 159 mm TL (Wang 1986, Miller and Lea 1972). Because of its small size, the dwarf perch has no commercial or economic value and is rarely taken by anglers.

Juveniles feed on small crustaceans, amphipods, polychaetes, and molluscs (Feder and others 1974). As it grows it becomes a partial herbivore (Hubbs 1921) and then remains omnivorous (Shrode and others 1983).

Methods

The beach seine data from 1980 to 1986 were used for annual and seasonal abundance and distribution, and temperature and salinity analyses. Abundance and distribution data are incomplete for 1980 due to lack of sampling from January to July. The otter trawl data from 1980 to 1995 were used for supporting evidence of abundance trends.

By visual inspection of length frequencies of dwarf perch collected in the beach seine, fish were classified into 2 age groups: age 0 and age 1+. All dwarf perch over 70 mm FL were age–1+ fish and those under 70 mm FL were age–0 fish. The annual index period was May to December for age–0 fish and February to October for age–1+ fish. Dwarf perch collected with the otter trawl were not separated into 2 age groups.

Results

Length Analyses

In the beach seine, dwarf perch ranged from 25 to 163 mm FL but fish >115 mm were uncommon (Figure 37). The modal length of 55 to 85 mm in winter represented juvenile fish overwintering in the estuary. Before parturition from March to May, the modal length was 85 to 145 mm. During parturition, the modal length declined to 35 to 75 mm and the catch of larger fish decreased.

In the otter trawl, dwarf perch ranged from 32 to 130 mm (Figure 38). Many age–1+ fish >70 mm overwintered in the deeper areas of the estuary. Most size groups disappeared in the summer otter trawl catches and reappeared in fall and winter.

Abundance

Typically, abundance of dwarf perch in the otter trawl was low and they were most abundant in the early 1980s. Abundance decreased after 1982 and none were collected after 1991 (Figure 39, Table 11).

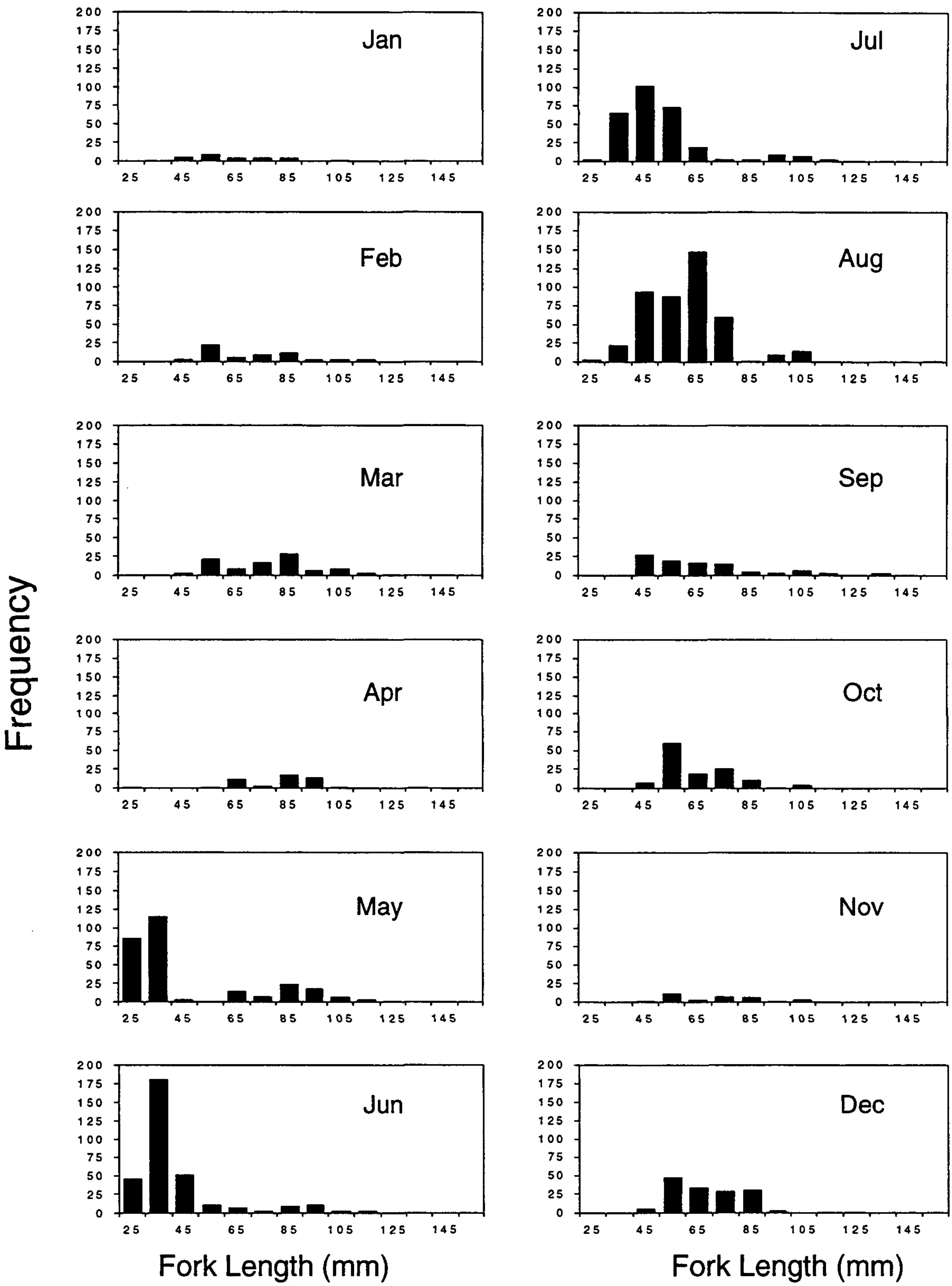

Figure 37 Monthly length frequencies of dwarf perch collected with the beach seine from 1980 to 1986. Values on the x-axis are lower class limits.

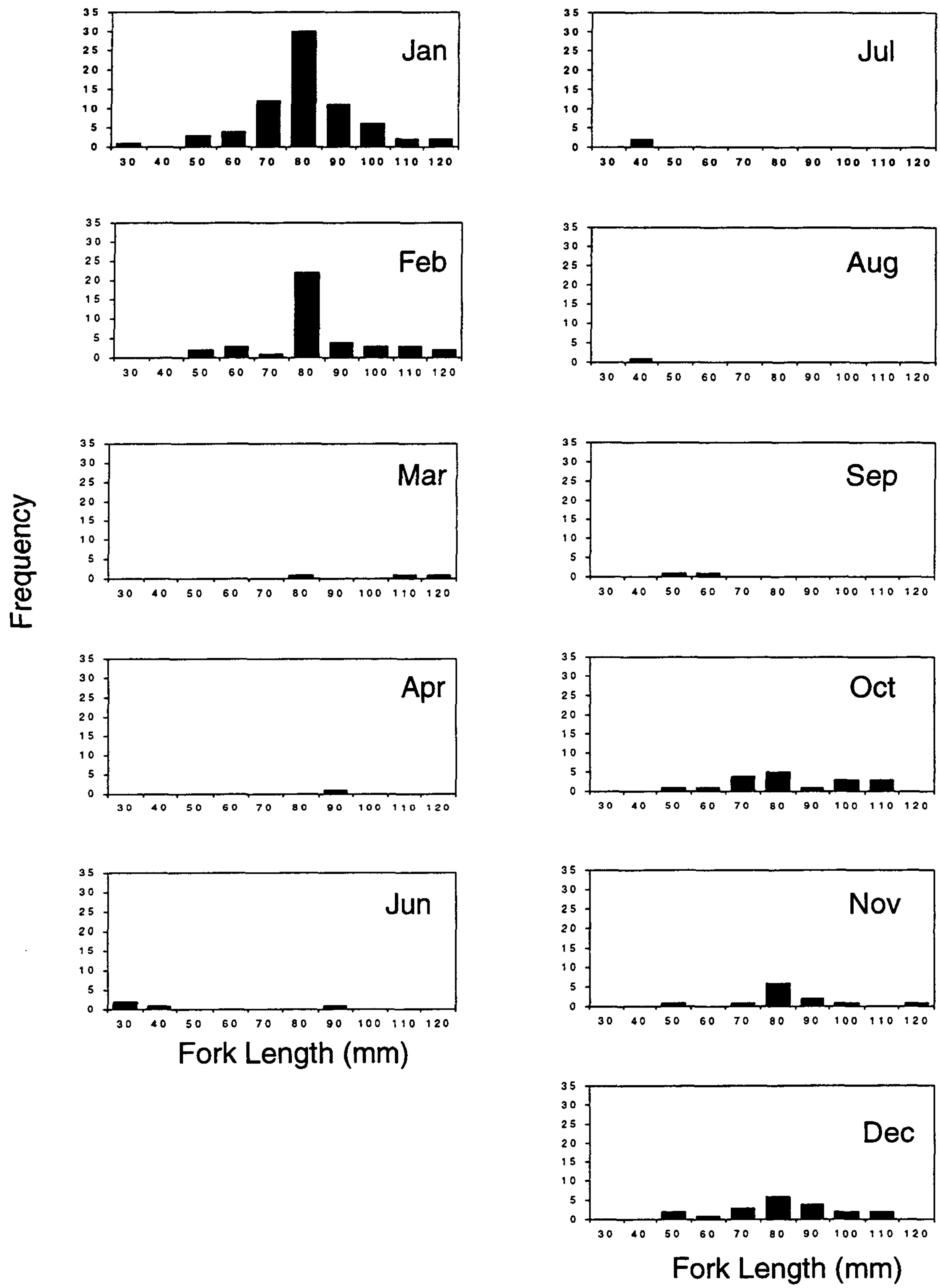

Figure 38 Monthly length frequencies of dwarf perch collected with the otter trawl from 1980 to 1995. Values on the x-axis are lower class limits. No dwarf perch were collected in May.

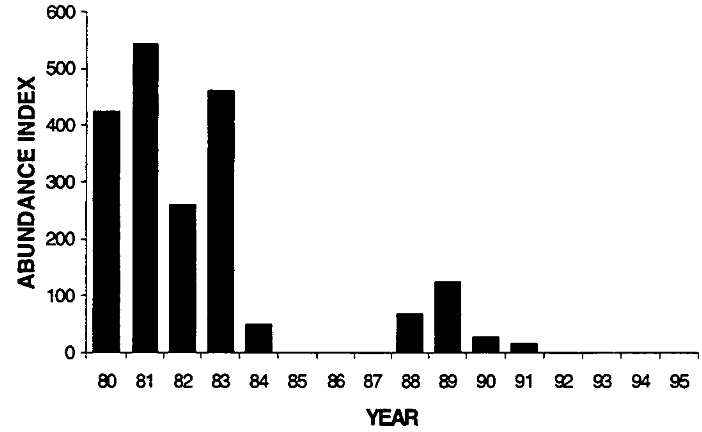

Figure 39 Abundance index of all sizes of dwarf perch collected with the otter trawl from 1980 to 1995

Table 11 Monthly abundance indices of all age groups of dwarf perch collected with the otter trawl from 1980 to 1995. The annual index period was February to October.

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Annual Index*
1980		0	0	0	0	0	0	0	450	3359	188	250	423
1981	2036	2849	0	0	0	0	719	0	0	1322	0	935	543
1982	6686	750	532	219	0	0	0	188	0	657	2752	1001	261
1983	6316	3533	94	0	0	313	0	0	219	0	188	1060	462
1984	0	438	0	0	0	0	0	0	0	0	0	625	49
1985	0	0	0	0	0	0	0	0	0	0	0	0	0
1986	438	0	0	0	0	0	0	0	0	0	0	188	0
1987	0	0	0	0	0	0	0	0	0	0	0	250	0
1988	1219	406	0	0	0	211	0	0	0	0	0	0	69
1989	532	876	0	0	0	0	0	0					125
1990		250	0	0	0	0	0	0	0	0			28
1991		0	0	0	0	134	0	0	0	0			15
1992		0	0	0	0	0	0	0	0	0			0
1993		0	0	0	0	0	0	0	0	0			0
1994		0	0	0	0	0	0	0	0	0			0
1995	0	0	0	0	0	0	0		0	0	0	0	0
1981–1988	2087	997	78	27	0	66	90	24	27	247	368	507	

Both age groups of dwarf perch collected with the beach seine were most abundant in 1981 and much less abundant after that year (Figures 40A and 40B). Age–0 fish were collected throughout the year (Table 12). Abundance was highest from May to August and peaked in June, then decreased from September to December (Figure 41A).

Age–1+ dwarf perch were also collected all year (Figure 41B, Table 13). Abundance was bimodal, with a major peak in spring and a secondary peak in October. When all years were combined they were most abundant in May.

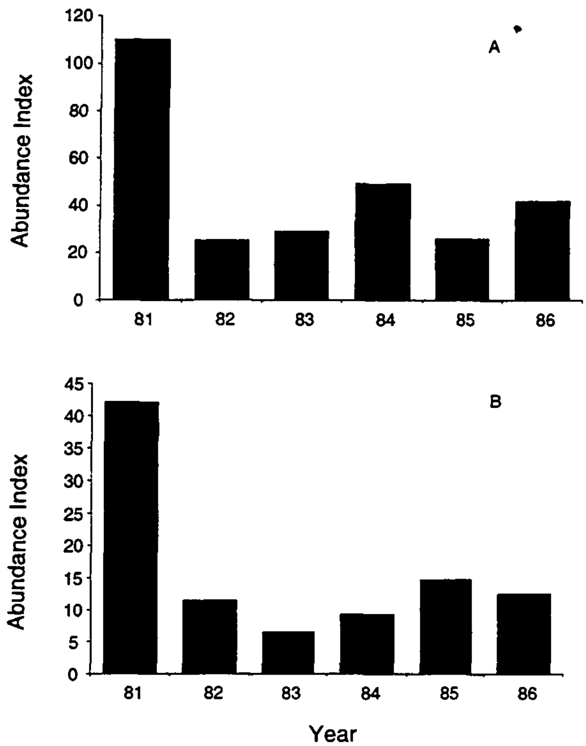

Figure 40 Annual abundance indices of dwarf perch collected with the beach seine from 1981 to 1986: (A) age 0, index period was May to December; (B) age 1+, index period was February to October

Table 12 Monthly abundance indices of age–0 dwarf perch collected with the beach seine from 1980 to 1986. The annual index period was May to December. No sampling occurred from January to July 1980.

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Index*
1980								242	19	40	4	216	
1981	0	11	14	7	296	221	165	108	33	20	15	23	110
1982	15	27	27	0	11	31	66	62	21	10	0	0	25
1983	0	0	2	0	70	32	15	19	24	54	19	0	29
1984	0	4	3	1	24	248	87	28	3	3	1	0	49
1985	2	3	2	0	22	31	35	104	2	11	3	0	26
1986	4	3	1	4	67	69	111	66	15	8	0	1	42
1981–1986	4	8	8	2	82	105	80	65	16	18	6	4	

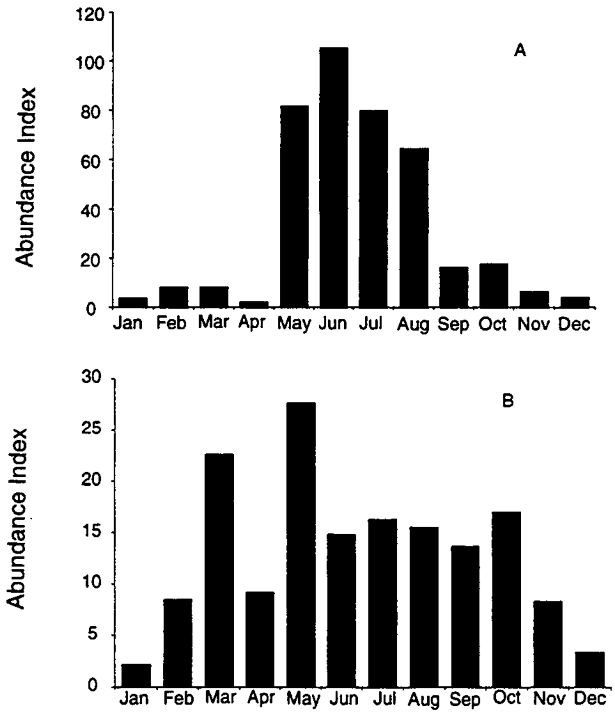

Figure 41 Seasonal abundance of dwarf perch collected with the beach seine from 1981 to 1986: (A) age 0 and (B) age 1+

Table 13 Monthly abundance indices of age–1+ dwarf perch collected with the beach seine from 1980 to 1986. No sampling occurred from January to July 1980. The annual index period was February to October. NI indicates no index calculated.

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Index*
1980								153	32	18	9	207	NI
1981	2	30	47	7	114	47	42	16	33	43	16	20	42
1982	2	13	40	6	11	8	2	20	2	2	0	0	12
1983	0	0	2	8	11	0	5	2	20	11	34	0	7
1984	3	5	7	10	2	14	26	10	8	2	0	0	9
1985	2	2	20	3	14	9	12	20	14	39	0	0	15
1986	4	1	20	21	14	11	11	25	5	5	0	0	13
1981–1986	2	9	23	9	28	15	16	16	14	17	8	3	

Distribution

Age–0 dwarf perch were collected from South to San Pablo bays (Figure 42). The highest annual CPUE was in Central Bay in every year except 1983, when CPUE was highest in South Bay. Age–1+ fish were also collected from South to San Pablo bays. The highest annual CPUE was in Central Bay in all years (Figure 43).

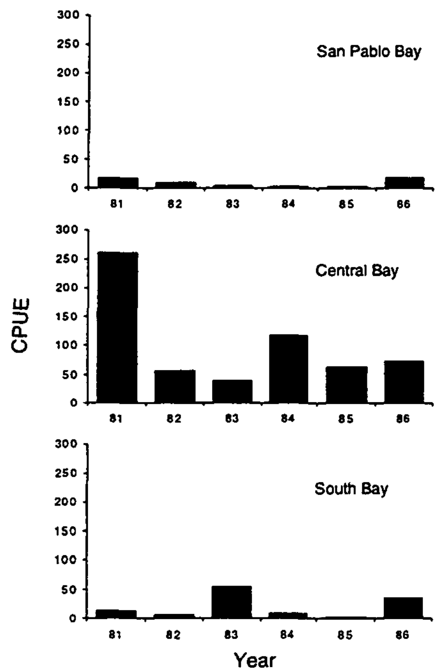

Figure 42 Annual distribution by bay of age–0 dwarf perch collected with the beach seine from 1981 to 1986. Values are annual CPUE from May to December. No dwarf perch were collected in Suisun Bay or the west delta.

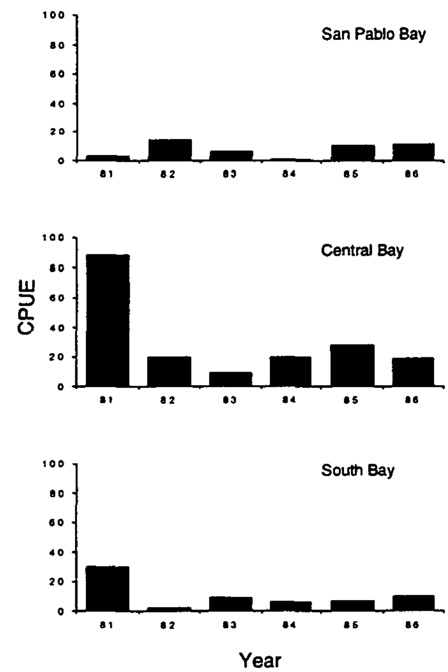

Figure 43 Annual distribution by bay of age–1+ dwarf perch collected with the beach seine from 1981 to 1986. Values are annual CPUE from February to October. No dwarf perch were collected in Suisun Bay or the west delta.

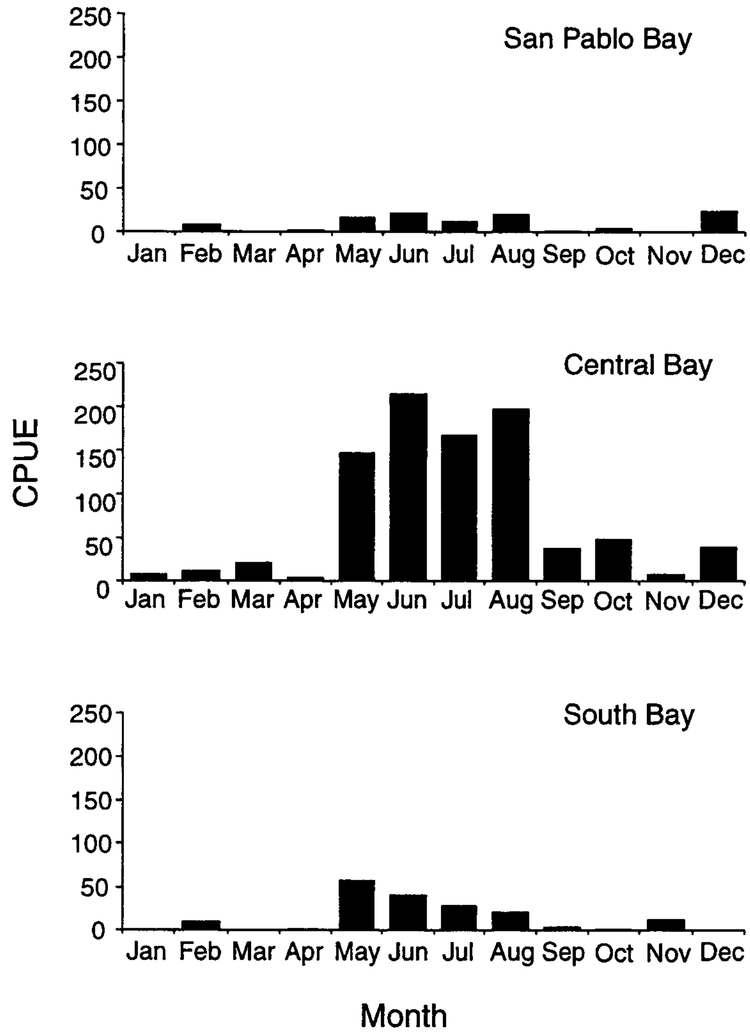

Figure 44 Seasonal distribution by bay of age-0 dwarf perch collected with the beach seine from 1981 to 1986. No dwarf perch were collected in Suisun Bay or the west delta.

Seasonally, the highest CPUE of age–0 dwarf perch was in Central Bay in all months except November when it was highest in South Bay (Figure 44). Coincident with parturition, CPUE increased in South, Central and San Pablo bays in summer.

With several exceptions, age–1+ fish were concentrated in Central Bay (Figure 45). The CPUE was highest in South Bay in February and November, equal in Central and San Pablo bays in April, and highest in San Pablo Bay in December. This erratic pattern may be due to low catches (<500) of age–1+ fish in the beach seine.

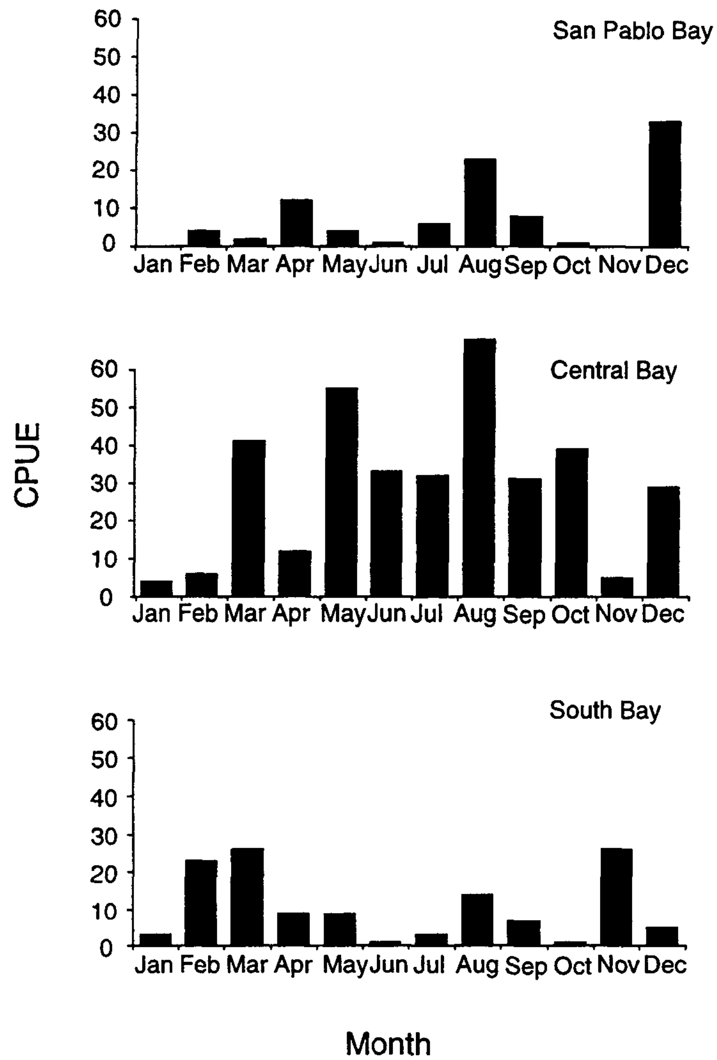

Figure 45 Seasonal distribution by bay of age–1+ dwarf perch collected with the beach seine from 1981 to 1986. No dwarf perch were collected in Suisun Bay or the west delta.

Temperature and Salinity

Age–0 and age–1+ dwarf perch were collected in similar temperature ranges, but age–0 fish were collected at slightly higher temperatures (Figures 46A and 47A). Age–0 fish were collected from 9.1 to 25.5 °C, $\bar{\chi}$ = 17.7 °C. The temperature range for age–1+ fish was 9.1 to 25.0 °C, $\bar{\chi}$ = 16.3 °C.

Both age groups were most abundant in polyhaline and euhaline water but were collected from 0.2‰ to 33.9‰. The age–0 mean salinity of 27.3‰ was somewhat higher than the age–1+ mean salinity of 25.5‰ (Figures 46B and 47B).

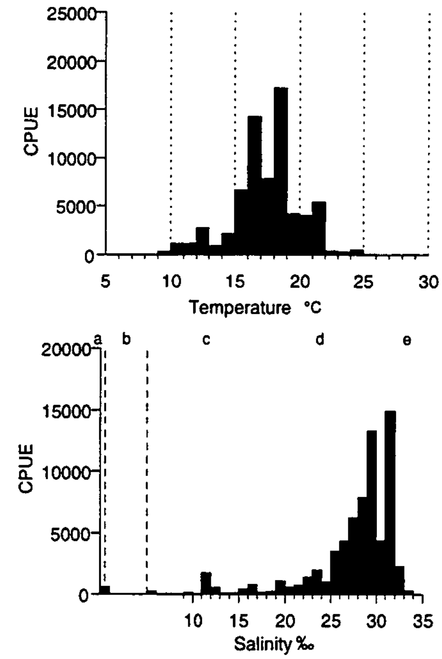

Figure 46 Temperature and salinity distributions for age–0 dwarf perch collected with the beach seine from 1980 to 1986. The vertical lines on the salinity graph mark the boundaries of the Venice system ranges: (a) limnetic, (b) oligohaline, (c) mesohaline, (d) polyhaline, and (e) euhaline.

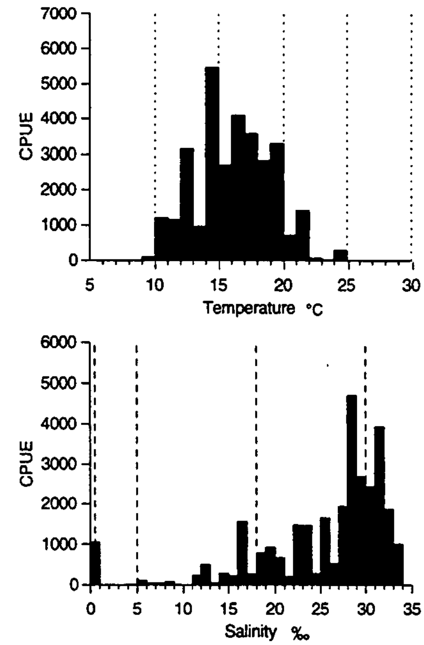

Figure 47 Temperature and salinity distributions for age–1+ dwarf perch collected with the beach seine from 1980 to 1986. The vertical lines on the salinity graph mark the boundaries of the Venice system ranges: (a) limnetic, (b) oligohaline, (c) mesohaline, (d) polyhaline, and (e) euhaline.

Discussion

Dwarf perch used the shallow areas of the estuary as demonstrated by the high beach seine catch and the small collections in the otter and midwater trawls. Age–0 and age–1+ fish were collected all year indicating the presence of a resident population in the estuary, as Hubbs (1921) and Wang (1986) also found.

Abundance of age–0 dwarf perch peaked from May to August when parturition occurred. There was an early peak of age–1+ fish in March comprised mostly of juveniles overwintering in the estuary and some adults migrating early into the shallows after wintering in deeper water. The abundance decrease in fall for both age groups may be due to movement out of the shallows to deeper areas. This is supported by the catch increase of all sizes in the otter trawl in fall and winter.

Age–0 fish ranged from South to San Pablo bays, but the highest CPUE was in Central Bay in most months. From May to August, when they became abundant, age–0 dwarf perch expanded their distribution from Central Bay to South and San Pablo bays. Age–1+ fish were also concentrated in Central Bay but did not expand or shift their distribution to the other embayments except in winter. Shrode and others (1983) found that depth or a factor correlated with depth, but not temperature, seemed important in the distribution of adults. Juveniles prefer warmer temperatures (Shrode and others 1983) and may have moved to the higher temperatures in South and San Pablo bays in the summer months to reach warmer water. Adults and juveniles overlapped in their summer distribution in southern California as they did in this estuary in Central Bay (Shrode and others 1983).

Abundance of both age groups was low. Although the beach seine data end in 1986, abundance of dwarf perch in the otter trawl remained low through 1995, as has abundance of the other common surfperch species collected in the estuary. One reason for this decline is that dwarf perch are restricted to shallow inshore marine and estuarine habitats which are subject to major environmental fluctuations due to urbanization, dredging, and water development projects (SFEP 1991).

Historically, the dwarf perch has not been an important sport fish. But dwarf perch, like the small shiner perch, are common in the nearshore areas where they can be caught easily by shore anglers, and hence may be declining due to increased fishing effort and lack of size and take limits.

White Seaperch

Introduction

The white seaperch, *Phanerodon furcatus,* ranges from Vancouver Island to Point Cabras, Baja California (Miller and Lea 1972). It is common around piers, jetties and in deeper waters in estuaries and bays (Bane and Bane 1971). It is found from the surface to 43 m but is concentrated from 2.5 to 34 m (Feder and others 1974). When not foraging, the white seaperch forms loose schools in midwater between the bottom and the kelp canopy (Baltz 1984). Seasonal migrations have been observed in northern California. In Elkhorn Slough, abundance increased in late summer and fall and decreased in spring (Antrim 1981). In Tomales Bay, males disappear when females are in their spawning stage (Banerjee 1971). The white seaperch is found in temperatures ranging between 7 and 21 °C (Tarp 1952).

The white seaperch is viviparous. Parturition occurs in late April through mid-July in Elkhorn Slough (Antrim 1981) and from May to July in southern California (Goldberg 1978). Maternal length and fecundity are positively correlated (Banerjee 1971, Goldberg 1978). For example, females <215 mm SL have an average brood size of 12.1 young, and females >252 mm have an average of 24.6 young. In Tomales Bay, the young school together after birth near the shore (Banerjee 1966).

Maximum size is 315 mm TL (Miller and Lea 1972). Males and females grow equally until their 4th year, after which females become larger (Banerjee 1966). Males and females may have equal longevity (Anderson and Bryan 1970) or females live longer than males (Eckmayer 1979). Maximum age is 8 years (Banerjee 1966).

The white seaperch preys on crustaceans including amphipods, isopods, and small crabs and polychaete worms. In spring, white seaperch preys on polychaetes and crustaceans; in winter they feed upon polychaetes; and in summer their diet shifts to copepods and amphipods (Antrim 1981). At one time, the white seaperch was the most important surfperch taken commercially by trawl fishermen and purse seiners (Feder and others 1974), but is no longer a significant component of the commercial catch (Karpov and others 1995).

Methods

Otter trawl data from 1980 to 1995 were used to analyze annual abundance, seasonal abundance and distribution, and temperature and salinity distributions. All age groups are combined because only 127 white seaperch were collected with the otter trawl. The annual abundance index period was May to October.

Results and Discussion

White seaperch were most abundant in 1981 and 1984 (Figure 48, Table 14). Abundance declined after 1987 and none were collected after 1990.

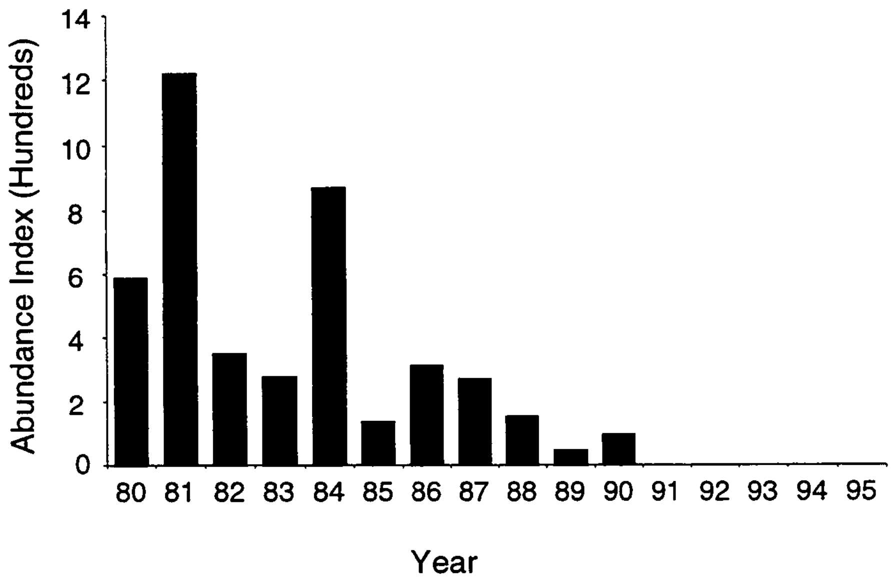

Figure 48 Annual abundance of white seaperch collected with the otter trawl from 1980 to 1995. The index period was May to October.

Table 14 Monthly abundance indices of all age groups of white seaperch collected with the otter trawl from 1980 to 1995. The annual index period was May to October.

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*June*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Index*
1980		0	0	0	0	0	1394	1745	189	189	0	0	586
1981	250	818	0	0	0	250	2064	3361	406	1241	281	0	1220
1982	281	0	0	0	938	435	216	500	0	0	216	134	348
1983	0	0	219	469	532	938	0	0	0	189	0	0	277
1984	0	0	0	0	192	0	0	3067	1025	949	0	0	872
1985	0	0	0	0	0	469	0	0	352	0	216	0	137
1986	0	0	0	0	0	0	0	837	379	649	0	0	311
1987	0	0	0	0	115	0	304	892	313	0	0	0	271
1988	0	0	0	0	250	313	0	216	135	0	0	0	152
1989	0	0	0	0	0	0	189	0					47
1990		0	281	0	0	0	329	243	0	0			95
1991		0	0	0	0	0	0	0	0	0			0
1992		0	0	0	0	0	0	0	0	0			0
1993		0	0	0	0	0	0	0	0	0			0
1994		0	0	0	0	0	0	0	0	0			0
1995	0	0	0	0	0	0	0		0	0	0	0	0
1981–1988	66	102	27	59	253	301	323	1109	326	379	89	17	

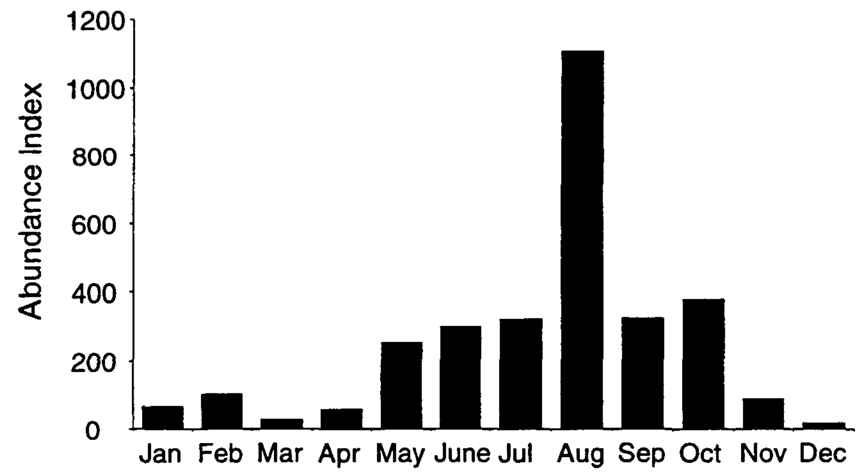

Figure 49 Seasonal abundance of white seaperch collected with the otter trawl from 1981 to 1988

They were collected all year from South to San Pablo bays. Abundance was highest from May to October and peaked in August (Figure 49). The highest CPUE was in South Bay from March to July and in Central Bay from August to November (Figure 50). In December they were collected only in San Pablo Bay.

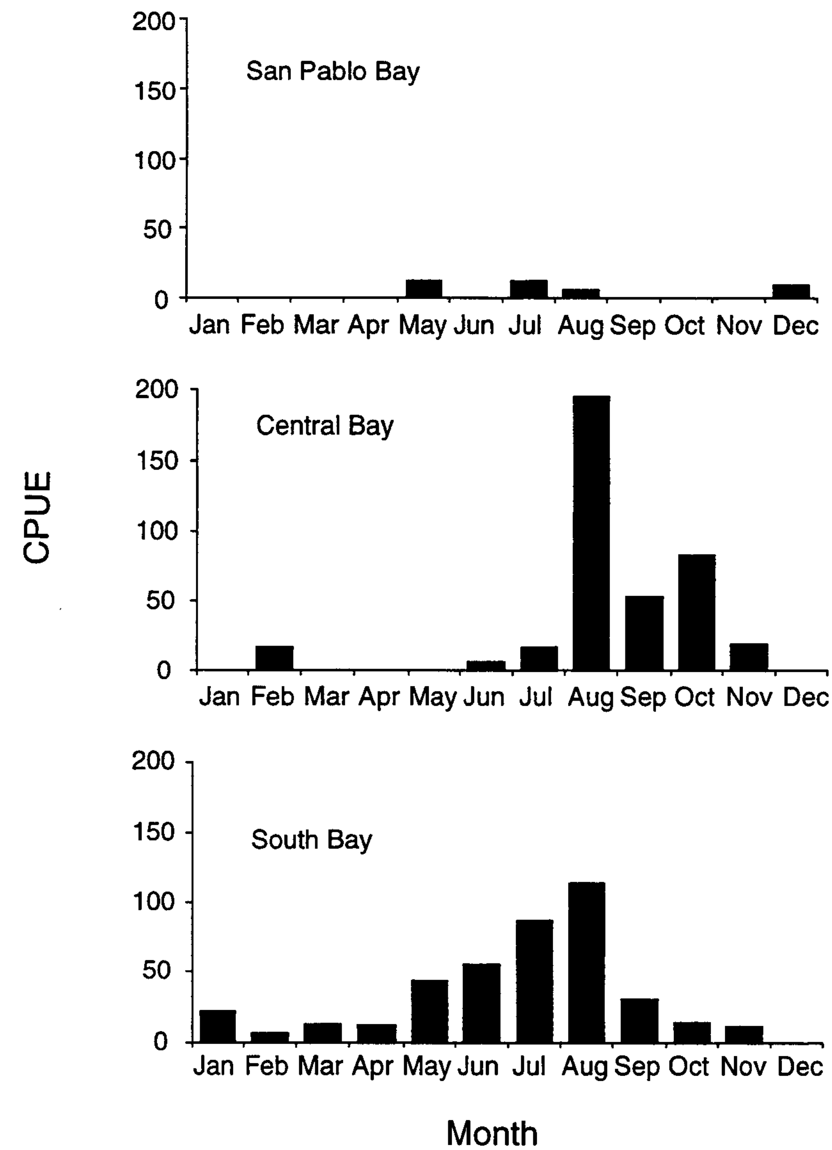

Figure 50 Seasonal distribution of white seaperch by bay collected with the otter trawl from 1981 to 1988. No white seaperch were collected in Suisun Bay or the west delta. Values are CPUE x 100.

White seaperch ranged from 47 to 291 mm FL (Figure 51). At least 2 age classes were collected from May to September when parturition occurred. The length frequency data show that some young fish stay in the estuary in winter but most leave in fall.

White seaperch were collected in temperatures ranging from 8.4 to 20.5 °C, $\overline{\chi}$ = 16.9 °C (Figure 52). They occurred in polyhaline and euhaline salinities, 13.3‰ to 33.6‰, $\overline{\chi}$ = 28.1‰.

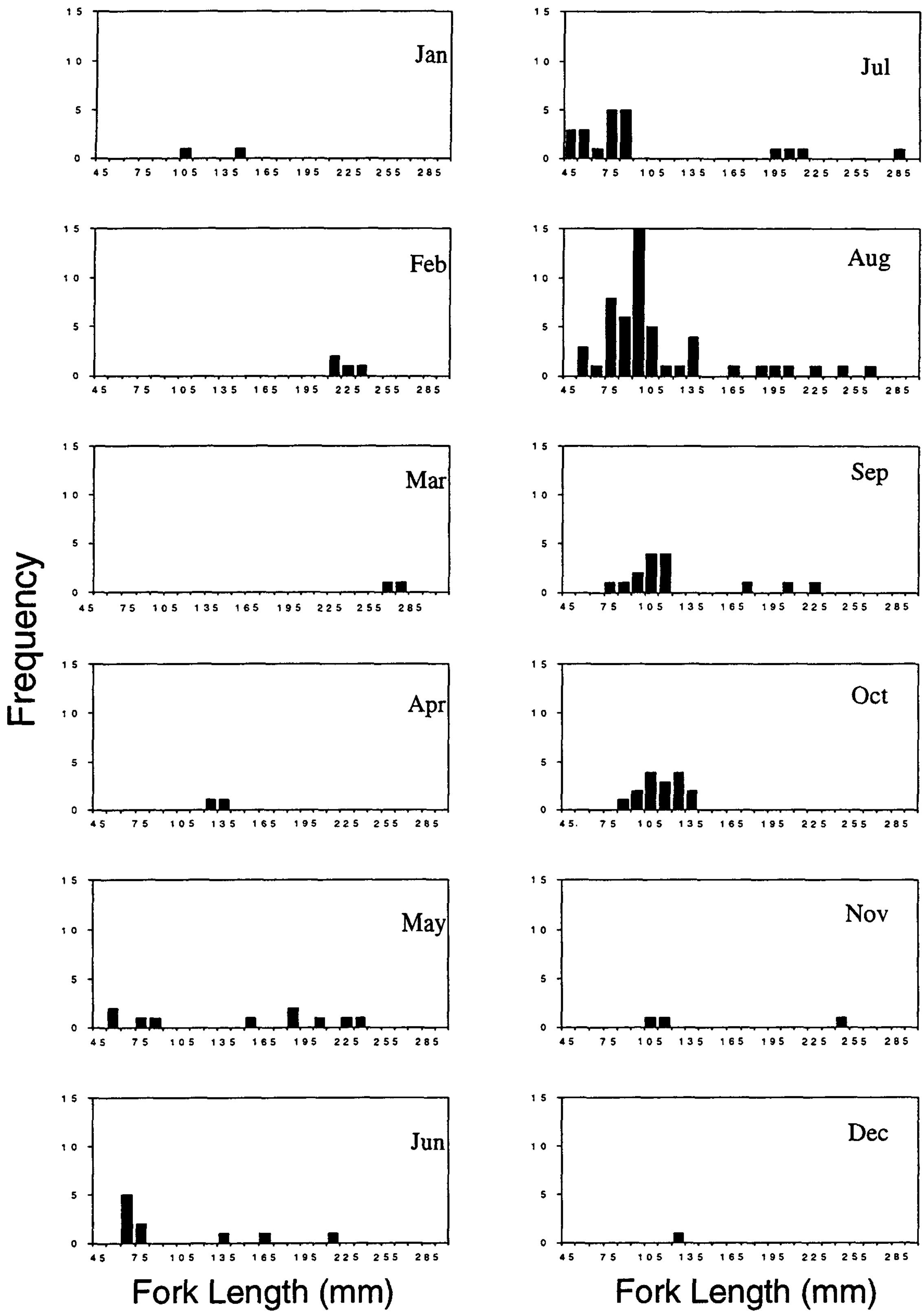

Figure 51 Monthly length frequencies of white seaperch collected with the otter trawl from 1980 to 1995. Values on x-axis are lower class limits.

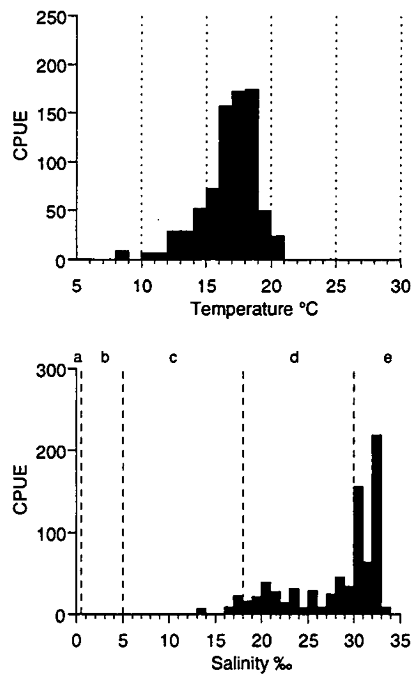

Figure 52 Temperature and salinity distributions for white seaperch collected with the otter trawl from 1980 to 1995. The vertical lines on the salinity graph mark the boundaries of the Venice system ranges: (a) limnetic, (b) oligohaline, (c) mesohaline, (d) polyhaline, and (e) euhaline.

Uncommon Species of Surfperches in the San Francisco Estuary

Barred Surfperch

The barred surfperch, *Amphistichus argenteus,* ranges from Playa Maria Bay, Baja California to Bodega Bay, California (Miller and Lea 1972). It is found along the coast, from the surface to 73 m and is common at sandy beaches in the surf zone. This species and the walleye surfperch form large schools all year, unlike other surfperch which school only during the birthing and mating seasons (Feder and others 1974). The barred surfperch is eurythermal and is commonly found from 7 to 21 °C. It feeds on crabs and small mussels. In La Jolla, California, it mates from November to December and the young are born in spring and summer. This species does not store sperm. It is reported to reach 9 years of age and 432 mm TL (Baxter 1980, Miller and Lea 1972). It is commonly caught from piers and along the surf line by sport anglers (Karpov and others 1995).

In the San Francisco Estuary, 165 barred surfperch were collected in the otter trawl, 73 in the beach seine, but only 4 in the midwater trawl (see Tables 1, 2, and 3 in the Introduction section of this chapter). In the otter trawl, they were collected in all years except 1986. Catches have declined since 1984 (see Table 2). The barred surfperch catch may have been low because it is more common in the ocean than in bays and estuaries (Karpov and others 1994). Barred surfperch were collected primarily in South Bay. From 1980 to 1984, they were collected all year long, but from 1985 to 1995 they were only collected from May to October. The minimum fork length was 45 mm, the maximum 328 mm.

Surfperch catch declined in Karpov's (1995) comparison of the marine recreational fishery between 1958 to 1961 and 1981 to 1986; this decline was due mainly to weight reductions for barred surfperch and redtail surfperch landed. Barred surfperch landed also declined in size during this period.

Black Perch

The black perch, *Embiotoca jacksoni*, ranges from Point Abreojos, Baja California to Fort Bragg, including Guadalupe Island, Baja California (Miller and Lea 1972). It is found to 55 m, but is most common from 6 to 24 m (Feder and others 1974). It is common in bays and estuaries on reefs, pilings, and kelp beds at temperatures from 11 to 21 °C. Prey items include, algae, amphipods, polychaetes, crustaceans and molluscs (Feder and others 1974, Baxter 1980).

Black perch mate from April through June and store sperm for less than 3 months. Gestation is about 6 months and parturition occurs from September to November. The average brood size is 14 (Baltz 1984). It reaches a maximum length of 389 mm (Miller and Lea 1972).

This study collected a total of 77 black perch: 1 in the midwater trawl, 59 in the otter trawl, and 17 in the beach seine (see Tables 1, 2, and 3 in the Introduction section of this chapter). Size ranged from 56 to 286 mm FL. Black perch ranged from South to Suisun bays but were most abundant in Central Bay. They were collected all year.

Rubberlip Seaperch

The rubberlip seaperch, *Rhacochilus toxotes*, ranges from Thurloe Head, Baja California to Mendocino County, including Guadalupe Island, Baja California (Miller and Lea 1972). It can be found in giant kelp forests from the surface to 46 m but is most abundant at 3 to 31 m (Feder and others 1974). Adults feed on crabs, shrimp, and octopi and juveniles feed on polychaetes, bryozoans, amphipods and mussels (Feder and others 1974). The rubberlip seaperch is found from 11 to 21 °C (Baxter 1980). Maximum size is 470 mm TL (Miller and Lea 1972). The reproductive life cycle of the rubberlip seaperch has not been well documented.

Only 28 rubberlip seaperch were collected: 4 in the midwater trawl, 12 in the otter trawl, and 12 in the beach seine (see Tables 1, 2, and 3 in the Introduction section of this chapter). In the otter trawl none were collected from 1990 to 1994 and only 1 was collected in 1995. Rubberlip surfperch were collected from Central and San Pablo bays and were most abundant in Central Bay. Lengths ranged from 72 to 401 mm FL.

Other Surfperches

Other species and numbers of surfperches collected during this study are the calico surfperch (3), redtail surfperch (1), spotfin surfperch (1), silver surfperch (8), and rainbow seaperch (1). All of these species were collected from 1980 to 1987, except 1 calico, which was captured in the midwater trawl in 1993, and 1 redtail surfperch in 1995 (see Tables 1, 2, and 3 in the Introduction section of this chapter).

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Gobiidae

Kevin Fleming

The Gobiidae family is one of the largest fish families. Found worldwide, most of its species are small and benthic or epibenthic. Six species of gobies were commonly collected in the San Francisco Estuary from 1980 to 1995: the bay goby, *Lepidogobius lepidus;* the arrow goby, *Clevelandia ios;* the cheekspot goby, *Ilypnus gilberti*; the yellowfin goby, *Acanthogobius flavimanus*; the shimofuri goby, *Tridentiger bifasciatus*; and the chameleon goby, *Tridentiger trigonocephalus.* The bay, arrow, and cheekspot gobies are native to the estuary; whereas the yellowfin, shimofuri, and chameleon gobies have all been introduced from Asia.

This chapter will discuss only the bay, yellowfin, and chameleon gobies. The data for the arrow gobies was previously reported (CDFG 1987). Very few cheekspot and shimofuri gobies were collected by the otter trawl. The longjaw mudsucker, although common in the estuary, was rarely collected. Its habitat, euhaline mud flats and salt ponds, was not well represented in the sampling program.

Bay Goby

Introduction

The bay goby is common in bays and estuaries from Baja California to Vancouver Island, British Columbia (Miller and Lea 1972). It is benthic and is often found living commensally with burrowing invertebrates (Grossman 1979b). It may live more than 7 years (Grossman 1979a), but based upon length frequency data, its life span may be as short as 2 to 3 years (CDFG 1987). Some individuals reach sexual maturity at the end of their 1st year and the rest by the end of their 2nd year (Grossman 1979a).

Spawning takes place throughout the year and peaks between June and October (CDFG 1987). The larvae are concentrated near the Golden Gate Bridge and Angel Island (Wang 1986). They are planktonic for 3 to 4 months (Grossman 1979a) and descend to the bottom as juveniles at about 25 mm TL (Wang 1986).

Methods

The otter trawl data were used for the descriptions of length, abundance, and distribution. The abundance index period was February through October. Fish were not separated into age classes.

Results

Length

The bay goby reached adult size (about 90 mm) within 1 year, suggesting that it may also complete its life span within 1 year. Most of the smallest bay gobies grew large enough to recruit to the otter trawl in winter and early spring. The fastest growth occurred during spring, particularly in March and April (Figure 1). By summer, as they reached the end of their 1st year, they had reached nearly the maximum size.

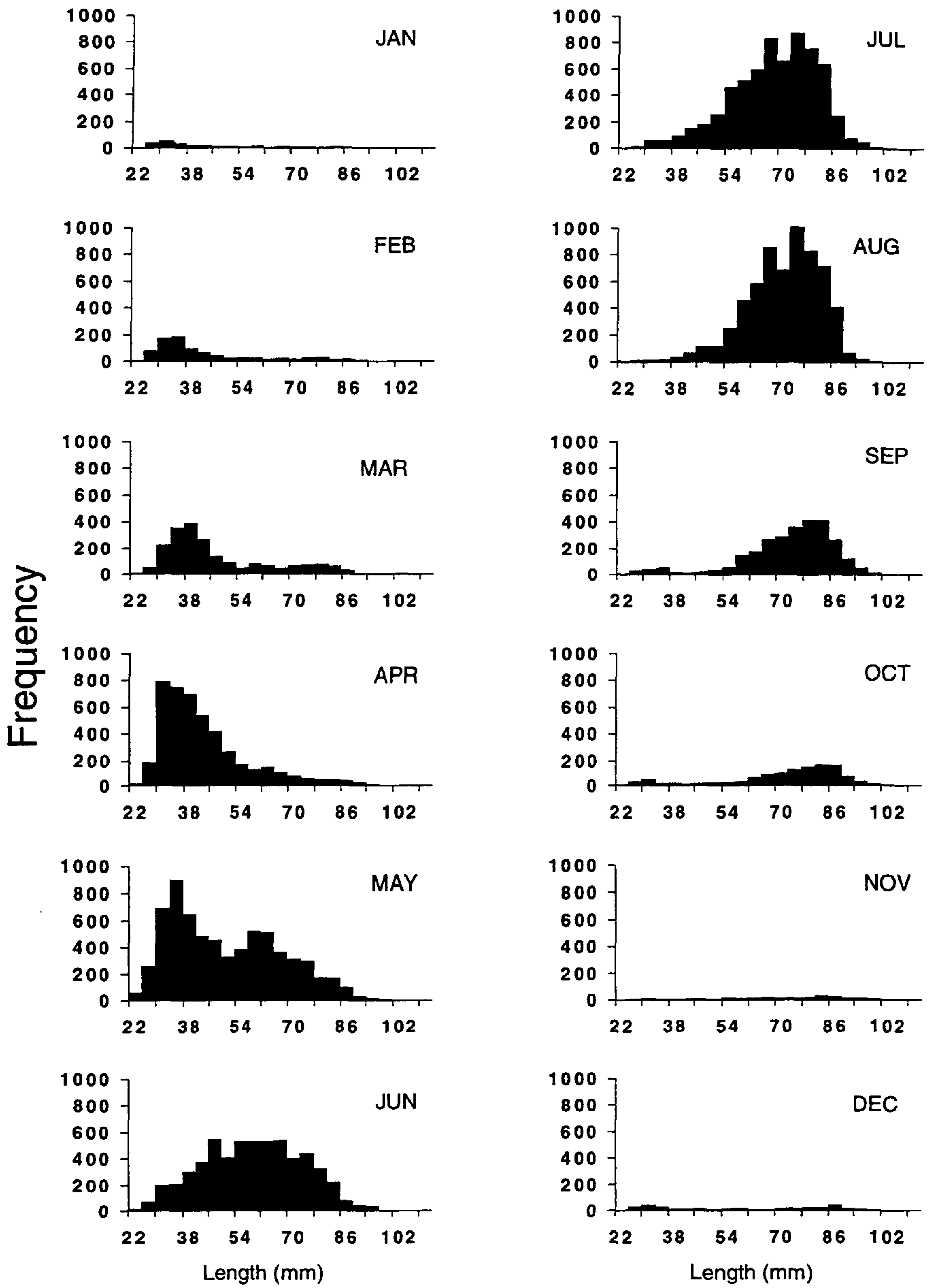

Figure 1 Length distribution of bay gobies by month from 1980 to 1988

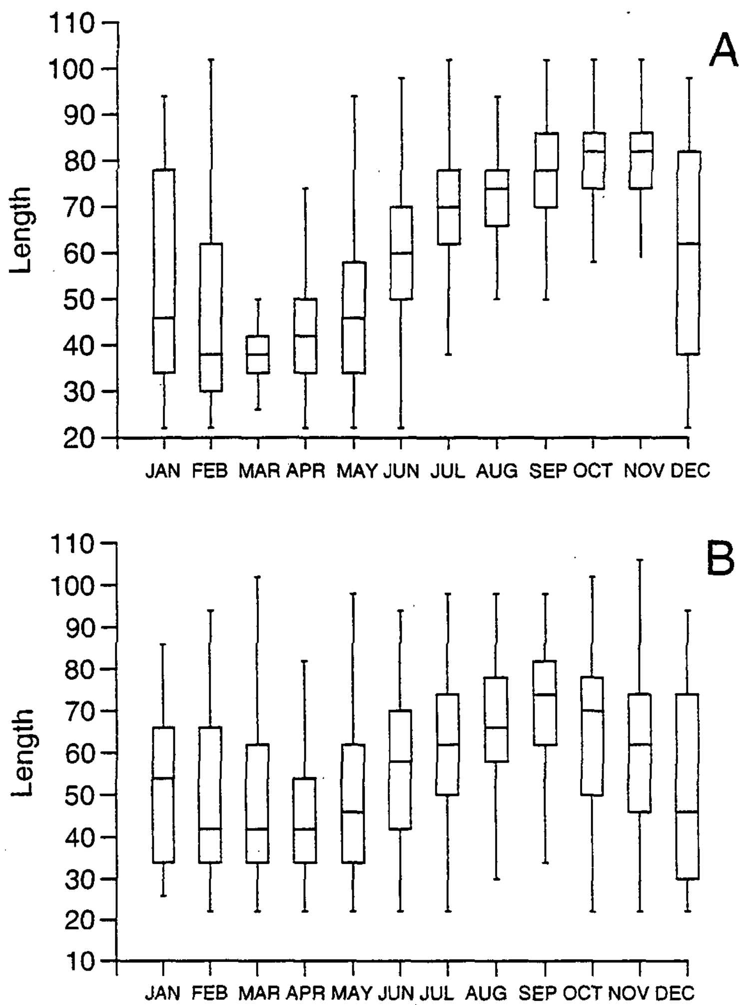

Figure 2 Length distribution of bay gobies by month in (A) wet years and (B) critical years

The annual age structure was affected by outflow. During wet years, small fish (<40 mm) were present primarily in winter and spring. Larger fish (>60 mm) were most abundant in summer and early fall (Figure 2). This pattern differed during dry years when both small and large fish were collected throughout the year.

Abundance

Abundance was highest in 1991 and lowest in 1985 (Figure 3, Table 1). The 4 lowest abundance years were in the early and mid-1980s. Abundance did not appear to be related to outflow as both dry and wet years (see Salinity and Temperature chapter, Table 1) had either low or high abundance. However, outflow may have influenced the seasonal pattern of abundance. During wet years, the monthly abundance indices peaked only once per year in late summer. But during dry years, the monthly indices showed 2 modes, the 1st in spring and the 2nd in midsummer (Figure 4).

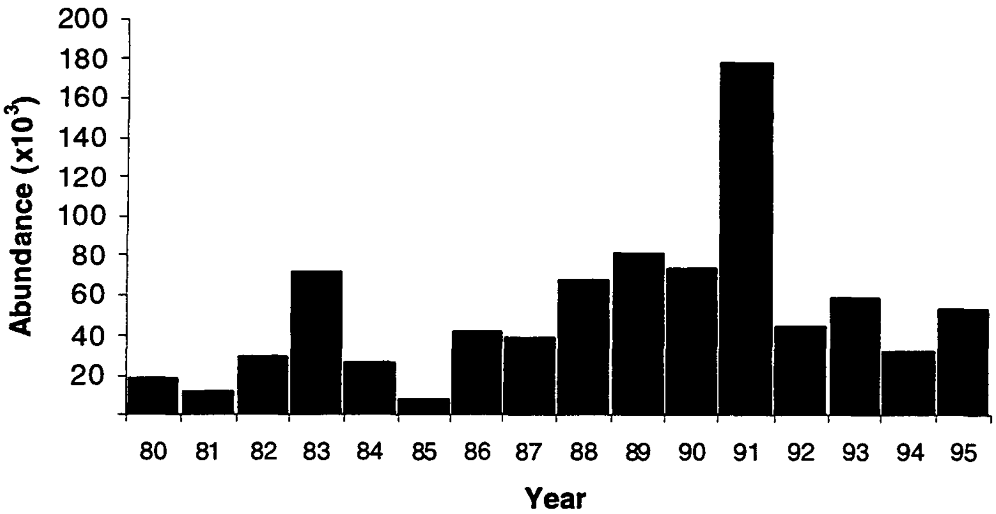

Figure 3 Annual abundance of bay goby

Table 1 Monthly abundance indices of bay gobies captured in the midwater trawl from 1980 to 1995. The last column is the annual index, the mean abundance from February to October. The bottom row is the average seasonal abundance from 1981 to 1988.

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Index*
1980		4788	6229	11318	13544	108158	12390	2532	2209	1026	2290	783	18022
1981	338	562	1970	16679	11232	6919	22230	37163	2630	7208	0	892	11844
1982	6225	850	36783	71633	55582	41107	4221	29704	23578	1862	1359	899	29480
1983	6016	5214	1667	90380	74092	48982	35228	383764	368	6901	2845	7095	71844
1984	2613	3297	3362	22850	18160	43830	87949	16068	21217	12364	328	1102	25455
1985	189	3937	816	411	3109	11156	10039	23690	1554	20148	4346	1255	8318
1986	1099	647	14845	12510	30296	21794	121092	141478	30490	5840	2092	3379	42110
1987	1867	5122	36118	3004	10265	32714	61403	68591	85801	48638	25367	29988	39073
1988	2787	2101	5342	136806	244439	54358	148078	10223	9474	424	4107	17840	67916
1989	35945	52260	40010	53216	135715	110777	114733	64779					81641
1990		24688	53104	38151	93611	155562	91647	50663	117376	34874			73297
1991		25673	107768	319502	291601	109642	355563	234439	90651	74140			178776
1992		13108	58187	13101	120432	79119	26833	16971	33906	34946			44067
1993		23504	12445	9318	53529	111226	201754	90487	19866	9642			59086
1994		3364	10761	14013	24328	38437	13224	103947	76419	7464			32440
1995	17322	21492	50897	46102	107234	38574	95895		62361	944	11262	20298	52937
1981–1988	2642	2716	12613	44284	55897	32607	61280	88835	21889	12923	5056	7806	

Distribution

In general, bay gobies were most common in Central Bay, which had the highest CPUE in 11 out of 16 years (Figure 5). During these years, the Central Bay annual CPUE was usually more than double that of the other bays. Bay gobies were collected in the west delta only in 1980, 1989, and 1991, but they were present in Suisun Bay in all years, although the CPUEs were very low.

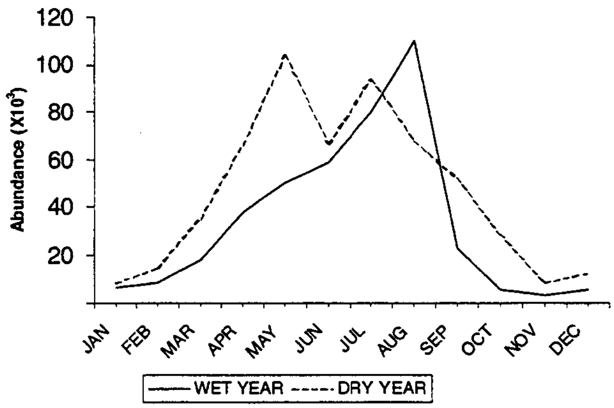

Figure 4 Seasonal abundance of bay goby by water year type from 1981 to 1988

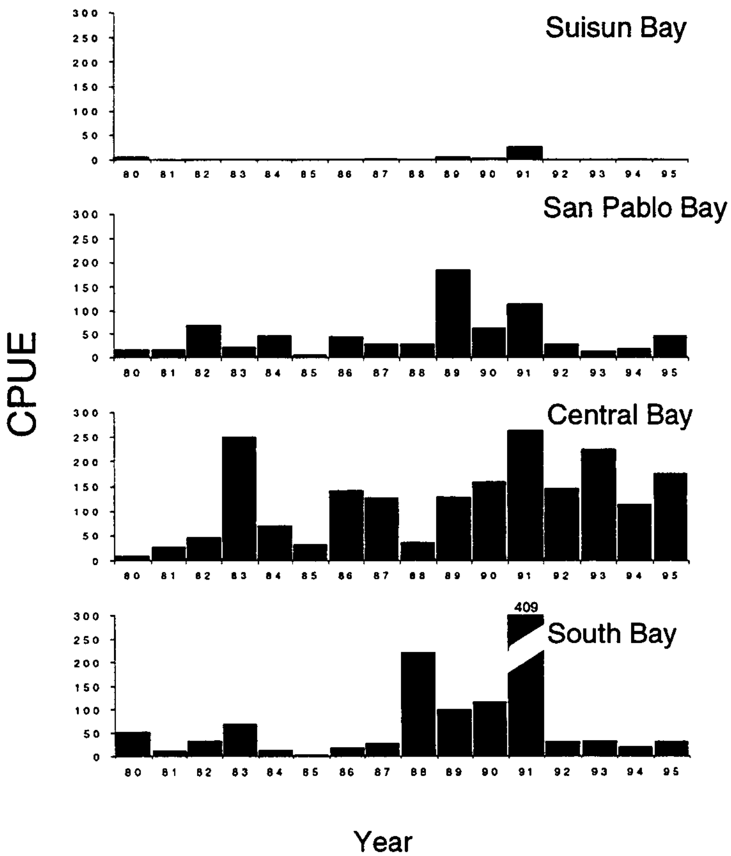

Figure 5 Annual bay goby distribution by region. Values are the average CPUE for February to October.

Bay gobies appeared to move between regions over the course of the year (Figure 6). In early spring, when most of the catch was made up of young bay gobies, the highest CPUE was in South and San Pablo bays. In late spring and summer, as the gobies matured, the center of distribution shifted from South to Central Bay, and in fall the CPUE decreased in all regions.

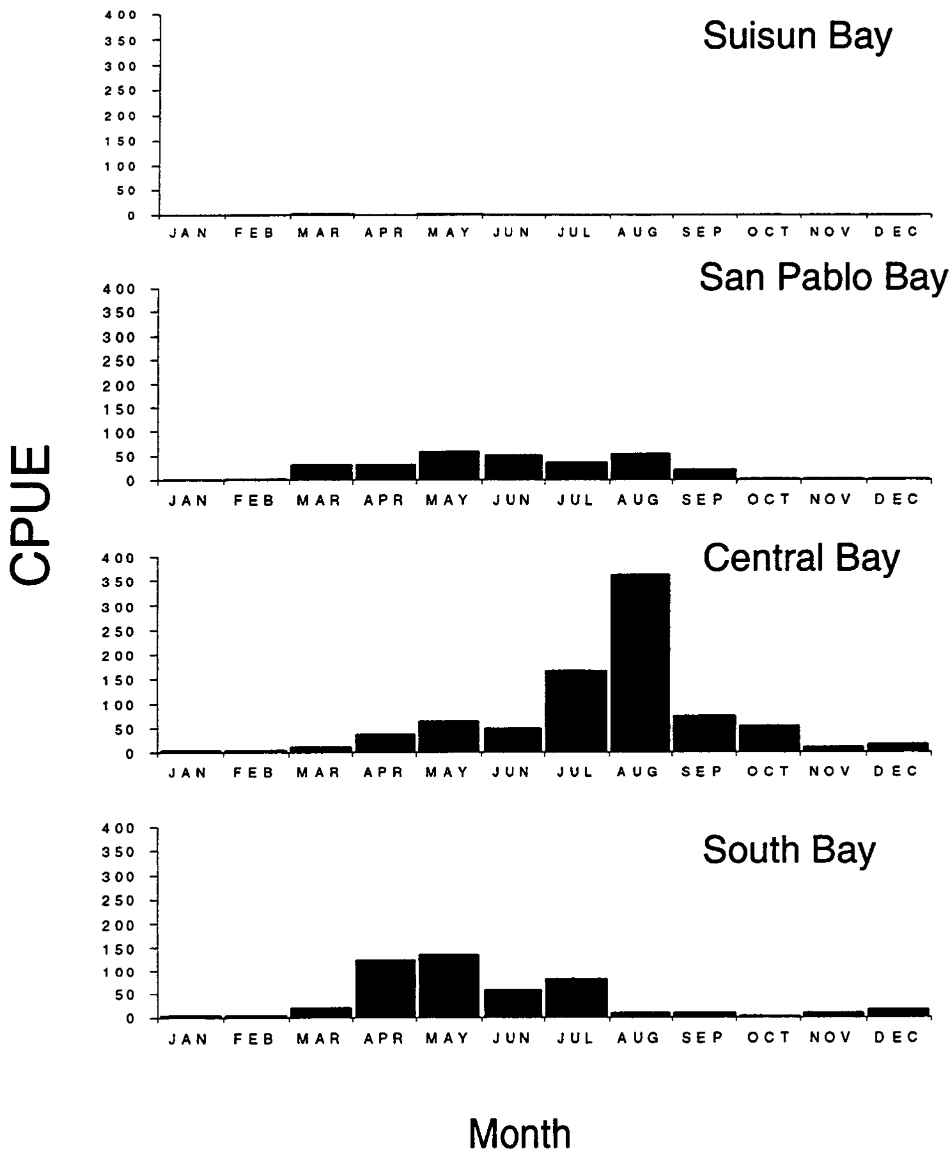

Figure 6 Seasonal bay goby distribution by region. Values are the average CPUE for 1981 to 1988.

Temperature and Salinity

Bay gobies remained in a fairly narrow temperature range, usually below about 18 °C (Figure 7). The salinity range was much more variable than the temperature range, particularly for the smaller gobies (see Figure 7). The salinity differences may be attributed to the reduced salinity in the estuary during winter and spring when small bay gobies were most common. However, bay gobies were mostly collected in upper polyhaline and euhaline salinities, at a mean of 27.5‰.

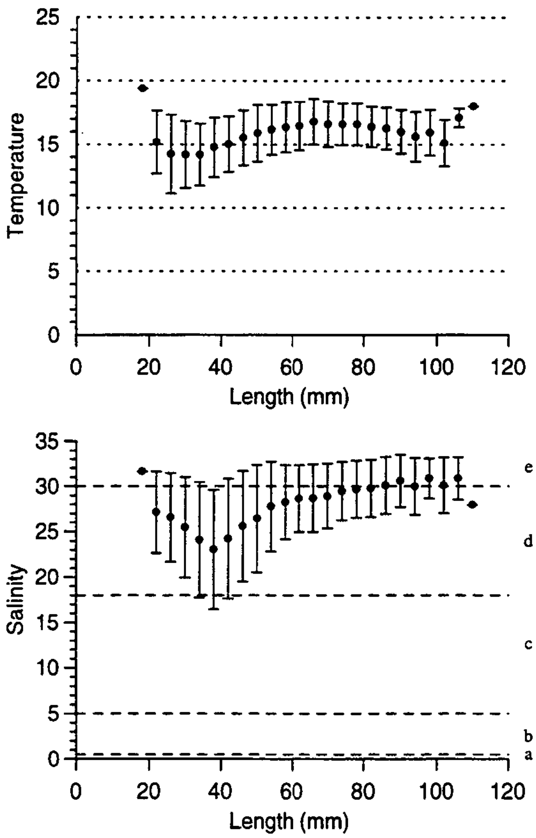

Figure 7 Temperature and salinity distributions of bay gobies by length. The dots are the means and the bars are 1 standard deviation. The horizontal lines on the salinity graph mark the boundaries of the Venice system ranges: (a) limnetic, (b) oligohaline, (c) mesohaline, (d) polyhaline, and (e) euhaline.

Discussion

The bay goby is the most abundant goby in the estuary. It is found primarily within the relatively cool, euhaline to upper polyhaline regions of Central, South, and San Pablo bays. Its range extends upstream from San Pablo Bay only in low outflow years. Of the 3 main areas used by the bay goby, San Pablo and South bays were used primarily as nursery areas, as few adults were collected in those bays. Mature fish were collected primarily in Central Bay, where the larvae were also found (Wang 1986).

Salinity and temperature appear to control their movements and distribution in the estuary. Abundance declined in South Bay when the average bottom temperature there increased above about 17 °C, which typically occurred by June. In San Pablo Bay the catches decreased by late fall when the average bottom salinity decreased to the lower polyhaline range.

River outflow directly affected reproduction, as seen in the seasonal recruitment pattern of juvenile bay gobies. During wet years, recruitment appeared to be restricted to June to October. During dry years, salinity remained high for a prolonged period and recruitment was prolonged, although the peak spawning still occurred in summer and fall.

Based upon the length frequency data, bay gobies appear to be short-lived and attain their maximum size within 1 to 2 years, rather than in the 7+ years reported in the literature (Grossman 1979a). The disagreement may be the result of sampling locations. Grossman conducted his research in Morro Bay and based his findings on the apparently slow growth rate of the bay goby (as shown in length frequency histograms) and the number of otolith annuli. A major difference between Morro Bay and San Francisco Bay is salinity, which does not fluctuate seasonally in Morro Bay as it does in San Francisco Bay. The constant high salinity in Morro Bay may have prolonged goby reproduction and generated multiple cohorts. These cohorts may have obscured the seasonal growth pattern and rates reported in Grossman (1979a), as they did in our data during the drought (see Figure 2). In addition, Grossman states that the occurrence of annuli is synchronous with reproduction. If so, then multiple spawnings would have led to an increased number of false "annuli" and an overestimate of age.

Yellowfin Goby

Introduction

The yellowfin goby is native to the estuaries of Japan, Korea, and northern China. It was accidentally introduced to the estuary in the late 1950s, was first collected in 1963, and is now well established (Brittan and others 1963, 1970). The yellowfin goby is a food item in Japan; in California, it supports a small, live bait fishery.

The yellowfin goby grows to about 240 mm, larger than any other California goby, native or introduced (Miller and Lea 1972), and may live from 1 to 3 years (Hoshino and others 1993). Males mature after their 1st year and females at the end of their 2nd year (Hoshino and others 1993). They move from fresh to saline waters to spawn from December to July (Wang 1986). The eggs are attached to the walls of Y-shaped burrows dug by males in the tidal flats (Dotu and Mito 1955) and are guarded by males until they hatch after 28 days (Dotu and Mito 1955). The pelagic larvae may use tidal currents either to maintain their position within the estuary or to ascend into fresher water areas during spring (Wang 1986). At about 15 mm, young gobies begin a benthic existence (Dotu and Mito 1955). Juveniles apparently prefer shallow water and can tolerate both low salinity and high temperature (Wang 1986).

Methods

Data from the otter trawl was used for the length-frequency histograms and to calculate the abundance indices. The index period was set from May to October to restrict it to age–0 fish.

Results

Length

Most yellowfin gobies caught in this survey were age 0. The smallest fish (about 20 mm) were first collected in spring and the largest, the age–1+ fish (about 175 to about 225 mm), were taken from late fall to early spring (Figure 8).

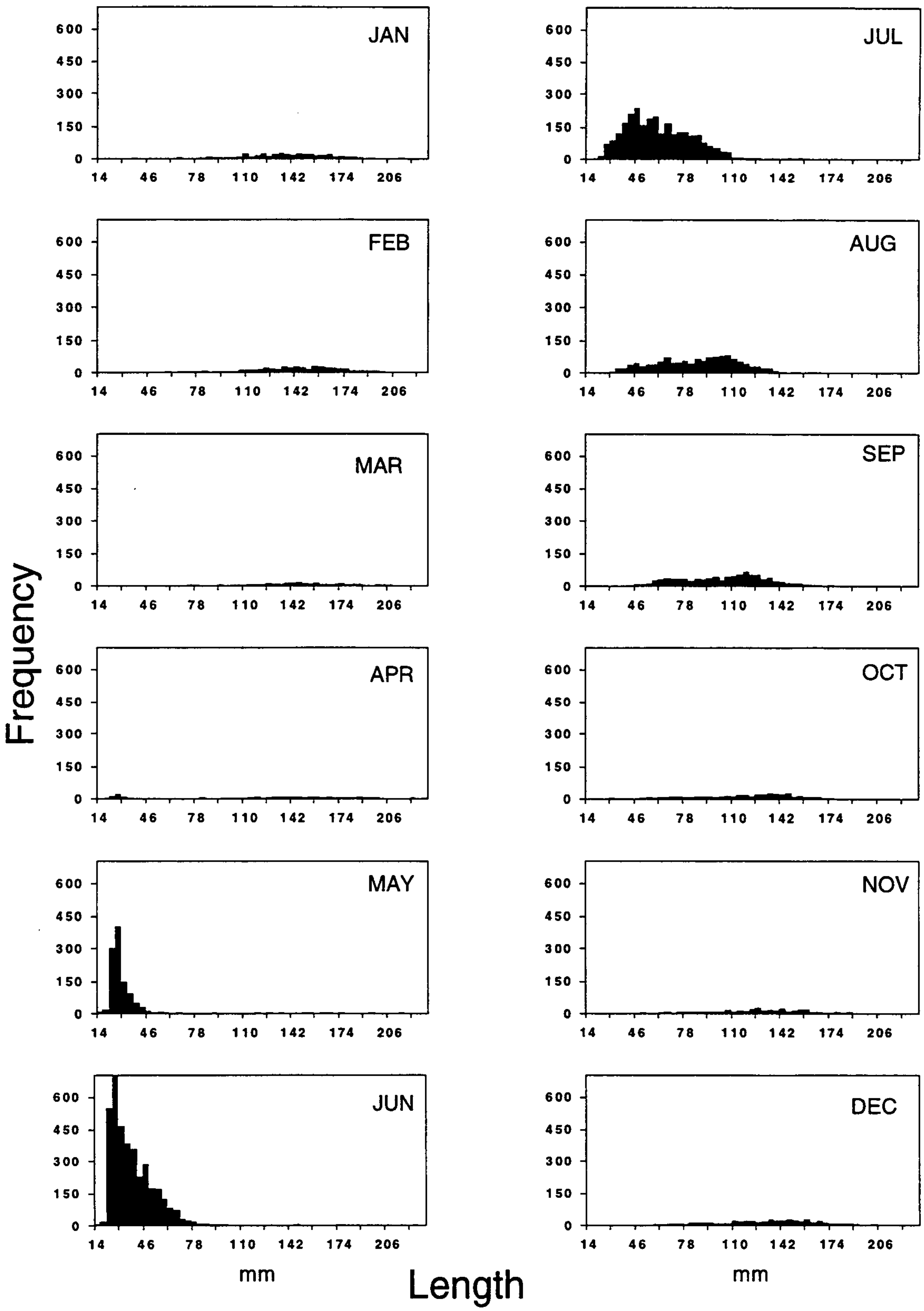

Figure 8 Length distribution of yellowfin gobies by month from 1980 to 1988

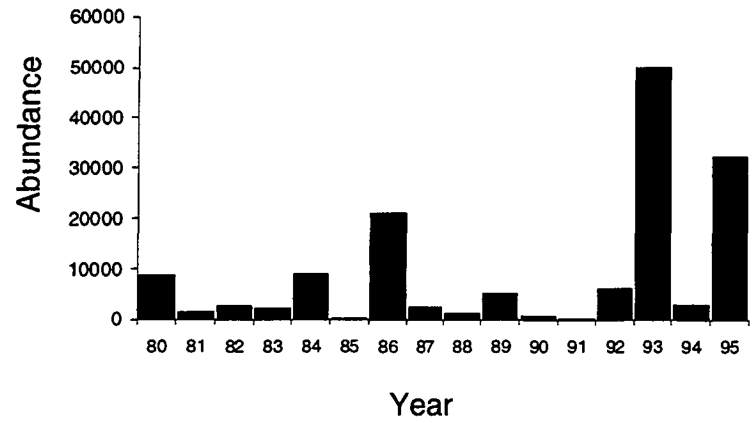

Figure 9 Annual abundance of age–0 yellowfin goby

Table 2 Monthly abundance indices of age–0 yellowfin gobies captured in the midwater trawl from 1980 to 1995. The last column is the annual index, the mean abundance from May to October. The bottom row is the average seasonal abundance from 1981 to 1988.

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Index*
1980		80	245	0	3992	24986	5751	6475	9469	2143	467	109	8803
1981	826	900	0	288	208	2943	1876	2126	587	0	66	443	1290
1982	815	553	78	0	231	5032	5347	2918	1002	965	2323	1264	2583
1983	1813	451	631	0	0	3560	5584	1651	128	1548	217	2006	2078
1984	0	0	0	199	1161	27740	16449	5822	2105	784	474	566	9010
1985	439	216	516	0	0	45	47	1265	57	64	186	0	247
1986	572	319	1226	130	1897	17706	37685	51412	15174	1609	571	4934	20914
1987	2516	709	367	99	0	207	2336	5692	5276	1634	6554	4794	2524
1988	3428	363	50	202	511	750	2078	1391	1442	166	0	57	1056
1989	156	532	324	281	1465	4687	6215	8174					5135
1990		151	388	57	57	183	1519	674	309	296			506
1991		230	136	99	0	0	0	284	495	0			130
1992		0	0	0	11970	9789	7137	5972	2173	746			6298
1993		981	68	301	83326	89922	94465	20933	10199	1631			50079
1994		3293	907	187	337	2264	2568	7996	3627	274			2844
1995	1042	154	0	6525	13286	80857	55060		10643	1852	1390	1746	32339
1981-1988	1301	439	358	115	501	7248	8925	9034	3221	846	1299	1758	

Abundance

Annual abundance of age–0 yellowfin gobies fluctuated more than 10 times (Figure 9, Table 2). It was highest in 1993, next highest in 1995, and lowest in 1985 and 1991. No trend in abundance was apparent. Seasonally, abundance typically peaked during summer, decreased in fall, and recovered somewhat during winter (see Table 2).

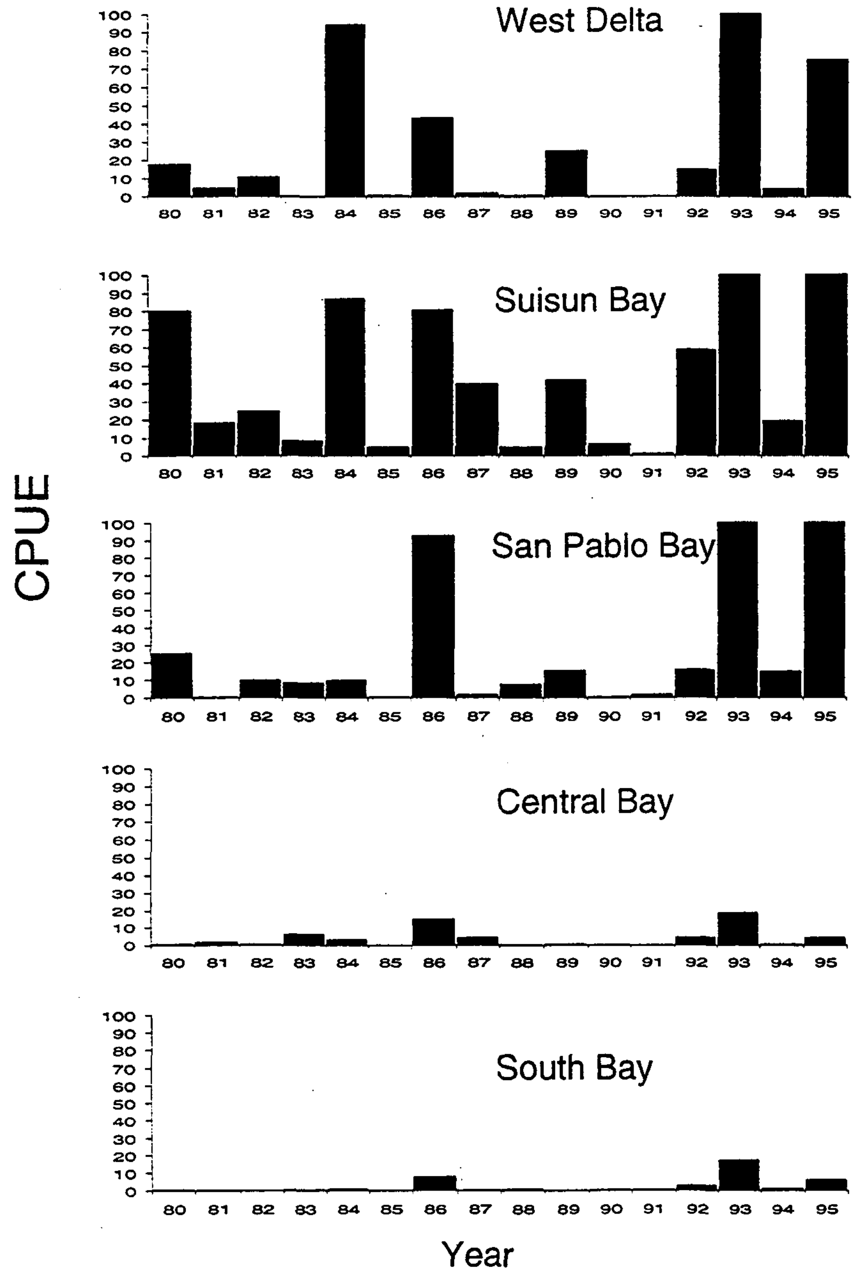

Figure 10 Annual yellowfin goby distribution by region. Values are the average CPUE for May to October.

Distribution

Yellowfin gobies were concentrated in Suisun Bay and the west delta in most years (Figure 10). The CPUE was usually highest in Suisun Bay and lowest in South and Central bays.

Yellowfin gobies moved seasonally between San Pablo and Suisun bays (Figure 11). Highest density occurred in San Pablo Bay in winter, shifted into Suisun Bay in spring, remained there during summer, and returned to San Pablo Bay in November. The CPUE also tended to be highest in Central Bay in fall and winter and in South Bay in winter.

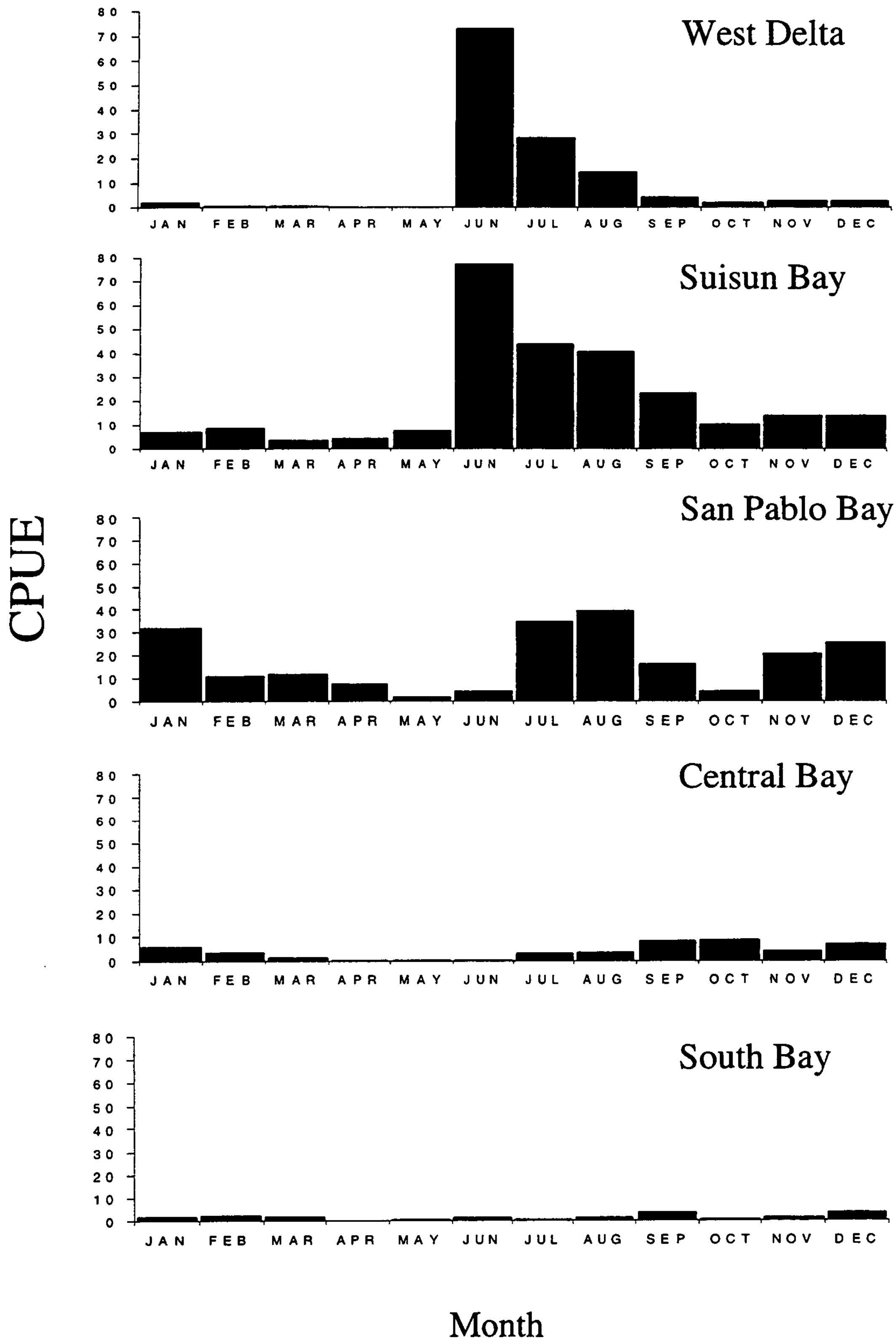

Figure 11 Seasonal yellowfin goby distribution by region. Values are the average CPUEs for 1981 to 1988.

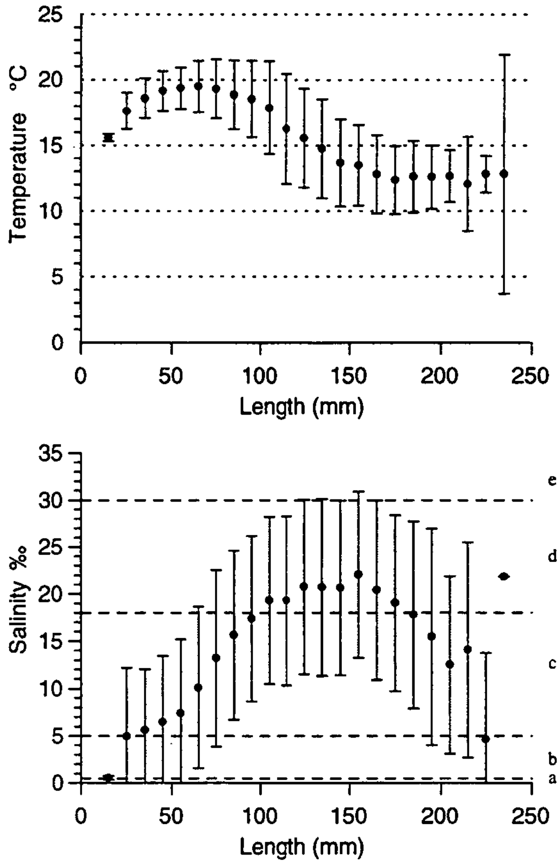

Figure 12 Temperature and salinity distributions of yellowfin gobies by length. The dots are the means and the bars are one standard deviation. The horizontal lines on the salinity graph mark the boundaries of the Venice system ranges: (a) limnetic, (b) oligohaline, (c) mesohaline, (d) polyhaline, and (e) euhaline.

Temperature and Salinity

Yellowfin gobies were collected over broad ranges of salinity and temperature. These ranges increased with size of fish. The smallest fish (20 to 30 mm) were collected at a mean salinity of 4.9‰ and a mean temperature of 19.3 °C; the larger fish (140 to 160 mm) were collected at a mean salinity of 20.7‰ and a mean temperature of 13.7 °C (Figure 12A). For the few fish that were >160 mm the mean salinity decreased with length.

Discussion

Yellowfin gobies are a fast growing, short-lived species whose abundance varied greatly from year to year. Each year was dominated by a year class. Because of the juvenile dispersion upstream, in most years the majority of the younger fish were in the west delta and Suisun Bay and the older fish were in San Pablo Bay.

Despite the fluctuating annual abundance, the seasonal movements followed a consistent pattern. During fall and late winter, females lay their eggs in burrows in the shallows of San Pablo Bay and the eggs hatch approximately 1 month later. The larvae are concentrated near the bottom of the water column (CDFG, unpublished), and are transported upstream by tidal currents (Wang 1986). The young fish begin an upstream migration in spring. By late fall, the maturing gobies migrate to San Pablo Bay. Their movements to the shallows for spawning make them less susceptible to our sampling and the catch drops in fall. After spawning, the surviving females either leave or remain with the males to guard the eggs (Wang 1986). Most yellowfin gobies die after their 1st year.

Chameleon Goby

Introduction

The chameleon goby is native to the Asian Pacific. It was introduced, presumably in ship ballast, during the 1960s (Brittan and others 1963). It is a marine fish that is only rarely collected in brackish water (Akihito and Sakamoto 1989, Matern and Fleming 1995).

Most larvae appear to reside in the open waters of South Bay (Wang 1986). The pelagic larvae settle to the bottom when they grow to about 15 mm (Dotu 1958, as cited in Wang 1986). They reach sexual maturity in 1 year and may live up to 3 years (Dotu 1958, as cited in Wang 1986), and reach a maximum length of about 110 mm (Eschmeyer and others 1983).

The chameleon goby spawns several times a year from May to September (Wang 1986). The eggs are deposited either on shells (Dotu 1958, as cited in Wang 1986) or on other firm substrates (Wang 1986) and are guarded by the males. Incubation averages 8.5 days (Dotu 1958, as cited in Haaker 1979).

Methods

Otter trawl data were used in the descriptions of length, abundance, distribution, salinity, and temperature. The annual index period was February through August. Fish were not separated into age classes because most of the age–0 fish were collected in late fall and winter, and winter sampling ended in 1989.

Results

Length Frequency

The chameleon goby appears to be short-lived. Each year's catch was primarily made up of a single year class (Figure 13). The smallest gobies (about 20 mm) were collected in late fall and winter, indicating probable late spring and summer spawning. Very few fish appeared to be over 1 year old; the majority were collected near the end of their 1st year and very few were >70 mm. Fish >90 mm were collected between March and April may have been about 2 years old.

Abundance

Abundance varied greatly between 1980 and 1995 (Figure 14, Table 3). No fish were collected in 1980 and abundance was very low from 1981 to 1987. Annual abundance was highest in 1993 and next highest in 1994.

Chameleon gobies were found throughout the year, although the abundance index tended to be highest in December and February (Figure 15). Abundance was lowest in late summer and early fall.

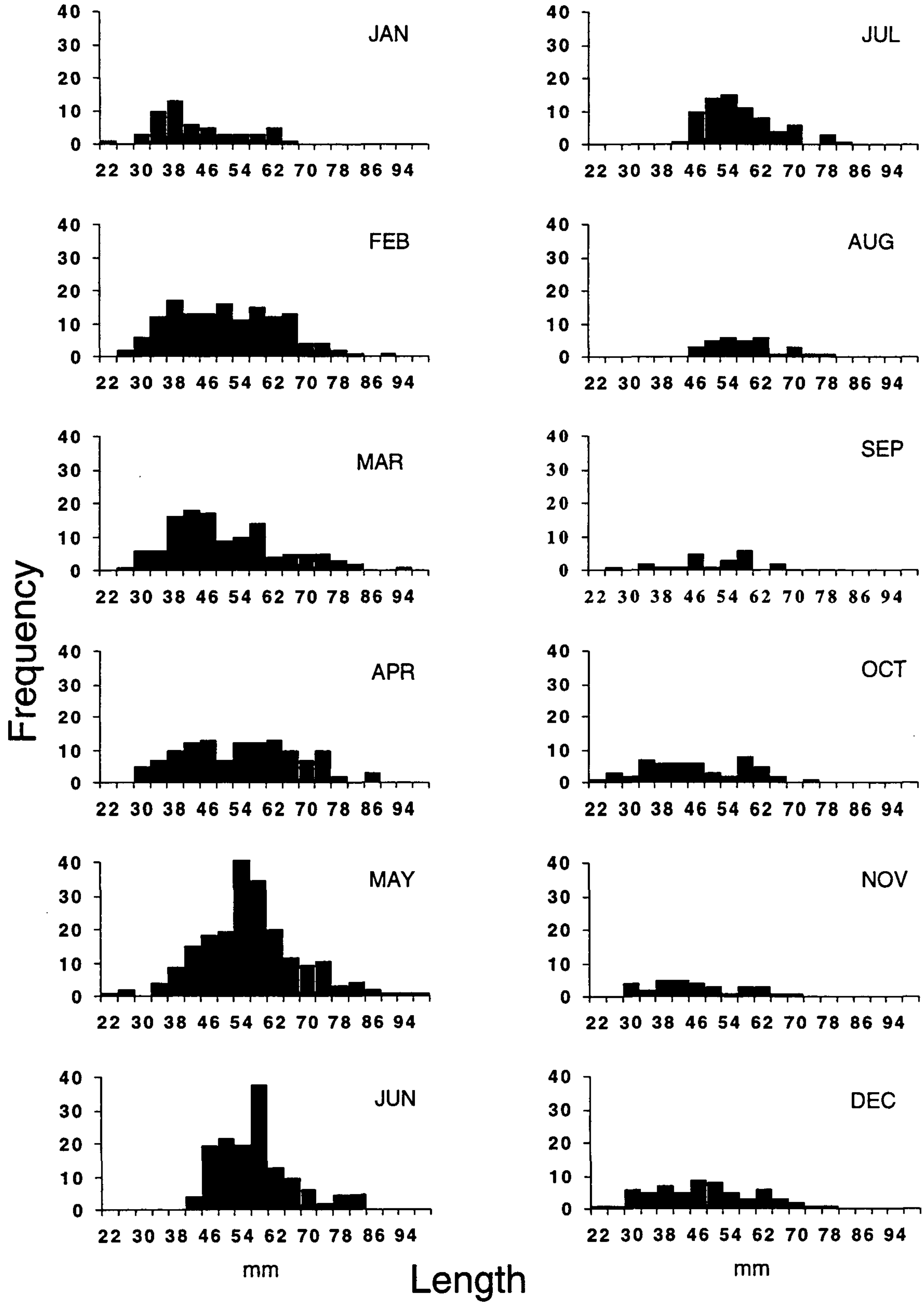

Figure 13 Length distribution of chameleon gobies by month from 1980 to 1988

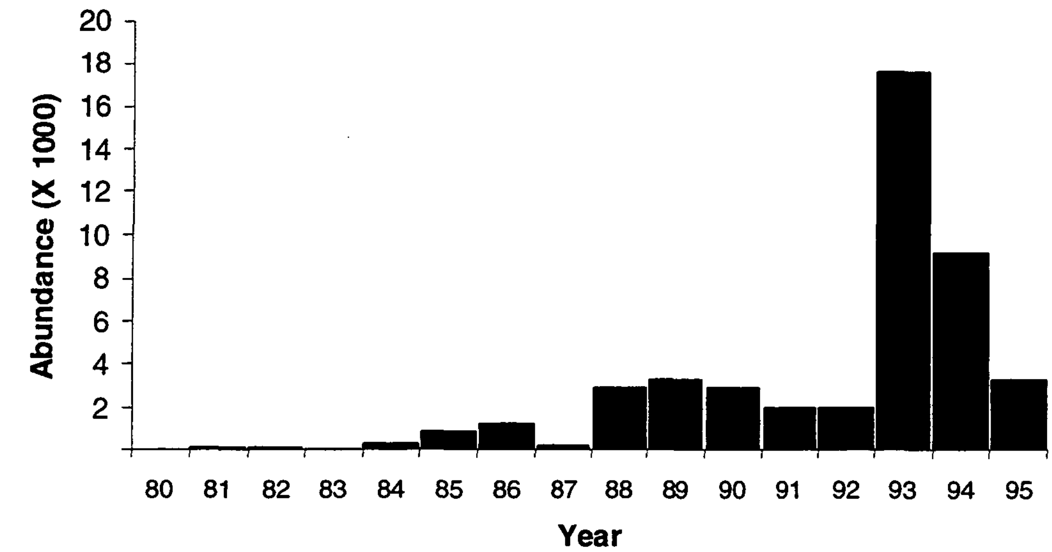

Figure 14 Annual abundance of chameleon goby

Table 3 Monthly abundance indices of chameleon gobies captured in the midwater trawl from 1980 to 1995. The last column is the annual index, the mean abundance from February to October. The bottom row is the average seasonal abundance from 1981 to 1988.

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Index*
1980		0	0	0	0	0	0	0	0	0	0	0	0
1981	1321	0	0	582	0	0	352	0	0	0	0	235	133
1982	0	0	0	0	1057	0	0	0	0	0	0	0	151
1983	170	0	0	290	0	329	0	0	0	235	0	987	88
1984	0	0	882	817	548	215	0	0	0	897	1645	429	352
1985	0	5612	224	380	0	352	0	0	0	480	0	3071	938
1986	0	4046	2657	0	457	1295	449	0	417	274	1242	563	1272
1987	0	523	519	0	0	290	0	0	0	247	5304	6306	190
1988	4106	1865	0	6671	7887	1730	1817	759	0	0	1303	1484	2961
1989	5935	3270	7961	448	2717	4945	1044	2609					3285
1990		1858	6243	737	2804	6979	1359	805	274	0			2969
1991		1640	1387	1233	5209	1004	2057	1132	1421	1758			1952
1992		1505	838	4169	3174	3551	203	308	1611	10377			1964
1993		15693	2777	7254	50714	32649	11315	2729	1157	2467			17590
1994		5406	11356	8588	6983	20208	4275	6766	2565	617			9083
1995	2940	2429	13297	1199	987	0	2193		931	658	0	1408	3351
1981-1988	700	1506	535	1093	1244	526	327	95	52	267	1187	1634	

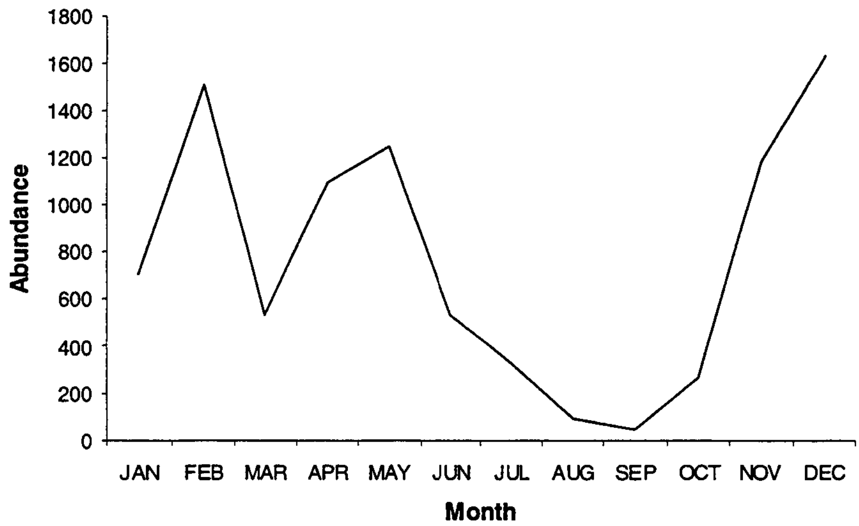

Figure 15 Seasonal abundance of chameleon goby from 1981 to 1988

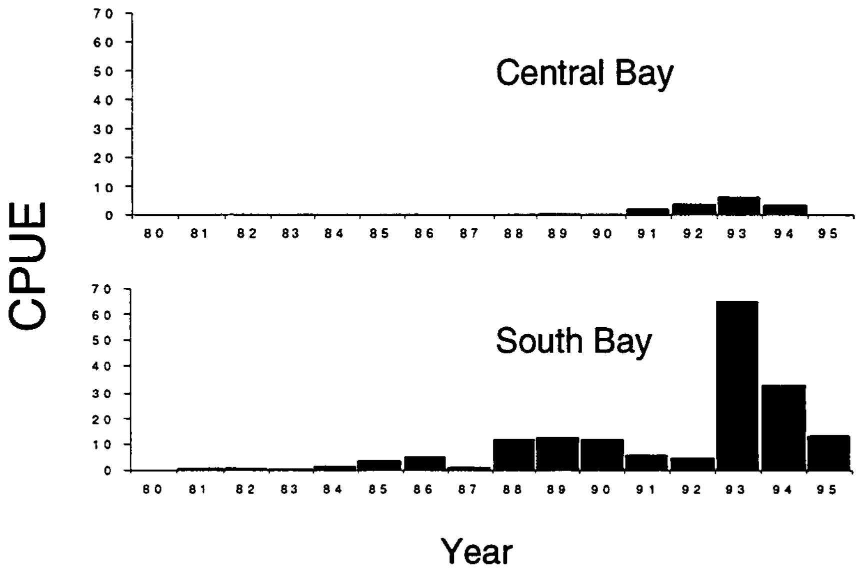

Figure 16 Annual chameleon goby distribution by region. Values are the average CPUE for February to August.

Distribution

From 1981 to 1987, catches of chameleon gobies were sporadic and limited primarily to the South Bay (Figure 16). They were first collected in Central Bay in 1986 and after that became more common there. No seasonal movements between areas were detected.

Temperature and Salinity

Throughout the year, chameleon gobies remained primarily within the polyhaline to euhaline salinity range, with a mean of 27.0‰ (Figure 17). Temperature varied with the season, ranging from 7.1 to 22.5 °C, with a mean of 15.4 °C.

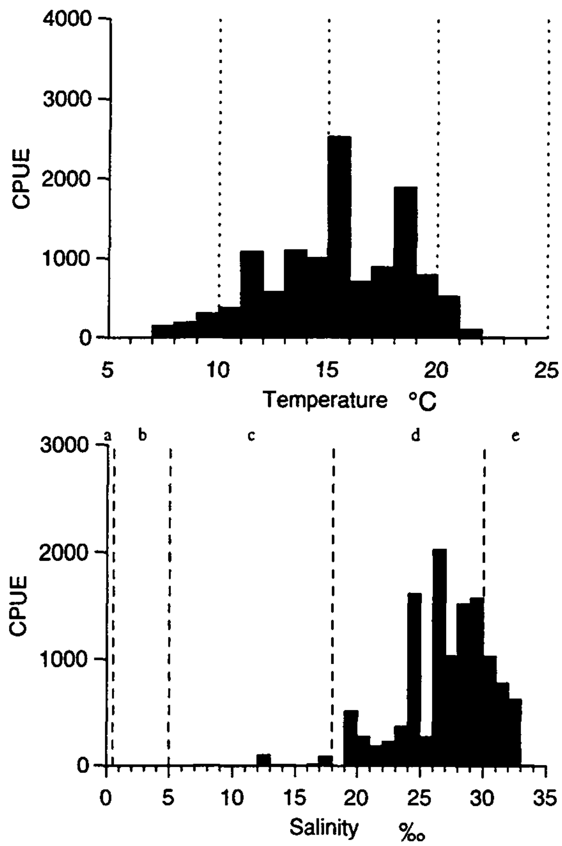

Figure 17 Temperature and salinity distributions of chameleon gobies. The vertical lines on the salinity graph mark the boundaries of the Venice system ranges: (a) limnetic, (b) oligohaline, (c) mesohaline, (d) polyhaline, and (e) euhaline.

Discussion

The abundance and distribution of the chameleon goby increased between 1980 and 1993, although there appeared to be a downward trend after 1993. Juveniles and adults were apparently restricted by salinity to South and Central bays, and only the larvae (Wang 1986) were collected upstream from Central Bay.

Like most other gobies, chameleon gobies are relatively short-lived. The annual decline in the abundance index from June through September is concurrent with the spawning period for this species (Wang 1986). Very few fish older than 1 year were collected, indicating a high post-spawning mortality.

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Pleuronectiformes

Randall Baxter

This chapter describes trends in abundance and distribution for flatfish species commonly collected in the San Francisco Estuary. For each species, abundance and distribution information is discussed in the context of life history. Brief descriptions for uncommonly collected species are contained in a concluding section.

The term flatfish refers to species belonging to several families that metamorphose from a bilaterally-symmetrical, pelagic larva to an asymmetrical, demersal juvenile. During this metamorphosis, 1 eye migrates to join the other on 1 side of the head, the body compresses and deepens, and pigment develops only on the "eyed" side.

Twelve species of flatfish from 3 families were collected from the San Francisco Estuary from 1980 through 1995: Bothidae—speckled sanddab, *Citharichthys stigmaeus*; Pacific sanddab, *Citharichthys sordidus*; California halibut, *Paralichthys californicus*; Pleuronectidae—English sole, *Pleuronectes vetulus*; starry flounder, *Platichthys stellatus;* diamond turbot, *Hypsopsetta guttulata*; sand sole, *Psettichthys melanostictus*; curlfin turbot, *Pleuronichthys decurrens*; C-O sole, *Pleuronichthys coenosus*; hybrid sole, *Inopsetta ischyra*; and hornyhead turbot, *Pleuronichthys verticalis*; Soleidae—California tonguefish, *Symphurus atricauda* (Robins and others 1991) (Table 1). All 12 species are native to the eastern Pacific Ocean.

Table 1 Total catch by species and gear type for flatfish collected between January 1980 and December 1995. See the Methods chapter, Table 1, for duration of use for different gear types.

Species	*Plankton Net Larvae*	*Plankton Net Juveniles*	*Beach Seine*	*Otter Trawl*	*Midwater Trawl*
English sole	429	94	381	19,941	426
Starry flounder	251	8	162	3,873	392
Speckled sanddab	0	46	7	17,173	82
California tonguefish	0	5	0	1,796	2
California halibut	74	0	27	590	19
Diamond turbot	268	0	23	255	9
Curlfin sole	0	0	0	123	0
Sand sole	20	0	4	70	5
Pacific sanddab	0	0	0	26	0
C-O sole	0	0	0	1	0
Hybrid sole	0	0	0	1	0
Hornyhead turbot	1	0	0	0	0

Speckled Sanddab

Introduction

The speckled sanddab, *Citharichthys stigmaeus,* is one of the most abundant shallow water flatfish, but due to its small size it is not generally caught in either recreational or commercial fisheries (Ford 1965). It does, however, contribute substantially as a food resource to flatfish that are important recreational and commercial species, such as bigmouth sole, *Hippoglossina stomata*, and California halibut, *Paralichthys californicus* (Ford 1965). The speckled sanddab ranges from Magdalena Bay, Baja California to Montague Island, Alaska (Miller and Lea 1972). It has been captured at depths from 3 to 366 m (Miller and Lea 1972), although, in southern California, it is found primarily from 1 to 60 m (Ford 1965).

Based upon ovarian egg sizes, the speckled sanddab spawns between March and October in southern California (Ford 1965, Goldberg and Pham 1987). However, maturing eggs are found in some females throughout the year, indicating that spawning is possible all year (Ford 1965). Spawning probably takes place on the open coast (Wang 1986). Multiple spawnings appear possible for mature females of all sizes (Ford 1965, Goldberg and Pham 1987).

Speckled sanddab eggs and larvae are pelagic (Ahlstrom and Moser 1975). Larvae are about 2.0 mm TL on hatching (Wang 1986). They are found throughout the year with high numbers occurring in June and July. The pelagic larval period extends for several months, and pelagic post-larval speckled sanddabs may grow larger than 40 mm (Ford 1965). Recently settled juveniles range from 26 to 54 mm TL (Ford 1965). Females reach sexual maturity at roughly 1 year and 70 to 80 mm TL (Ford 1965). They reach a maximum length of approximately 171 mm (Miller and Lea 1972), but individuals >127 mm are uncommon (Fitch and Lavenberg 1975).

Methods

Length frequency analysis (mm TL) of 1981 to 1988 otter trawl data was used to separate life stages. Fish 25 to 39 mm were considered recently settled (Ford 1965, Kramer 1990a, Kramer 1991b). The approximate size at maturity was considered to be 70 mm. For abundance and distribution analyses fish were separated into juvenile and adult age groups by a 70 mm TL cutoff length. Due to a protracted and variable pelagic period, juvenile fish (<70 mm) were grouped for analyses by year of capture rather than year of hatching.

Abundance indices and distribution analyses for both age groups were derived using the same monthly and annual grouping periods. The annual abundance index was calculated as the mean of the February to October monthly indices. To describe seasonal abundance, monthly indices were averaged for 1981 through 1988, when sampling was conducted all year. Annual distribution was the mean CPUE by region for February to October. Seasonal distribution was the mean CPUE by region and month for 1981 to 1988. Seasonal depth distribution was the mean CPUE by month for channel and shoal stations separately from 1981 to 1988. Seasonal salinity distribution was the monthly mean ±1 standard deviation of CPUE-weighted bottom salinity using 1981 to 1988 data. Seasonal temperature distributions were calculated as salinity was using CPUE-weighted bottom temperature.

Results

Catch and Length Analyses

Over 17,000 speckled sanddabs were captured in the estuary with the otter trawl, but only 82 with the midwater trawl, 46 with the plankton net, and 7 with the beach seine (see Table 1). Based upon the otter trawl catch, the speckled sanddab was the 2nd most abundant flatfish in the estuary.

Fish caught by the otter trawl ranged from 19 to 152 mm TL. Only 5 post–larval sanddabs, all <25 mm, were caught during May and June (Figure 1). Recently settled juveniles were collected all year, but relatively few were captured from July to September. Juvenile recruitment was highly variable, but occurred in 2 periods: November to January and April to June (see Figure 1). Adults were collected throughout the year. The adult age group was composed of at least 2 year classes and became more abundant during the year as juveniles grew to adult size. Few adults >125 mm were captured, and all were less than 20 mm of the maximum size of the species (that is, 171 mm, see Figure 1).

Abundance and Distribution of Juveniles and Adults

Annual Abundance

Juvenile speckled sanddab abundance increased through the study period, ranging from low of 1,544 in 1981 to a high of 38,573 in 1994 (Figure 2, Table 2). Juvenile abundance often remained stable for 2-year periods. Adult abundance ranged from a low of 1814 in 1981 to a high of 35,330 in 1993. After a large drop between 1980 and 1981, adult abundance also increased for the rest of the study period (see Figure 2, Table 3). Adults were more abundant than juveniles before 1987, but juveniles were more abundant after 1987.

Seasonal Abundance

Juvenile speckled sanddab abundance was generally lowest in late summer and early fall just before recruitment of the next year class (Figure 3, see Table 2). Juveniles began entering the estuary in late fall, reaching a minor peak during winter. After a slight decline in the spring, juvenile abundance generally peaked in late spring and early summer. Abundance declined rapidly during the summer as some juveniles grew to adult size (see Figure 1).

Adult speckled sanddab abundance increased from a spring low to a summer peak as adults returned to the estuary and as juveniles grew to adult size (see Figure 3, see Table 3). Abundance declined during the late summer and fall, leveled off in December and showed a minor mode in winter.

Annual Distribution

Juvenile speckled sanddabs were usually distributed from South Bay northward into San Pablo Bay, but during the 1987–1992 drought they were occasionally caught in Suisun Bay and the west delta (Figure 4). In years with relatively low abundance and high outflow (for example, 1982 and 1983), juvenile sanddabs did not enter San Pablo Bay. The use of South and San Pablo bays increased as overall abundance increased from 1988 to 1994. Use of South and San Pablo bays declined in 1995 with increased outflow.

Adult speckled sanddabs were distributed from South Bay northward into San Pablo Bay, except in 1983 and 1985 when they did not enter San Pablo Bay (Figure 5). Adult CPUE was always highest in Central Bay. Increased adult use of South or San Pablo bays coincided with increased juvenile use there.

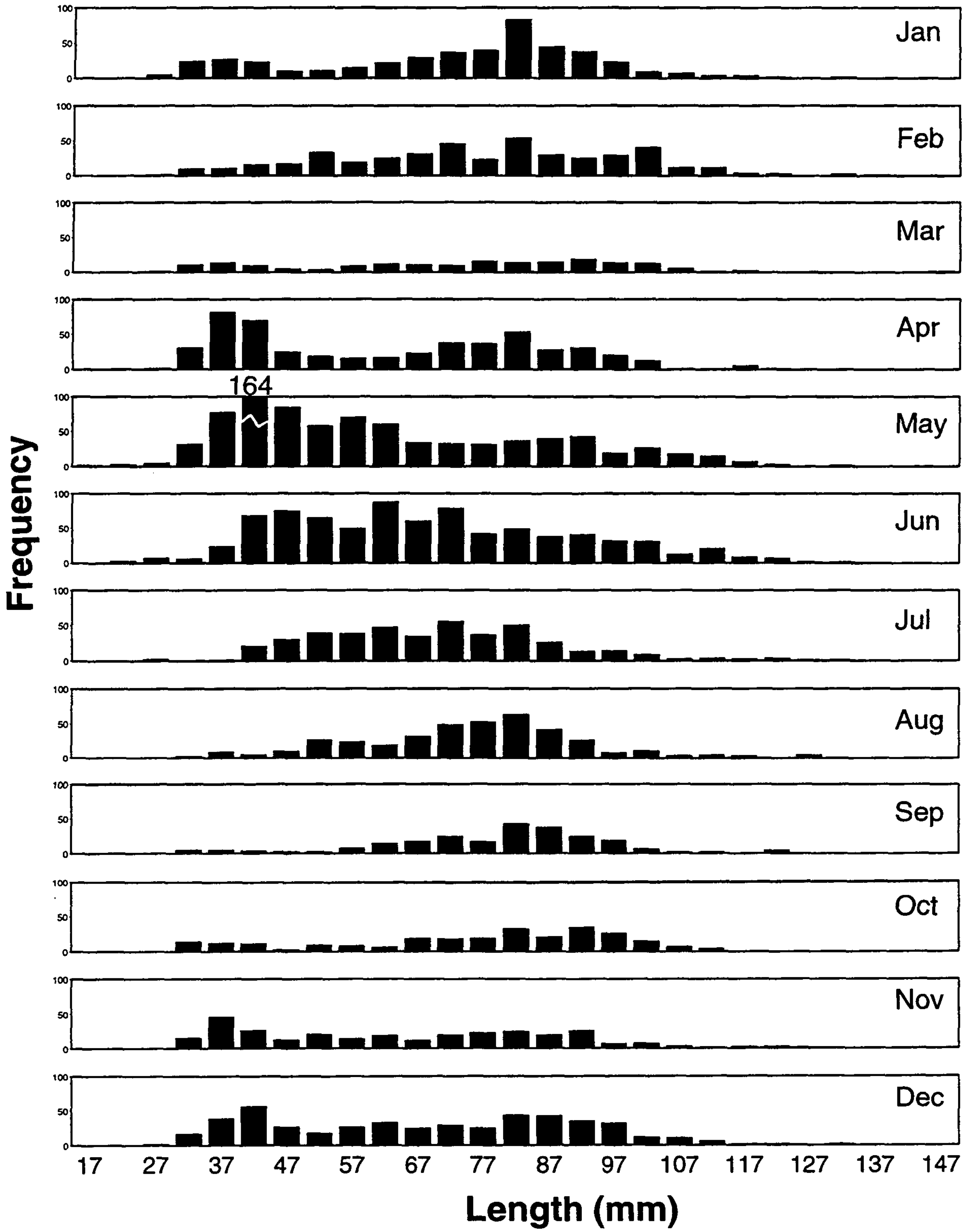

Figure 1 Length frequency (mm TL) by month of speckled sanddabs collected with the otter trawl from 1981 to 1989

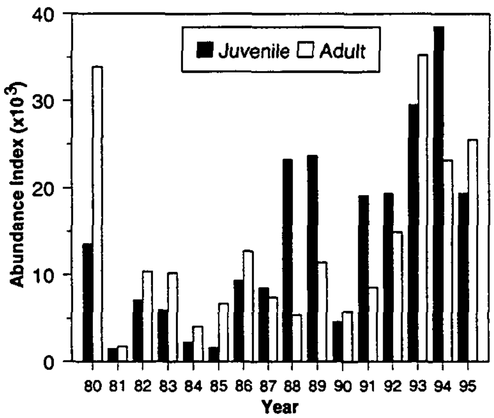

Figure 2 Annual abundance of juvenile and adult speckled sanddabs collected with the otter trawl from 1980 to 1995. Data are the means of February to October monthly indices.

Table 2 Monthly abundance of juvenile speckled sanddabs captured in the otter trawl from 1980 to 1995. Annual abundance indices are in the far right column. Seasonal abundance indices are in the bottom row (mean 1981 to 1988 monthly abundance).

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Feb–Oct*
1980		44820	16309	1603	6640	20826	13273	6150	10438	2217	1286	216	13586
1981	1205	154	1016	2154	514	250	2102	6923	216	568	406	2929	1544
1982	10530	278	281	17374	21544	6330	3696	216	1250	13042	1261	436	7112
1983	854	649	534	3482	8407	16698	9097	11493	1236	2542	4993	3419	6015
1984	406	0	1605	189	6506	10934	1460	0	216	0	0	0	2323
1985	115	3732	325	1001	1277	3387	2704	838	620	892	586	4644	1642
1986	4489	5412	1563	14400	6784	40961	7898	4508	412	2140	3092	7424	9342
1987	2890	27857	7713	538	6939	8492	9031	6911	6688	3000	26407	24389	8574
1988	16797	2192	4915	37698	101672	29398	26921	4884	1728	270	1315	5031	23298
1989	5882	15402	19871	40836	13943	50470	15142	10452					23731
1990		9143	14876	1540	2785	6519	1062	2627	1512	2012			4675
1991		26456	18962	12958	34140	17539	24961	19423	10873	7012			19147
1992		25817	15832	20002	18841	15807	2970	1352	14108	59879			19401
1993		15255	9401	11996	49989	88539	60971	12991	7751	9168			29562
1994		41786	28553	28169	43352	78834	26246	45174	43753	11292			38573
1995	28953	19852	22793	4685	68672	12469	15673		9454	1758	20367	17967	19420
1981–1988	4661	5034	2244	9605	19205	14556	7864	4472	1546	2807	4758	6034	

Table 3 Monthly abundance of adult speckled sanddabs captured in the otter trawl from 1980 to 1995. Annual abundance indices are in the far right column. Seasonal abundance indices are in the bottom row (mean 1981 to 1988 monthly abundance).

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Feb–Oct*
1980		81864	101011	11299	36868	46416	11109	1650	12827	2654	5280	466	33966
1981	9783	2438	830	1313	346	466	1366	8406	647	514	676	3393	1814
1982	45777	3096	1626	4610	33047	32519	404	757	7277	10316	907	728	10406
1983	3096	1582	3878	2670	3840	17437	24311	31882	1217	5598	6679	12627	10268
1984	4733	1001	1732	784	10306	6896	5145	595	4144	6598	838	1379	4133
1985	3554	23511	3608	1596	865	5190	1244	10952	6222	7518	8086	12180	6745
1986	14401	11896	6320	29366	6622	24557	17573	12012	4078	2918	1405	4737	12816
1987	4292	17222	5181	0	3459	2216	11466	8840	12683	6382	12124	13327	7494
1988	8112	2945	2040	19157	9707	7722	5106	487	1340	568	704	1890	5452
1989	3424	8303	10075	22032	9126	16079	7448	7270					11476
1990		7702	11195	5577	8747	6869	2170	6122	1053	3218			5850
1991		18713	10256	3110	5447	4721	6178	13494	8497	7220			8626
1992		24077	19083	22889	32649	17230	3894	189	5589	9099			14967
1993		19651	61742	37042	78058	85626	17109	9205	3924	5615			35330
1994		27912	15311	20272	27917	41190	15931	27747	26096	6975			23261
1995	51607	24233	82028	13251	33215	7443	27508		16475	592	39077	57353	25593
1981–1988	11719	7961	3152	7437	8524	12125	8327	9241	4701	5052	3927	6283	

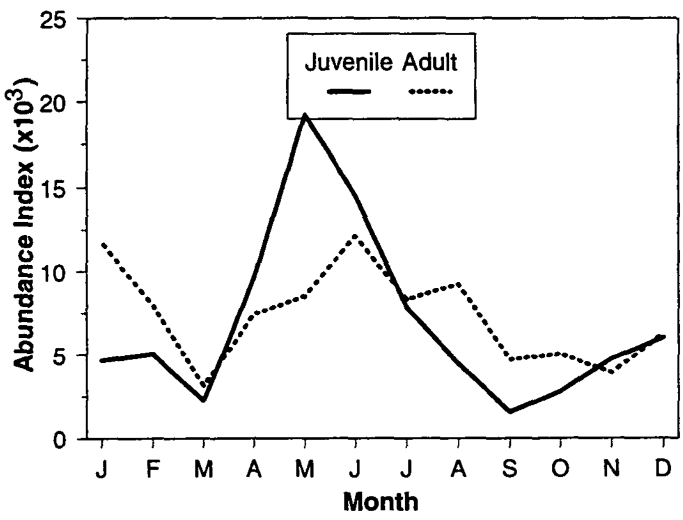

Figure 3 Seasonal abundance of juvenile and adult speckled sanddabs collected with the otter trawl. Data are mean abundance by month for 1981 through 1988.

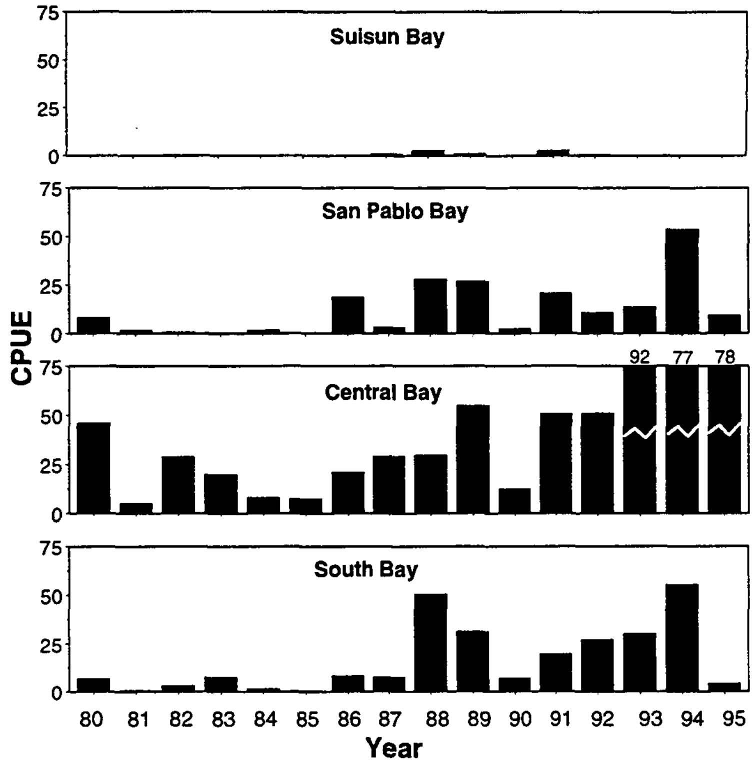

Figure 4 Annual distribution of juvenile speckled sanddabs collected with the otter trawl from 1980 to 1995. Data are mean CPUE by region for February to October.

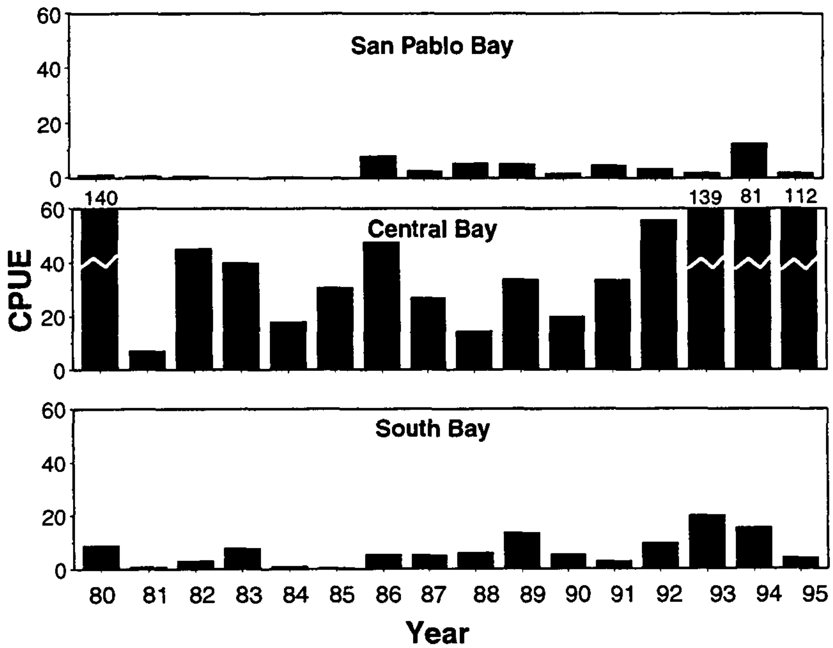

Figure 5 Annual distribution of adult speckled sanddabs collected with the otter trawl from 1980 to 1995. Data are mean CPUE by region for February to October.

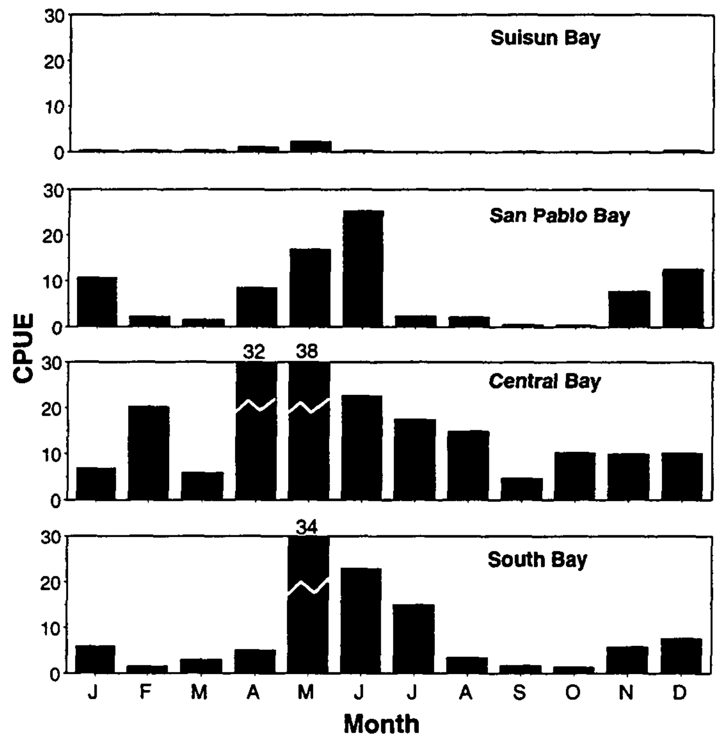

Figure 6 Seasonal distribution of juvenile speckled sanddabs collected with the otter trawl. Data are mean CPUE by region for 1981 to 1988.

Seasonal Distribution

Juvenile speckled sanddabs were most widely distributed (from South through Suisun bays) during their major immigration periods, November to January and April to June (Figure 6). During summer juveniles moved from Suisun, San Pablo, and South bays to Central Bay. A similar migration occurred in February and March.

Adult speckled sanddab CPUE increased in San Pablo and South bays during their summer and winter abundance peaks (Figure 7), a pattern similar to that of juveniles. However, most adult sanddabs appeared to remain in Central Bay all year.

During much of the year juvenile speckled sanddabs were almost equally distributed in both channel and shoal areas (Figure 8). From August to October, the warmest period of the year, more juveniles were in channels than on shoals. This pattern reversed in November and December, as the water cooled. Adult sanddabs were collected in higher numbers in channels than on shoals during most of the year (see Figure 8).

Both age groups were captured over wide salinity ranges: 4.9‰ to 34.4‰ for juveniles and 6.2‰ to 34.4‰ for adults. Both age groups inhabited primarily polyhaline and euhaline salinities, and were in the lowest and most variable salinities in March and April (Figure 9). The mean salinity for both groups increased from March or April to July and then remained >27‰ the rest of the year.

Juveniles were found at temperatures ranging from 8.2 to 22.4 °C and adults from 8.2 to 20.5 °C. Mean temperatures ranged from about 9.5 to 17.5 °C for both groups (Figure 10).

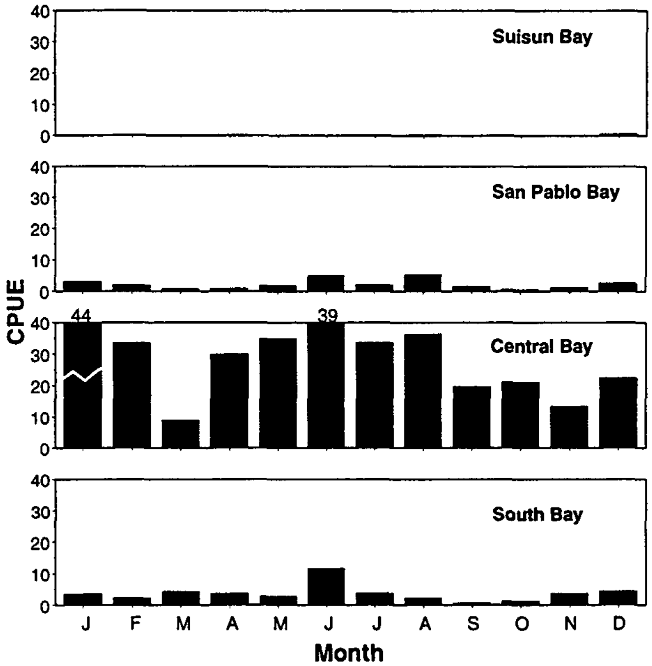

Figure 7 Seasonal distribution of adult speckled sanddabs collected with the otter trawl. Data are mean CPUE by region for 1981 to 1988.

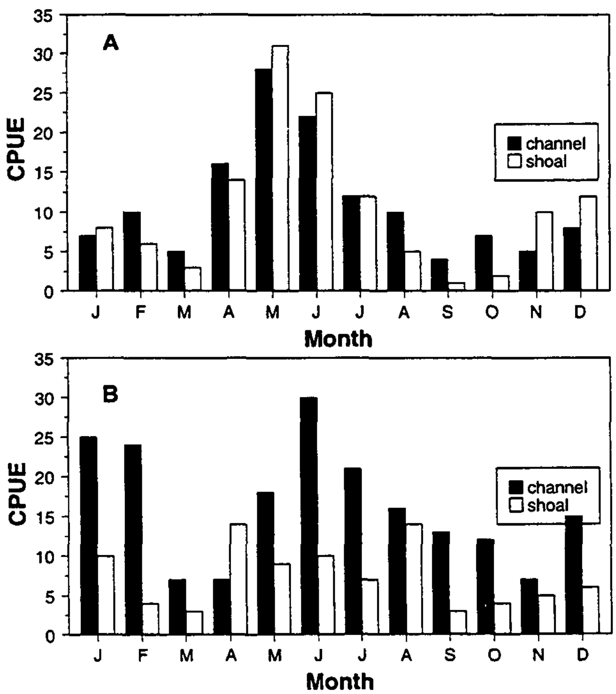

Figure 8 Depth distribution (shoal/channel) of (A) juvenile and (B) adult speckled sanddabs collected with the otter trawl. Data are mean CPUE by month and age group for 1981 to 1988.

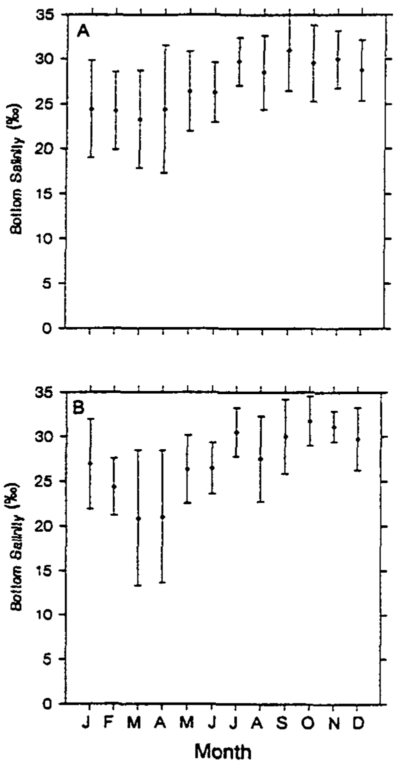

Figure 9 Salinity (‰) distributions of (A) juvenile and (B) adult speckled sanddabs collected with the otter trawl. Data are mean (±1 standard deviation) CPUE-weighted bottom salinity by month for 1981 to 1988.

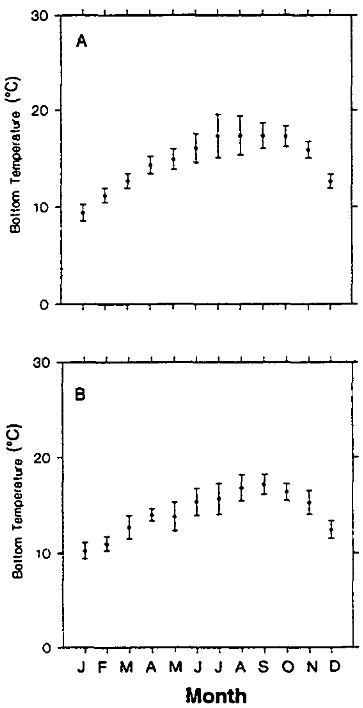

Figure 10 Temperature (°C) distributions of (A) juvenile and (B) adult speckled sanddabs collected with the otter trawl. Data are mean (±1 standard deviation) CPUE-weighted bottom temperature by month for 1981 to 1988.

Discussion

The speckled sanddab used the estuary as a nursery and rearing area before migrating to the open coast to spawn. No spawning took place in the estuary, as no larvae were collected in it (see Table 1). The importance of the estuary as rearing habitat was shown by the high juvenile catch (see Table 1). The speckled sanddab is also abundant in other Pacific coast estuaries. It ranked among the top 4 species in trawl catches from lower Yaquina Bay, Oregon, and Elkhorn Slough, California (Pearcy and Myers 1974, Nybakken and others 1977). Larvae were rarely collected from these locations, supporting the conclusion that spawning takes place on the open coast, and metamorphosing larvae and juveniles enter estuaries.

Estuarine entry of juveniles took place all year, but occurred mainly from October to January and from April to June. These periods fit within a broad period of settlement observed for locally spawned fish. Otoliths from recently settled fish, read to back-calculate hatch and settlement dates, showed speckled sanddabs hatched along the coast from April to December and settled from October to May (M. Kendall, personal communication, see "Notes"). The monthly settlement pattern observed by Kendall was unimodal and so does not explain the bimodal entry pattern of juveniles.

Low salinity influenced juvenile distribution in the estuary from late winter to spring, and high water temperatures influenced it from summer to fall. Juvenile winter entry and adult winter to spring rearing appeared to be inhibited by reduced salinity caused by high outflows. Both juvenile and adult abundance indices were at seasonal minima in March, coincident with the seasonal salinity minimum (compare Figure 3 with Figures 1, 2, and 3 in the Salinity and Temperature chapter). During the drought years, juveniles extended well upstream into both San Pablo and Suisun bays, but during the high outflow years 1982 and 1983 none were captured in either bay. In northern estuaries, speckled sanddabs were primarily associated with marine influenced areas and channel bottoms, and were most abundant in May and June after river flows had subsided (Pearcy and Myers 1974, Bottom and others 1984). During late spring and summer, speckled sanddabs moved toward Central Bay and into deeper and cooler water from Suisun, San Pablo, and South bays; a reverse movement was observed in fall and early winter before salinity declined (compare Figures 6 through 8). In both lab and field observations, Ehrlich and others (1979) found higher abundance of speckled sanddabs at 8 to 13 °C, and argued that a significant negative correlation between field occurrence and temperature was evidence that temperature limited use of shallow King Harbor in summer and fall. Similarly, Ford (1965) found significant negative correlations between sanddab abundance and bottom temperatures for both juveniles and adults, though juveniles did not respond as strongly as adults. Juveniles appear less constrained by temperature and more likely to inhabit warmer, shallower water than adults.

In recent years, the speckled sanddab has become the most numerous flatfish in the estuary (see Appendix C, otter trawl annual catch). Like many other flatfish whose range is primarily south of the estuary (for example, California halibut, diamond turbot, and California tonguefish), speckled sanddab abundance increased through the late 1980s and early 1990s. During the drought it benefited from higher estuarine salinity and expanded its range upstream. Abundance continued to increase in 1993, even though moderate outflow reduced upstream habitat in winter and spring. Since spawning and larval rearing take place outside the estuary, oceanic conditions were probably responsible for the increase.

California Halibut

Introduction

The California halibut, *Paralichthys californicus*, ranges from Magdalena Bay, Baja California, to the Quillayute River, Washington (Miller and Lea 1972). It occurs from the surface to 185 m (Haaker 1975). It is an important species in both commercial and recreational fisheries of central and southern California (Kramer and Sunada 1992). In San Francisco Bay, the California halibut has supported a strong recreational and commercial passenger fishing vessel fishery since the mid-1980s.

Based upon distribution of larvae, spawning occurs in shallow coastal water from Magdalena Bay northward to about San Francisco Bay (Frey 1971, Ahlstrom and Moser 1975, Haaker 1975, Plummer and others 1983) from February to August (Fitch and Lavenberg 1971, Frey 1971, Feder and others 1974). Newly hatched larvae measure about 2.0 mm TL (Wang 1986) and are pelagic. Recently metamorphosed fish 8 to 12 mm standard length (SL), are between 20 and 29 days old (Allen 1988).

In southern California, newly settled halibut are found primarily in shallow water marine habitats (Allen 1988, Allen and Herbinson 1990, Kramer 1990a, Kramer 1991a). These authors state that virtually all young-of-the-year halibut move into bays before or soon after settlement, and that bays and other protected coastal areas are crucial nursery areas. Young halibut remain in shallow water embayments until they reach 150 to 200 mm SL, then migrate to the open coast (Haaker 1975, Kramer 1990a, Kramer 1991a). California halibut off the northern San Diego County coast are found in deeper water as they grow (Plummer and others 1983, Kramer 1990b). Males grow slower than females and mature at a length of about 200 mm SL, whereas, females mature at about 375 mm (Haaker 1975). All males are mature at 320 mm TL and all females at 590 mm TL (Love and Brooks 1990). They reach a maximum length of 1,525 mm TL (Miller and Lea 1972). The minimum size for the recreational fishery is 559 mm TL.

Methods

I examined length-frequency histograms to separate age groups. These histograms were derived by combining beach seine data from 1981 to 1986 with otter trawl data from 1981 to 1988. A cutoff length of 200 mm TL was used to separate age–0 and age–1+ fish in all months. Although somewhat subjective, 200 mm corresponds to the upper end of a size range poorly sampled in the estuary and was a reasonable approximation of the minimum size of age–1 halibut (Pattison and McAllister 1990). Standard length (SL) data from the literature were converted to total lengths (TL) with the following equation: $TL = 1.196 \times SL$ (Kramer 1990a).

Larval abundance and distribution analyses were based on the plankton net catches. Larvae were separated into stages based upon the presence (yolk sac larvae) or absence (post-yolk sac larvae) of yolk, and for post-yolk sac larvae into those <8 mm and those $\geq$8 mm (transforming larvae) (compare to Gadomski and Caddell 1991). For otter trawl caught fish, the 200 mm cutoff identified age–0 fish by year of capture rather than year of hatching, and may have included a sizeable number of age–1 fish. Except for the annual beach seine catch of age–0 fish, abundance and distribution analyses were based on otter trawl data only. Annual abundance and distribution indices for both age groups were based on a February to October sampling period. Seasonal abundance, distribution and channel-shoal comparisons for both age groups were based on 1981 through 1988 data. Salinity and temperature statistics were based upon bottom measurements taken during otter trawl sampling and weighted by CPUE for each life stage. Since few age–0 fish were taken with the otter trawl between 1981 and 1988, salinity and temperature statistics were calculated for all months combined. Monthly salinity and temperature statistics were calculated for age–1+ fish.

Results

Catch and Length Analyses

We captured 27 California halibut ranging from 40 to 173 mm TL with the beach seine and 590 halibut from 47 to 1,130 mm TL with the otter trawl (Figure 11). Based on 1981 to 1988 sampling, age–0 fish (<200 mm) were collected from November to the following June, and represented about 20% of the combined otter trawl and beach seine catch (see Figure 11). Of the age–0 fish, 75% ($n = 36$) were collected by beach seining, including all but 3 fish <100 mm TL. Only 10 fish between 100 and 200 mm TL were collected by both gear types. Almost 60% of the halibut caught in the otter trawl were 200 to 500 mm, with another 20% ≥500 mm TL (see Figure 11). Most halibut mature at or before 500 mm TL (Love and Brooks 1990), indicating that mature fish used the estuary.

Abundance and Distribution of Larvae

Seventy-four California halibut larvae were collected from 1980 to 1989 (Table 4); 59% of these were caught in 1983. Larvae were caught from South Bay to Suisun Bay but 78% were collected in Central Bay (see Table 4). Larvae were collected all year, except for April, June, and August (Table 5). Peak catches (78%) occurred from September to November (see Table 5) during or immediately after annual peaks in estuarine and coastal water temperatures (see Salinity and Temperature chapter, Figure 12). Pre-settlement (transforming) larvae were caught only from September to December.

Abundance and Distribution of Age–0 and Older Fish

Annual Abundance

Age–0 California halibut were collected with the beach seine in only 4 years: 1983, 1984, 1985, and 1986. Age–0 fish were rarely caught with the otter trawl in the estuary before 1991, occurring only in 1982, 1984, and 1985 (Figure 12, Table 6). Their abundance increased sharply after 1990 to a peak in 1993, then declined to 1995. Similarly, age–1+fish were not abundant during the early 1980s. But their abundance increased in the middle to late 1980s to a minor mode in 1987, declined in 1988 and 1989, increased to a major mode in 1993, then declined again (see Figure 12, Table 7). The 1986–1987 peak in age–1+ abundance occurred after local recruitment (that is, the capture of age–0 fish) was observed, whereas the 1993 peak occurred in the same year as the peak in age–0 abundance. From 1991 to 1995 both groups had similar abundance patterns.

Seasonal Abundance

Age–0 California halibut were first collected with the beach seine in November (see Figure 11) and in the otter trawl in December (Figure 13, see Table 6). These dates corresponded well with the peak of larval settlement in September and October (see Table 5). Age–0 fish were caught sporadically to the following June. After 1991, age–0 fish were caught regularly during the February to October sampling period (see Table 6).

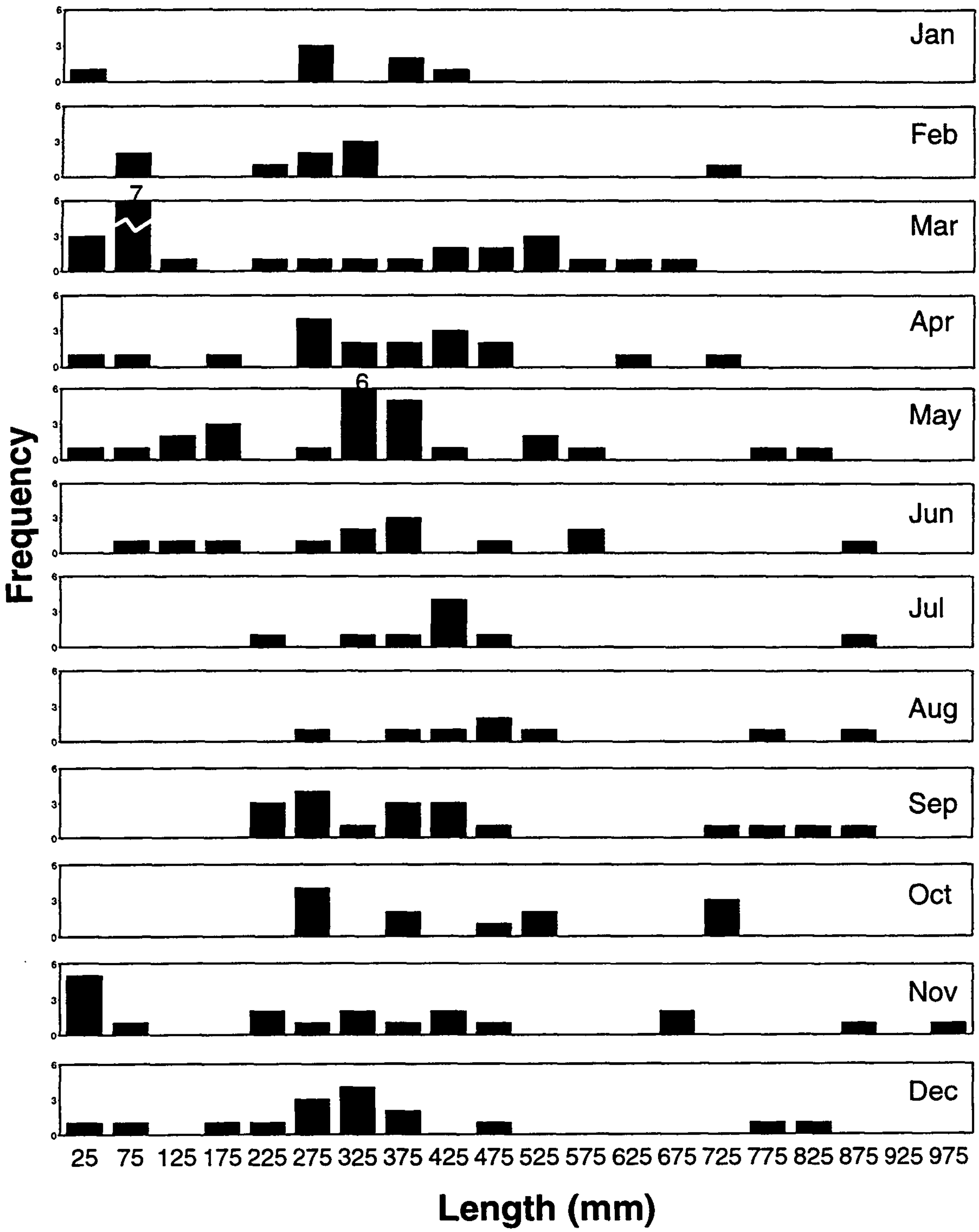

Figure 11 Length frequency (mm TL) by month of California halibut collected with the beach seine and otter trawl for 1981 to 1988. One 1,035 mm fish captured in October is not shown.

Table 4 Annual abundance (total catch) and distribution of larval California halibut collected by the plankton net from 1980 to 1989. Only the months of January through May were sampled in 1989. None were collected in the west delta.

Year	*South Bay*	*Central Bay*	*San Pablo Bay*	*Suisun Bay*	*Total Catch*
1980	1	1	0	0	2
1981	0	1	0	0	1
1982	0	1	0	0	1
1983	2	40	2	0	44
1984	0	8	0	0	8
1985	1	5	1	0	7
1986	3	0	2	0	6
1987	0	1	0	0	1
1988	0	1	1	2	4
1989	0	0	0	0	0
Total	7	58	7	2	74

Table 5 Seasonal abundance (catch) of larval California halibut by stage captured in the plankton net from 1980 to 1989

Month	*Yolk Sac*	*Post Yolk Sac*	*Pre-settlement*	*Total*
Jan	0	1	0	1
Feb	0	1	0	1
Mar	0	2	0	2
Apr	0	0	0	0
May	0	1	0	1
Jun	0	0	0	0
Jul	4	3	0	7
Aug	0	0	0	0
Sep	0	7	7	14
Oct	2	23	6	31
Nov	2	10	1	13
Dec	0	3	1	4
Total	8	51	15	74

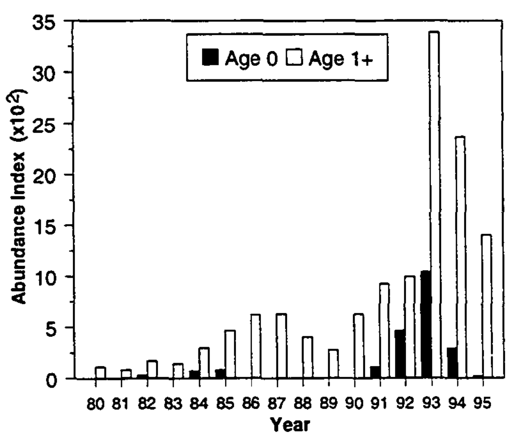

Figure 12 Annual abundance of age–0 and age–1+ California halibut collected with the otter trawl from 1980 to 1995. Data are the means of February to October monthly indices.

Table 6 Monthly abundance of age–0 California halibut captured in the otter trawl from 1980 to 1995. Annual abundance indices are in the far right column. Seasonal abundance indices are in the bottom row (mean 1981 to 1988 monthly abundance).

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Feb–Oct*
1980		0	0	0	0	0	0	0	0	0	0	0	0
1981	0	0	0	0	0	0	0	0	0	0	0	0	0
1982	0	0	0	0	309	0	0	0	0	0	0	0	34
1983	0	0	0	0	0	0	0	0	0	0	0	0	0
1984	0	0	0	0	438	250	0	0	0	0	0	0	76
1985	0	563	0	0	221	0	0	0	0	0	0	154	87
1986	0	0	0	0	0	0	0	0	0	0	0	0	0
1987	0	0	0	0	0	0	0	0	0	0	0	0	0
1988	0	0	0	0	0	0	0	0	0	0	0	0	0
1989	0	0	0	0	0	0	0	0					0
1990		0	0	0	0	0	0	0	0	0			0
1991		384	473	0	0	173	0	0	0	0			114
1992		0	0	344	0	0	0	876	723	2270			468
1993		2139	4978	1171	138	480	154	0	0	344			1045
1994		0	0	0	297	250	0	576	1353	219			299
1995	0	192	0	0	0	0	0		0	0	0	281	24
1981–1988	0	70	0	0	121	31	0	0	0	0	0	19	

Table 7 Monthly abundance of age–1+ California halibut captured in the otter trawl from 1980 to 1995. Annual abundance indices are in the far right column. Seasonal abundance indices are in the bottom row (mean 1981 to 1988 monthly abundance).

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Feb–Oct*
1980		0	135	362	377	189	0	0	0	0	0	250	118
1981	0	162	154	322	0	0	155	0	0	0	552	594	88
1982	281	313	278	0	559	219	0	0	0	185	219	0	173
1983	0	0	0	0	297	281	216	379	162	0	243	250	148
1984	0	250	243	281	219	250	0	219	1248	0	625	1028	301
1985	408	365	610	837	326	284	189	243	590	783	514	316	470
1986	271	97	250	250	1874	1220	381	250	352	919	652	0	621
1987	162	0	1347	1190	135	0	521	487	1362	625	297	737	630
1988	0	216	408	714	250	0	586	460	710	297	0	281	405
1989	0	0	985	270	0	216	0	480					279
1990		487	1082	662	768	250	0	784	1213	439			632
1991		947	895	838	1173	525	2138	281	909	633			927
1992		953	730	1164	493	1233	0	489	1345	2548			995
1993		2904	3822	3944	905	5811	5453	5514	748	1420			3391
1994		2513	2156	2451	1398	2279	1478	5478	3317	270			2371
1995	677	1521	509	1580	1511	1812	2554		1215	540	2319	1323	1405
1981–1988	140	175	411	449	458	282	256	255	553	351	388	401	

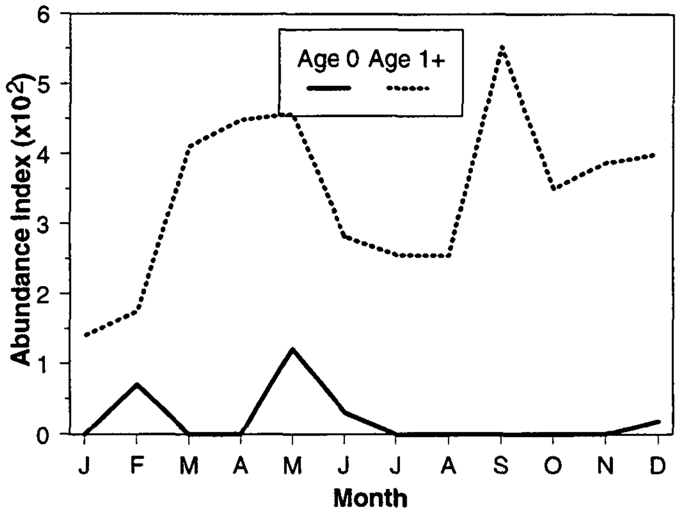

Figure 13 Seasonal abundance of age–0 and age–1+ California halibut collected with the otter trawl. Data are mean abundance by month for 1981 to 1988.

Age–1+ California halibut were captured in the estuary all year, but were most abundant during March to May and September to December (see Figure 13, see Table 7). But this pattern was based upon the catch of relatively few fish and may not be representative of the entire population. As abundance increased in the early 1990s, some shifts in the timing of peak abundance occurred. In 1993, age–1+ abundance peaked in June, July and August, months that had low abundance from 1981 to 1988 (see Table 7).

Annual Distribution

Age–0 California halibut were caught in all regions, but CPUE was highest in South and San Pablo bays; they were rare in Suisun Bay and the west delta (Figure 14). Age–1+ fish were also collected from all regions, and were also rare upstream from San Pablo Bay (Figure 15). Unlike age–0 fish, age–1+ CPUE was highest in most years in Central Bay. As annual abundance increased from 1990 to 1993, densities in South and San Pablo bays increased until they were equivalent to or higher than those of Central Bay (see Figure 15). This pattern reversed in 1994 and 1995.

Seasonal Distribution

Data for age–0 California halibut from 1981 to 1988 were not sufficient to describe seasonal distribution.

Age–1+ California halibut concentrated in Central Bay, except from December to February when they were primarily in South Bay (Figure 16). They entered Suisun Bay only in February and never reached the west delta during the 1981 to 1988 period.

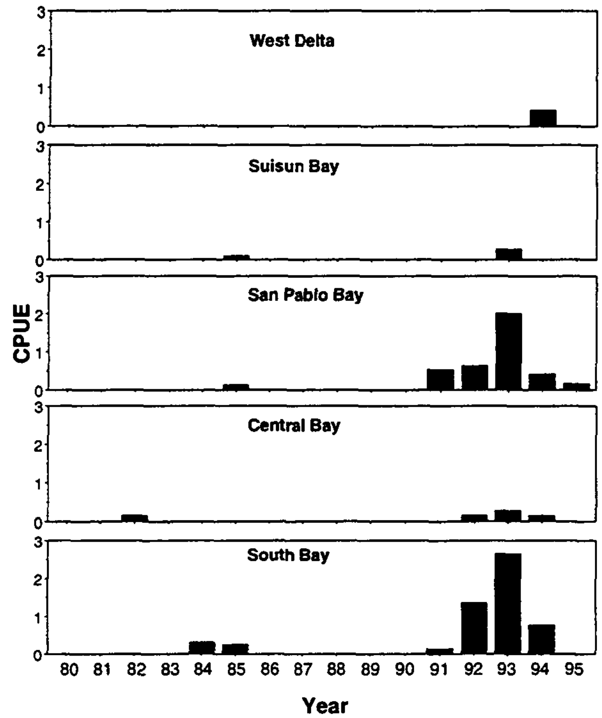

Figure 14 Annual distribution of age–0 California halibut collected with the otter trawl for 1980 to 1995. Data are mean February to October CPUE by region.

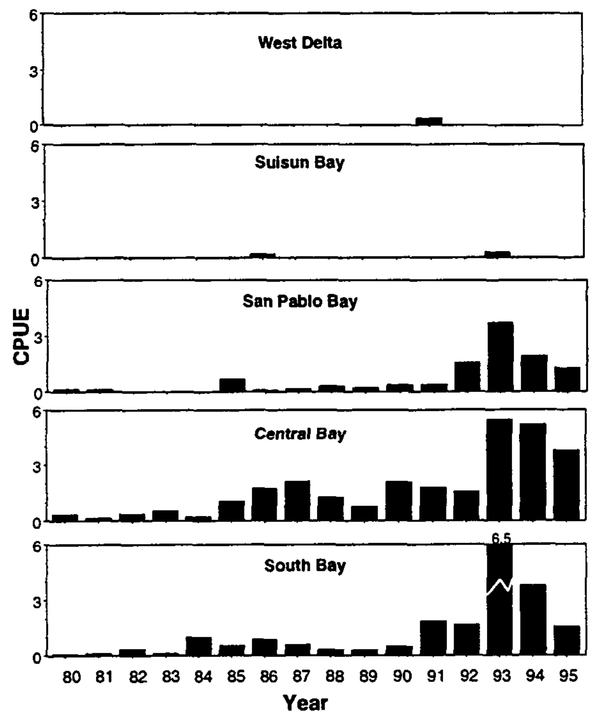

Figure 15 Annual distribution of age–1+ California halibut collected with the otter trawl from 1980 to 1995. Data are mean February to October CPUE by region.

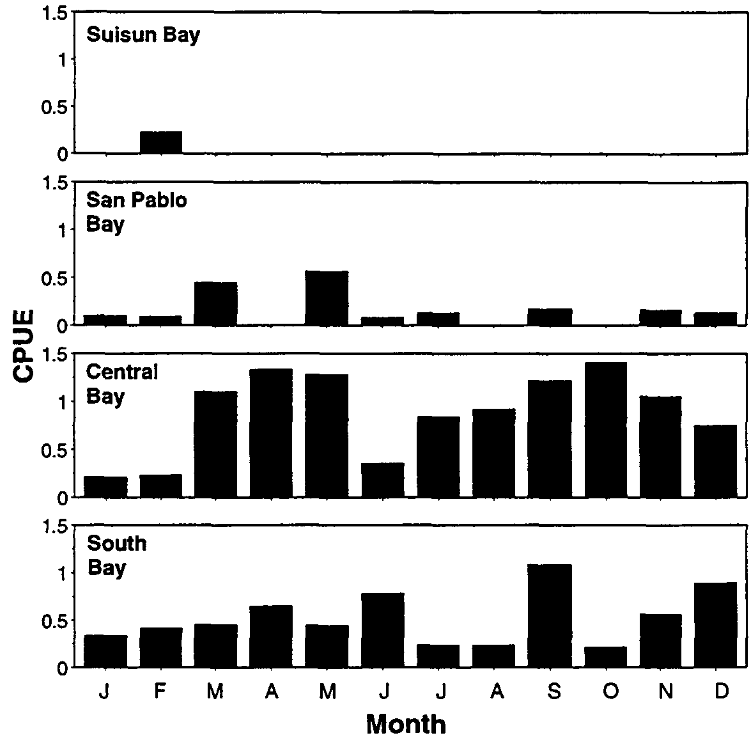

Figure 16 Seasonal distribution of age–1+ California halibut collected with the otter trawl. Data are mean CPUE by month and region from 1981 to 1988.

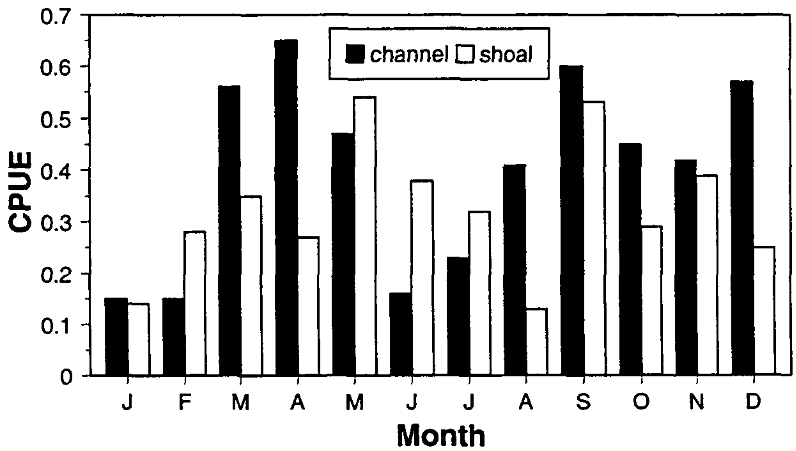

Figure 17 Depth distribution (channel/shoal) of age–1+ California halibut collected with the otter trawl from 1981 to 1988

Age–0 California halibut were 3 times as numerous in shoal areas as in channels, based on 1981 to 1988 data (overall channel CPUE = 0.01, overall shoal CPUE = 0.03). When 1980 to 1995 data were combined, this ratio increased to 7 to 1 in favor of shoals (overall channel CPUE = 0.03, overall shoal CPUE = 0.22). The channel to shoal ratio of age–1+ fish was close to 1:1 on an annual basis, but shoal use was slightly higher from May to July, and channel use was usually slightly higher the rest of the year (Figure 17).

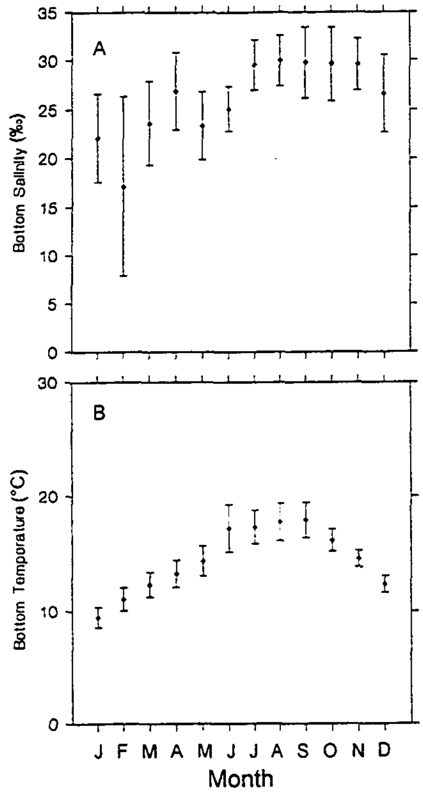

Figure 18 Salinity (‰) and temperature (°C) distributions of age–1+ California halibut collected with the otter trawl. Data are mean (±1 standard deviation) CPUE-weighted bottom salinity and temperature by month from 1981 to 1988.

Data for age–0 California halibut were not sufficient to describe monthly salinity or temperature distributions, but otter trawl data for all months combined showed that age–0 fish were caught at 9.6‰ to 27.5‰, $\bar{\chi}$ = 21.9‰, and from 9.3 to 21.6 °C, $\bar{\chi}$ = 14.0 °C. Age–0 fish captured with the beach seine were found in higher salinity and temperature: 15.1‰ to 32.4‰, $\bar{\chi}$ = 24.6‰, and 9.5 to 25 °C, $\bar{\chi}$ = 16.9 °C. The higher beach seine temperatures were partially attributed to the high overall catch at the Hunter's Point site, which receives thermal effluent.

Age–1+ California halibut had a much broader salinity range than age–0 fish; they were taken from 1.7‰ to 34.3‰. The fish collected at 1.7‰ came from Suisun Bay in February 1986, after salinity dropped sharply from about 15‰ in January. From January to May, no age–1+ fish were caught at <14‰ and from June to December none were caught at <20‰. From July to November, the age–1+ salinity distribution stabilized at monthly means from 29‰ to 30‰ (Figure 18). Thus, most age–1+ fish were collected within the polyhaline range throughout the year.

Age–1+ fish were collected from 8.5 to 21.6 °C, similar to age–0 fish. Mean temperatures for age–1+ halibut ranged from 17 to 18 °C from June to September (see Figure 18).

Discussion

Although all life stages of the California halibut, except eggs, were collected in the estuary, age–0 fish were uncommon until the 1990s. The absence of juveniles was attributed to poor local recruitment and to limited sampling of their shallow water habitat.

San Francisco Bay is considered to be at the northern edge of the California halibut spawning range based upon the distribution of larvae (Ahlstrom and Moser 1975, Moser and Watson 1990). This suggests a link between spawning and water temperature. Laboratory observations indicate that both spawning and recruitment may be controlled by temperature. Successful spawning in the laboratory started between 15.0 and 16.5 °C (Caddell and others 1990). Although halibut eggs hatched from 12 to 20 °C, only about 3% of the larvae survived to 17 days at 12 °C, and only 33% survived to 17 days at 16 °C (Gadomski and Caddell 1991). Survival of older larvae improved with increasing temperatures. If similar temperatures were necessary for egg and larval survival in the wild, survival would have been low in the ocean off San Francisco Bay during most years, as sea surface temperatures ≥15 °C were rare (see Salinity and Temperature chapter, Figure 11).

The first substantial collections of larvae and small juveniles (which are evidence of local spawning and recruitment) came in fall 1983 and lasted until spring 1984. These collections appeared to be associated with elevated coastal ocean temperatures. From June to September 1983, average monthly sea surface temperatures for the Gulf of the Farallones increased from 11.5 to 16.3 °C and remained about 15 °C through November (see Salinity and Temperature chapter, Figure 11). From September to November 1983, a record 44 halibut larvae were collected (see Table 4), followed in early 1984 by collections of age–0 fish in the beach seine and otter trawl. However, not all periods of high water temperature resulted in evidence of local recruitment, and in some years minor recruitment was observed at low water temperatures. Larvae and age–0 fish were collected annually from 1984 to 1986 even though temperatures were never exceptionally high. In fall 1987, sea surface temperatures were again >14 °C, but plankton sampling showed little evidence of local spawning; only 1 larva and no age–0 fish were caught by the otter trawl in late 1987 and late 1988. Warm water periods during fall in 1990, 1991, 1992, and 1993 (including warm water through most of 1992) probably led to relatively high age–0 abundance from 1991 to 1994 (see Figure 12). Thus, some but not all recruitment was associated with warmer than normal fall sea surface temperatures and in at least 1 year, 1987, warmer than normal conditions did not result in detectable recruitment to the estuary.

Limited sampling of inshore areas may have hindered our ability to detect local recruitment and follow trends in age–0 abundance, especially after 1986 when beach seine sampling ended. In this estuary and near San Diego, age–0 fish abundance was highest in shoreline habitats (Plummer and others 1983, Kramer 1990b). Termination of beach seining eliminated the most effective gear for collecting small age–0 fish, and this termination occurred before the elevated sea surface temperatures in fall 1987 and in several years during the early 1990s. Yet even with the beach seine, it was possible to miss evidence of recruitment. Sampling in the estuary at the Hunter's Point station and along the southern California coast indicated that young halibut settle and remain in the warmest habitats available. There was a significant positive relationship between temperature and settlement and the subsequent distribution of age–0 halibut (Allen and others 1990). So, age–0 fish may have been attracted to unsampled areas such as locations receiving thermal effluent and warm South Bay sloughs. Moreover, most beach seine sites faced the open estuary and though protected from ocean swells, they were not as protected as sloughs or many of the inner harbors. Fully protected areas attract higher densities of age–0 halibut than semi-protected areas (Allen and others 1990). So, when recruitment was low it was possible to miss it. At higher levels of recruitment some age–0 fish might stray from optimal habitats into deeper water. During the early 1990s, the relatively high catches of age–0 fish in the otter trawl may have resulted from straying or from intraspecific competition for food or space forcing fish into deeper water. Due to the strong ontogenic change in depth observed for California halibut (Kramer 1990b), these otter trawl fish were believed to represent even larger numbers in inshore areas.

The increase in California halibut abundance in the estuary over the last 2 decades appears to have occurred as a result of a succession of warm water and El Niño years, each of which incrementally increased the local adult population. This increase was probably accomplished through a combination of northward movement of juveniles and adults along the coast and local recruitment. Information derived from tagging studies indicates that most fish did not move away from the release point (Haaker 1975, Tupen 1990, Domeier and Chun 1995). Of the fish that did move, equal numbers moved north and south. Larger fish (>500 mm TL) moved significantly farther than smaller fish, and those moving north traveled significantly farther and faster than those moving south (Domeier and Chun 1995). A northward movement of adult halibut was detected before abundance increased in the estuary. Between 1978 and 1983, commercial trawl catches off northern California increased 4 to 5 times before stabilizing from 1984 to 1986 at levels 2 to 3 times pre-1978 levels (Jow 1990). During winter 1977–1978, local recruitment may have increased halibut abundance in South Bay (Pearson 1989). The increase in commercially available adult halibut probably set the stage for local recruitment by dramatically increasing local fecundity. When local fecundity is relatively high even conditions leading to marginal egg and larval survival could result in some recruitment. Successful local recruitment led to increased age–1+ abundance in the estuary during the middle to late 1980s. Although age–1+ indices declined through 1989, this reflected the lack of additional strong year classes recruiting to the estuary and reduced catchability of previous year classes. A strong local sport fishery during this period indicated that large halibut were locally abundant. It was the fecundity of these fish that produced the local recruitment observed in the early 1990s.

Although both age groups of halibut were captured in all regions of the estuary, low salinity appeared to limit their upstream distribution. Fish were occasionally caught between 1.7‰ and 14‰ salinity, but only during winter and spring when sharp increases in outflow changed salinity rapidly. Halibut did not appear to select salinity <20‰.

Bays, estuaries, and other protected habitats are important, possibly critical nursery areas for halibut (Haaker 1975, Plummer and others 1983, Allen 1988, Allen and others 1990, Allen and Herbinson 1990, Hammann and Ramirez–Gonzalez 1990, Kramer 1990b, Kramer 1991a). Our data suggest that the San Francisco Estuary may also be an important nursery area, but that more extensive shallow water and shoreline sampling will be required to assess its importance.

English Sole

Introduction

The English sole, *Pleuronectes vetulus*, ranges from San Cristobal Bay, Baja California, northward to northwest Alaska (Miller and Lea 1972). It is distinguished from other flatfish by an eye being visible from the blind side. It is not commonly caught in the sport fishery, but in California's commercial trawl fishery, the English sole generally ranks 2nd in pounds landed behind the Dover sole (Pearson and Owen 1992). Mature fish are found between 18 and 305 m deep, but juveniles rear in intertidal and subtidal habitats in bays and estuaries (Toole 1980, Bayer 1981, Krygier and Pearcy 1986, Pearson and Owen 1992).

Spawning occurs in coastal waters from September through April (Budd 1940, Ketchen 1956, Jow 1969, Laroche and Richardson 1979), but primarily during January and February in California (Jow 1969). English sole larvae are dominant in the winter to early spring ichthyoplankton community, 1 to 28 km off the coast of Oregon (Richardson and Pearcy 1977).

Under laboratory conditions larvae hatch at 2.8 mm and survive best at 25‰ to 28‰ salinity, and 8 to 9 °C (Alderdice and Forrester 1968). Their pelagic period lasts 6 to 10 weeks based upon the difference between peak spawning and when transforming individuals appear in nursery areas (Ketchen 1956). Using otolith increments, Laroche and others (1982) found most larvae transformed in less than 70 days and the oldest at 74 days. Metamorphosis is generally complete at 20 mm SL (Ahlstrom and Moser 1975, Misitano 1976).

Few early-stage larvae are collected in estuaries or bays (Pearcy and Myers 1974, Misitano 1977); however, transforming larvae and young juveniles are very common in them (Ketchen 1956, Olson and Pratt 1973, Pearcy and Myers 1974, Misitano 1976, Toole 1980). Settlement occurs both on the open coast and in bays and estuaries (Krygier and Pearcy 1986, Gunderson and others 1990). A large proportion of English sole settling on the open coast rapidly migrate to bay and estuarine nursery areas (Ketchen 1956, Olson and Pratt 1973, Krygier and Pearcy 1986, Gunderson and others 1990).

English sole inhabit intertidal areas in northern bays and estuaries, but remain primarily in channels in southern ones (Toole 1980, Bayer 1981, Krygier and Pearcy 1986, Yoklavich and others 1991). Throughout their range, juveniles move to deeper water as they grow and continue to do so after they emigrate to the open coast (Day and Pearcy 1968, Toole 1980, Krygier and Pearcy 1986). Juveniles rear in bays or estuaries through their 1st summer, then emigrate to the open coast during fall or winter at 80 to 150 mm TL (Smith and Nitsos 1969, Olson and Pratt 1973, Misitano 1976, Krygier and Pearcy 1986, Gunderson and others 1990). Males reach sexual maturity at 2 years and 250 to 295 mm TL and females at 3 to 4 years (Ketchen 1956). Males mature as small as 210 mm and almost all are mature by 290 mm, whereas females began to mature at 260 mm and most are mature by 350 mm (Harry 1959). The English sole reaches a maximum length of approximately 570 mm (Miller and Lea 1972).

Methods

In the plankton net, English sole were categorized as yolk sac larvae, post-yolk sac larvae, and age–0 fish. Yolk sac (stage I, Misitano 1976) were distinguished from post-yolk sac larvae by the presence of yolk or an oil droplet. After yolk absorption, larvae were post-yolk sac (stages II to V, Misitano 1976) until eye migration was complete. In the beach seine and otter trawl catches, all fish were considered age–0 or older, but those <30 mm TL were defined as recently settled. Monthly cutoff lengths (the minimum size of age–1+ fish) used to separate age–0 from older fish were 65, 80, 95, 112, 123, 130, 138, 145, 150, 155, 160, and 165 mm TL for January to December. Length data for 1981 to 1988 from both the beach seine and the otter trawl were combined for length frequency analyses.

For larvae (yolk sac and post-yolk sac combined) and age–0 fish in the plankton net, annual abundance indices were calculated as mean of volume-weighted monthly indices for December to May, and labeled as the year beginning January 1. Seasonal abundance was calculated as the mean of monthly indices for 1981 to 1988. Annual distribution was calculated as mean January to May CPUE by region.

Otter trawl data were used for abundance and distribution analyses for age–0 and age–1+fish. Annual abundance indices were the means of the February to October monthly indices for age–0 and age–1+ fish. Beach seine and otter trawl CPUE data were used to examine channel and shoal distribution. Salinity and temperature distributions were developed for each age group as the monthly means ±1 standard deviation of the CPUE-weighted bottom measurement (that is, salinity or temperature) for 1981 to 1988.

Results

Length Analyses

In the plankton net, English sole larvae ranged from 2.5 to 22 mm TL and age–0 fish ranged from 18 to 50 mm TL. Those from the beach seine ranged from 19 to 162 mm TL, and from the otter trawl 16 to 334 mm TL (Figure 19). There was no sharp separation of age–0 fish from older individuals (age–1+), but cutoff lengths provided reasonably accurate separation. The age–1+ group was composed primarily of age–1 fish.

Recently settled English sole (<30 mm) were collected all year, but primarily from March through August. Several abrupt increases in catch indicated estuarine entry of different sized fish in different years. Thus, in March there was an increase in previously settled 50 to 80 mm fish; in April an increase in recently settled 20 to 40 mm fish; and in May 40 to 70 mm fish increased (see Figure 19). However, growth can not be assessed well from these data. By December, age–0 fish had reached a maximum length of about 160 mm. Age–1+ fish <160 mm remained in or returned to the estuary during the next winter and spring. Fish >180 mm were uncommonly caught and mature fish (>250 mm) were rarely caught (see Figure 19).

Abundance and Distribution of Larvae

Of the 429 larval English sole collected during the study, 293 (68%) were caught in 1982. Hence, the 1982 annual abundance index was an order of magnitude higher than in other years (Figure 20, Table 8). Abundance was also high in 1983 but low thereafter. No larvae were caught in 1984. In the plankton net, there was no apparent relationship between larval abundance and that of age–0 fish (see Figure 20).

The 1st English sole larvae of the year were caught in December (Figure 21, see Table 8). Their abundance increased rapidly until February and then declined to zero in June. Larvae were collected from South Bay to Suisun Bay in 1982, but their distribution was more restricted in other years when they were absent from either South or Suisun bay (Table 9).

Abundance and Distribution of Age–0 and Older Fish

Annual Abundance

Although there was no consistent trend in age–0 English sole abundance indices, year to year fluctuations were greater after 1989 (Figure 22, Table 10). These fluctuations reached an extreme in 1993 and 1994 when the lowest index followed the highest.

The abundance of age–1+ English sole was highest in 1980 (see Figure 22, Table 11). After a sharp drop in 1981, age–1+ abundance rose to another mode in 1984, then declined to a record low in 1987. Abundance fluctuated thereafter but remained well below 1980 to 1985 levels (with the exception of 1981).

Seasonal Abundance

Age–0 English sole were first collected in December and their abundance increased until May before declining to lower level in December (Figure 23, see Table 10). Thus, December abundance was sometimes composed of 2 year classes: those individuals of the present year class remaining in the estuary and a small proportion of early settling individuals of the next year class (see Figure 19). Abundance of age–1+ fish had a peak in January and then declined for the remainder of the year (see Figure 23, see Table 11). Abundance increased slightly from September to December when all sizes of age–1+ fish were collected again (see Figure 23).

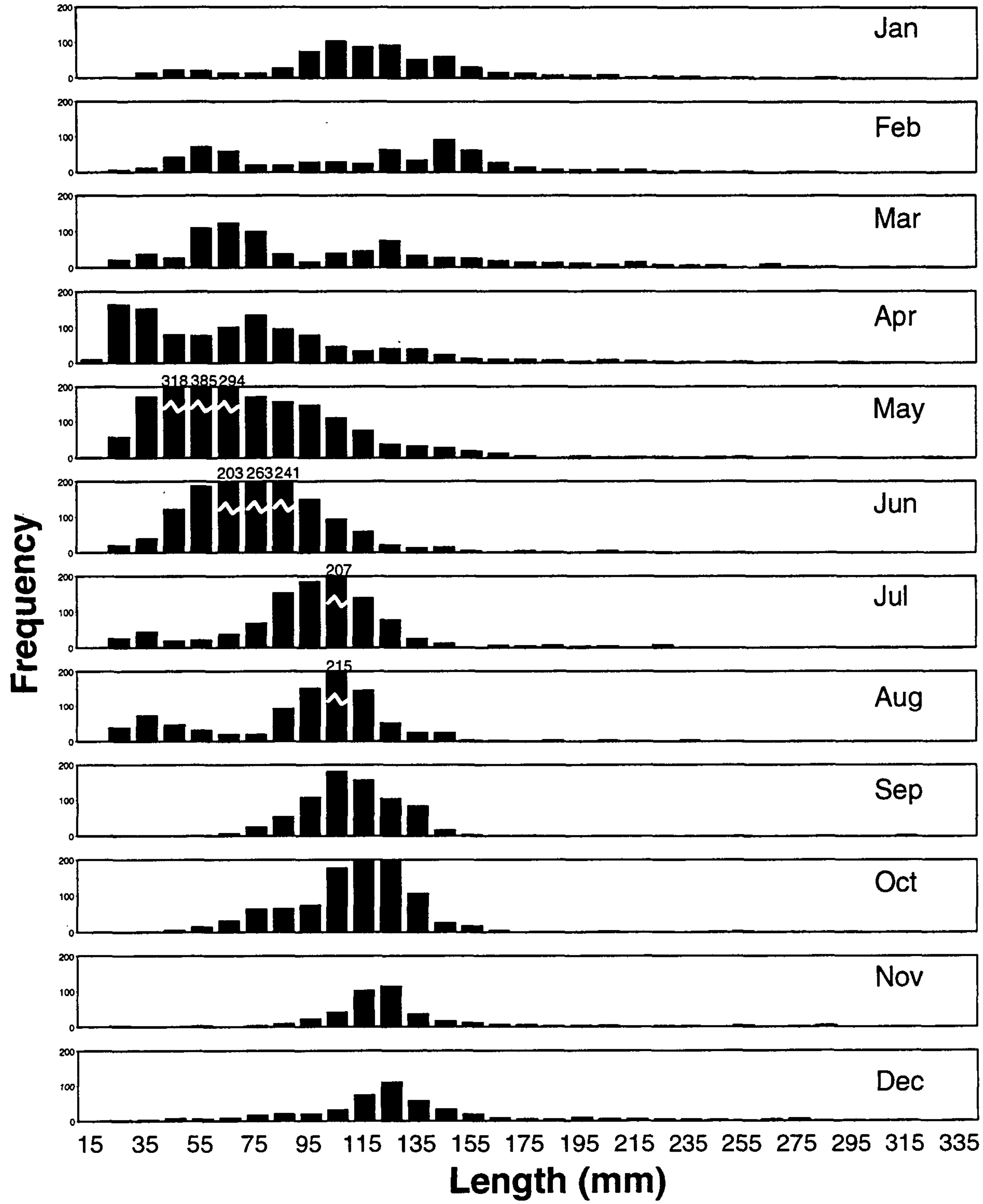

Figure 19 Length frequency (mm TL) by month of English sole collected with the beach seine and otter trawl from 1981 to 1988. Fish <30 mm were considered recently settled and those >250 mm were considered mature.

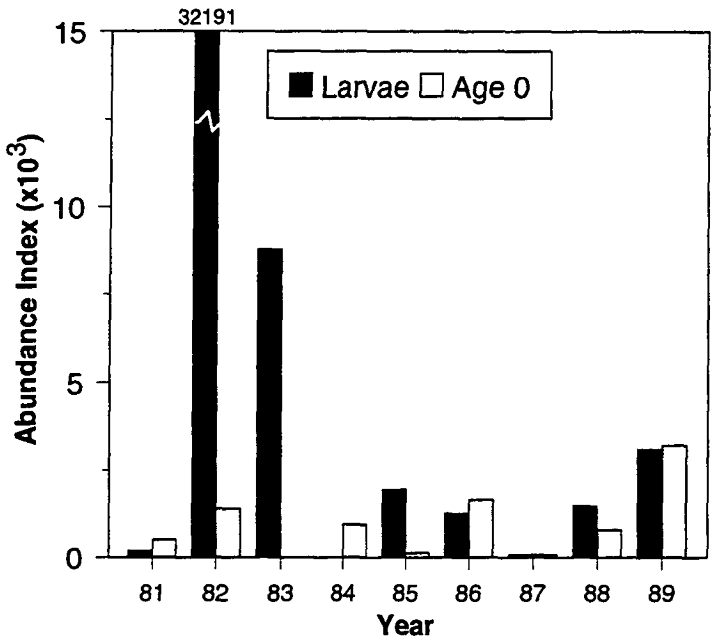

Figure 20 Annual abundance of larval and age–0 English sole from the plankton net from 1981 to 1989. Data are mean December to May abundance indices.

Table 8 Monthly abundance larval English sole captured in the plankton net from 1980 to 1989. Annual abundance indices are in the far right column. Seasonal abundance indices are in the bottom row (mean 1981 to 1988 monthly abundance).

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Dec–May*
1980		5372	27219	861	0	0	0	0	0	0	0	0	
1981	1074	0	0	0	0	0	0	0	0	0	0	0	179
1982	716	191353	1074	0	0	0	0	0	0	0	0	6921	32191
1983	5664	26502	7521	2149	3940	0	0	0	0	0	0	0	8783
1984	0	0	0	0	0	0	0	0	0	0	0	0	0
1985	4698	5947	1074	0	0	0	0	0	0	0	0	1074	1953
1986	4656	0	753	1074	0	0	0	0	0	0	0	431	1260
1987	0	0	0	0	0	0	0	0	0	0	0	0	72
1988	0	8954	0	0	0	0	0	0	0	0	0	0	1492
1989	2938	11053	4613	0	0								3101
1981–1988	2101	29095	1303	403	493	0	0	0	0	0	0	1053	

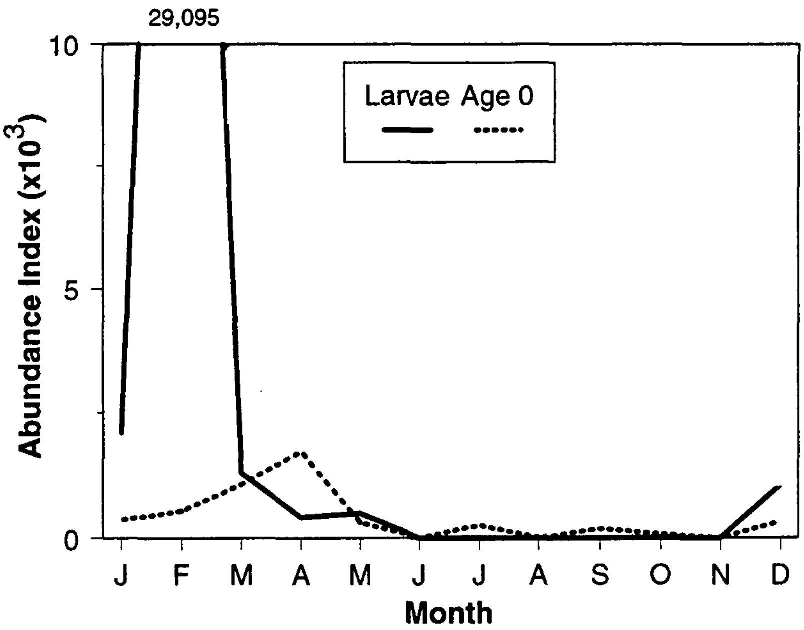

Figure 21 Seasonal abundance of larval and age–0 English sole from the plankton net. Data are mean monthly abundance indices for 1981 to 1988.

Table 9 Annual distribution of larval English sole collected by the plankton net. Data are mean January to May CPUE by region. None were collected in the west delta.

Year	*South Bay*	*Central Bay*	*San Pablo Bay*	*Suisun Bay*
1980	0	2.8	0.3	0
1981	0	0.1	0	0
1982	0.4	9.8	11.6	0.4
1983	0.1	3.0	0.5	0
1984	0	0	0	0
1985	0	0.3	1.2	1.0
1986	0.1	0.4	0	0
1987	0	0	0	0
1988	0	0.5	0.5	0.1
1989	0.8	0.8	0.3	0
1980–1989	0.1	1.8	1.4	0.2

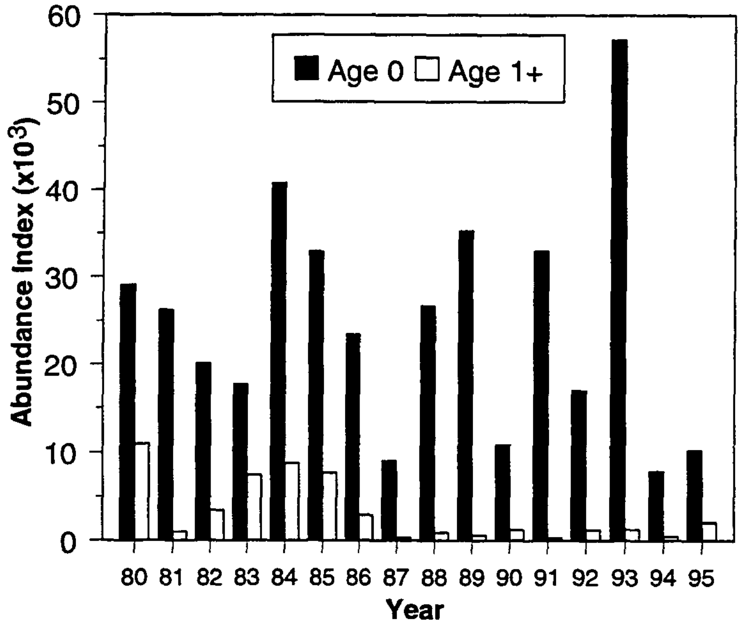

Figure 22 Annual abundance of age–0 and age–1+ English sole collected with the otter trawl from 1980 to 1995. Data are mean February to October abundance indices.

Table 10 Monthly abundance age–0 English sole captured in the otter trawl from 1980 to 1995. Annual abundance indices are in the far right column. Seasonal abundance indices are in the bottom row (mean 1981 to 1988 monthly abundance).

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Feb–Oct*
1980		3393	2581	8725	39814	53935	81196	30376	14715	27097	20176	921	29092
1981	5094	17709	37521	33495	42697	21701	20147	40907	3222	18481	946	2228	26209
1982	1217	134	11303	35086	37879	42946	13062	22615	8483	9617	3670	5233	20125
1983	0	288	907	14757	9303	3590	42592	51111	752	36075	3674	14865	17708
1984	502	281	2164	10092	22474	109014	62839	16183	76690	67552	6611	16469	40810
1985	0	192	216	706	53821	27538	33516	81388	39458	60077	55951	40736	32990
1986	2266	12310	17206	19486	52563	37495	45034	12615	7845	6516	1301	1791	23452
1987	0	1379	3919	766	14712	15936	14226	8699	17203	4570	787	2353	9046
1988	563	423	3219	61116	112880	42836	15544	1541	1541	595	173	461	26633
1989	1503	13149	28383	60144	72336	27295	35940	9834					35297
1990		3985	10497	24536	30896	24002	562	1677	1617	0			10864
1991		68241	97181	60166	24231	20992	16877	6267	1028	2217			33022
1992		32820	49477	43735	16797	9298	779	0	0	0			16990
1993		1374	697	50330	180950	179547	77990	18114	3591	2163			57195
1994		0	1106	2932	6222	34457	9452	11193	4814	622			7866
1995	2372	2609	20445	13073	8663	27767	7496		2163	0	811	9308	10277
1981–1988	1205	4090	9557	21938	43291	37632	30870	29382	19399	25435	9139	10517	

Table 11 Monthly abundance age–1+ English sole captured in the otter trawl from 1980 to 1995. Annual abundance indices are in the far right column. Seasonal abundance indices are in the bottom row (mean 1981 to 1988 monthly abundance).

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Feb–Oct*
1980		24896	16263	9659	34617	2548	8059	1055	550	1325	974	0	10997
1981	23909	1209	1425	805	1250	885	1823	773	162	649	487	595	998
1982	102019	1641	3227	2476	10347	6274	1360	2950	930	2040	2144	473	3472
1983	11219	17772	20868	21522	2704	1680	487	1812	0	433	0	1100	7475
1984	18013	12766	43985	9164	8894	1271	3110	0	0	0	676	1003	8799
1985	23142	55653	10222	1190	514	162	379	0	595	811	3029	4056	7725
1986	13119	3686	2930	6409	4762	2250	4165	359	656	1028	0	352	2916
1987	1890	687	663	162	628	0	0	0	487	595	325	4543	358
1988	4509	2294	2243	2329	784	622	0	0	162	0	0	0	937
1989	921	1484	1846	243	0	216	703	0					642
1990		5184	4706	1011	427	0	0	0	0	162			1277
1991		703	1614	381	0	0	0	0	0	568			363
1992		3575	4600	2228	715	216	0	0	0	0			1259
1993		1442	1970	4246	2574	1379	297	0	0	0			1323
1994		470	1231	1433	757	730	0	0	0	0			513
1995	0	216	3407	2433	250	8113	2299		216	0	649	0	2117
1981–1988	24728	11964	10695	5507	3735	1643	1416	737	374	695	833	1515	

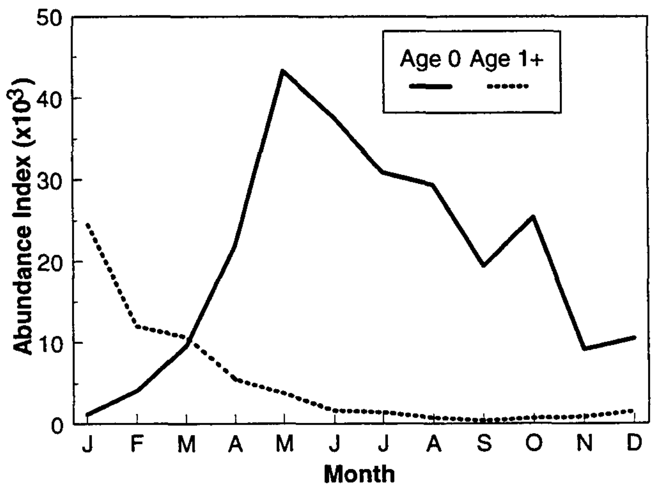

Figure 23 Seasonal abundance of age–0 and age–1+ English sole from the otter trawl. Data are mean monthly abundance indices for 1981 to 1988.

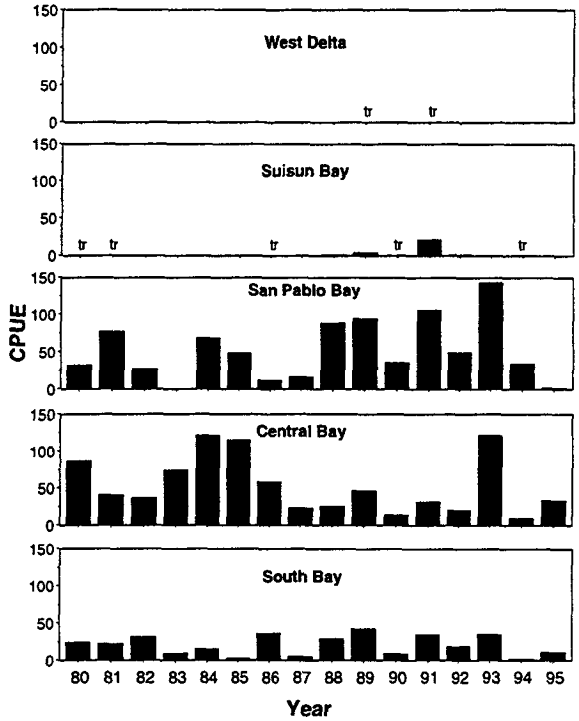

Figure 24 Annual distribution of age–0 English sole collected with the otter trawl from 1980 to 1995. Data are mean February to October CPUE by region. The letters "tr" indicate CPUE too low to plot.

Annual Distribution

Age–0 English sole were always present from South Bay to San Pablo Bay, were occasionally in Suisun Bay, but were rarely in the west delta and then only during the drought years 1989 and 1991 (Figure 24). Age–0 fish were concentrated in Central Bay from 1980 to 1987, except for 1981. From 1988 to 1994, during the drought, peak CPUE shifted into San Pablo Bay. However, in 1995, a high outflow year, peak CPUE was again in Central Bay.

Except for 1985, age–1+ English sole ranged from South to San Pablo bays and, in 1992, into Suisun Bay (Figure 25). Density was highest in Central Bay, except in 1989 and 1990.

Seasonal Distribution

Early settling age–0 English sole entered Central Bay in December and were not distinguished from the previous year class. They quickly migrated, so that from January to March CPUE increased more quickly in San Pablo and South bays than in Central Bay (Figure 26). Few age–0 fish moved into Suisun Bay and none were caught in the west delta. In all 3 lower bays, immigration continued and CPUE increased from January to May. Use of South and San Pablo bays remained high to June then declined rapidly as fish returned to Central Bay. CPUE in Central Bay peaked in July, remained high in August, and then declined as many age–0 fish left the estuary in fall.

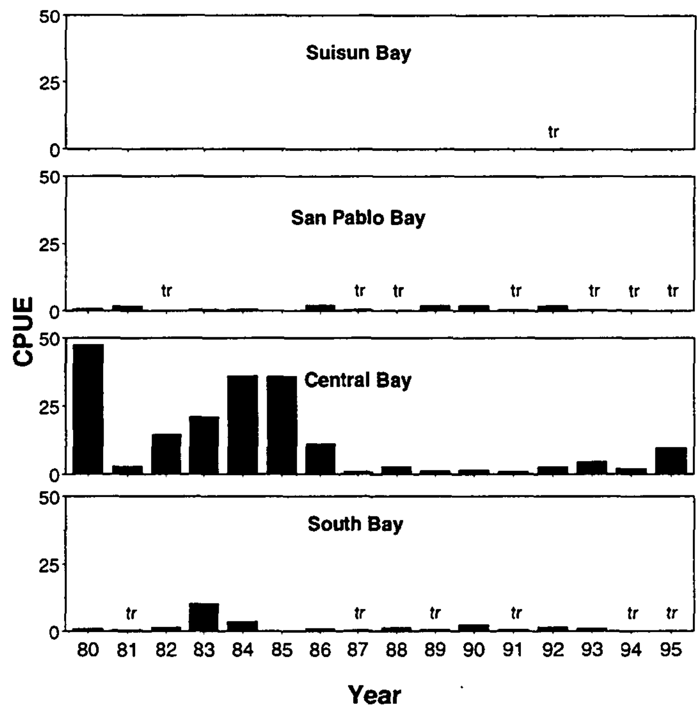

Figure 25 Annual distribution of age–1+ English sole collected with the otter trawl from 1980 to 1995. Data are mean February to October CPUE by region. The letters "tr" indicate CPUE too low to plot.

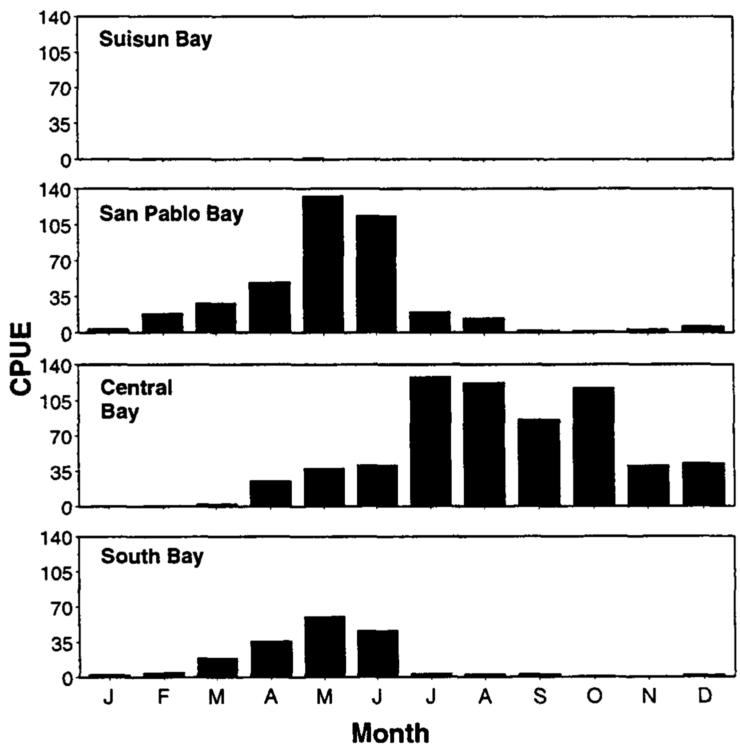

Figure 26 Seasonal distribution of age–0 English sole in the otter trawl. Data are mean CPUE by month and region for 1981 to 1988.

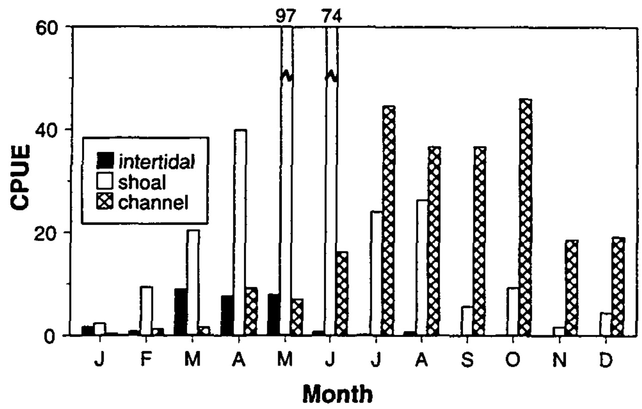

Figure 27 Depth distribution of age–0 English sole collected with the beach seine (intertidal) and the otter trawl (shoal and channel). Data are mean CPUE by month for 1981 to 1986 (beach seine) and for 1981 to 1988 (otter trawl).

Geographical movements of age–0 English sole were accompanied by shifts along depth, salinity, and temperature gradients. As age–0 fish entered the estuary in spring, they sought shallow subtidal and intertidal areas for rearing (Figure 27). Intertidal areas were used primarily from March to May; only a few fish were captured in them from June to October. Use of subtidal shoal areas peaked in May, then declined through September as channel use increased and remained higher than shoal use for the rest of the year.

The use of primarily shallow intertidal and subtidal habitats from February to April exposed age–0 English sole to mean salinities of 18‰ to 20‰ and mean temperatures of 11.8 to 15.0 °C. (Figure 28). Decreased outflow and movement to channels and Central Bay in summer put age–0 fish in average salinities of 30‰ (see Figure 28). From July through the end of the year, mean salinity ranged from 28.9‰ to 32.2‰. Mean temperature rose steadily from about 10 °C in January to a peak of 17 °C in June remained stable to September and then declined (see Figure 28).

Age–1+ English sole were most widely distributed in January from South Bay to Suisun Bay (Figure 29). From about January through July, CPUE declined in all regions as fish emigrated to the open coast. During the remainder of the summer and fall age–1+ fish were rarely caught outside Central Bay, and catch in Central Bay declined to September before increasing again until December. By December, a few were being caught again in South and San Pablo bays.

Age–1+ English sole were strongly channel oriented during the January to April period when most remained in the estuary (Figure 30). Only in May did shoal CPUE surpass that of the channels. Intertidal CPUE was very low from February to May and zero during the remainder of the year. By June, most age–1+ fish had left the shoal and intertidal areas (see Figure 30).

Age–1+ English sole were strongly concentrated in channels and in Central Bay, and, therefore were not exposed to the low January to May salinity and rapidly warming temperatures faced by age–0 fish. However, they inhabited areas of distinctly lower salinity during high outflow months: mean salinity ranged from 22.2‰ to 25.8‰ between January and May (Figure 31). From April through July mean salinity increased rapidly to 31.4‰, then similar to age–0 fish, the distributions were stable through the end of the year, with means between 28.2‰ and 31.4‰ (see Figure 31). As estuarine water temperatures warmed from January to June, the age–1+ fish that remained were found in progressively warmer water; their mean temperature rose from 10.4 to 15 °C (see Figure 31). After June, the few remaining age–1+ fish inhabited even warmer water through September, when their mean temperature reached a peak of 16.7 °C, then declined as estuary temperatures did.

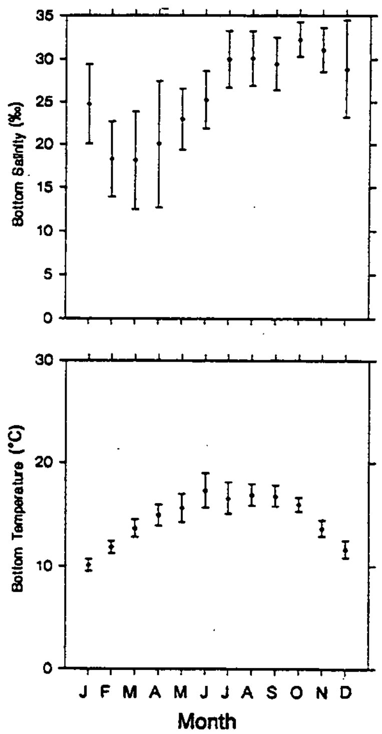

Figure 28 Salinity (‰) and temperature (°C) distributions of age–0 English sole collected with the otter trawl. Data are mean (±1 standard deviation) CPUE-weighted bottom salinity and temperature by month from 1981 to 1988.

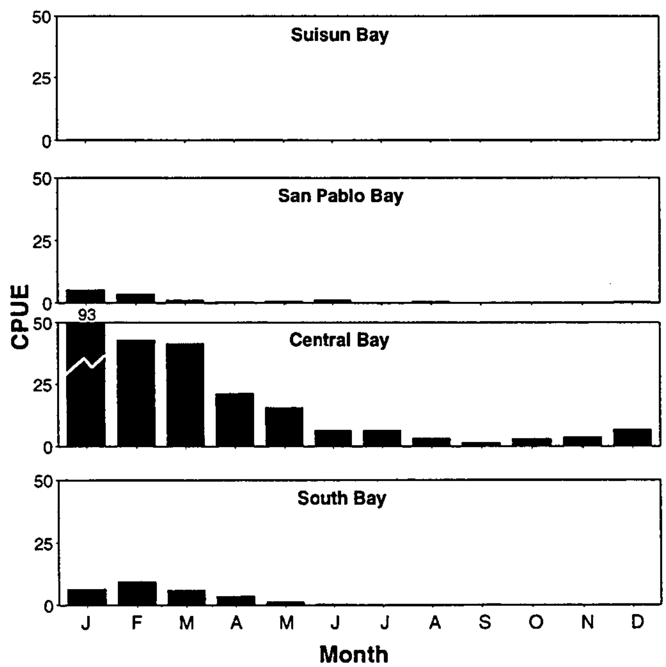

Figure 29 Seasonal distribution of age–1+ English sole collected with the otter trawl. Data are mean CPUE by month and region from 1981 to 1988.

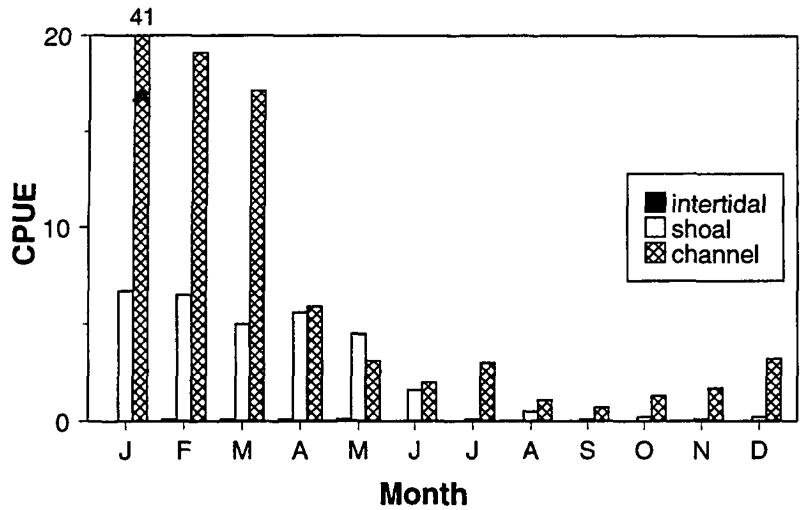

Figure 30 Depth distribution of age–1+ English sole collected with the beach seine (intertidal) and the otter trawl (shoal and channel). Data are mean CPUE by month from 1981 to 1986 (beach seine) and from 1981 to 1988 (otter trawl).

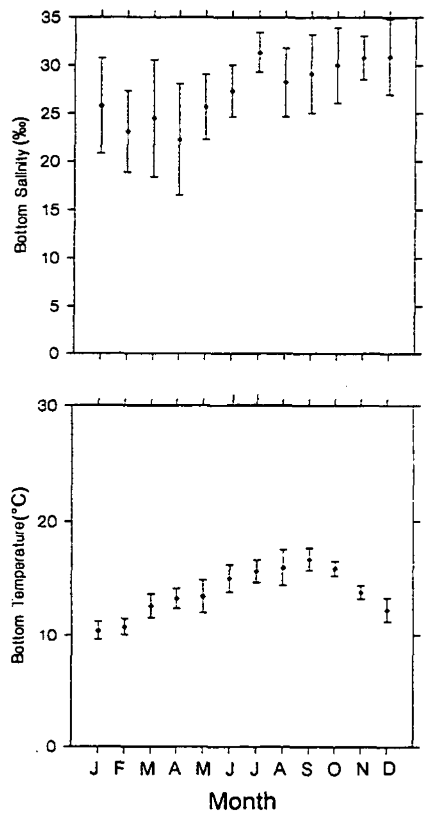

Figure 31 Salinity (‰) and temperature (°C) distributions of age–1+ English sole collected with the otter trawl. Data are mean (±1 standard deviation) CPUE-weighted bottom salinity and temperature by month from 1981 to 1988.

Discussion

English sole used the San Francisco Estuary as a nursery area, immigrating primarily as settled age–0 fish, remaining for 6 to 18 months, then emigrating to the coast to mature and complete their life cycle (see Figure 19). During this estuarine nursery period, they underwent ontogenetic changes in their depth, temperature, and salinity distributions. These patterns of estuarine use were very similar to those described for other locations from Elkhorn Slough, California to British Columbia (Ketchen 1956, Olson and Pratt 1973, Pearcy and Myers 1974, Misitano 1976, Toole 1980, Bayer 1981, Bottom and others 1984, Krygier and Pearcy 1986, Rogers and others 1988, Gunderson and others 1990, Yoklavich and others 1991). On the Oregon coast, a majority of the age–0 population appears to rear in bays and estuaries (Olson and Pratt 1973, Krygier and Pearcy 1986, Rogers and others 1988). The large number of English sole collected here compared to other flatfish suggests that this is also true in California (see Table 1), in which case the large size of the San Francisco Estuary would make it an important nursery area for local stocks. However, little is known about coastal rearing. Limited otter trawl sampling in the Gulf of the Farallones (2 tows at 7 stations in February, June and October, 1984 to 1988; City of San Francisco Outfall Monitoring Program, unpublished data) caught age–0 fish in each month, but most were caught in October as would be the case if estuary-reared fish emigrated in fall. Thus, as in Yaquina Bay, the estuary appears to be an important but not an exclusive nursery area. Another way to evaluate the importance of estuarine rearing would be to compare estuarine abundance with the commercial catch 3 to 5 years later.

The ontogenetic shifts in the depth, salinity and temperature distributions of English sole in the San Francisco Estuary have also been seen in other bays and estuaries (Toole 1980, Bottom and others 1984, Krygier and Pearcy 1986, Yoklavich and others 1991). The geographic distribution of English sole in the estuary appeared to be related to salinity and temperature. Age–0 fish initially migrated to intertidal and subtidal areas where, in March, most of the population was in 12‰ to 24‰ salinity and 12.8 to 14.5 °C. In most years these conditions were found in San Pablo Bay, but in low outflow years, particularly 1987 to 1992, they extended into Suisun Bay (see Figure 24). Conversely, during extremely high outflow years such as 1983 or when high outflow occurred during early spring, as in 1986, salinity <12‰ eliminated or reduced use of San Pablo and Suisun bays. Later in spring as salinity increased, temperatures appeared to limit use of these bays. Laboratory experiments determined an LL_{50} of 26.1 °C for age–1+ fish (Ames and others 1978). In the estuary, fish left intertidal habitats at high temperatures. As intertidal temperatures approached and passed 20 °C in May and June, age–0 fish began to move to deeper and cooler shoal and then channel areas and toward Central Bay (see Figure 27). As this movement continued through the summer, it effectively stabilized the temperature distribution of age–0 fish (see Figure 28). In Elkhorn Slough, English sole were not collected from intertidal areas (Yoklavich and others 1991). Yoklavich (1991), referring to an earlier paper, suggests that thermal tolerance limited shallow water use in Elkhorn Slough and similar areas at the southern edge of their range.

Their depth, salinity and temperature ranges initially separated age–0 English sole from similar-sized speckled sanddabs which did not inhabit intertidal areas and tended to be more evenly distributed across channel and shoals, and from starry flounder which were found in fresher and warmer waters.

Starry Flounder

Introduction

The starry flounder, *Platichthys stellatus,* ranges from Santa Barbara, California northward to Arctic Alaska, then southwest to the Sea of Japan (Miller and Lea 1972). It is found from <1 m to about 275 m (Miller and Lea 1972). Juveniles seek shallow, fresh to brackish water in bays and estuaries to rear, but adults primarily inhabit coastal marine water (Orcutt 1950, Haertel and Osterberg 1967, Bottom and others 1984, Hieb and Baxter 1993). Though seldom targeted, the starry flounder is common in both commercial and recreational fisheries of northern and central California (Orcutt 1950, Haugen 1992, Karpov and others 1995).

In Monterey Bay, spawning occurs between November and February (Orcutt 1950) in shallow, coastal marine areas near river and slough mouths (Orcutt 1950, Garrison and Miller 1982, Wang 1986). Some spawning may occur within San Francisco Bay (Radtke 1966, Moyle 1976). However, no ripe female starry flounder were collected in San Francisco Bay during winter surveys in the mid-1980s (B. Spies, personal communication, see "Notes"), nor were any mature flounder, eggs or prolarvae collected from the estuary between 1978 and 1982 (Wang 1986).

Starry flounder eggs and larvae are pelagic and are found mostly in the upper water column (Orcutt 1950, Wang 1986). Larvae are approximately 2 mm long at hatching and settle to the bottom about 2 months later at approximately 7 mm SL (Policansky and Sieswerda 1979, Policansky 1982). They depend upon favorable ocean currents to keep them near their estuarine nursery areas prior to settlement. Transforming larvae and the smallest juveniles migrate from the coast to brackish or freshwater where they rear for 1 or more years (Haertel and Osterberg 1967, Bottom and others 1984, Wang 1986, Hieb and Baxter 1993).

As they grow, juveniles move to higher salinity, but appear to remain within estuaries through at least their 2nd year (Haertel and Osterberg 1967, Bottom and others 1984, Hieb and Baxter 1993). Most males mature by the end of their 2nd year of life and 220 to 276 mm SL, whereas, females mature at age 3 or 4 and 239 to 405 mm SL (Orcutt 1950). During the late fall and winter, mature starry flounder probably migrate to shallow coastal waters to spawn (Orcutt 1950). They reach a maximum length of 915 mm (Miller and Lea 1972).

Methods

Fish were grouped by length into several developmental and age categories. In the plankton net, 1 to 4 mm and 6 to 12 mm TL larvae were classified as recently hatched and pre-settlement larvae, respectively (Policansky and Sieswerda 1979, Policansky 1982). In the beach seine and otter trawl, fish in the 10 to 29 mm size range were classified as recently settled; settlement occurs at about 10 mm (Policansky and Sieswerda 1979, Policansky 1982). Visual inspection of length frequency data (mm TL) was used to determine cutoff lengths to separate age–0 fish from age–1+ (all older age classes). Fish $\geq$ 410 mm were classified as mature (Orcutt 1950).

A January 1 birth date was assigned to all larvae and age–0 fish. Larval abundance and distribution were based on total catch, without correction for effort or for incomplete sampling in 1980 and 1989. Monthly cutoff lengths used to separate age–0 and age–1+ fish were 60, 60, 70, 80, 95, 110, 125, 140, 150, 155, 160, and 165 mm TL for January through December. Annual abundance indices for age–0 and age–1+ fish were the means of May to October and February to October monthly indices from the otter trawl. No correction was made for the lack of data for August to October 1989 or August 1995. All distribution analyses were based upon monthly mean CPUE for 1981 to 1988.

Results

Length Analyses

Larval starry flounder captured by the plankton net ranged from 1.7 to 11.3 mm and age–0 fish ranged from 34.5 to 53 mm. Recently hatched larvae were collected throughout the year, but pre-settlement larvae were only collected from March to June (Table 12). Starry flounder collected by the beach seine ranged from 17 to 475 mm; those collected by the otter trawl were 19 to 638 mm. Beach seine and otter trawl capture of recently settled fish occurred during 2 periods: December to February and May to July (Figure 32). There was very little evidence of growth and recruitment of fish that settled during the winter period, but those caught in the spring-summer period followed the collection of pre-settlement larvae (see Table 12) and preceded collection of larger individuals, evidence of further growth and recruitment (see Figure 32).

There was a clear distinction between the lengths of age–0 and age–1+ starry flounder from April to July, and only a slight overlap for the rest of the year (see Figure 32). Growth of age–0 fish was rapid through summer and early fall, reaching 70 to 90 mm by August. Growth slowed considerably between September and December when the modal size range increased to only 90 to 110 mm. Nonetheless, by December, some age–0 fish reached 150 mm. Age–1 and age–2 fish were not easily separable using length data, but length frequency modes indicated that both age groups were present in the estuary (see Figure 32). Older age groups were also present but length modes were not apparent. Mature-sized (≥410 mm) fish were collected in the estuary primarily from May to October (see Figure 32).

Abundance and Distribution of Larvae

Annual larval catch reached a peak of 59 in 1980, declined precipitously in 1981, rose sharply in 1982, and then, after a moderate downturn in 1983 and 1984, returned to intermediate levels from 1985 through 1988 (Tables 13 and 14). Annual catch reached a minimum of 2 in 1989, when sampling took place only from January through May (see Table 13). Larvae were collected throughout the estuary, but over half came from Central Bay (see Table 13). Greater numbers of larvae were caught in San Pablo than in South Bay. Catches from San Pablo Bay, Suisun Bay, and the west delta increased between 1984 and 1988.

Table 12 Length frequency (mm TL) of larval starry flounder captured in the plankton net from 1980 to 1989

Length	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Total*
1.0 - 1.9				1				3					4
2.0 - 2.9	2	1	1	7	2	3	21	14	31	15	15	7	119
3.0 - 3.9		9	4	10	2			1	1		2	1	30
4.0 - 4.9		2	1	3							1		7
5.0 - 5.9													
6.0 - 6.9					9								9
7.0 - 7.9			1	4	24								29
8.0 - 8.9			1	8	37	1							47
9.0 - 9.9				2	3								5
10.0 - 10.9													
11.0 - 11.9			1										1
Total	2	12	9	35	77	4	21	18	32	15	18	9	251

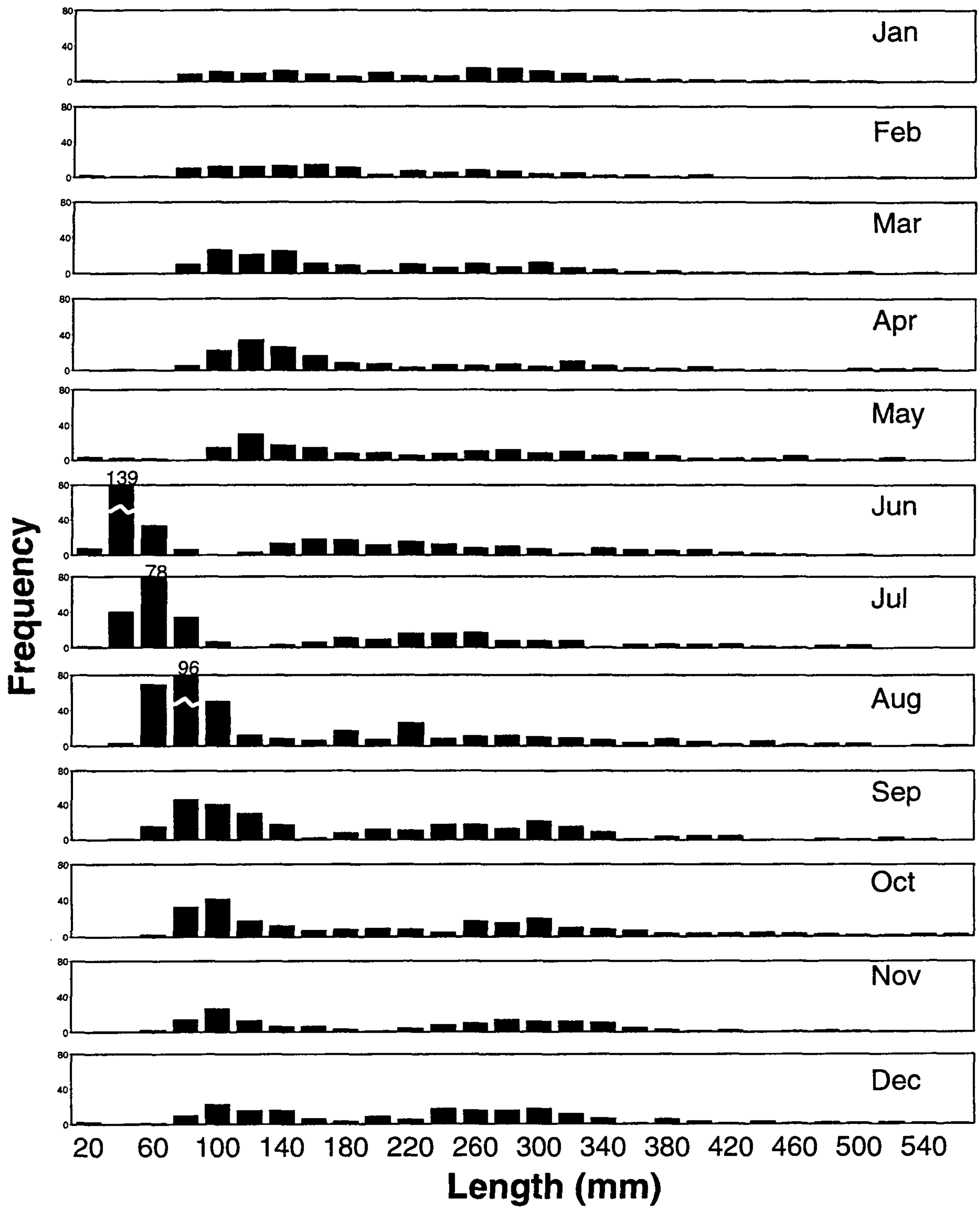

Figure 32 Length frequency (mm TL) by month of starry flounder collected with the beach seine and otter trawl from 1981 to 1988. Fish <30 mm were considered recently settled and those ≥410 mm were considered mature.

Table 13 Annual abundance (right column) and distribution of starry flounder larvae collected in the plankton net from 1980 to 1989. Data are annual catches by region with no correction for partial-year sampling in 1980 and 1989.

Year	*South Bay*	*Central Bay*	*San Pablo Bay*	*Suisun Bay*	*West Delta*	*Total*
1980	5	41	13	0	0	59
1981	1	7	0	0	0	8
1982	4	22	8	0	0	34
1983	1	11	2	0	0	14
1984	0	3	6	4	0	13
1985	1	18	12	2	1	34
1986	2	14	20	2	0	38
1987	4	12	7	3	0	26
1988	1	10	10	2	0	23
1989	0	2	0	0	0	2
Total	19	140	78	13	1	251

Table 14 Monthly abundance larval starry flounder captured in the plankton net from 1980 to 1989. Annual abundance indices are in the far right column. Seasonal abundance indices are in the bottom row (mean 1981 to 1988 monthly abundance).

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Feb–Oct*
1980		0	0	3514	53120	0	0	1074	754	969	3666	0	5736
1981	0	0	0	1433	1433	0	0	1433	2507	0	1469	0	752
1982	0	11497	0	5197	2938	0	0	565	1039	1578	0	6509	2666
1983	0	0	2507	3976	3188	0	0	0	0	358	431	1074	1049
1984	1074	0	0	0	4147	0	0	323	431	0	0	0	446
1985	0	1433	1828	1349	0	0	19024	1074	1433	0	2367	0	2592
1986	2015	0	0	0	6317	1074	0	2938	9719	2402	6088	0	2594
1987	0	0	0	3806	4856	1433	0	4909	4370	3942	990	646	2268
1988	0	0	538	4355	0	1397	716	4728	1613	1828	1074	0	1477
1989	0	0	1791	0	0								
1981–1988	386	1616	609	2515	2860	488	2468	1996	2639	1264	1552	1029	

Abundance and Distribution of Age–0 and Older Fish

Annual Abundance

The abundance of age–0 starry flounder was at a maximum in 1980, declined precipitously in 1981, rose sharply in 1982, and then declined to and remained at low levels from 1987 to 1994, reaching zero in 1992 (Figure 33, Table 15). After 1986, only 1995 was a good year for age–0 abundance. Age–1+ fish abundance rose to a peak of 6,954 in 1983, then declined to and remained at low levels from 1988 through 1995 (see Figure 33, Table 16). Age–1+ fish abundance reached a minimum of 100 in 1993.

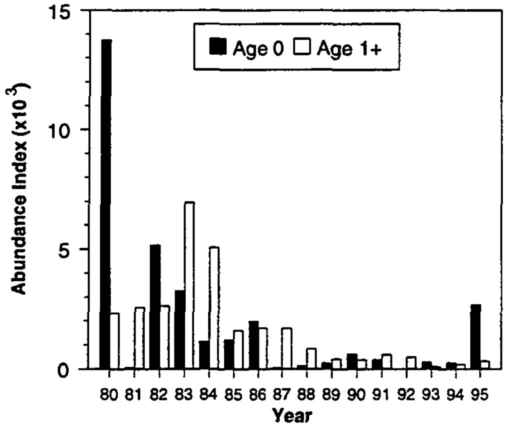

Figure 33 Annual abundance of age–0 and age–1+ starry flounder collected with the otter trawl from 1980 to 1995. Data are mean May to October (age 0) and February to October (age 1+) abundance indices.

Table 15 Monthly abundance age-0 starry flounder captured in the otter trawl from 1980 to 1995. Annual abundance indices are in the far right column. Seasonal abundance indices are in the bottom row (mean 1981 to 1988 monthly abundance).

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*May–Oct*
1980		0	0	0	0	4515	12809	32572	16370	16227	4673	1173	13749
1981	0	0	0	55	71	69	116	0	134	0	65	55	65
1982	0	497	0	0	65	4701	5943	7717	5767	6868	4351	2414	5177
1983	0	134	0	0	256	2278	4374	6994	1306	4353	1928	2627	3260
1984	0	0	0	0	0	2284	1426	1221	1175	666	0	269	1129
1985	0	0	0	0	0	687	55	2243	3827	409	228	202	1204
1986	0	0	0	0	0	381	2159	8656	629	62	0	522	1981
1987	0	0	0	0	0	84	0	69	195	0	0	0	58
1988	0	0	0	0	0	335	145	0	346	0	103	65	138
1989	0	0	0	0	0	55	328	589					243
1990		0	0	0	84	881	479	1537	678	62			620
1991		0	0	0	0	343	1110	311	511	0			379
1992		0	0	0	0	0	0	0	0	0			0
1993		0	0	0	0	117	553	445	483	0			266
1994		0	0	0	0	0	560	574	416	0			258
1995	0	0	0	0	0	1277	8962		2031	1135	317	343	2681
1981–1988	0	79	0	7	49	1352	1777	3363	1672	1545	834	769	

Table 16 Monthly abundance age–1+ starry flounder captured in the otter trawl from 1980 to 1995. Annual abundance indices are in the far right column. Seasonal abundance indices are in the bottom row (mean 1981 to 1988 monthly abundance).

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Feb–Oct*
1980		3133	1571	1846	3540	848	3671	1591	461	4267	1409	666	2325
1981	2082	3040	3120	3834	1705	818	2447	4656	1905	1402	1822	2997	2547
1982	2992	422	959	1632	3766	5087	1778	2907	2355	4627	5393	901	2615
1983	3584	2068	3993	6831	11117	7916	6265	9117	7028	8255	3375	5724	6954
1984	4871	2569	9998	4728	5901	4132	6999	4941	3727	2523	797	2299	5058
1985	523	1939	1320	556	1414	761	1514	2812	2976	971	563	626	1585
1986	624	993	961	810	2389	470	2970	1716	2022	2951	1515	706	1698
1987	1011	1457	666	1049	791	3821	1375	2098	1419	2422	2232	2898	1678
1988	1395	260	1297	1631	1131	521	333	514	1833	0	1146	69	836
1989	292	180	433	857	625	0	300	459					408
1990		0	0	438	1172	473	329	281	188	541			380
1991		55	647	250	97	576	920	767	910	1089			590
1992		207	1441	814	384	0	0	549	567	461			491
1993		173	0	0	173	0	331	0	0	219			100
1994		55	0	0	75	651	0	705	243	0			192
1995	138	48	0	669	192	173	269		1203	0	1102	959	319
1981–1988	2135	1594	2789	2634	3527	2941	2960	3595	2908	2894	2105	2028	

Seasonal Abundance

The initial weak recruitment of age–0 starry flounder to the estuary from January to May was followed by a steady increase in abundance from June to August, then by a decline to December (Figure 34, see Table 15). In January, age–1+ abundance was high relative to that of age–0 fish in December (see Figure 34, see Table 16). After a small decline in February, age–1+ abundance increased to an initial mode in May followed by a second mode in August, then declined slowly to December (see Figure 34). The monthly abundance of age–1+ fish was consistently higher than that of age–0 fish, in part, because the age–1+ group contained several age classes. The low abundance period for age–1+ fish, November to February, coincided with a reduction in the number of mature-sized fish caught in the estuary (compare to Figure 32).

Annual Distribution

Age–0 starry flounder were captured throughout the estuary, but annual CPUE was always highest upstream of Central Bay (Figure 35). Age–0 fish were rarely caught in Central Bay or South Bay, and when they were it was usually during a high outflow year (that is, 1980, 1982, 1983, 1984, 1986, 1993, and 1995). Maximum CPUE was in Suisun Bay or the west delta during low outflow years (1981, 1985, 1987–1992, 1994) and in San Pablo Bay during most high outflow years. Although outflow was high during the winter of 1984, flows diminished to low flow conditions by May and June when age–0 fish entered the estuary, resulting in a distribution typical of low outflow conditions.

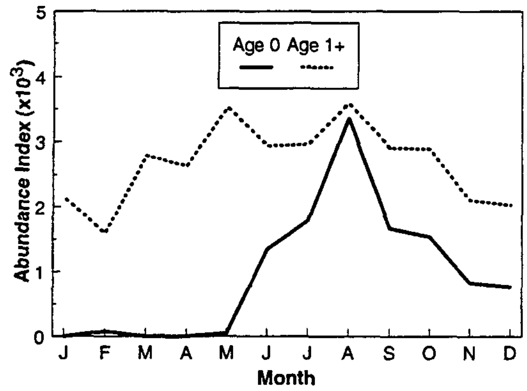

Figure 34 Seasonal abundance of age–0 and age–1+ starry flounder collected with the otter trawl. Data are mean monthly abundance indices from 1981 to 1988.

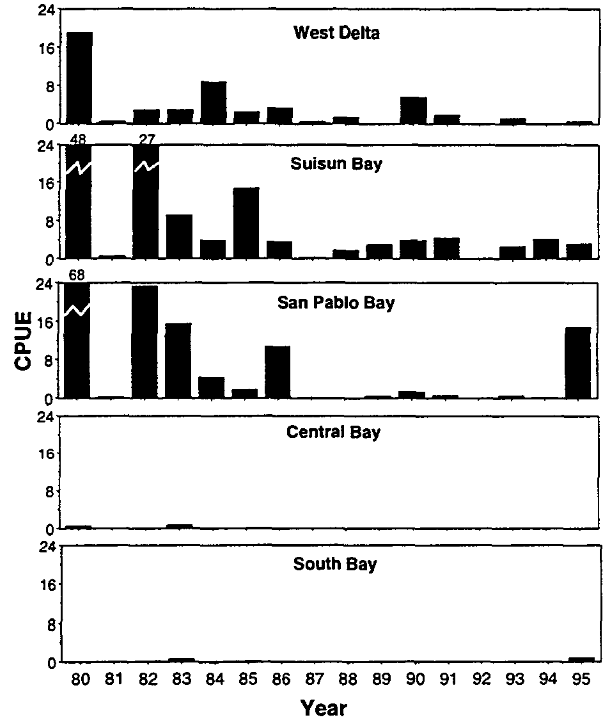

Figure 35 Annual distribution of age–0 starry flounder collected with the otter trawl from 1980 to 1995. Data are mean May to October CPUE by region.

Age–1+ starry flounder were also captured throughout the estuary, but were centered in San Pablo Bay (Figure 36). Unlike age–0, age–1+ fish were common in Central and South bays, and were relatively rare in the west delta. The distribution of age–1+ fish did not change with outflow.

Seasonal Distribution

Catches of age–0 starry flounder were low before June. In May and June, age–0 fish were found primarily in Suisun Bay and the west delta (Figure 37). By July, few age–0 fish were captured in the west delta, but catches were relatively high in Suisun and San Pablo bays, and remained relatively high through December. In December, CPUE again increased in the west delta.

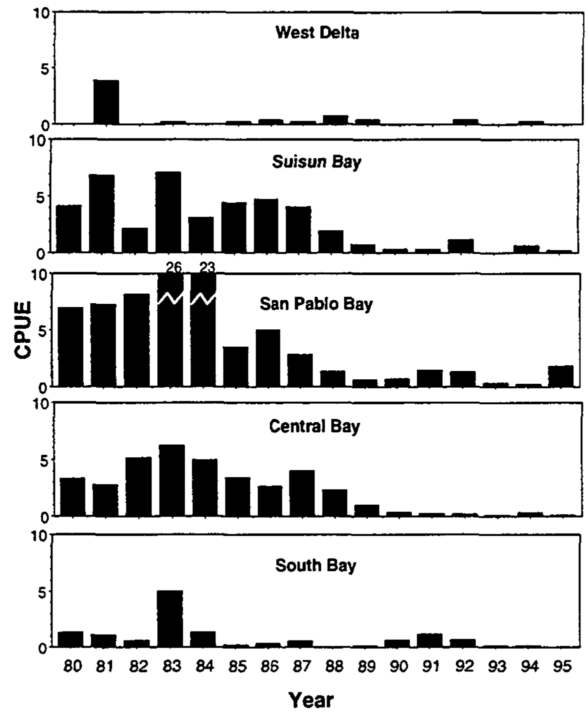

Figure 36 Annual distribution of age–1+ starry flounder collected with the otter trawl for 1980 to 1995. Data are mean February to October CPUE by region.

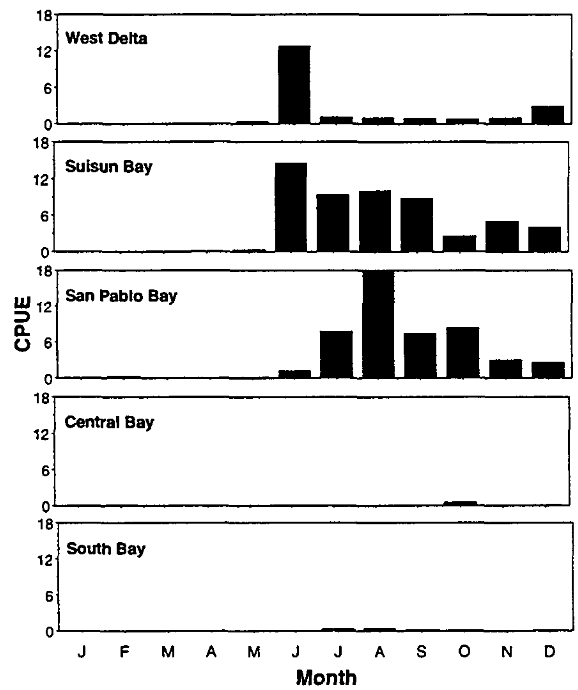

Figure 37 Seasonal distribution of age–0 starry flounder collected with the otter trawl. Data are mean CPUE by month and region from 1981 to 1988.

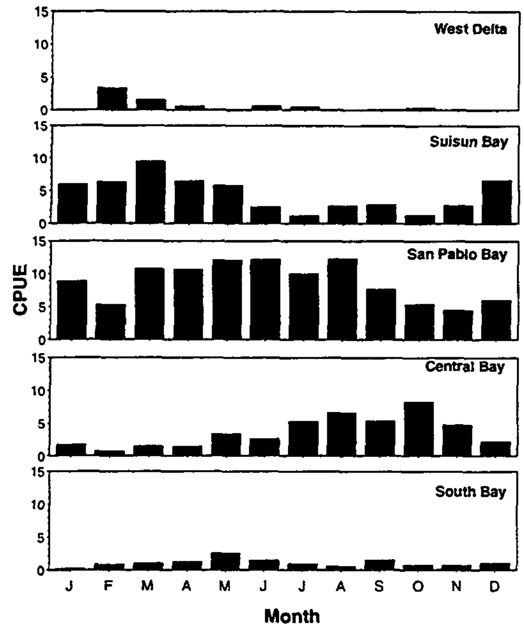

Figure 38 Seasonal distribution of age–1+ starry flounder collected with the otter trawl. Data are mean CPUE by month and region for 1981 to 1988.

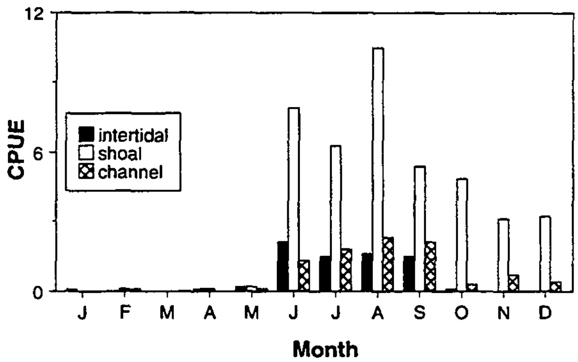

Figure 39 Depth distribution of age–0 starry flounder collected with the beach seine (intertidal) and the otter trawl (shoal and channel). Data are mean CPUE by month for 1981 to 1986 (beach seine) and for 1981 to 1988 (otter trawl).

In January, age–1+ starry flounder were distributed primarily in Suisun and San Pablo bays (Figure 38). Use of the west delta was highest in February and March. A February through May decline in CPUE in the west delta coincided with the start of a general downstream movement toward San Pablo and Central bays that continued into the fall (see Figure 38). After March, few age–1+ fish were captured in the west delta. Use of South Bay occurred primarily from March to June. By July and continuing through November, most age–1+ fish were caught in Central and San Pablo bays. In December, their range shifted back upstream slightly (see Figure 38).

Age–0 starry flounder were collected in higher numbers over shoals than in channels or in the intertidal zone throughout the year (Figure 39). Catches of age–0 fish were low in all areas from January to April and began to rise in May. They were highest over shoals during the period of maximum abundance from June to September and a little higher in the channels than in intertidal areas during these months.

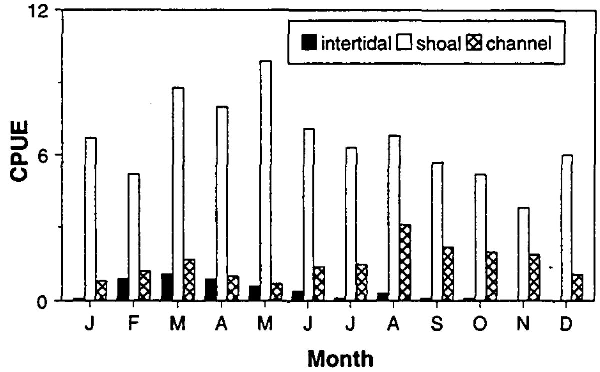

Figure 40 Depth distribution of age–1+ starry flounder collected with the beach seine (intertidal) and the otter trawl (shoal and channel). Data are mean CPUE by month for 1981 to 1986 (beach seine) and for 1981 to 1988 (otter trawl).

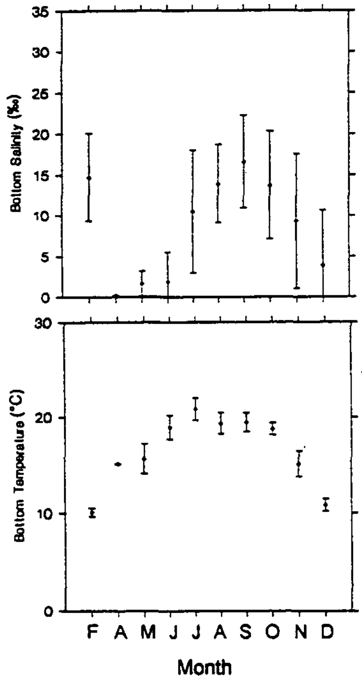

Figure 41 Salinity (‰) and temperature (°C) distributions of age–0 starry flounder collected with the otter trawl. Data are mean (±1 standard deviation) CPUE-weighted bottom salinity and temperature by month from 1981 to 1988.

Age–1+ starry flounder were always most abundant over shoals and always least abundant in the intertidal (Figure 40). Shoal abundance peaked from March to May, intertidal abundance from February to June, and channel abundance from August to October.

Salinity and Temperature

Age–0 starry flounder tended to seek warm, low salinity areas to rear, and though as a group they shifted into higher salinity water during late summer and fall, part of the population remained in freshwater all year (Figure 41). In February, a few age–0 fish were captured from 9.1‰ to 22.1‰, but from April to June monthly salinity means were all <2‰, and the maximum salinity was only 12.2‰. From June to September, age–0 fish were found in progressively higher salinities (see Figure 41) as a result of their downstream movement (see Figure 37). From September to December, age–0 fish faced progressively lower salinity water as a result of a slight upstream movement (see Figure 37) and increased outflows in the fall of 1982 and 1983, when abundance was high. In June, age–0 fish were found in temperatures ranging from 16.4 to 22.6 °C (mean about 19 °C, see Figure 41). Except for a few found as high as 23.8 °C in July, most remained within this 16.4 to 22.6 °C temperature range from June through October. After October, they inhabited progressively cooler water through the end of the year.

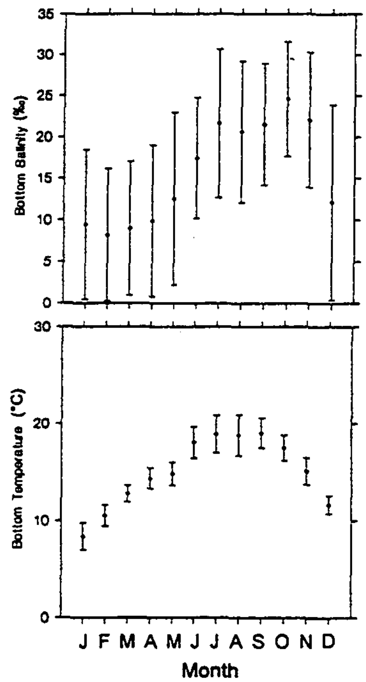

Figure 42 Salinity (‰) and temperature (°C) distributions of age–1+ starry flounder collected with the otter trawl. Data are mean (±1 standard deviation) CPUE-weighted bottom salinity and temperature by month from 1981 to 1988.

Age–1+ starry flounder had broad monthly salinity and temperature ranges, reflecting their extensive geographical distribution (Figure 42). From January through April, age–1+ fish faced mean salinities from 8‰ to 10‰, and monthly ranges of 0.1‰ to >15‰. From May through July, age–1+ fish moved into more saline waters (see Figure 42). Age–1 salinity ranges stabilized somewhat from July to November, except for an upward shift in October; means ranged from 20.6‰ to 22.1‰ (24.6‰ in October). Although monthly salinity ranges were broad for August to October, age–1+ fish were no longer collected from freshwater: salinity minima ranged from 3.7‰ to 6.9‰. In December, the age–1+ fish that remained in the estuary were found in lower salinity water.

Discussion

Although all life stages of starry flounder, except eggs, were captured in the estuary, it was primarily used as a nursery area for fish age 2 and younger. The magnitude and range of use were probably underestimated because starry flounder inhabit areas not sampled by the study, for example, the Napa Marsh (California Department of Fish and Game (CDFG), unpublished data), the Suisun Marsh (Moyle and others 1986), and the central, eastern, and southern delta (Radtke 1966, CDFG unpublished data). Historically, starry flounder may have spawned in the estuary (Radtke 1966, Moyle 1976), but few larvae were collected by this study and by Wang (1986) and no ripe adults were captured (B. Spies, personal communication, see "Notes"). Low larval catches were also recorded for other estuaries used by juvenile starry flounder. In the Columbia Estuary, no larvae were taken during a year of monthly plankton sampling at 7 locations (Misitano 1977), even though the upper estuary was an important nursery for juveniles (Haertel and Osterberg 1967). During 11 years of sampling Yaquina Bay, another important nursery area (Bayer 1981), only 3 larvae were collected (Pearcy and Myers 1974). On the other hand, starry flounder larvae were common in nearshore coastal waters off Oregon (Richardson and Pearcy 1977). Thus, most spawning probably takes place in the coastal marine environment, and transforming larvae and small juveniles seek out estuaries for rearing.

Although there was evidence of some immigration by pre-settlement (that is, transforming) larvae, most starry flounder immigrated as settled, 30 to 70 mm juveniles (Radtke 1966, this study). Otter trawl and beach seine sampling during April and May failed to collect sufficient numbers of 10 to 29 mm age–0 fish to account for the large numbers of 30 to 69 mm of fish caught in June and July (see Figure 32). Sudden estuarine entry of ≥30 mm fish in late May or June is common in Elkhorn Slough, California (Yoklavich and others 1991), and in the Columbia River Estuary (Haertel and Osterberg 1967, McCabe and others 1983, Bottom and others 1984). However, in the Salinas River, California, Orcutt (1950) collected numerous 10 to 29 mm fish from March through May.

Immigration of age–0 fish may be triggered by rising estuarine temperature. Typically, by March estuarine temperatures surpass those of the nearshore coastal areas (see Salinity and Temperature chapter, Figure 12). In April, the difference becomes more pronounced as coastal temperatures decline with the start of upwelling and estuarine temperatures continue to seasonally warm. Thus, temperature and salinity may act as cues to guide juveniles to the estuary.

The importance of estuarine rearing for starry flounder may be inferred from age–0 habitat that was predominantly fresh to mesohaline during their 1st year (see Figure 41), and from the relative lack of age–0, age–1 and age–2 fish in coastal marine areas (City of San Francisco Bureau of Water Pollution Control, unpublished data 1987 to 1990; Rogers and others 1988; Yoklavich and others 1991). In previous analyses, specific habitat criteria were established for starry flounder <70 mm in the San Francisco Estuary: 90% were collected from habitat having bottom depth <7 m, and salinity <22‰ (Hieb and Baxter 1993). These criteria defined "critical" habitat for recently immigrating fish and habitat for age–1 fish remained very similar (Hieb and Baxter 1993). Based on these criteria, habitat area in the estuary was significantly and positively related to March through June freshwater outflow ($r^2 = 0.917$, $P < 0.001$, df = 9). Abundance in the estuary was also significantly related to outflow during the same period ($r^2 = 0.646$, $P < 0.01$, df = 9). In the Columbia River Estuary, age–0 and age–1 starry flounder are found in similar low salinity, and intertidal and subtidal habitats (McCabe and others 1983, Bottom and others 1984). Though age–0 starry flounder were common in the estuary, they were rarely collected in the Gulf of the Farallones (B. Sak, personal communication, see "Notes"). This pattern of estuarine rearing with little or no evidence of marine rearing is found elsewhere in their range (Rogers and others 1988, Yoklavich and others 1991). The exclusiveness of their fresh and brackish water rearing habitat and the relationship between freshwater outflow and their abundance is strong evidence for estuarine dependence (Emmett and others 1991, Hieb and Baxter 1993, this study). However, coastal spawning and the wide variation in abundance during high outflow years suggest that ocean conditions and outflow in combination affect year class strength (Hieb and Baxter 1993).

Age–0 starry flounder inhabit lower salinity and warmer water than other flatfish species in the estuary and hence, face little competition during their first few months of settled life. These same conditions lead to rapid growth, which in turn can reduce the period of extreme vulnerability to predation.

Diamond Turbot

Introduction

The diamond turbot, *Hypsopsetta guttulata,* ranges from Magdalena Bay, Baja California, northward to Cape Mendocino, California. There is also an isolated population in the Gulf of California (Miller and Lea 1972). The diamond turbot is captured by both commercial and recreational fishers, but not in sufficient numbers to be important to either group (Leos 1992a). It ranges in depth from 1 to 50 m.

Spawning occurs from September through late February but peaks between November and January (Lane 1975, Wang 1986). Most spawning takes place within 2 km of shore (Barnett and others 1984), and often within or just off the mouths of bays and estuaries (Eldridge 1975, Lane 1975, Kramer 1990a, Kramer 1991b). Transforming larvae (4.4 to ≤8.8 mm SL, Ahlstrom and others 1984) appear to seek out bays, sloughs, and estuaries as nursery areas (Lane 1975, Kramer 1990a, Kramer 1991b). Recently settled juveniles (≤14 mm SL) concentrate mainly in shallow, backbay areas and there is a positive relationship between depth of capture and length (Kramer 1990a, Kramer 1991b). Diamond turbots live nearshore throughout their lives. Females mature in 2 to 3 years at about 180 mm TL (Lane 1975). Diamond turbots reach a maximum size of about 450 mm TL (Miller and Lea 1972).

Methods

Plankton net, beach seine, and otter trawl length data were used in length frequency analyses. Juveniles <17 mm TL were considered recently settled. A single cutoff length of 120 mm TL was used to separate juveniles from adults in all months.

The annual abundance of larvae was calculated as mean April to December monthly abundance. Monthly abundance indices were averaged for 1980 to 1988 to show seasonal abundance. Annual distribution was based upon the mean April to December CPUE by region. A January 1 hatch date was assumed for all juvenile fish. Annual abundance of juveniles was based upon total catch in the beach seine, whereas adult annual abundance was calculated as the mean of February to October monthly abundance indices from the otter trawl. No corrections were made for missing months in 1989 or 1995.

Results

Length Analyses

Diamond turbot larvae collected with the plankton net ranged from 1.5 to 11.5 mm TL. No juvenile fish were caught with this net, although the 11.5 mm individual was almost a juvenile. Diamond turbot collected with the otter trawl ranged from 23 to 454 mm and those in the beach seine ranged from 30 to 329 mm. Thus, no recently settled fish were captured with either the beach seine or the otter trawl. Between 1981 and 1988, all fish <120 mm were collected with the beach seine and all larger fish except 2 were collected with the otter trawl (Figure 43). No pattern of growth was apparent from length frequency of the few juveniles collected. There was a broad band of sizes (about 120 to 180 mm) not collected with either gear type. Most fish collected with the otter trawl were >180 mm and were adults (Lane 1975).

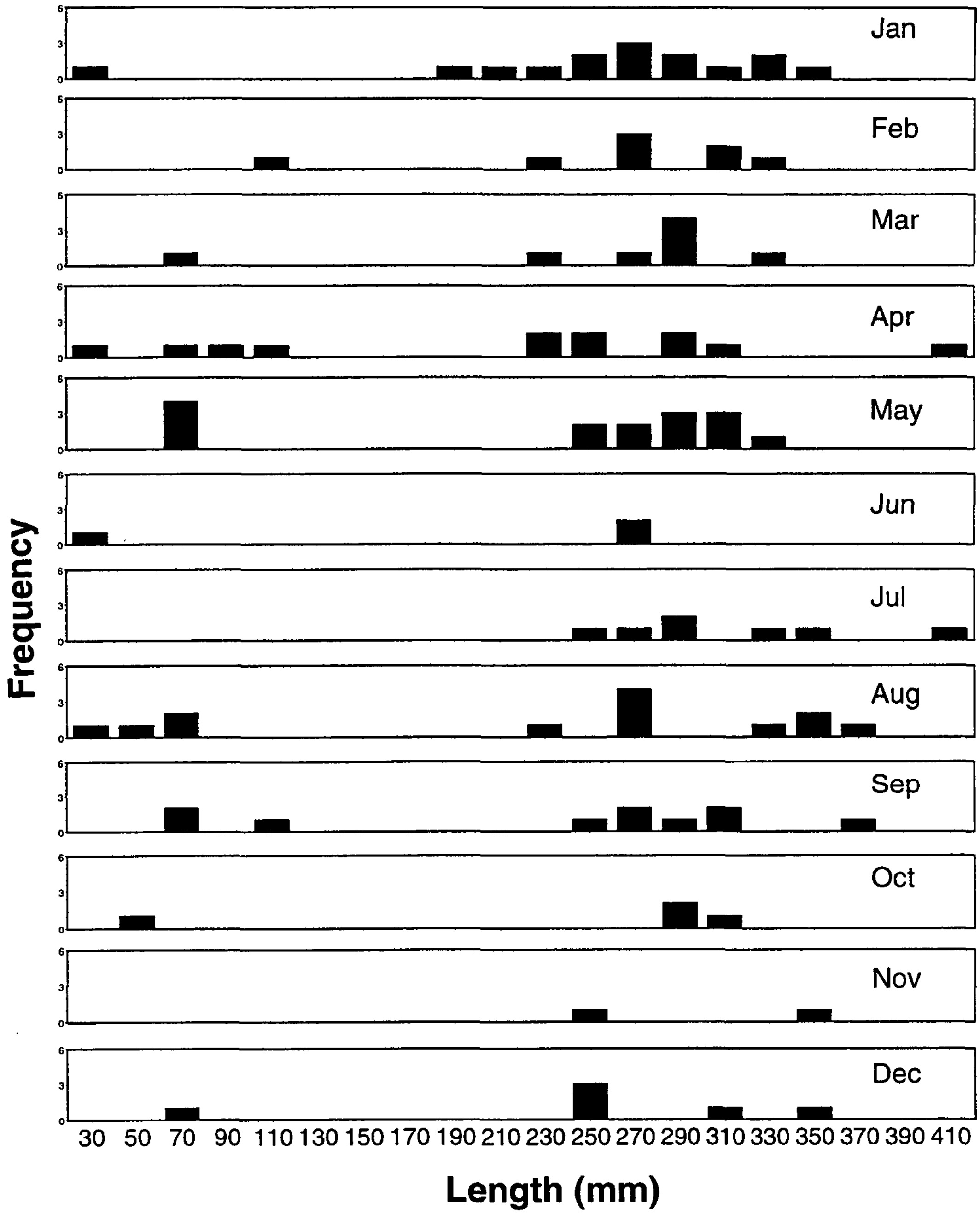

Figure 43 Length frequency (mm TL) by month of diamond turbot collected with the beach seine and otter trawl from 1981 to 1988. Fish <17 mm were considered recently settled and those ≥180 mm were considered mature.

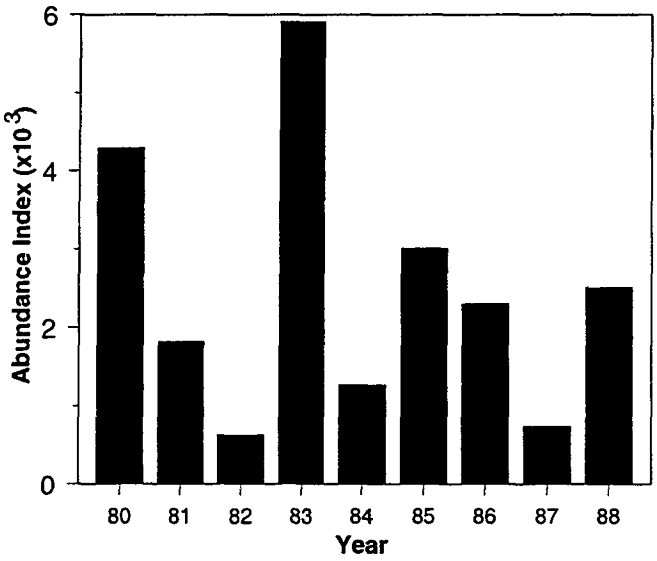

Figure 44 Annual abundance of larval diamond turbot collected with the plankton net from 1980 to 1988. *Data are mean April to December abundance indices.*

Table 17 Monthly abundance of larval diamond turbot captured in the plankton net from 1980 to 1989. Annual abundance indices are in the far right column. Seasonal abundance indices are in the bottom row (mean 1980 to 1988 monthly abundance).

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Apr–Dec*
1980		0	0	0	0	0	860	3369	2582	861	16807	14155	4293
1981	0	0	0	3871	2893	3995	574	1245	1749	1147	0	941	1824
1982	0	0	0	0	0	0	0	0	565	716	4338	0	624
1983	0	0	0	0	0	0	1791	0	14465	19211	17729	0	5911
1984	0	0	0	0	0	0	2221	3610	3368	431	1791	0	1269
1985	0	0	0	0	0	2823	4877	3290	565	4090	11478	0	3014
1986	0	0	0	0	0	0	1317	1756	13149	1505	2258	753	2304
1987	0	0	0	0	0	1505	538	1292	538	1938	861	0	741
1988	0	0	0	0	0	0	0	431	15831	3715	2646	0	2514
1989	0	0	0	376	0								
1980–1988	0	0	0	484	362	1040	1415	1453	6279	4094	5138	212	

Abundance and Distribution of Larvae

Annual larval abundance oscillated widely without a trend from 1980 to 1988 (Figure 44, Table 17). Abundance was highest in 1983, lowest in 1982. Larvae were collected from April to December and abundance was highest from September to November (Figure 45, see Table 17). Larvae were caught from South Bay to Suisun Bay, but were rare in Suisun Bay (Table 18). Use of Suisun Bay occurred only during low outflow years with higher than average larval abundance, 1985 and 1988. Larval abundance was highest in South Bay in 5 of 9 years.

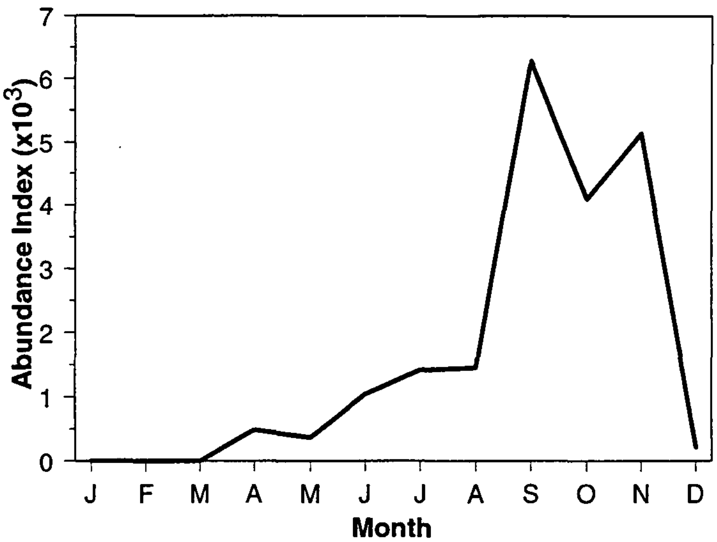

Figure 45 Seasonal abundance of larval diamond turbot collected with the plankton net. Data are mean monthly abundance indices for 1981 to 1988.

Table 18 Annual distribution of larval diamond turbot from the plankton net. Data are mean April to December CPUE by region. None were caught in the west delta.

Year	*South Bay*	*Central Bay*	*San Pablo Bay*	*Suisun Bay*
1980	1.7	0.4	0.5	0
1981	0.6	0.1	0.7	0
1982	0.2	0.1	0	0
1983	0.7	1.6	0.3	0
1984	0.1	0.3	0.3	0
1985	1.2	0.2	0.5	0.5
1986	0.5	0.4	0.4	0
1987	0.1	0	0.7	0
1988	0.7	0.4	0.2	0.3
Mean	0.6	0.4	0.4	0.1

Abundance and Distribution of Juvenile and Adult Fish

Annual Abundance

Juvenile catch in the beach seine was zero in 1980 (Table 19). After an increase to a catch of 3 and a decline to 1 in 1981 and 1982, respectively, annual catch remained between 3 and 5 from 1983 through 1986. Adult abundance dropped sharply between 1980 and 1981, remained stable through 1985, then declined to a minimum of 132 in 1986 (Figure 46, Table 20). In 1987, adult abundance began a steady increase to a maximum of 812 in 1994, followed by a sharp decline in 1995.

Table 19 Annual abundance and distribution of juvenile diamond turbot from the beach seine. Data are total annual catch by region. None were collected in San Pablo Bay, Suisun Bay or the west delta.

Year	*South Bay*	*Central Bay*	*Total*
1980	0	0	0
1981	2	1	3
1982	0	1	1
1983	0	3	3
1984	2	1	3
1985	0	5	5
1986	2	2	4
Total	6	13	

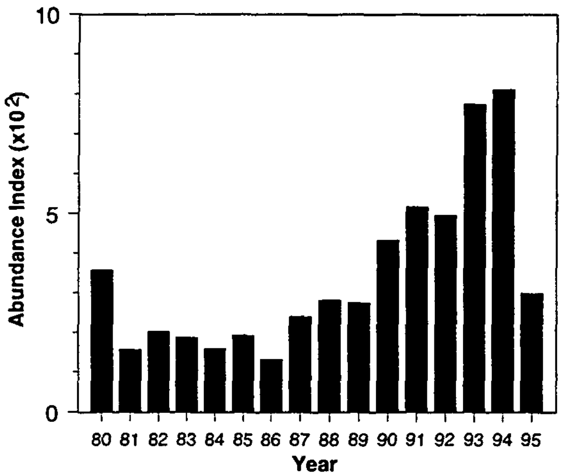

Figure 46 Annual abundance of adult diamond turbot collected with the otter trawl for 1980 to 1995. Data are mean February to October abundance indices.

Table 20 Monthly abundance of adult diamond turbot captured in the otter trawl from 1980 to 1995. Annual abundance indices are in the far right column. Seasonal abundance indices are in the bottom row (mean 1981 to 1988 monthly abundance).

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Feb–Oct*
1980		2395	556	250	0	0	0	0	0	0	188	0	356
1981	701	288	250	0	250	0	344	278	0	0	0	0	157
1982	132	0	382	219	907	0	0	0	0	309	0	474	202
1983	156	134	0	344	0	0	250	965	0	0	270	0	188
1984	854	676	134	0	219	243	0	0	162	0	0	0	159
1985	281	0	0	435	0	0	188	706	162	243	0	0	193
1986	297	0	0	188	271	219	297	0	216	0	0	0	132
1987	115	344	216	0	0	0	541	189	683	189	211	622	240
1988	134	76	500	870	750	0	188	0	154	0	0	307	282
1989	0	0	563	0	0	297	1074	0					276
1990		915	817	0	115	345	281	250	737	439			433
1991		1229	1987	313	0	0	250	281	433	173			518
1992		1490	622	934	173	216	352	0	270	406			496
1993		1796	469	836	416	486	1035	1083	326	540			776
1994		1226	1419	935	0	1595	0	1097	819	216			812
1995	634	192	911	505	0	365	281		0	134	216	344	299
1981–1988	334	190	185	257	300	58	226	267	172	93	60	175	

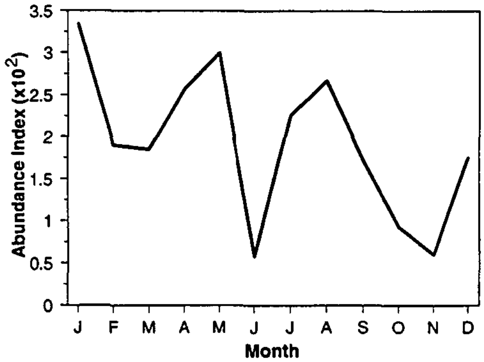

Figure 47 Seasonal abundance of adult diamond turbot collected with the otter trawl. Data are mean monthly abundance indices for 1981 to 1988.

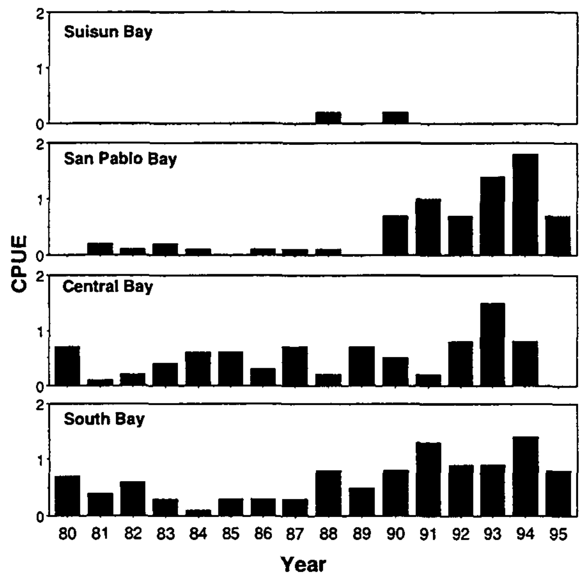

Figure 48 Annual distribution of adult diamond turbot collected with the otter trawl from 1980 to 1995. Data are mean February to October CPUE by region.

Seasonal Abundance

Juveniles were caught sporadically throughout the year, with slightly higher numbers caught in April, May, August, and September (see Figure 43). Adult abundance varied widely during the year. It was relatively high from December through May, declined sharply in June, increased sharply in July and remained high through September before declining and remaining relatively low in October and November (Figure 47, see Table 20).

Annual Distribution

Juveniles were collected only in Central and South bays (see Table 19). They were collected in Central Bay in every year except 1980 but were found in South Bay only in 1981, 1984 and 1986. Similar to larvae, adult diamond turbot were caught from South Bay to Suisun Bay (Figure 48). Captures from Suisun Bay only occurred during the drought years 1988 and 1990. Although some fish were caught in San Pablo Bay in most years, CPUE there was relatively low until the 1990s, when it was about as high or higher than the CPUE of other regions (see Figure 48).

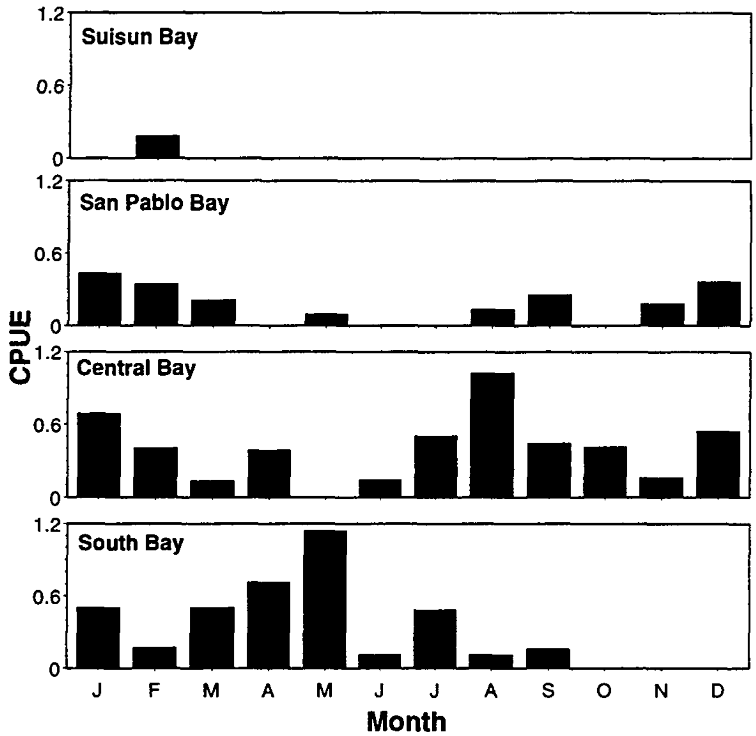

Figure 49 Seasonal distribution of adult diamond turbot collected with the otter trawl. Data are mean CPUE by month and region for 1981 to 1988.

Seasonal Distribution

Adult diamond turbot were generally distributed from South Bay to San Pablo Bay, though some were caught as far upstream as Suisun Bay in February of 1988 and 1990 (Figure 49). From spring to fall, they were only sporadically present in San Pablo Bay, but were consistently captured there from November to March. In Central Bay, adult CPUE was highest in August and lowest in May, the only month with 0 catch. Adults were present in South Bay only from January to September. Peak abundance in South Bay was in May when none were collected from Central Bay.

The depth distributions of juveniles and adults were assessed by comparing beach seine and otter trawl catches, and by comparing average monthly CPUE at channel and shoal stations. Of the 25 juvenile diamond turbot caught throughout the study period, 21 were caught in the beach seine and 4 in the otter trawl; 3 of 4 in the otter trawl came from shoal stations. Adults showed a preference for shallow water in winter.

Two adults were collected in the beach seine: 1 each in December and January. From November to February, adult shoal CPUE was about as high or higher than that for channels (Figure 50). From March to May, shoals were used almost exclusively. From June through October there was a shift from higher shoal use to higher channel use.

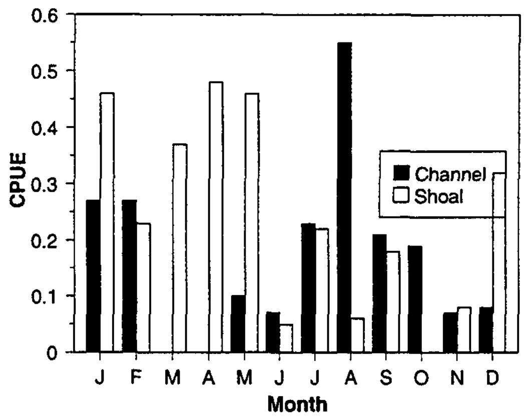

Figure 50 Depth distribution of adult diamond turbot collected with otter trawl (shoal and channel). Data are mean CPUE by month for 1981 to 1988.

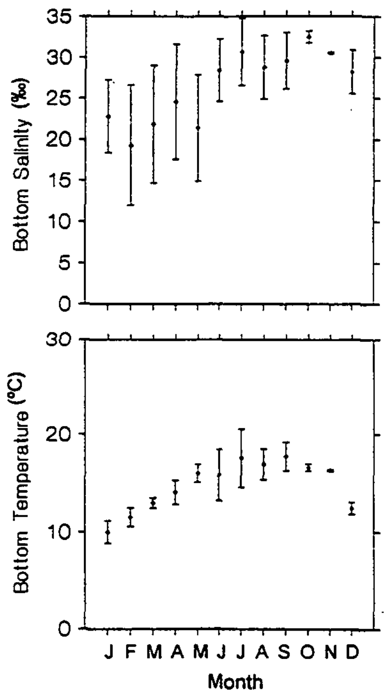

Figure 51 Salinity (‰) and temperature (°C) distributions of adult diamond turbot collected with the otter trawl. Data are mean (±1 standard deviation) CPUE-weighted bottom salinity and temperature by month from 1981 to 1988.

In the beach seine, juvenile diamond turbot were captured at salinities ranging from 4.9‰ to 33.3‰ ($\bar{\chi}$ = 24.5 ± 7.6‰) and at temperatures from 12.0 to 24.8 °C ($\bar{\chi}$ = 17.8 ± 4.4 °C). Only 4 of the 19 juveniles caught by the beach seine came from salinity <22.2‰. Adult diamond turbot were captured primarily from polyhaline and euhaline regions, though 1 was captured at a salinity of 8.4‰ (Figure 51). The lower end of their salinity distributions ranged from 8.4‰ to 14.8‰ during January to May, when their shoal orientation increased their vulnerability to rapidly declining salinity associated with high outflow events (see Figure 51). From June through December, adults were collected from salinity ≥22‰. This increase in their salinity distribution was also reflected in a move into channels by some fish (see Figure 50).

Adult diamond turbot faced temperatures from 8 to 21.3 °C. As estuarine temperatures increased from January to May, adults were found in increasingly warm temperatures: means ranged from 8.0 °C in January to 16.0 °C in May (see Figure 51). From May to November, mean temperatures increased only slightly, ranging from 16 to 17.7 °C before declining in December. Although a few adults were collected at temperatures from 19 to 21.3 °C from June to September, only 5 of 24 fish collected within this period during 1981 to 1988 were from temperatures ≥19 °C.

Discussion

Diamond turbot used the estuary during all life stages, including spawning (Eldridge 1975, this study), but the species was relatively uncommon nonetheless. Based upon larval abundance and a 5 to 6 week larval period (Gadomski and Peterson 1988), spawning in the estuary took place from March through October, primarily from July to October, when water temperature was highest. A similar June to October spawning period was observed in Richardson Bay (Eldridge 1977), but Wang (1986) collected larvae in the estuary all year and found a winter peak. In southern California waters, winter-spring (Lane 1975, Kramer 1990a, Kramer 1991b) or spring and fall (Walker and others 1987) spawning peaks were observed. Emmett and others (1991) suggest a spawning temperature preference for 14 to 16 °C was responsible for the winter-spring spawning in southern California and the summer-fall spawning near San Francisco. Although no studies link diamond turbot spawning or egg and larval survival to water temperature, the California halibut, a species with similar spawning and early life history characteristics, needs temperatures >14 °C to insure larval survival (Gadomski and Caddell 1991). Furthermore, the seasonal pattern of larval abundance is very similar for the 2 species in southern California waters (Walker Jr. and others 1987). In this estuary, adult halibut abundance increased in a pattern very similar to that of adult diamond turbot, strongly suggesting that the same factors may be influencing the abundance of each species.

The estuary is close to Cape Mendocino, the northern edge of the diamond turbot's range (Miller and Lea 1972), so juvenile and adult turbot habitats are probably limited by low temperatures. In this estuary and elsewhere, juvenile diamond turbot settled and reared in shallow inshore water (Lane 1975, Kramer 1990a, Kramer 1991b). This shallow water rearing during fall and winter made them vulnerable to rapid drops in salinity from outflow events. Only 2 age–0 fish were collected from <12‰, indicating that high outflow could affect juvenile survival. Juveniles would have been most at risk from San Pablo Bay upstream where none were collected. Increased adult abundance during the 1987–1994 drought suggests that increased salinity during winter and spring either improved juvenile recruitment or increased adult habitat in the estuary. Increased use of San Pablo and South bays, and occasional use of Suisun Bay from 1987 to 1992 showed that adult habitat increased during the drought.

The diamond turbot may be more abundant in the estuary than indicated by present indices because several aspects of its early life history limit its vulnerability to the sampling gear when compared to other flatfish species. First, the diamond turbot spawns within the estuary (Eldridge 1975), reducing the distance between hatching and nursery areas, the distance over which larvae can be captured. Second, its larvae are <2 mm at hatching (Eldridge 1975), smaller than can be efficiently retained by 500 micron mesh. Third, they settle at a small size (4.4 to 8.8 mm SL, Ahlstrom and others 1984), indicating a short pelagic period, 5 to 6 weeks by 1 estimate (Gadomski and Peterson 1988). These traits reduce the number of monthly sampling opportunities that overlap their pelagic period. Finally, late-stage larvae and small juveniles seek backbays and very shallow water (about 1 m) for early rearing (Kramer 1990a, Kramer 1991b). Beach seine sampling was only conducted on open beaches, not in the backbays or sloughs that may be principal habitat. This mismatch between sampling areas and turbot habitat may have extended to otter trawl sampling too. The lack of fish in the 120 to 180 mm range suggests that these fish may have selected depths less than the 2 to 2.5 m minimum depths sampled with the otter trawl.

California Tonguefish

Introduction

The family Soleidae has only one representative in the Pacific Ocean, the California tonguefish, *Symphurus atricauda,* (Robins and others 1991). Due to its small size (maximum length = 210 mm, Miller and Lea 1972), the tonguefish has no commercial or recreational fishery value, but is eaten by the California halibut (Ford 1965). It ranges from Baja California northward to Big Lagoon, Humboldt County, California (Miller and Lea 1972). After the 1982–1983 El Niño, tonguefish were caught as far north as Greys Harbor and Samish Bay, Washington (Dinnel and Rogers 1986).

Egg development studies show that in southern California waters, the tonguefish spawns from May through October (Goldberg 1981). The larvae are pelagic and transform between 19 and 24.2 mm SL (Ahlstrom and others 1984). They settle in deeper coastal waters (≥9 m), then move to shallow (<7 m) open coastal waters and bays (Kramer 1990a, Kramer 1991b). The 51 to 100 mm length class is collected from bays but not the open coast, whereas, larger size classes are collected from both areas (Kramer 1990a, Kramer 1991b). It is found from 1.5 to 84 m (Miller and Lea 1972). Maturing females average 136 mm SL and range from 114 to 155 mm SL (Goldberg 1981). The lower end of this range approximates the size at first maturity for females. No information exists for male size at maturity.

The California tonguefish is a nocturnal feeder, remaining buried in the bottom during the day (Allen 1982). This diel behavior reduces its vulnerability to daytime trawling (DeMartini and Allen 1984).

Methods

The otter trawl length frequency data (mm TL) were used to separate fish into juvenile and age–1+ classes. A 1 January hatch date was assumed for all juveniles, even though data suggests fish were hatched in the previouse calendar year. Monthly cutoff lengths for separation of age–0 from age–1+ fish were: 65, 70, 80, 90, 95, 100, 110, 115, 120, 125, 130, and 135 mm for January to December, respectively. Tonguefish were considered recently settled until ≥40 mm TL. Abundance indices for each age class were based upon February to October monthly indices. Seasonal abundance indices were based upon mean CPUE by month for 1981 to 1988. For seasonal distribution descriptions, monthly CPUE was averaged for 1981 to 1988. These same years were used for salinity, temperature, and channel-shoal analyses. Conversion of standard length (SL) to total length (TL) was accomplished by using the following equation: SL = 0.917 × TL (mm) (Kramer 1990a).

Results

Length Analyses

The plankton net caught 5 juvenile California tonguefish but no larvae (see Table 1). The 4 juveniles caught in February 1983 measured 25, 26, 26, and 41 mm TL, and 1 caught in May 1983 measured 44 mm. The smallest tonguefish in the otter trawl, 34 mm, was collected in February 1992. The only other recently settled fish (36 mm) captured by the otter trawl was taken in February 1994.

Based on length, 2 age classes were common in the estuary (Figure 52). Most juveniles entered the estuary when ≥40 mm. Between March and October, juveniles grew about 7 mm per month (see Figure 52). Because of the timing of juvenile entry and age–1+ emigration both age classes were present coincidentally only from June to August. A 3rd age class, represented by fish >150 mm, was present from March to May, but very few were collected. The largest tonguefish, 186 mm, was taken in March 1983.

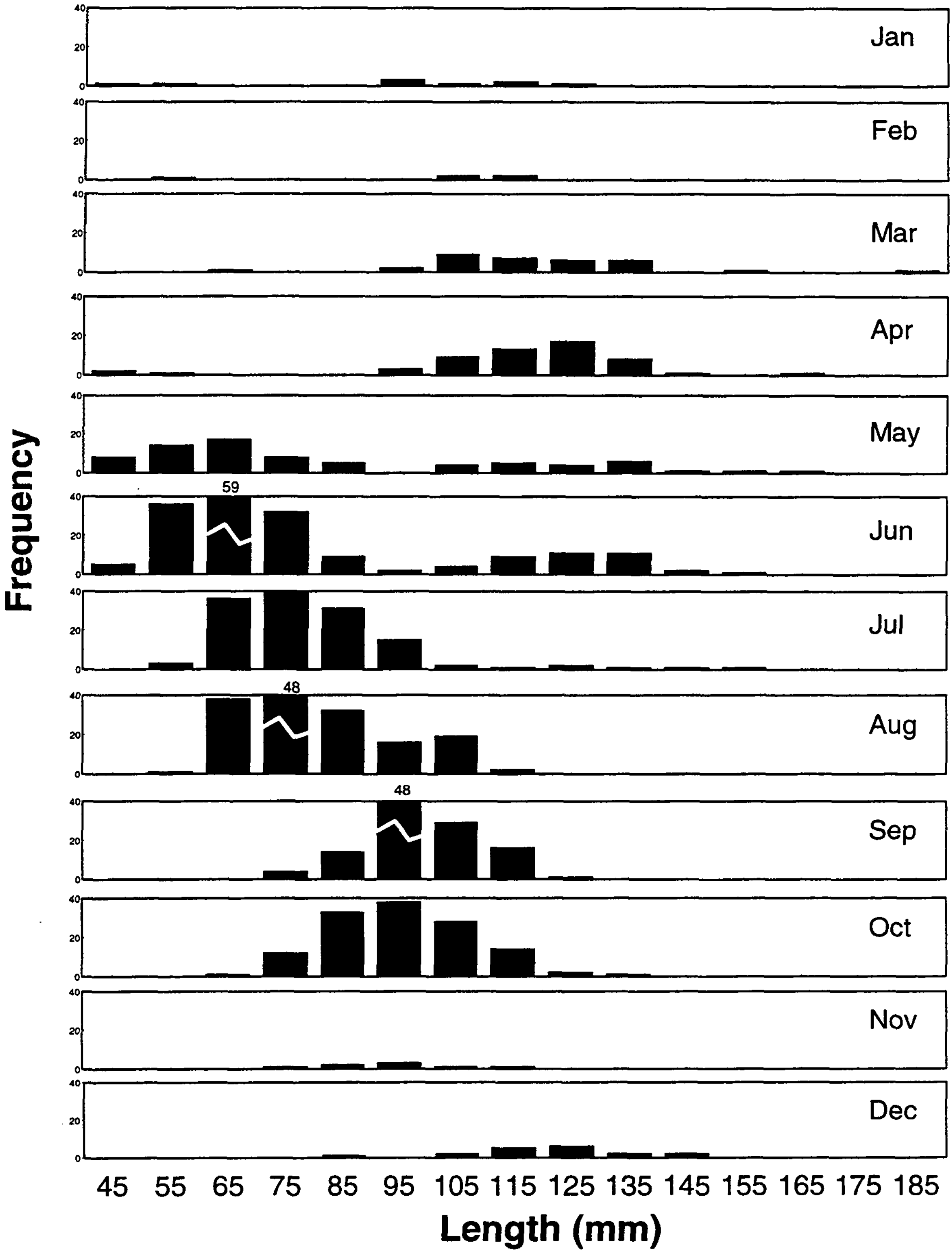

Figure 52 Length frequency (mm TL) by month of California tonguefish collected with the otter trawl from 1981 to 1988. Fish <40 mm were considered recently settled.

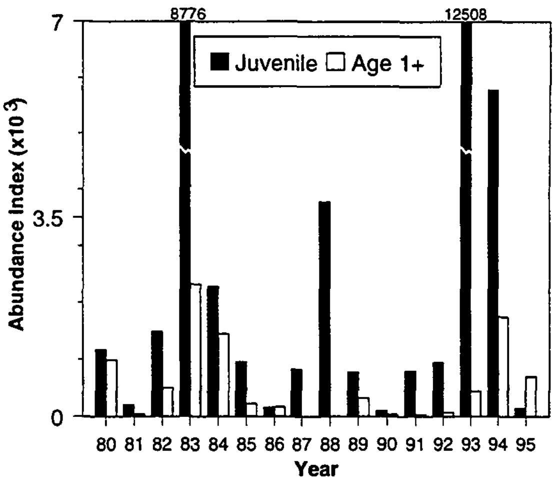

Figure 53 Annual abundance of juvenile and age–1+ California tonguefish collected with the otter trawl from 1980 to 1995. Data are mean February to October abundance indices for both age classes.

Table 21 Monthly abundance of juvenile California tonguefish captured in the otter trawl from 1980 to 1995. Annual abundance indices are in the far right column. Seasonal abundance indices are in the bottom row (mean 1981 to 1988 monthly abundance).

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Feb–Oct*
1980		156	135	0	0	1001	1797	4062	1677	1704	505	0	1170
1981	0	0	0	0	0	0	216	1298	134	243	0	0	210
1982	532	0	0	0	6006	1823	2720	717	3400	4790	216	216	1494
1983	0	0	0	668	1786	20213	13317	26657	1617	16510	1406	2006	8776
1984	0	0	0	0	2757	6858	4866	1417	5605	1758	0	162	2278
1985	0	281	281	0	0	1650	1355	892	2921	1244	0	0	958
1986	0	0	0	0	0	243	688	406	162	0	0	189	167
1987	0	0	0	0	0	0	467	1584	5047	378	435	352	831
1988	0	0	0	219	2432	9492	8496	9288	5638	865	0	557	3778
1989	0	0	0	529	779	748	1001	3187					781
1990		0	0	0	0	219	281	281	0	189			108
1991		0	0	0	438	1392	1695	2807	1007	313			802
1992		375	0	0	2038	4770	2134	0	1248	0			947
1993		0	344	6381	10970	25004	40392	32880	1850	5717			12508
1994		250	297	532	2126	14449	9162	16303	9280	1800			5786
1995	0	0	0	0	831	641	500		0	0	0	0	143
1981–1988	67	35	35	111	0	5035	4016	5282	3066	3224	257	435	

Abundance and Distribution of Juvenile and Age–1+ Fish

Annual Abundance

Juvenile California tonguefish abundance peaked 3 times during the study period: high peaks in 1983 and 1993 to 1994, and a smaller peak in 1988 (Figure 53, Table 21). Minima occurred in 1981, 1986, 1990 and 1995 (see Figure 53). Age–1+ abundance indices followed a pattern much like that of juveniles, but at much reduced levels. They peaked in either the same year as juveniles did (for example, 1983) or in the next year (for example, 1988 and 1993) (see Figure 53, Table 22). No age–1+ fish were caught in 1987 and very few in 1988.

Table 22 Monthly abundance of age–1+ California tonguefish captured in the otter trawl from 1980 to 1995. Annual abundance indices are in the far right column. Seasonal abundance indices are in the bottom row (mean 1981 to 1988 monthly abundance).

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Feb–Oct*
1980		2091	3813	1433	258	1298	0	0	0	0	0	0	988
1981	568	0	0	189	0	0	0	0	0	216	0	0	45
1982	0	0	0	402	3461	379	0	0	0	278	0	0	502
1983	278	402	4361	10808	0	4456	838	0	0	0	0	0	2318
1984	216	0	4793	243	2082	5517	189	0	0	216	0	0	1449
1985	568	216	189	0	0	1298	352	0	0	0	0	0	228
1986	0	162	0	784	0	433	162	0	0	0	0	0	171
1987	0	0	0	0	0	0	0	0	0	0	0	0	0
1988	0	0	0	0	0	0	0	0	115	0	0	651	13
1989	594	625	0	541	189	243	0	657					322
1990		0	379	0	0	0	0	0	0	0			42
1991		0	297	0	0	0	0	0	0	0			33
1992		0	0	0	0	0	0	0	657	0			73
1993		0	0	0	0	0	0	1936	0	2049			443
1994		3972	6986	594	1157	1444	514	344	281	352			1738
1995	649	3229	1777	560	0	0	0		0	0	0	0	696
1981–1988	204	98	1168	1553	693	1510	193	0	14	89	0	81	

Seasonal Abundance

Juvenile California tonguefish entered the estuary post-settlement starting in January, but their abundance was low until June when it increased sharply (Figure 54, see Table 21). Juvenile abundance was high from June to August, then declined through November and remained low in December (see Figure 54). In high abundance years (that is, 1983, 1988, 1993, and 1994), juveniles were consistently collected in April or earlier, whereas in low abundance years (that is, 1981, 1986, 1990, and 1995) they were not collected until May or later (see Table 21). Age–1+ California tonguefish either remained in or returned to the estuary in low numbers in January and February (see Figure 54, see Table 22). Age–1+ abundance increased in March and April, declined in May, increased in June, then declined to zero in August. From September through December, they were rare in the estuary.

Annual Distribution

Juvenile California tonguefish were generally collected from South Bay to San Pablo Bay, but in 1991 their distribution extended into Suisun Bay (Figure 55). Peak CPUE occurred in either South Bay or Central Bay. CPUE was high in San Pablo Bay during 1988 and 1994, both low outflow years. In most low abundance years (for example, 1986, 1990, and 1995), juveniles were not collected in San Pablo Bay and in 1981 they were not collected in South Bay (see Figure 55). Although age–1+ fish were collected in Suisun Bay and San Pablo Bay, they were extremely rare there (Figure 56). Before 1992, adults were abundant in South Bay only in 1983. After 1992, adults became more common in South Bay and were quite abundant in 1994.

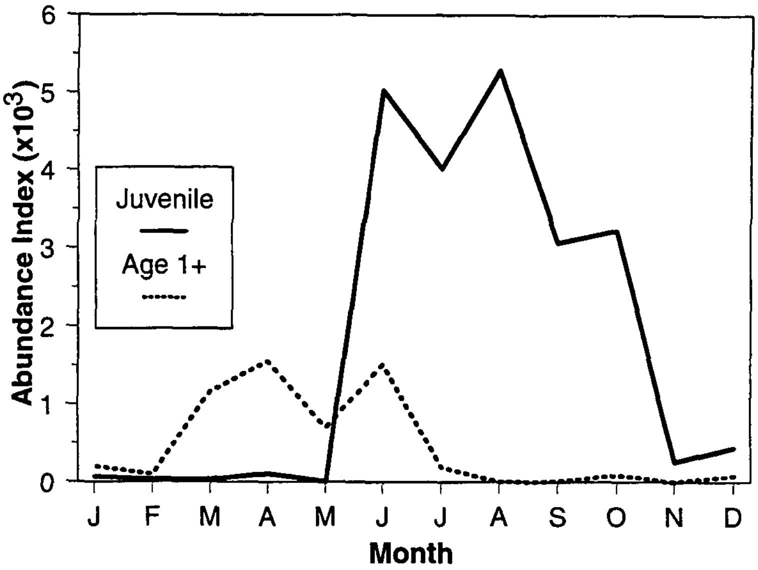

Figure 54 Seasonal abundance of juvenile and age–1+ California tonguefish collected with the otter trawl. Data are mean monthly abundance indices for 1981 to 1988.

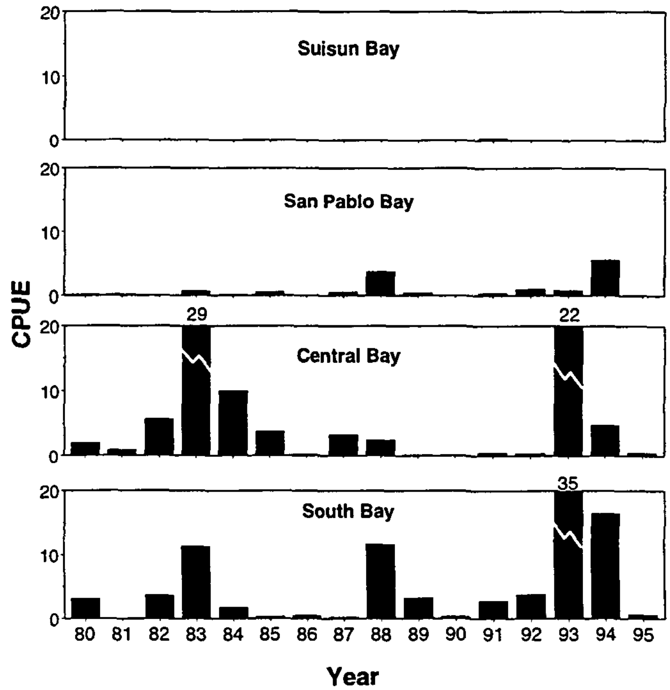

Figure 55 Annual distribution of juvenile California tonguefish collected with the otter trawl from 1980 to 1995. Data are mean February to October CPUE by region.

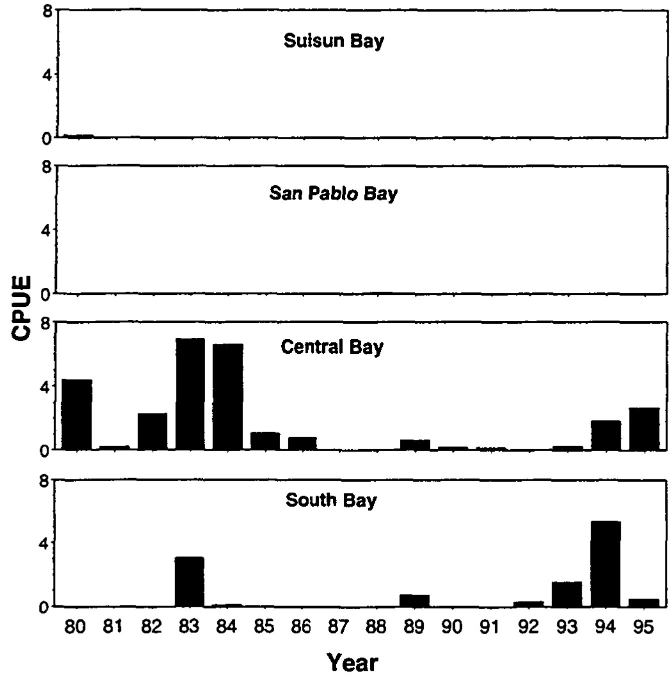

Figure 56 Annual distribution of age–1+ California tonguefish collected with the otter trawl from 1980 to 1995. Data are mean February to October CPUE by region.

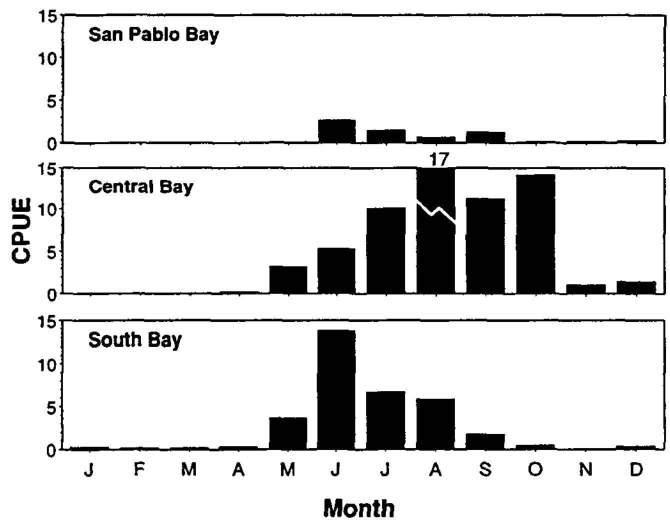

Figure 57 Seasonal distribution of juvenile California tonguefish collected with the otter trawl. Data are mean CPUE by month and region for 1981 to 1988.

Seasonal Distribution

From January through March, juvenile California tonguefish were captured only in South Bay (Figure 57). Beginning in April, CPUE increased in South and Central bays and by May fish entered San Pablo Bay. Juvenile CPUE in South and San Pablo bays increased to a peak in June, then declined to low levels the rest of the year. In Central Bay, juvenile CPUE continued to increase until August and remained high from August through October before declining rapidly in November and remaining low in December.

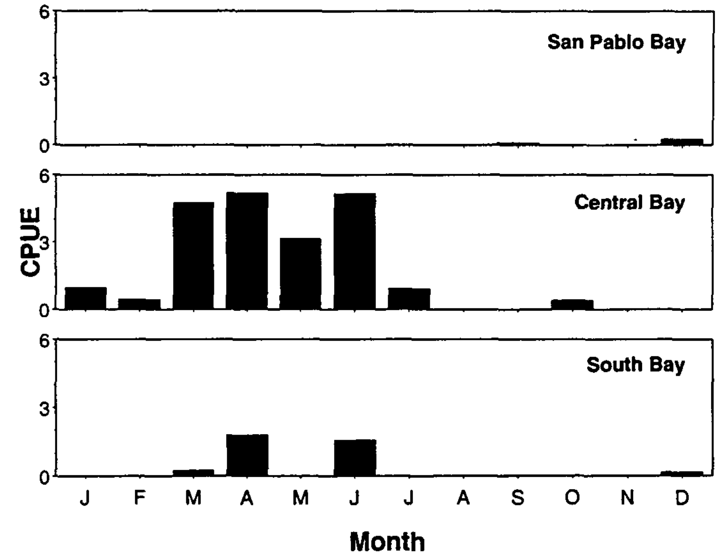

Figure 58 Seasonal distribution of age–1+ California tonguefish collected with the otter trawl. Data are mean CPUE by month and region for 1981 to 1988.

In January and February, age 1+ California tonguefish were present only in Central Bay (Figure 58). In March, CPUE increased in Central Bay and to a lesser degree in South Bay. CPUE remained relatively high in Central Bay and low in South Bay from March to June and then declined in both regions. After July, age–1+ tonguefish were rare in the estuary.

From January to March, the few juvenile California tonguefish collected were in channels (Figure 59). Beginning in April and continuing to July, juveniles inhabited both channels and shoals but favored the channels. Higher shoal use in August was an anomaly resulting from a single high catch at a relatively deep (9 m) shoal station (#211) in August 1983. When most juveniles emigrated from San Pablo and South bays in September and October, the use of channels increased sharply (see Figure 59). In November and December, the few remaining juveniles were more evenly distributed, but still favored channels.

The depth distribution of age–1+ California tonguefish in January and February was similar to that of juveniles during the previous November and December (see Figure 59). From March to June, when abundance was high most age–1+ fish were collected in channels. From July through November the few remaining age–1+ fish were caught at channel locations. In December, a few age–1+ fish were again collected from both channel and shoal locations.

Juvenile California tonguefish were collected at salinities from 12.6‰ to 34.3‰. During their estuarine immigration period (April to June), juvenile tonguefish were collected over a broad salinity range of 12.6‰ to 31.6‰ and monthly means of 24.3‰, 22.4‰, and 23.9‰ (Figure 60). From June to October, juveniles inhabited progressively more saline water as estuarine salinity increased as outflow decreased seasonally (see Figure 60), and also as juveniles moved to Central Bay (see Figure 57). In October, juveniles inhabited salinities ranging from 27.4‰ to 34.2‰ and a mean of 31.8‰. By December, juveniles were again collected from salinity as low as 19.8‰ and a mean of 24.1‰.

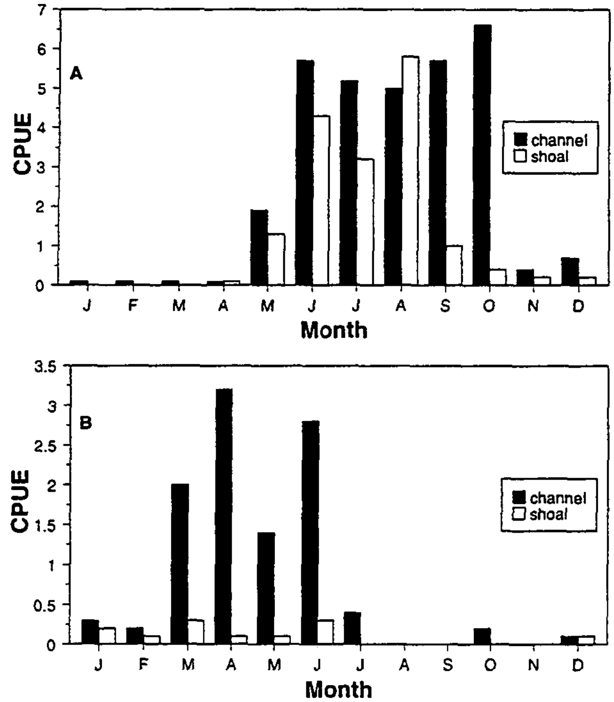

Figure 59 Depth distribution (shoal and channel) of (A) juvenile and (B) age–1+ California tonguefish collected with the otter trawl. Data are mean CPUE by month for 1981 to 1988.

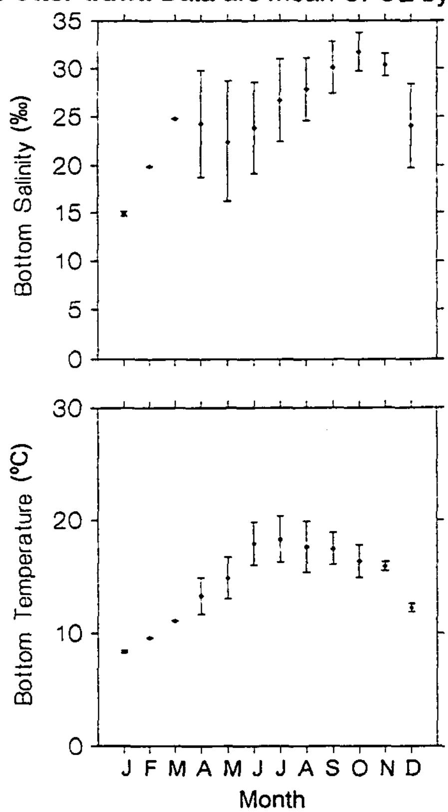

Figure 60 Salinity (‰) and temperature (ºC) distributions of juvenile California tonguefish collected with the otter trawl. Data are mean (±1 standard deviation) CPUE-weighted bottom salinity and temperature by month for 1981 to 1988.

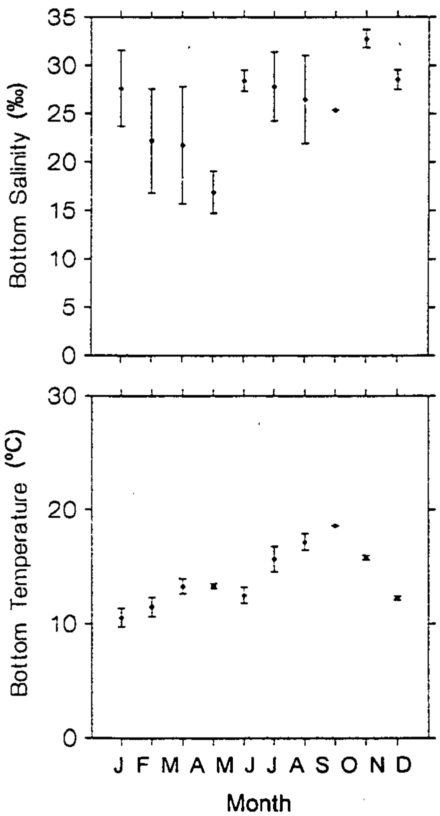

Figure 61 Salinity (‰) and temperature (°C) distributions of age–1+ California tonguefish collected with the otter trawl. Data are mean (±1 standard deviation) CPUE-weighted bottom salinity and temperature by month for 1981 to 1988.

The mean monthly temperature juveniles were found in ranged from 8.4 °C in January to 18.3 °C in July (see Figure 60). Temperature increased steeply from January to June but was fairly stable from June to October, and declined sharply in December. Their overall temperature range was from 8.3 to 22.4 °C.

Age–1+ California tonguefish were collected at lower salinity and from a narrower temperature range than juveniles: 5.4‰ to 33.7‰ and 9.6 to 18.6 °C. The age–1+ salinity distribution was initially high in January ($\bar{\chi}$ = 27.6‰) and declined to April ($\bar{\chi}$ = 16.9‰), reflecting the delay between outflow and the salinity response in Central Bay. In particular, their salinity distribution was strongly influenced by high outflow in 1983 when bottom salinity was depressed throughout the estuary from February to May (see Salinity and Temperature chapter, Figures 1 through 5). From May to July, mean salinities ranged from 26.5‰ to 28.4‰ (Figure 61). From January through March, the age–1+ fish were found in increasingly warm water: means ranged from 10.5 to 13.3 °C (see Figure 61). In April and May, mean temperature remained stable between 12.5 to 13.5 °C, before increasing from June to peak in September of 18.6 °C. During the later period very few age–1+ fish remained in the estuary (see Figure 58).

Discussion

California tonguefish used the estuary as a nursery and feeding area, entering as 40 to 80 mm juveniles, and dispersing onto shoals during summer, then moving to channels in fall and, for some, temporarily out of the estuary during winter. Cooling water temperatures may have stimulated a migration to warmer coastal waters in November and December. Low winter abundance may also have resulted from low activity (low catchability) in the cool water. Presumably fish remain buried in the substrate when not foraging, and most foraging occurs at night (Allen 1982).

Most California tonguefish left the estuary after their 1st summer or before completing their 2nd summer of residence. Emigration during their 2nd summer may be a spawning migration based upon the size of age–1 fish May to July (this study), female size at maturity (Goldberg 1981), and their May to October spawning period (Goldberg 1981, Kramer 1990a, Kramer 1991b). A few post-spawning fish returned during the next winter and spring as age–2 fish, but the estuary did not appear to be their principal habitat.

Elsewhere, the California tonguefish uses inshore waters similarly to that of the San Francisco Estuary. In southern California, tonguefish settle on the open coast at depths ≥9 m from fall through early spring, move to shallow (3.5 to 5 m) bay waters at 51 to 100 mm SL (56 to 109 mm TL) in summer, and then move to deeper water as they grow beyond 100 mm SL (Kramer 1990a, Kramer 1991b). Although they inhabit bays during other seasons, fish >101 mm SL are most common on the open coast during summer (Kramer 1990a, Kramer 1991b). Since this author separated fish into 50-mm size groups, it was not possible to determine a more precise length at emigration. In the estuary, juvenile tonguefish appeared to emigrate at 110 to 120 mm, or by November, based upon the reduced catch.

The abundance of juvenile tonguefish in the estuary appeared to be partly a function of fall and winter water temperature. The center of the California tonguefish distribution is considered to be the San Diegan Faunal Region (Allen 1982 in Kramer 1990a); thus, tonguefish in the estuary are near the historic northern limit of their range (Roedel 1953). Moreover, tonguefish spawning and early larval periods coincide with peak water temperatures in southern California (Walker and others 1987), suggesting a link between water temperature and the abundance of tonguefish at the northern end of their range. Increased abundance occurred during 1983, 1988, 1993, and 1994; each increase occurred after a year with higher than average fall sea-surface temperatures (see Salinity and Temperature chapter, Figure 11).

A 2nd factor apparently influencing California tonguefish abundance was northward transport of eggs and larvae. In October, at the end of the tonguefish spawning period, the northward Davidson current begins to flow and by January the current reached speeds of 0.2 knot (288 km per month) (Reid and Schwartzlose 1962, Wyatt and others 1972). Based upon a size at settlement similar to or larger than that of the English sole, tonguefish larvae should remain pelagic for more than 2 months, allowing about 575 km of northward transport for fall-spawned larvae before settlement. During extreme conditions considerably longer transport distances can occur. Anomalous warm ocean temperatures and strong downwelling during fall 1982 and winter 1983 (Norton and others 1985) were responsible for the >400 km range extension of tonguefish in 1983 (Dinnel and Rogers 1986). These same processes resulted in increased abundance in the San Francisco Estuary. The 2 El Niño events in 1982–1983 and 1992–1993, produced strong, positive, fall to winter temperature anomalies, strong to moderate Davidson currents (Norton and others 1985), and the 2 largest tonguefish year classes recorded (see Figure 53). Other, more moderate, temperature anomalies (not El Niño conditions) also resulted in increased abundance: 1979–1980, 1983–1984, 1987–1988 and 1993–1994 (compare Salinity and Temperature chapter Figure 11 with Figure 53). Thus, increased local ocean temperatures lead to increased abundance, possibly through local spawning and recruitment, but the largest year classes resulted from increased temperatures and strong northward transport of eggs and larvae.

Once in the estuary, California tonguefish inhabited intermediate to deep waters (primarily channel stations) in the mostly euhaline conditions of Central Bay and northern South Bay. Although juveniles and adults were captured in mesohaline waters there was no indication that they sought these conditions. On the contrary, capture at low salinity occurred in Central and South bays (normally euhaline) only during extremely high outflow conditions. Their persistent capture in low salinity water suggests some tolerance for it and no mechanism to avoid it.

Uncommonly Collected Flatfish Species

Pacific sanddab, *Citharichthys sordidus,* range from Cape San Lucas, Baja California northward to the Bering Sea, and reach a maximum size of 406 mm (Miller and Lea 1972). Due to their relatively small size, Pacific sanddabs are not as important commercially as other flatfish, nonetheless, they are highly prized by commercial and recreational fishers for their excellent taste (Leos 1992b). In the estuary, 26 Pacific sanddabs were collected between 1980 and 1995, all in the otter trawl (see Table 1). These fish ranged from 36 to 284 mm and all were larger than 159 mm (except for 1 at 36 mm). Almost all were collected from Central Bay (25 of 26) and from January through April (23 of 26). Thus, older juvenile and young adult Pacific sanddabs inhabit the polyhaline and euhaline portions of the estuary during the cooler months, but the estuary is not prime habitat for them.

Sand sole, *Psettichthys melanostictus,* range from Port Hueneme to the northern Gulf of Alaska, and reach a maximum length of 533 mm (Miller and Lea 1972). In the estuary, sand sole from 2.7 (yolk sac larvae) to 453 mm were collected. All the larvae ($n = 20$) were collected from February through May and recently settled fish (15 to 30 mm, $n = 7$) were taken from April to August, with an additional fish caught in October. Seventy-nine juvenile and adult sand sole were collected during the study period, primarily in the otter trawl (see Table 1). Annual catch (February to October) varied from 0 in 1988 to 10 in 1993. Catch in all other years varied between 1 and 6. About 64% of the sand sole collected in the otter trawl ($n = 70$) came from Central Bay, 12% from South Bay, 17% from San Pablo Bay, and 7% from Suisun Bay. The small number of larvae collected indicates that sand sole spawning takes place on the open coast. Near Yaquina Bay, Oregon, nearshore, coastal spawning was indicated based upon larval densities (Pearcy and Myers 1974, Richardson and Pearcy 1977). Sand sole of all ages use the estuary as an extension of their coastal habitat.

Curlfin sole, *Pleuronichthys decurrens,* range from San Quintin Bay, Baja California, northward to northwest Alaska, and reach a maximum size of 368 mm (Miller and Lea 1972). One hundred and twenty-one curlfin sole ranging in length from 36 to 188 mm were collected in the estuary with the otter trawl (see Table 1). About 81% of the catch came from the deepwater station #213, and an additional 16% from Central Bay channel stations #110, #214 and #215. There was no seasonal pattern to their capture, but there was an annual pattern. Before 1992, annual catch (February to October) varied from 0 in 1981 to 4 in 1985; subsequently, annual catch was 14, 34, 20, and 7 for 1992 to 1995, respectively. Juvenile curlfin sole habitat appears to be in the deepest stations in Central Bay.

Only single individuals of several other species have been captured (see Table 1). A 109 mm C-O sole, *Pleuronichthys coenosus,* was caught at station #105 in January 1987. A single larval hornyhead turbot, *Pleuronichthys verticalis,* was caught at station 211 in July 1987. A single hybrid sole, *Inopsetta ischyra,* at 120 mm was taken at station #214 in October 1990. This form is considered a hybrid cross between the English sole and the starry flounder rather than a true species (Miller and Lea 1972). The specimen was right-eyed, had the body shape (that is, a pointed head and 1 eye visible from the blind side) and olive tan coloration of an English sole, but distinct, alternating light tan and dark gray bands similar to a starry flounder. Fin ray counts were dorsal 68, anal 54, caudal 18, pelvic 6, and pectoral on the blind side 11. The dorsal ray count is intermediate to counts for the English sole and the starry flounder (Miller and Lea 1972).

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Notes

Marissa Kendall (San Francisco State University, MS student). Letter including draft tables from thesis. April 1991.

Bob Spies (Lawrence Livermore Laboratory). Phone conversation with author. February 1992.

Brian Sak (City of San Francisco Bureau of Water Pollution Control). Phone conversation with author. September 1994.

Miscellaneous Species

Randall Baxter

Brown Rockfish

Introduction

The brown rockfish, *Sebastes auriculatus*, is a demersal, marine fish, which ranges from Hipolito Bay, Baja California, to southeast Alaska (Miller and Lea 1972). It is found from the subtidal zone to 55 m, and grows to about 550 mm TL (Miller and Lea 1972). It is a minor component of sport fisheries in San Francisco Bay and offshore and of commercial fisheries along the coast (Adams 1980).

Both males and females reach maturity as early as age 3 at 260 mm TL. Half reach maturity at age 5 at 310 mm TL, and some mature as late as age 10 at 380 mm TL (Wyllie–Echeverria 1987). Brown rockfish can live to 19 years and possibly longer (Wyllie–Echeverria 1987, Stein and Hassler 1989). Fertilization is internal and larvae hatch within the ovary and are released at the 1st feeding stage during winter and early spring (Kendall and Lenarz 1986, Wang 1986). Multiple broods in 1 year are possible (Willie–Echeverria 1987). Although some gravid females are found in San Francisco Bay, most parturition is believed to occur in coastal waters (Kendall and Lenarz 1986, Wang 1986). The larvae and early juveniles are pelagic, whereas older juveniles settle out of the water column and are found in association with structure near the bottom (Turner and others 1969, Feder and others 1974). San Francisco Bay appears to be an important habitat for juvenile brown rockfish, which enter it and remain within a limited "territory" for several years before moving to deeper water and offshore (Kendall and Lenarz 1986).

Methods

A January 1 birth date was assigned to all age–0 fish, which were separated from age–1+ fish by an examination of the length frequencies. Cutoff lengths (minimum size of age–1+ fish) for the separation of age–0 and age–1+ fish were set at 30, 35, 45, 55, 65, 75, 85, 90, 98, 102, 106, and 110 mm TL for January to December, respectively. Most brown rockfish were collected in the otter trawl, so only otter trawl data were analyzed for this species. April to October and February to October index periods were used for age–0 and age–1+ life stages, respectively. No corrections were made for missing 1989 data.

Results

Catch and Length

Most brown rockfish were taken in the otter trawl: 1,165 fish ranging from 31 to 340 mm TL. Twelve brown rockfish, 34 to 72 mm TL, were caught in the beach seine, and 19 from 29 to 92 mm TL were taken in the midwater trawl. Only 3 unmeasured larvae and 1 juvenile of 36.5 mm TL were collected by the plankton net. The length data for 1981 to 1988 show that 3 age groups (age 0, age 1, and age 2), were present in the estuary (Figure 1).

Annual Abundance

Abundance of age–0 brown rockfish was highest in 1993 and much lower in all other years (Figure 2, Table 1). None were collected during the April to October index period in 1983, 1992, and 1995. No trend was apparent and no relationship with water year type existed.

Age–1+ brown rockfish showed an annual abundance pattern similar to that of age–0 fish. The abundance of age–1+ fish was highest in 1994 and 1995, much lower in all other years, and showed no trend or relationship with water year type (see Figure 2, Table 2).

Seasonal Abundance

The month when age–0 fish were first captured varied greatly, ranging from April to November (Figure 3, see Table 1). Seasonal abundance varied annually but age–0 fish were usually present from at least June to September (see Table 1). On the average, abundance was highest in August. The high December abundance (see Figure 3) was due to late and high immigration in 1983, when age–0 fish did not appear until November (see Table 1).

The monthly mean abundance of age–1+ fish peaked in March and June but there were wide variations from year to year (see Figure 3, see Table 2).

Annual Distribution

Age–0 brown rockfish ranged from South Bay to San Pablo Bay in most years and in 1984 they reached Suisun Bay (Figure 4). The CPUE was most often highest in Central Bay and in some years was highest in San Pablo Bay or South Bay. Distribution did not appear to be related to water year type.

Although age–1+ brown rockfish ranged from South to San Pablo bays, the CPUE was much higher in Central Bay than in other regions (Figure 5). Age–1+ fish were collected in San Pablo Bay only in 1981, and in South Bay only from 1980 to 1984, and again in 1994 and 1995.

Seasonal Distribution

The seasonal distribution of age–0 brown rockfish was irregular. In April, May, and June, when age–0 fish were first entering the estuary or were just large enough for capture in the otter trawl, they ranged from South Bay to San Pablo Bay (Figure 6). They were found in Suisun Bay only in July 1984, a month after high CPUE occurred in San Pablo Bay. On the average, CPUE in San Pablo Bay declined after July and was low or 0 for the rest of the year. The South Bay CPUE increased later in the year than that of San Pablo Bay and remained relatively high through October. Data from 1980, 1985, 1988, and 1991 show that the increase in Central Bay CPUE in November and December coincided with a CPUE decline in South Bay and to a lesser degree in San Pablo Bay (see Figure 6).

Most age–1+ brown rockfish remained in Central Bay all year (Figure 7). Age–1+ fish were in South Bay from midwinter through summer and San Pablo Bay only in February 1981.

Soon after they first appeared in the estuary from April to June, age–0 brown rockfish were found mainly in shoal areas, a distribution that persisted until November (Figure 8). By December, all age–0 fish had moved to channels. Age–1+ fish were found only in channels, except from February to May and again in October when a few were captured at shoal stations.

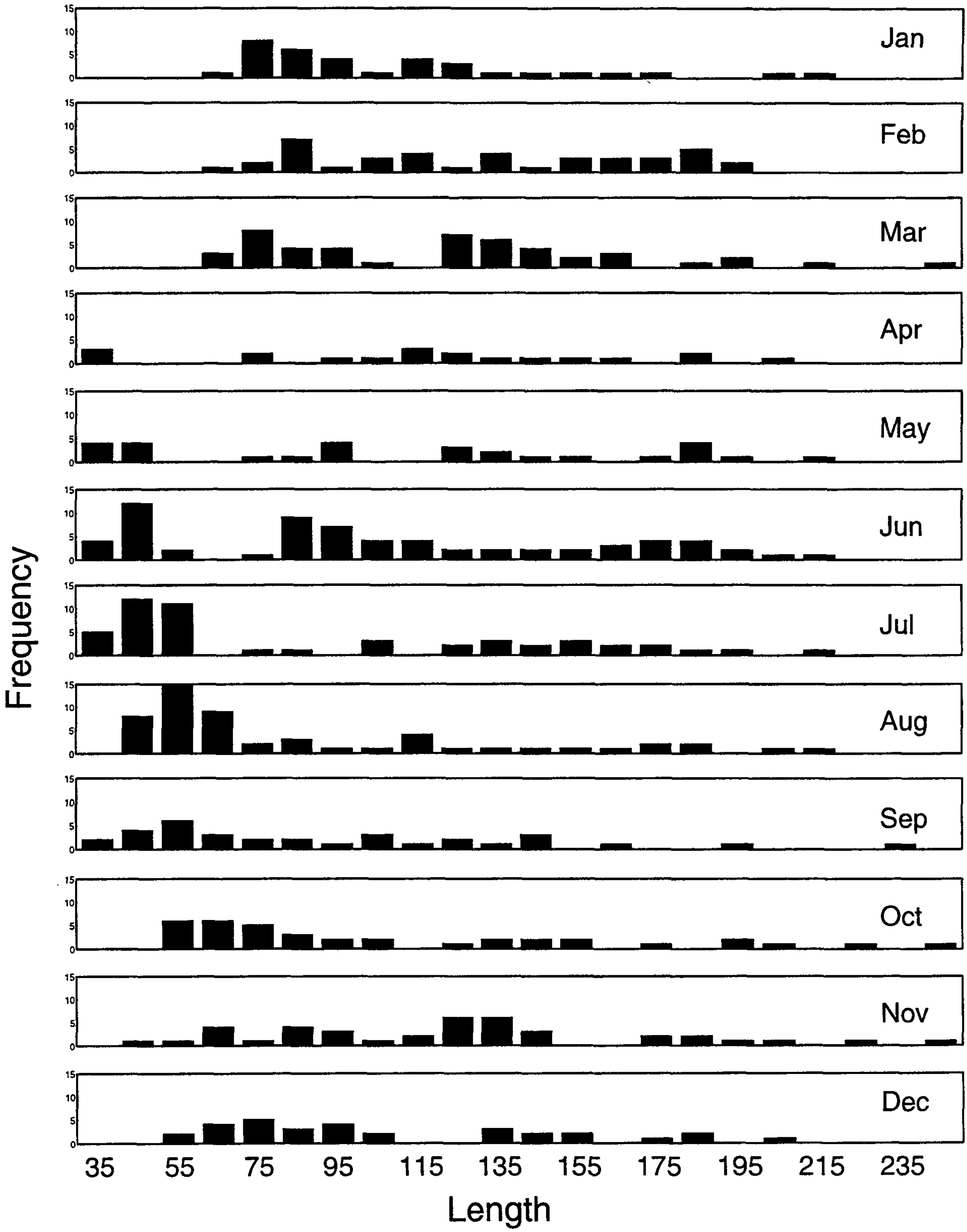

Figure 1 Length frequency (mm TL) by month of brown rockfish collected with the otter trawl from 1981 to 1988. Fish at 268 and 340 mm are not shown.

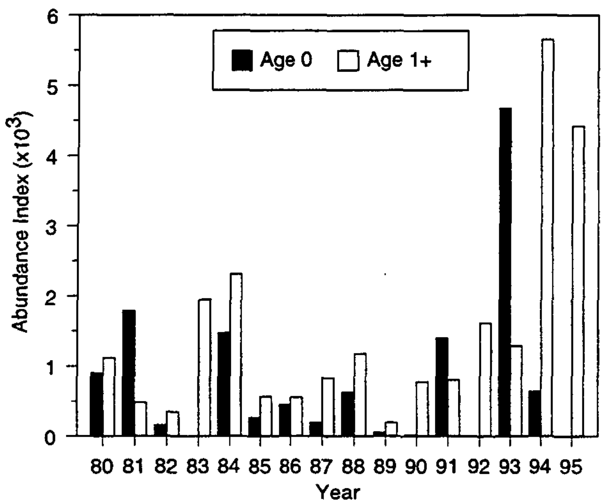

Figure 2 Annual abundance of age–0 and age–1+ brown rockfish from the otter trawl from 1980 to 1995. Data are the means of April to October and February to October monthly indices, respectively.

Table 1 Monthly abundance of age–0 brown rockfish captured in the otter trawl from 1980 to 1995. Annual abundance indices are in the far right column. Seasonal abundance indices are in the bottom row (mean 1981 to 1988 monthly abundance).

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Apr–Oct*
1980		0	0	154	0	134	3124	2150	154	572	469	216	898
1981	0	0	0	0	0	532	4299	2663	979	4078	406	156	1793
1982	0	0	0	219	497	134	0	0	262	0	625	134	159
1983	0	0	0	0	0	0	0	0	0	0	243	6639	0
1984	0	0	0	0	0	1452	975	5747	1753	408	162	703	1476
1985	0	0	0	0	0	115	324	189	269	985	460	0	269
1986	0	0	0	0	0	1205	802	750	438	0	469	189	456
1987	0	0	0	0	0	0	525	606	0	216	1514	919	192
1988	0	0	0	583	1219	622	344	487	1163	0	0	0	631
1989	0	0	0	0	281	0	0	0					56
1990		0	0	0	0	173	0	0	0	0			25
1991		0	0	189	344	622	2846	2094	2423	1271			1398
1992		0	0	0	0	0	0	0	0	0			0
1993		0	0	0	0	5526	17002	5755	1517	2932			4676
1994		0	0	0	325	297	1190	838	1866	0			645
1995	0	0	0	0	0	0	0		0	0	0	0	0
1981–1988	0	0	0	100	215	508	909	1305	608	711	485	1093	

Table 2 Monthly abundance of age–1+ brown rockfish captured in the otter trawl from 1980 to 1995. Annual abundance indices are in the far right column. Seasonal abundance indices are in the bottom row (mean 1981 to 1988 monthly abundance).

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Feb–Oct*
1980		721	1103	2299	865	0	2650	1109	1325	0	721	1607	1119
1981	1758	857	1244	0	1385	0	216	278	0	406	0	0	487
1982	2298	0	0	219	714	1623	0	0	0	618	0	340	353
1983	688	185	3256	696	649	2054	8681	594	811	622	243	8545	1950
1984	216	2954	5895	1219	811	6925	1109	1758	0	162	0	0	2315
1985	1336	1028	541	0	216	703	0	622	433	1568	2596	0	568
1986	243	0	162	352	0	3705	811	0	0	0	406	0	559
1987	0	1677	1325	892	865	379	1001	325	1055	0	2245	784	835
1988	2380	4922	865	379	919	297	0	1433	1487	270	649	0	1175
1989	0	1163	0	216	0	0	0	0					197
1990		541	1947	2136	1623	216	270	0	297	0			781
1991		568	297	0	1433	2136	865	919	433	595			805
1992		2623	1866	4570	2758	1568	0	865	325	0			1619
1993		865	2136	2921	2731	622	1325	433	0	568			1289
1994		3358	9179	4558	5825	11845	4273	4874	6328	649			5654
1995	3743	3624	22426	865	1839	1055	2136		2975	460	216	1136	4423
1981–1988	1115	1453	1661	470	695	1961	1477	626	473	456	767	1209	

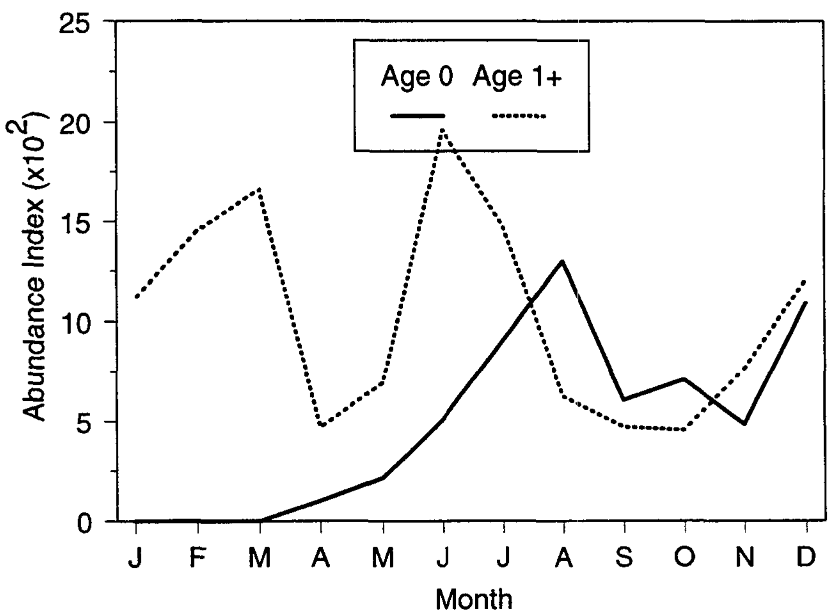

Figure 3 Seasonal abundance of age–0 and age–1+ brown rockfish collected with the otter trawl. Data are mean abundance by month from 1981 to 1988.

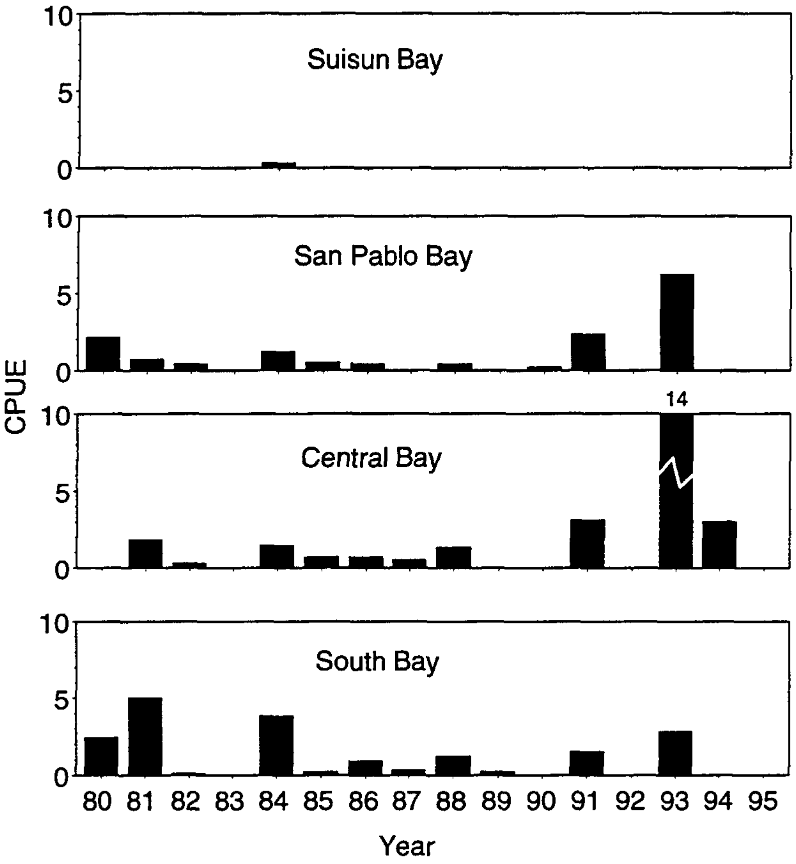

Figure 4 Annual distribution of age–0 brown rockfish collected with the otter trawl from 1980 to 1995. Data are mean CPUE by region for April to October. None were captured in the west delta.

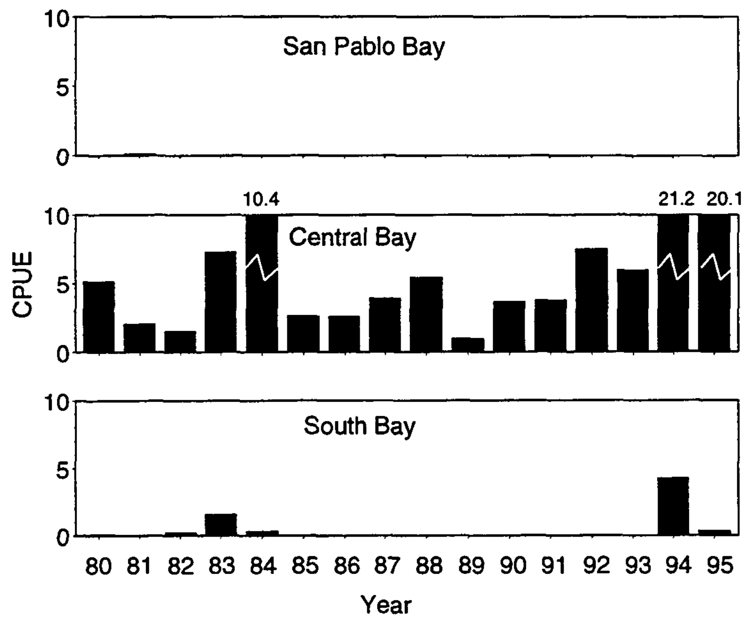

Figure 5 Annual distribution of age–1+ brown rockfish collected with the otter trawl from 1980 to 1995. Data are mean CPUE by region for February to October. None were captured in Suisun Bay or the west delta.

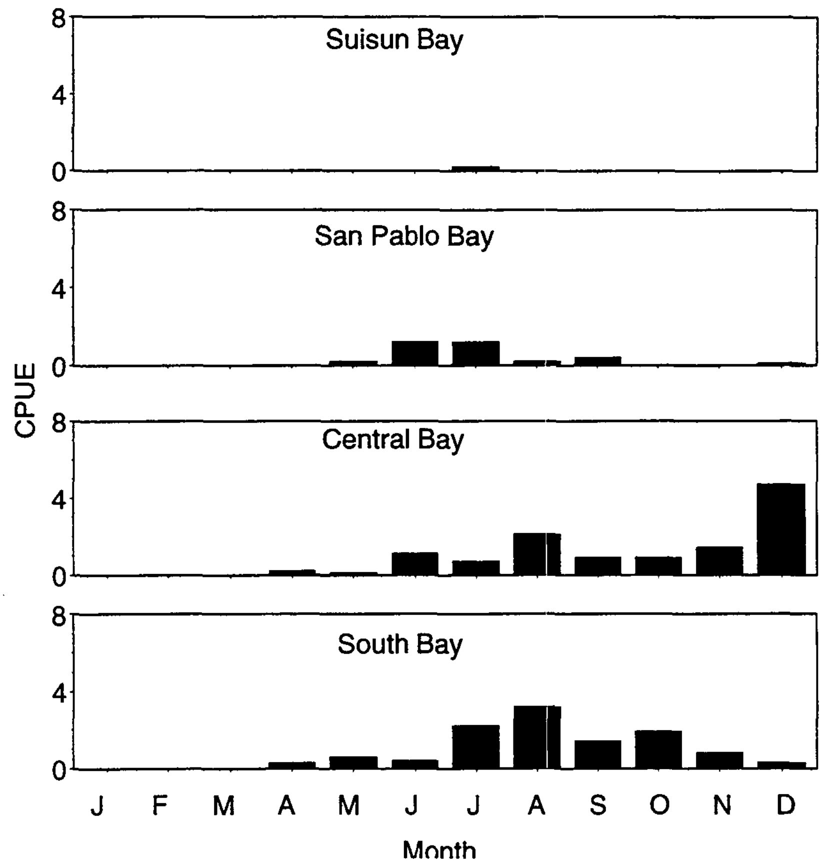

Figure 6 Seasonal distribution of age–0 brown rockfish collected with the otter trawl. Data are mean CPUE by region for 1981 to 1988. None were captured in the west delta.

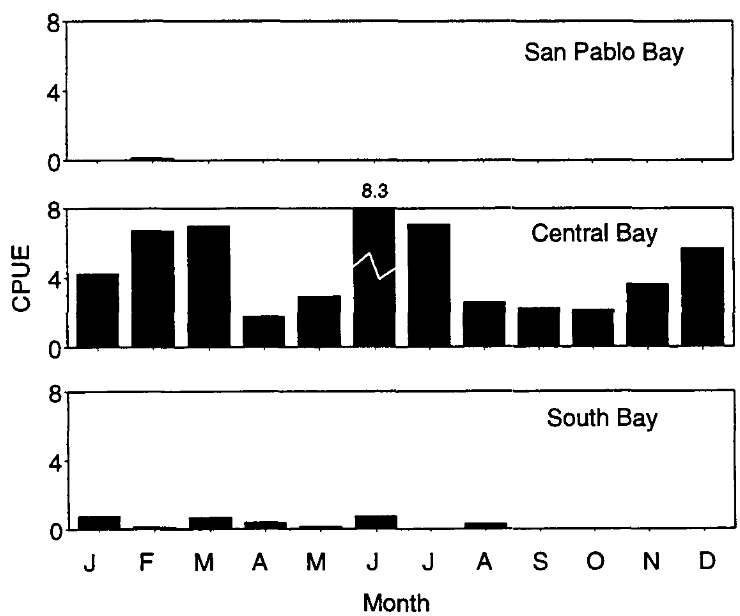

Figure 7 Seasonal distribution of age–1+ brown rockfish collected with the otter trawl. Data are mean CPUE by region for 1981 to 1988. None were captured in Suisun Bay or the west delta.

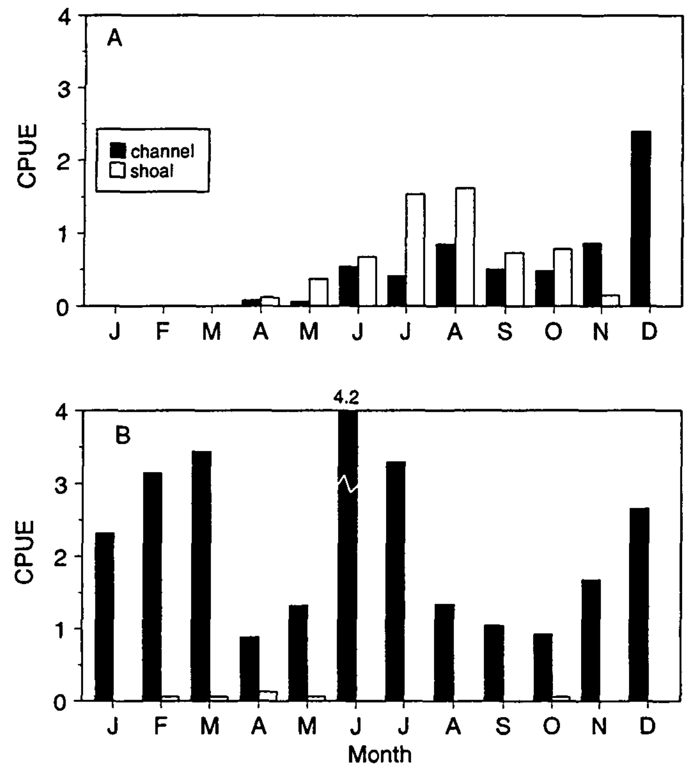

Figure 8 Depth distribution (shoal and channel) of (A) age-0 and (B) age-1+ brown rockfish collected with the otter trawl. Data are mean CPUE by month and age group for 1981 to 1988.

Salinity and Temperature

Both age–0 and age–1+ brown rockfish were primarily found in salinities >20‰, yet changes in monthly mean salinity still reflected seasonal changes in the estuary (Figures 9 and 10). For age–0 fish, salinity means increased from a minimum of 26.4‰ in April to a maximum of 32.9‰ in October, before declining to 29.0‰ in December (see Figure 9). Age–1+ fish, though found in salinity ranges similar to age–0, were caught earlier in the year and their salinity means (24.1‰, 27.6‰, 23.6‰, and 24.3‰ from January to April) reflected reduced Central Bay salinity in winters of 1983 and 1984 (see Figure 10). As estuarine salinity increased from May to July, mean salinity for age–1+ fish increased to about 31‰ then remained at that level through the rest of the year.

Except for July, monthly temperature means for age–0 and age–1+ brown rockfish closely approximated one another for months when both groups were present and varied with the seasonal patterns in the estuary (see Figures 9 and 10). The temperature means for age–0 fish increased from 14.2 °C in April to a maximum of 19.5 °C in July before declining to a minimum of 13.0 °C in December (see Figure 9). In January, the temperature mean of age–1+ fish was at a minimum of 9.4 °C (see Figure 10). They were found in increasingly warm water through August when the mean reached a maximum of 18.7 °C before declining to 13.3 °C in December.

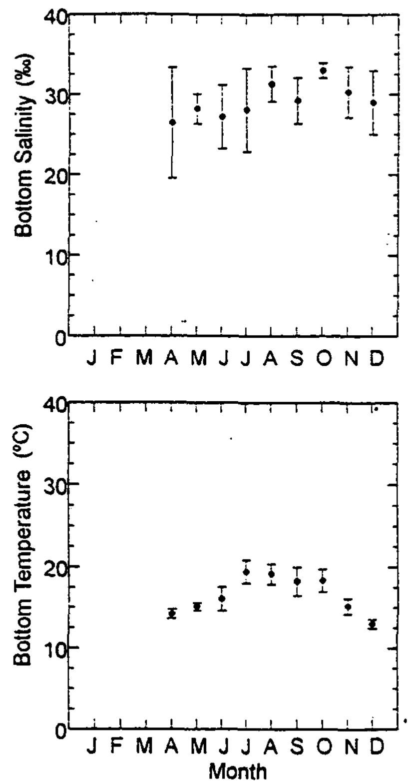

Figure 9 Salinity (‰) and temperature (°C) distributions of age–0 brown rockfish collected with the otter trawl. Data are mean ±1 standard deviation CPUE-weighted bottom salinity and temperature by month for 1981 to 1988.

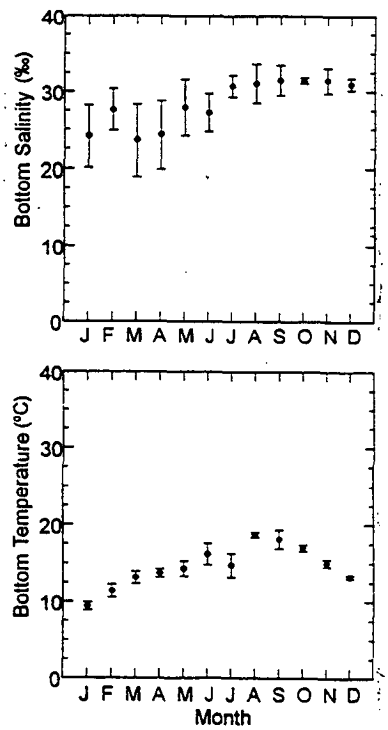

Figure 10 Salinity (‰) and temperature (°C) distributions of age–1+ brown rockfish collected with the otter trawl. Data are mean ±1 standard deviation CPUE-weighted bottom salinity and temperature by month from 1981 to 1988.

Discussion

Brown rockfish reproduce primarily on the open coast—fish <34 mm were rarely caught in the estuary—and age–0 fish immigrate to the estuary and use it as a nursery area (Kendall and Lenarz 1986, this study). They remain in the estuary for 1 to 2 years before migrating to the open coast to complete their life cycle (Kendall and Lenarz 1986, this study). The sporadic abundance and distribution of both age classes probably did not reflect their true abundance and distribution, but was caused by the difficulty in sampling with an otter trawl around their preferred habitat: rocks, pilings, and other bottom structures. The seasonal changes in age–1+ abundance (see Figure 3) may be caused by a change habitat in response to environmental conditions. Declining salinity during winter and early spring may cause fish to move from shallow water habitat, where they are protected by structure, to deeper, open water habitats where salinity is higher but they are more vulnerable to the otter trawl. Likewise, the summer abundance peak may result from increased vulnerability either as fish move to deeper, cooler water as temperature rises or as fish emigrate from the estuary.

The age–0 index is probably also biased because some age–0 fish may have been caught either before settlement, when entering the estuary post-settlement, or when moving between areas. Regardless of the potential biases, the data substantiate the claims of Kendall and Lenarz (1986) that brown rockfish use the estuary as a nursery area.

The differences in the salinity and temperature distributions of the age groups reflects the presence of age–1+ fish in the estuary during winter, whereas age–0 fish were generally not caught until late spring or summer when both salinity and temperature had increased. As was the case for other "marine" species such as speckled sanddab, age–0 fish had a broader geographic range than age–1+ fish.

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Pacific Pompano

Introduction

The Pacific pompano, also called the Pacific butterfish, *Peprilus simillius*, is a schooling, pelagic, marine fish, which is found from Magdalena Bay, Baja California, northward to the mouth of the Fraser River, British Columbia (Miller and Lea 1972). It reaches a maximum size of about 280 mm TL and generally inhabits depths between 9 and 90 m (Miller and Lea 1972). It is not taken very often by anglers and because of its small size is not commercially important.

Age at maturity is not known. Spawning probably takes place from spring through midsummer in coastal marine waters (Fitch and Lavenberg 1971, Goldberg 1980, Walker and others 1987). Eggs and larvae are pelagic and are found in both inshore and offshore coastal waters (Gruber and others 1982). Juveniles and adults form small, dense schools and inhabit inshore coastal areas (Fitch and Lavenberg 1971).

Methods

Age classes were not clearly distinguishable in length frequency distributions, so all fish were treated as a single group. Annual abundance indices were calculated as the average of February through October monthly midwater trawl indices without correction for months when no sampling occurred (for example, February, March, and August 1995). No index was calculated for 1994 due to insufficient sampling. Distribution analyses were based on midwater trawl CPUE averaged for February to October for annual distribution and for 1981 to 1988 for seasonal distribution. Salinity and temperature statistics were calculated from CPUE-weighted mean profile measurements, also for the period 1981 to 1988.

Results

Catch and Length

Most Pacific pompano (1,461 fish) were collected in the midwater trawl. They ranged from 62 to 201 mm FL (Figure 1). Only 19 fish from 87 to 177 mm FL were caught with the otter trawl, and none were caught in the beach seine or the plankton net. The length frequency data indicates that at least 2 year classes were present. One year class had abundance modes between 90 and 110 mm FL and was present between April and August. The other year class had modes >130 mm FL and was present in all months except December.

Annual Abundance

Pacific pompano were collected in all years except 1985. The annual abundance indices had 3 modes: a small one in 1981, the highest mode in 1992, and an intermediate one in 1995 (Figure 2, Table 1). Abundance was usually higher in years after 1986.

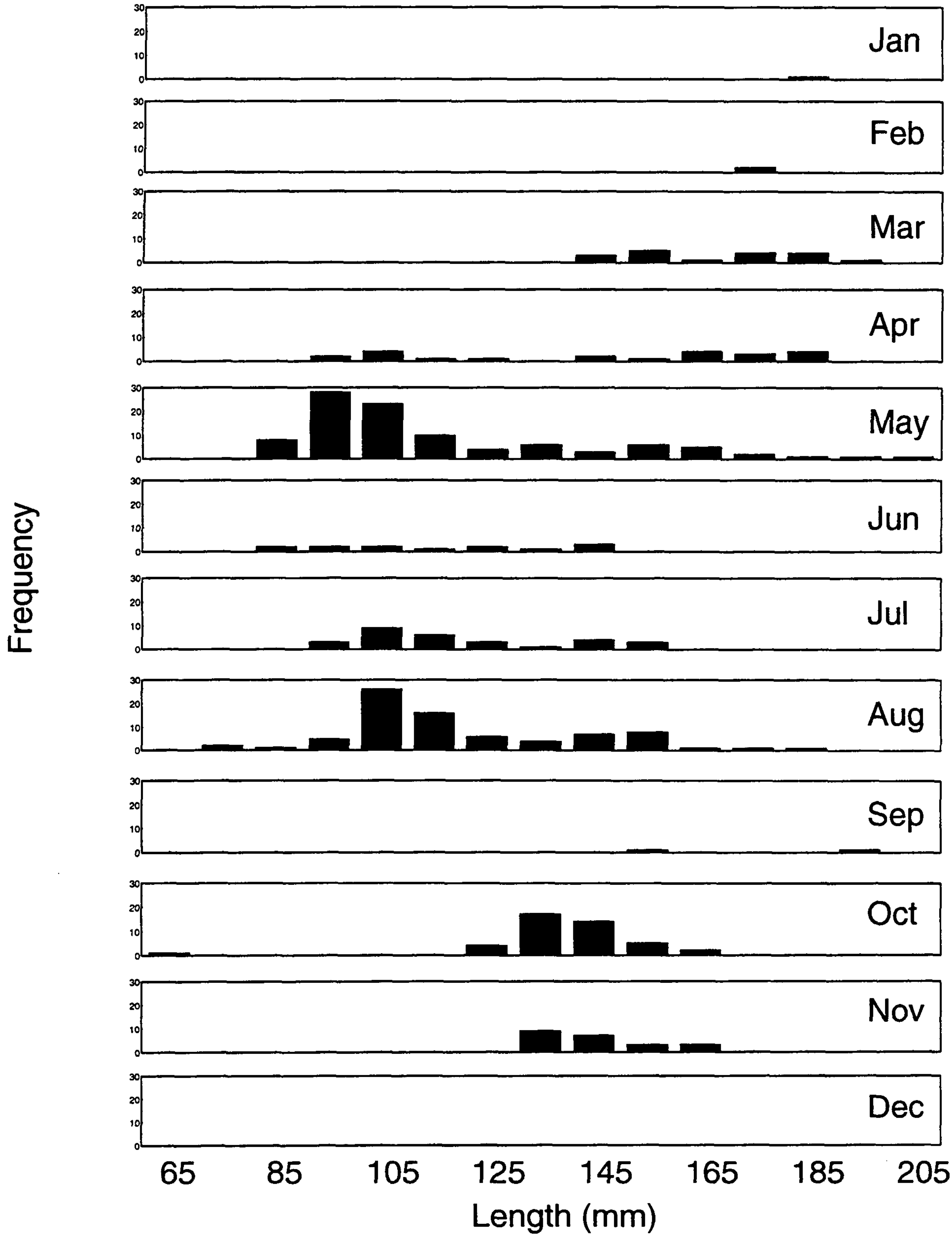

Figure 1 Length frequency (mm FL) of Pacific pompano captured with the midwater trawl from 1981 to 1988

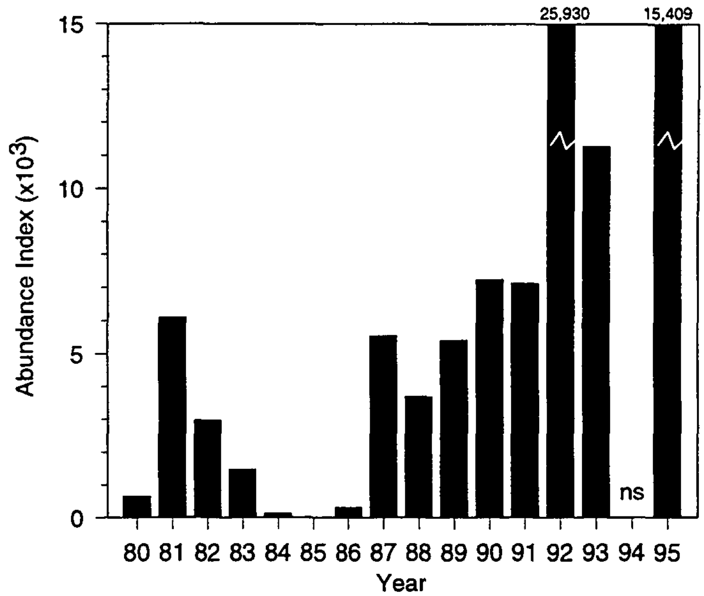

Figure 2 Annual abundance of Pacific pompano (all ages) captured with the midwater trawl from 1980 to 1995. Sampling in 1994 was not sufficient (ns) to calculate an index.

Table 1 Annual and seasonal abundance of all ages of Pacific pompano collected with the midwater trawl from 1980 to 1995

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Feb–Oct*
1980		1239	0	0	0	570	4057	0	0	0	0	0	652
1981	0	0	4357	5796	7561	2871	2698	31520	0	0	267	0	6089
1982	0	493	2362	0	6192	1265	0	12183	1186	3020	0	0	2967
1983	602	0	0	6010	0	257	6919	0	0	0	0	0	1465
1984	0	0	0	0	1159	0	0	0	0	0	0	0	129
1985	0	0	0	0	0	0	0	0	0	0	0	0	0
1986	0	0	0	0	504	0	2147	0	0	0	0	0	295
1987	0	0	0	610	34861	4238	7716	0	0	1823	0	0	5472
1988	0	0	0	1266	11708	0	1127	0	0	19629	13722	0	3748
1989	0	0	705	12253	21383	1866	1920	0					5447
1990		1641	1436	7293	14230	24900	11670	4017	493	0			7298
1991		0	0	14507	3169	7487	10436	23014	2277	26204			9677
1992		0	0	60877	59797	1661	0	42355	8261	60890			25982
1993		0	0	1662	42499	14191	39821	642	0	2174			11221
1994		0	3634	10708									4781
1995				588	56870	20723	5787		6900	1315	0	548	15364
1981–1988	75	62	840	1710	7748	1079	2576	5463	148	3059	1749	0	

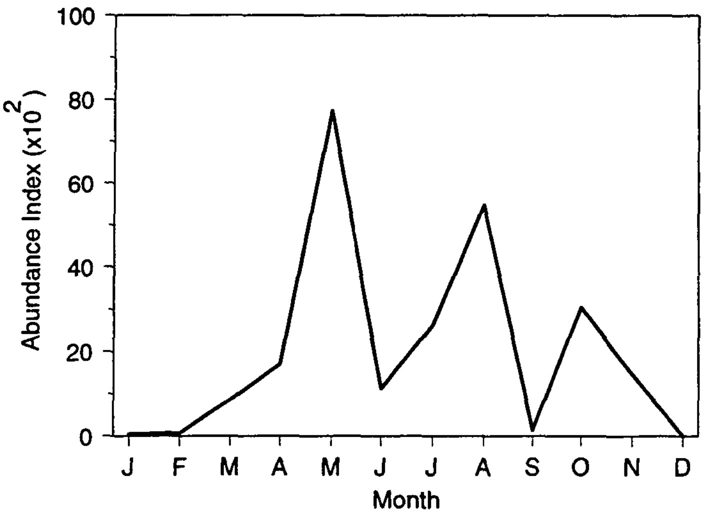

Figure 3 Seasonal abundance of Pacific pompano captured in the midwater trawl from 1981 to 1988

Seasonal Abundance

Pacific pompano collections were highly variable from month to month in most years (see Table 1). Yet, they have been collected in every month of the year in different years. They were generally most abundant from April or May to August (Figure 3); however, abundance remained high in the falls of 1988, 1991, and 1992 (see Table 1). In several years (1981, 1982, 1988, 1991, and 1992) there were spring and late summer or fall abundance modes. Few fish were collected from November to March.

Distribution

Although Pacific pompano were collected from South Bay to Suisun Bay, very few were collected outside of Central Bay (Figure 4). The use of South and San Pablo bays occurred in spring, mostly from 1981 to 1992 (Figure 5), years when CPUE was high in Central Bay.

Pacific pompano were collected from mesohaline salinities, but were mostly in polyhaline and euhaline salinities that averaged 29.6‰ (Figure 6). The collection temperature averaged 15.2 °C (see Figure 6).

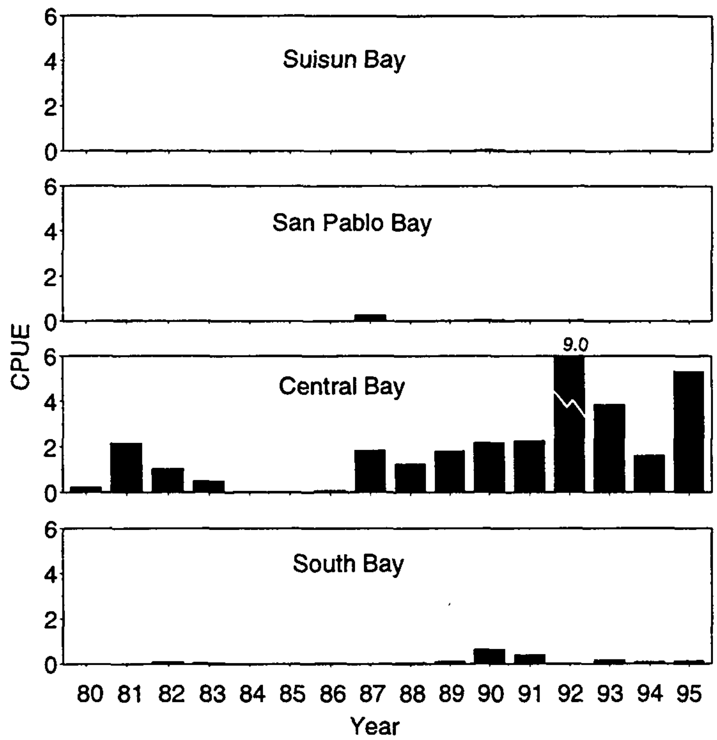

Figure 4 Annual distribution of Pacific pompano captured in the midwater trawl. Data are the average CPUE for February to October.

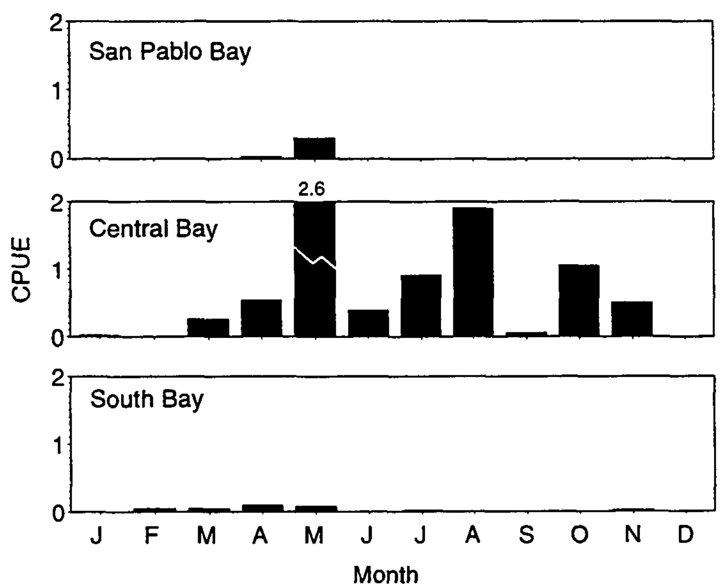

Figure 5 Seasonal distribution of Pacific pompano captured in the midwater trawl. Data are the average CPUE for 1981 to 1988.

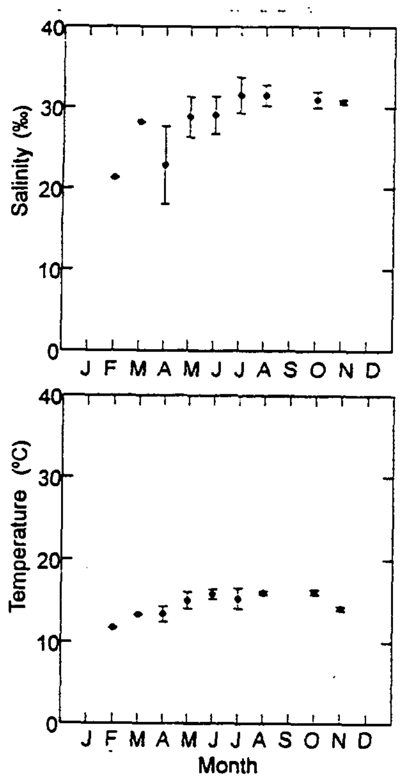

Figure 6 Salinity (‰) and temperature (°C) distributions (mean ±1 standard deviation) of Pacific pompano captured in the midwater trawl

Discussion

The Pacific pompano appears to use San Francisco Bay as an extension of its coastal marine habitat. Its salinity and temperature distributions and seasonal abundance suggest that it might be seeking relatively warmer euhaline water in the estuary once cold oceanic upwelling starts in the spring and it leaves the estuary in fall when upwelling ceases and estuary temperatures peak (see Salinity and Temperature chapter, Figure 12).

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Pacific Tomcod

Introduction

The Pacific tomcod, *Microgadus proximus*, is a demersal, marine fish found from Point Sal, California, to Unalaska Island, Alaska (Miller and Lea 1972). It is found from near surface to about 220 m and reaches a maximum size of 305 mm TL (Miller and Lea 1972). Because of its small size it has little sport or commercial value but shows up occasionally in coastal fisheries for other types of fish.

Maturity is probably reached at age 2 and >200 mm TL (Emmett and others 1991). Spawning occurs in marine coastal waters during winter and spring (Richardson and Pearcy 1977, Matarese and others 1981), but can extend into the summer off San Francisco Bay (Wang 1986). Eggs have not been identified from plankton samples and consequently are believed to be demersal and adhesive (Dunn and Matarese 1987). Larvae and small juveniles (<50 mm) are pelagic and most common in nearshore coastal waters (Richardson and Pearcy 1977, Matarese and others 1981), but they can occasionally be found in estuaries (Misitano 1977, Wang 1986). Juveniles become demersal at about 50 mm TL and remain associated with the bottom for the rest of their lives (Richardson and Pearcy 1977, Matarese and others 1981). They inhabit bays and estuaries from San Francisco Bay northward and their abundance increases with latitude (Emmett and others 1991).

Methods

A January 1 birth date was assigned to all age–0 Pacific tomcod. These were separated from age–1+ fish by visual inspection of length frequency data. Cutoff lengths (minimum size of age–1+ fish) for the separation of ages 0 and 1+ were set at 70, 80, 90, 100, 110, 120, 130, 140, 150, 155, 160, and 165 mm TL for January through December, respectively. Since virtually all Pacific tomcod were collected with the otter trawl, only otter trawl data was analyzed for this species. A July to October index period was used for age–0 fish and a February to August period for age–1+ fish. No correction was made for missing 1989 data. Seasonal distributions of both age groups included data only from years in which all 12 months were sampled and in which fish in these age classes were collected.

Results

Catch and Length

Six larvae and no age–0 Pacific tomcod were collected with the plankton net and none with the beach seine. We captured 24 fish with the midwater trawl, ranging from 104 to 225 mm TL. The otter trawl was by far the most effective gear, capturing 931 fish, ranging from 13 to 271 mm TL.

Only 2 of the age–0 Pacific tomcod caught with the otter trawl were <50 mm TL. They measured 13 and 29 mm. Most age–0 fish were >90 mm and were easily distinguished from older age classes by length (Figure 1).

Annual Abundance

No age–0 Pacific tomcod were collected from 1984 to 1987 or in 1989 and 1992 (Figure 2, Table 1). Annual abundance was very low in most years compared to the peak in 1995 (see Figure 2). There was no trend in abundance.

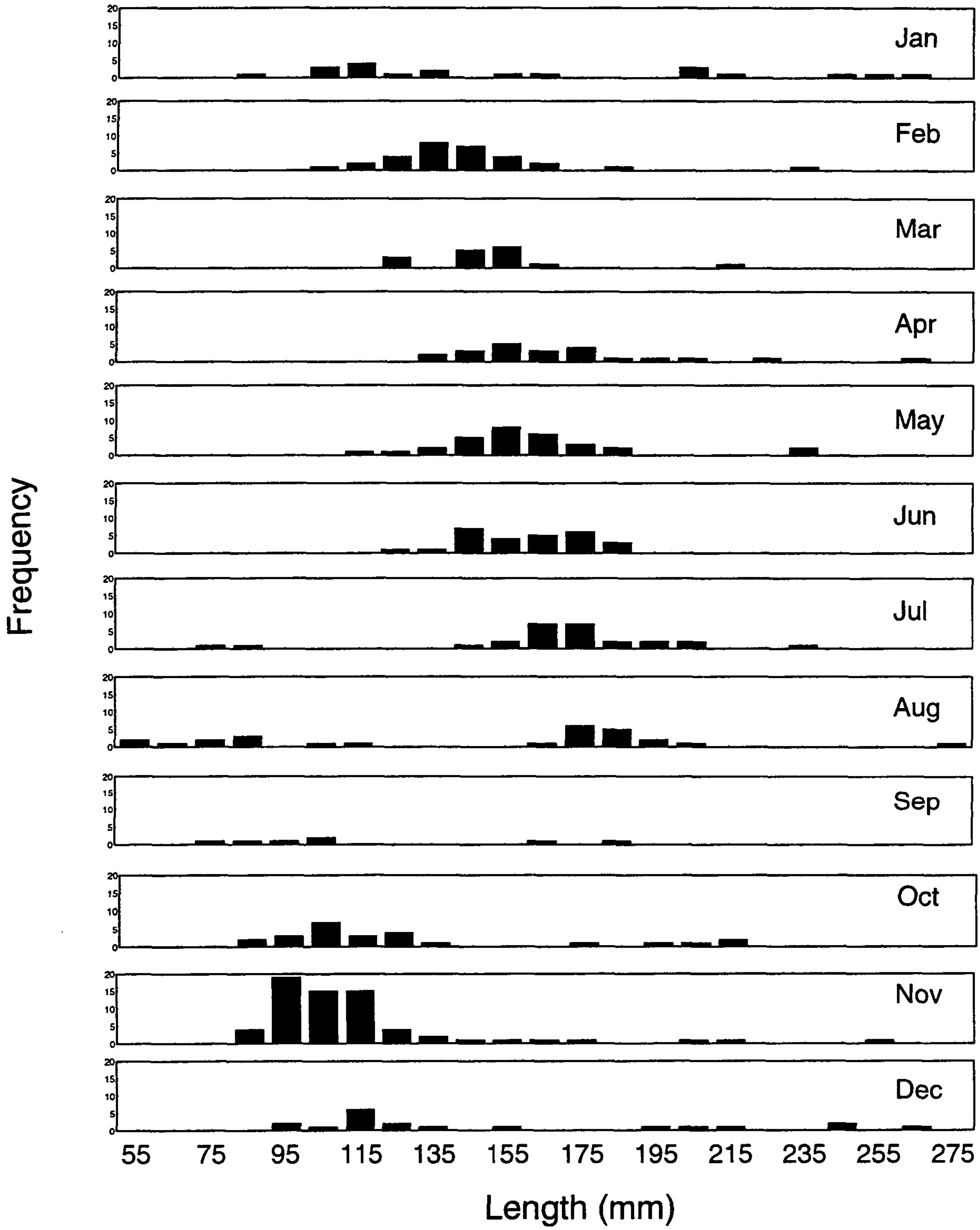

Figure 1 Length frequency (mm TL) by month of Pacific tomcod captured in the otter trawl from 1981 to 1988. Two fish, 13 and 29 mm TL, are not shown.

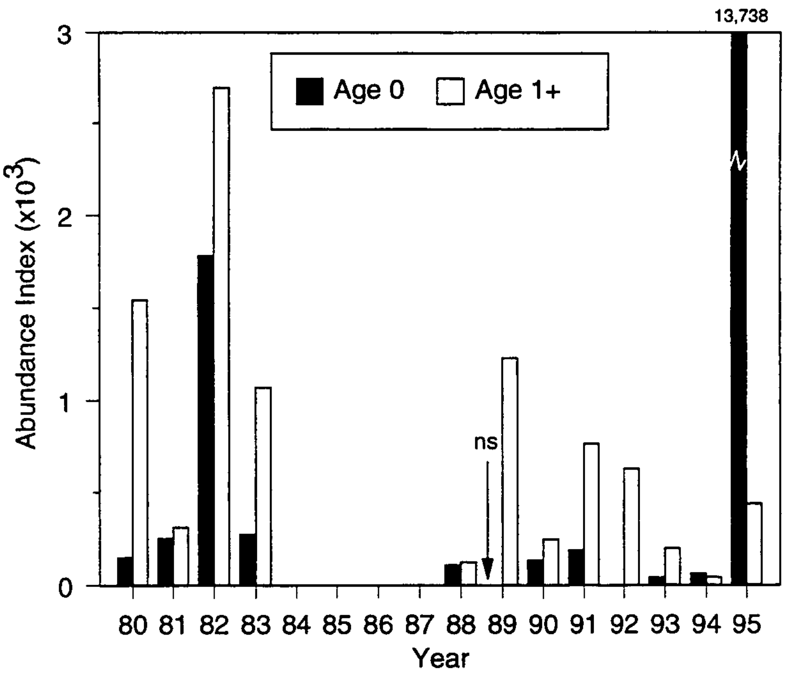

Figure 2 Annual abundance of Pacific tomcod captured in the otter trawl from 1980 to 1995

Table 1 Monthly abundance of age-0 Pacific tomcod captured with the otter trawl from 1980 to 1995. Annual abundance indices are in the far right column. Seasonal abundance indices are in the bottom row (mean 1981 to 1988 monthly abundance).

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Jul–Oct*
1980		0	409	0	0	0	194	0	186	0	970	404	95
1981	0	0	0	0	0	0	0	0	0	1004	11141	870	251
1982	0	0	0	0	0	0	576	1461	978	4026	2245	719	1760
1983	0	0	0	0	0	0	0	1060	0	0	0	0	265
1984	0	0	0	0	0	0	0	0	0	0	0	0	0
1985	0	0	0	0	0	0	0	0	0	0	0	0	0
1986	0	0	0	0	0	0	0	0	0	0	0	0	0
1987	0	0	0	0	0	0	0	0	0	0	0	0	0
1988	0	0	0	0	0	0	0	0	142	284	1147	2146	107
1989	0	0	0	0	0	0	0	0					0
1990		0	0	0	0	0	0	0	225	328			138
1991		0	0	0	0	0	0	427	328	0			189
1992		0	0	0	0	0	0	0	0	0			0
1993		0	0	0	0	0	0	0	0	171			43
1994		0	0	0	0	0	0	0	0	237			59
1995	0	0	0	0	0	0	0		29636	11596	31196	21217	13744
1981–1988	0	0	0	0	0	0	72	315	140	664	1817	467	

Table 2 Monthly abundance of age–1+ Pacific tomcod captured with the otter trawl from 1980 to 1995. Annual abundance indices are in the far right column. Seasonal abundance indices are in the bottom row (mean 1981 to 1988 monthly abundance).

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Feb–Aug Index*
1980		3466	1098	2034	1907	1340	1138	1067	1229	759	979	0	1721
1981	1104	400	549	665	341	0	212	557	0	0	0	569	389
1982	2248	3906	1784	740	3919	4923	4716	2246	439	1540	1074	792	3176
1983	1270	2132	874	2608	1925	768	358	966	0	0	0	0	1376
1984	0	0	0	0	0	0	0	0	0	0	0	305	0
1985	0	0	0	0	0	0	0	0	0	0	0	0	0
1986	0	0	0	0	0	0	0	0	0	0	0	0	0
1987	305	0	0	0	0	0	0	0	0	0	0	0	0
1988	186	213	247	655	0	0	0	0	0	0	0	0	159
1989	1314	2225	764	1084	1949	900	1647	0					1224
1990		1440	237	376	0	0	0	0	0	194			293
1991		1266	0	1618	178	1355	290	2133	0	0			977
1992		1645	1717	2294	0	0	0	0	0	0			808
1993		0	693	838	237	0	0	0	0	0			253
1994		0	388	0	0	0	0	0	0	0			55
1995	194	189	717	0	1067	1262	284		0	0	261	978	586
1981–1988	639	831	432	583	773	711	661	471	55	193	134	208	

No age–1+ Pacific tomcod were collected from 1984 to 1987 during the February to August index period (see Figure 2, Table 2). However, some age–1+ fish were collected in December 1984 and January 1987 (see Table 2). Abundance of age–1+ fish peaked in 1982 but no trends in abundance were apparent.

Seasonal Abundance

Two age–0 Pacific tomcod were collected in March 1980, otherwise the month of 1st collection ranged from July to October (see Table 1). No age–0 fish were collected in 1989 and 1992, but sampling ended early in those years. Abundance was highest from October to December (Figure 3, see Table 1).

Age–1+ Pacific tomcod were collected throughout the year, although they were least abundant from September to December (see Figure 3, see Table 2). On the average, abundance was highest in February and May.

Annual Distribution

The distribution of age–0 Pacific tomcod was restricted to Central Bay in all years except 1982, when they entered San Pablo Bay (Figure 4). Age–1+ fish were more widely distributed and were generally found from South to San Pablo bays, but the age–1+ CPUE was always highest in Central Bay (Figure 5). In 1980, a few age 1+ fish were collected in Suisun Bay.

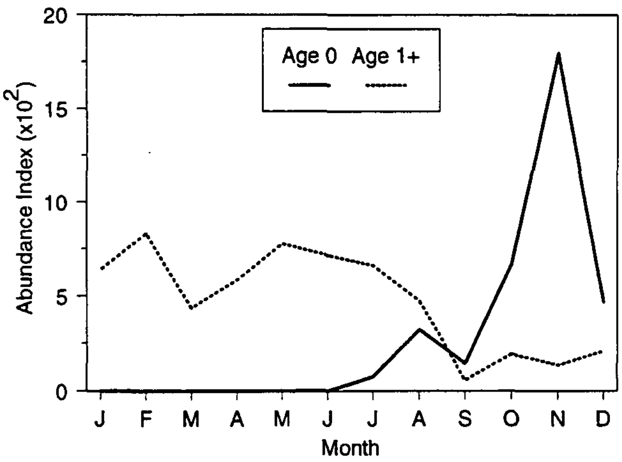

Figure 3 Seasonal abundance of Pacific tomcod captured in the otter trawl from 1981 to 1988

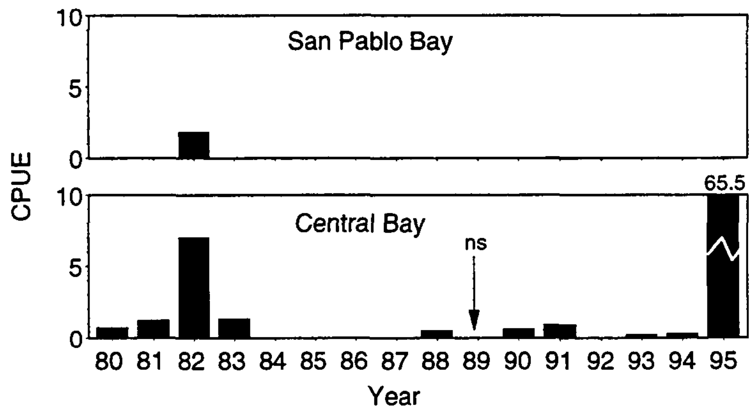

Figure 4 Annual distribution of age–0 Pacific tomcod by region. Data are the mean CPUE for July to October.

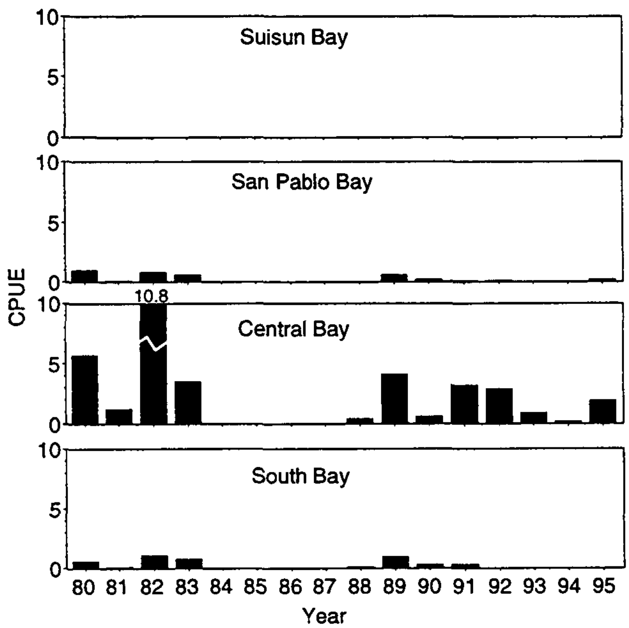

Figure 5 Annual distribution of age–1+ Pacific tomcod by region. Data are the mean CPUE for February to October.

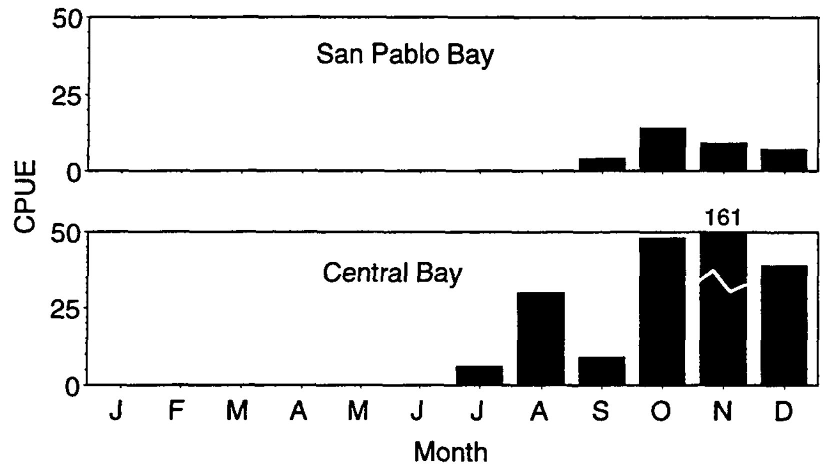

Figure 6 Seasonal distribution of age–0 Pacific tomcod by region. Data are the mean CPUE x 10 for 1980 to 1983 and 1988.

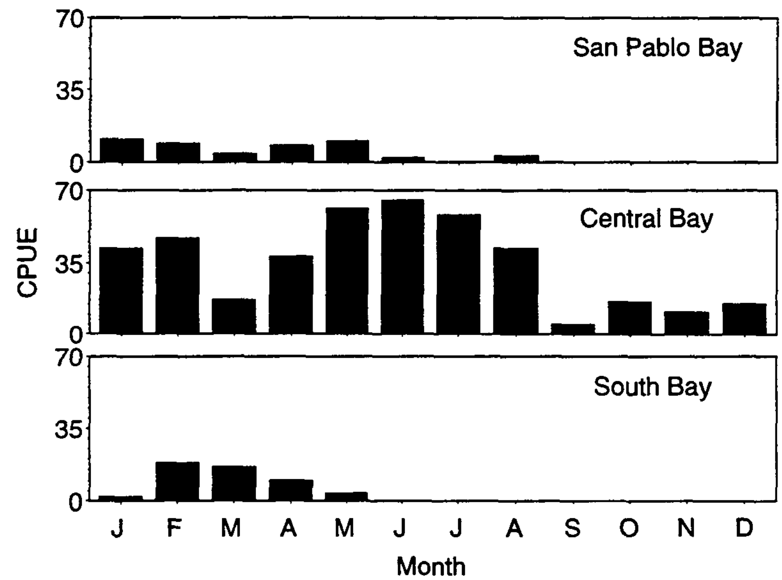

Figure 7 Seasonal distribution of age–1+ Pacific tomcod by region. Data are the mean CPUE x 10 for 1981 to 1983 and 1988.

Seasonal Distribution

Age–0 Pacific tomcod were concentrated in Central Bay in all months (Figure 6). The highest CPUE was in November. They were found in San Pablo Bay only from September to December 1982.

Age–1+ Pacific tomcod were caught in South and San Pablo bays primarily from January to May when Central Bay catches were usually high (Figure 7). By June or July age–1+ fish had left both South and San Pablo bays and CPUE in Central Bay peaked.

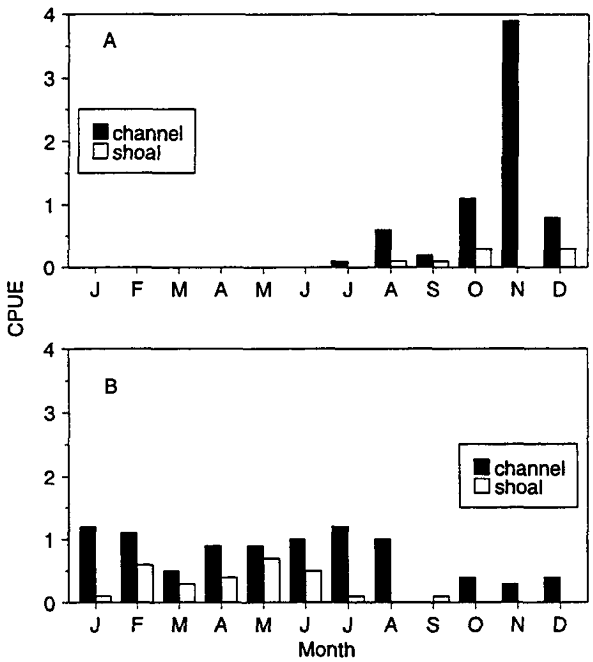

Figure 8 Seasonal depth distribution of (A) age–0 and (B) age–1+ Pacific tomcod captured in the otter trawl from 1981 to 1988

Pacific tomcod were strongly channel oriented throughout their residence in the estuary (Figure 8). This orientation was most distinct as age–0 fish entered the estuary in fall and winter. The use of shoal areas increased for age–1+ fish in late winter and spring before declining in summer (see Figure 8). Few age–1+ fish were caught on shoals in late summer and fall when most of them were leaving the estuary for the coast as shown by the declining catches in all bays (see Figure 7).

Salinity and Temperature

The Pacific tomcod is one of the few species for which the salinity distribution of age–0 fish was narrower and higher than that of the age–1+ fish (Figures 9 and 10). Age–0 Pacific tomcod were found only in polyhaline and euhaline salinities, but age–1+ fish also extended into mesohaline salinities.

Age–1+ Pacific tomcod were found at temperatures as low as 7 °C, but age–0 fish were not found below 11 °C (see Figures 9 and 10). Nevertheless, the mean temperatures for both age groups were similar: 13.8 °C for age 0 and 13.3 °C for age 1+. Neither age group was found above 18 °C.

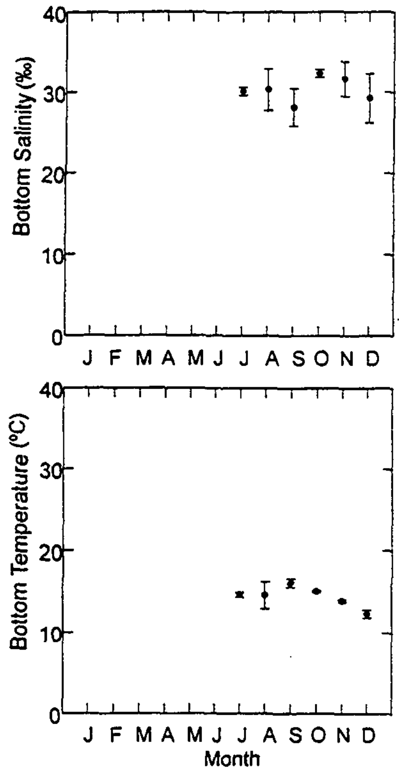

Figure 9 Seasonal temperature (°C) and salinity (‰) distributions (mean ±1 standard deviation) of age–0 Pacific tomcod

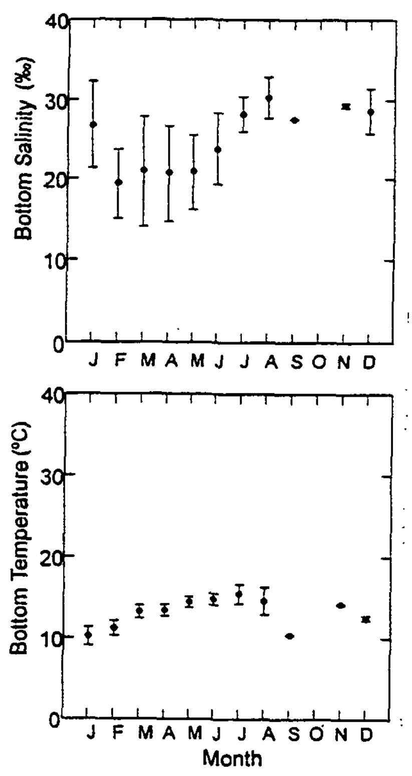

Figure 10 Seasonal temperature (°C) and salinity (‰) distribution (mean ±1 standard deviation) of age–1+ Pacific tomcod

Discussion

Pacific tomcod appear to use the estuary starting late in their 1st year of life; they remain for another year or more, then return to the open coast. However, not all year classes were represented in estuary sampling (see Figure 2). The distribution and abundance patterns of Pacific tomcod suggest that the estuary represents a range expansion of a marine population, rather than a nursery habitat.

Many factors could have contributed to the absence of both age groups from the estuary between 1984 and 1987 including temperature, food supply in the estuary, and overall abundance in the ocean. We lack information to assign a cause, however, the estuary is at the southern limit of the Pacific tomcod's range. If ocean conditions did not bring the fish far enough south they would not have appeared in the estuary. Within the estuary, distribution of both age groups appears more limited by high temperatures than by low salinities. Neither age group was collected from temperatures >18 °C, though such temperatures were common during the summer and fall in regions other than Central Bay (see Salinity and Temperature chapter, Figures 6 through 10). High temperature could be expected to limit the distribution of a species at the southern edge of its range.

The higher salinity distribution of age–0 fish appears to be a result of fall collection and a January 1 birth date rather than a change in salinity tolerance with age. There was considerable size overlap (and probably age overlap also) between age–0 fish in late fall and age–1+ fish in winter. Age–1 fish dispersed farther into the estuary than age–0 fish and remained through winter as salinity decreased to the low to middle 20‰ range. This suggests that size or development stage were not responsible for the difference. High temperatures in the fall may have limited estuarine dispersal of age–0 fish.

The possibility of bias in calculating the annual abundance of age–0 fish and to a lesser degree age–1+ fish was increased by the reduction in sampling effort in the late 1980s and early 1990s (see Methods chapter, Table 1). Age–0 fish were most abundant in the estuary from late fall to December. Hence, not including November and December (and September and October in 1989) in index calculations made some indices lower than they might have been otherwise.

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Plainfin Midshipman

Introduction

The plainfin midshipman, *Porichthys notatus*, is a demersal marine fish found in the Gulf of California and from Gorda Bank, Baja California, northward to Sitka, Alaska (Miller and Lea 1972). It reaches a maximum size of 380 mm TL and inhabits depths from the intertidal to 328 m (Miller and Lea 1972). It is trapped commercially in San Francisco Bay for striped bass bait.

The age at maturity is not known, but Wang (1986) collected mature individuals from 165 to 181 mm TL. In San Francisco Bay, spawning takes place from April through August (Wang 1986). Males excavate nests under solid structures in the intertidal zone. Females enter the nests to deposit demersal, adhesive eggs, which the male fertilizes and guards until the larvae are free-swimming (Hart 1973). Larvae develop rapidly into juveniles and settle to the bottom. Both sexes are believed to die after spawning (Fitch and Lavenberg 1971).

Juveniles and adults bury themselves in soft sediments during the day and move into the water column at night to feed (Fitch and Lavenberg 1971). Juveniles tolerate lower salinities than adults and have occasionally been found in freshwater in the lower Sacramento–San Joaquin Delta (Wang 1986).

Methods

A January 1 birth date was assigned to all age–0 fish. Cutoff lengths for the separation of age–0 and age–1+ fish were determined by examination of length frequency data. Cutoff lengths were set at 25, 30, 35, 40, 45, 55, 65, 75, 80, 85, 90, and 95 mm TL for January to December, respectively. This resulted in some fall-hatching fish being designated as age–1+ at 4 to 5 months of age and <70 mm TL. Such fish were designated as small age–1+ fish to distinguish them from older individuals. Only otter trawl data were used in the analyses.

Abundance indices for age–0 fish were calculated for the June to October period, and for age–1+ fish, from February to September.

Results

Length Analysis

Four larval and 205 age–0 plainfin midshipman were captured in the plankton net. Eighteen plainfin midshipman ranging from 21 to 36 mm TL were caught in the beach seine, and 5,645, ranging from 22 to 340 mm, were caught in the midwater trawl. The otter trawl was by far the most effective gear, capturing 10,766 fish from 17 to 348 mm (Figure 1).

Age–0 plainfin midshipman (25 to 65 mm) were caught from June to December. They showed little indication of growth during the months they were present.

Small, 35 to 65 mm, age–1+ plainfin midshipman were present in January and grew until July or August when they disappeared from the catch (see Figure 1). Larger, ≥125 mm, age–1+ fish appeared in April and became more abundant during summer but disappeared by October. The largest fish were present in May and June.

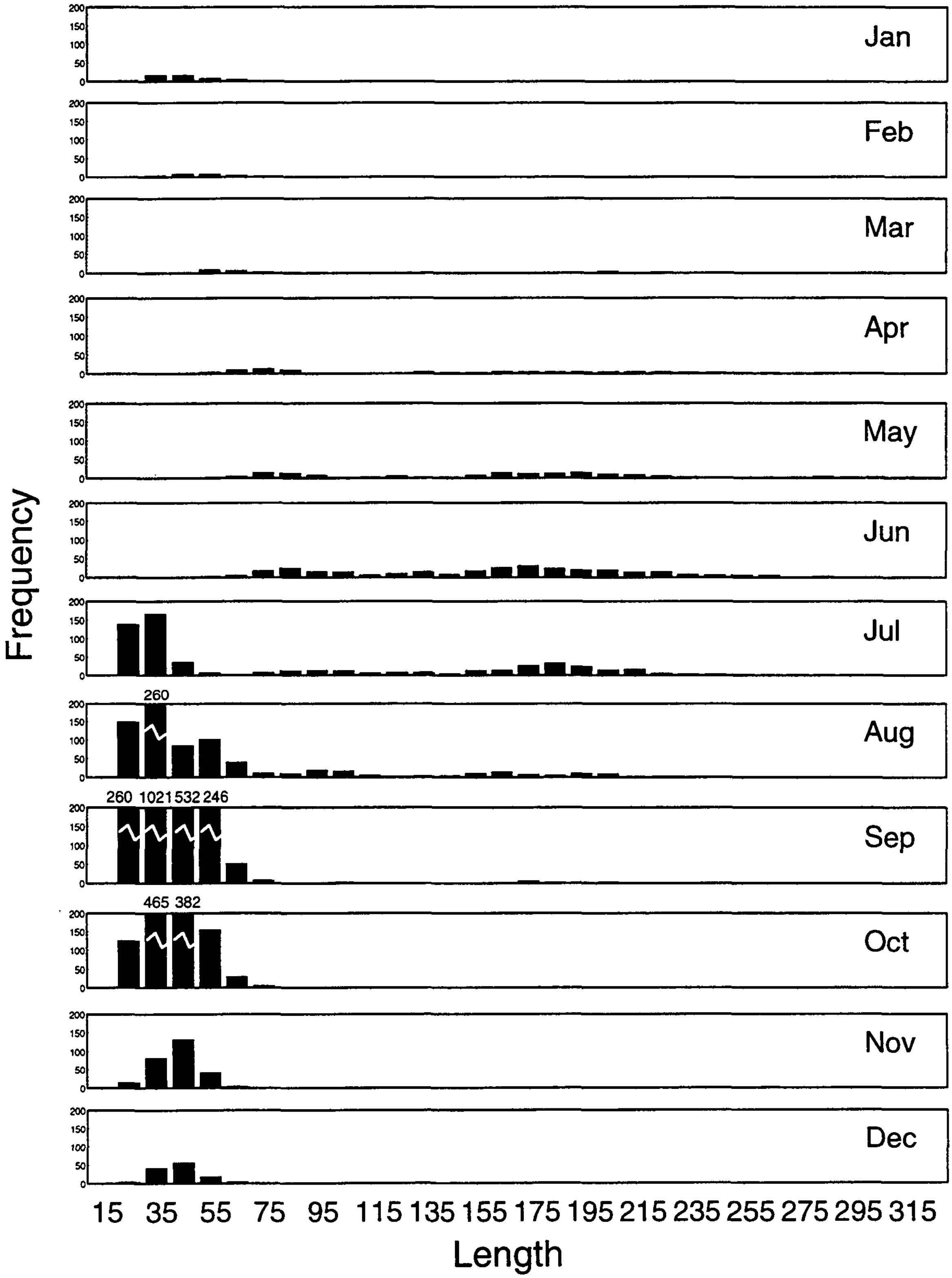

Figure 1 Length frequency (mm TL) by month of plainfin midshipman captured in the otter trawl from 1981 to 1988

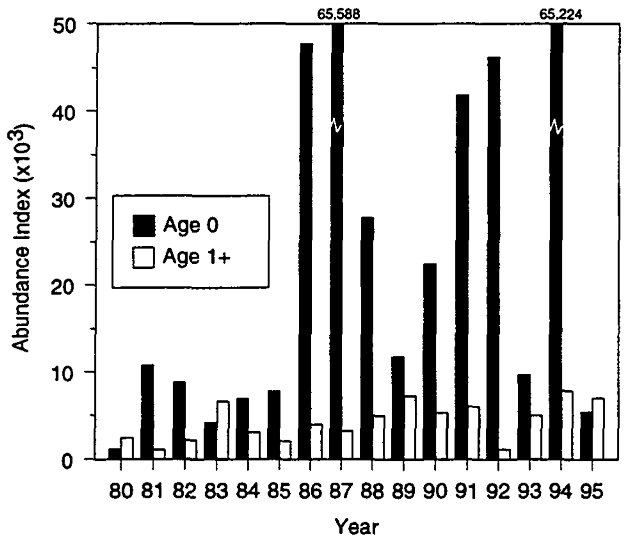

Figure 2 Annual abundance of plainfin midshipman captured in the otter trawl from 1980 to 1995

Table 1 Monthly abundance of age–0 plainfin midshipman collected with the otter trawl from 1980 to 1995. Annual abundance indices are in the far right column. Seasonal abundance indices are in the bottom row (mean 1981 to 1988 monthly abundance).

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*June–Oct*
1980		0	0	0	0	0	0	154	4511	1396	3114	649	1212
1981	0	0	0	0	0	0	11288	3871	5898	32903	0	188	10792
1982	0	0	0	0	0	0	0	12416	12440	19404	1799	1730	8852
1983	0	0	0	0	0	0	1016	1393	3376	15099	14779	10876	4177
1984	0	0	0	0	0	0	4380	10412	17052	2943	2494	4376	6957
1985	0	0	0	0	0	0	9703	4082	10507	14808	1471	667	7820
1986	0	0	0	0	0	0	117	20429	192760	25603	9260	4276	47782
1987	0	0	0	0	0	0	10582	37418	134580	145361	31156	2073	65588
1988	0	0	0	0	0	622	34323	50201	42730	11093	2956	933	27794
1989	0	0	0	0	216	500	6270	28464					11745
1990		0	0	0	0	3150	46477	20148	28824	13777			22475
1991		0	0	0	0	216	2540	15424	139236	51760			41835
1992		0	0	0	0	1313	2552	37463	117471	72678			46295
1993		0	0	0	0	0	2119	8425	9403	28557			9701
1994		0	0	0	0	6316	12385	56663	175813	74945			65224
1995	0	0	0	0	0	0	0		15367	6489	5304	14277	5464
1981–1988	0	0	0	0	0	78	8926	17528	52418	33402	7989	3140	

Annual Abundance

The abundance of age–0 plainfin midshipman was bimodal with peaks in 1987, the highest year, and 1994 (Figure 2, Table 1). Abundance showed no relationship with water year type and had no trend, although it was consistently low from 1980 to 1985. Age–1+ fish were much less abundant than age–0 fish and their abundance showed less variability (see Figure 2, Table 2). Abundance of age–1+ fish was highest in 1994 and almost as high in 1983, 1989, and 1995. With the exception of 1992, abundance was consistently high from 1988 to 1995. As for age–0 fish, no relationship existed between abundance and water year type.

Table 2 Monthly abundance of age–1+ plainfin midshipman collected with the otter trawl from 1980 to 1995. Annual abundance indices are in the far right column. Seasonal abundance indices are in the bottom row (mean 1981 to 1988 monthly abundance).

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Feb–Sep*
1980		0	373	1823	1641	4922	8107	1906	974	0	48	0	2468
1981	250	0	404	1998	1269	694	3245	1298	0	0	0	0	1114
1982	770	0	1201	3223	4822	6781	1420	0	0	0	0	0	2181
1983	703	402	288	1952	5601	12112	17694	15277	0	0	270	0	6666
1984	3867	0	243	992	4340	14108	4732	281	0	0	0	0	3087
1985	156	2246	648	622	649	3939	3651	4976	0	0	0	0	2091
1986	344	379	644	919	2706	13297	11917	1812	162	0	0	0	3980
1987	2217	313	1839	922	4801	5341	6303	4036	2272	0	0	0	3228
1988	597	1117	1379	8177	6629	16536	4206	2031	0	0	0	219	5009
1989	0	216	1487	10368	4907	22271	10128	1682					7294
1990		1320	4070	8729	9234	10868	6636	1731	0	0			5324
1991		0	865	1704	8654	9710	18724	8951	0	0			6076
1992		0	947	2697	1768	1757	1557	622	0	703			1169
1993		682	777	4563	9044	6106	13989	4752	243	0			5020
1994		1859	1885	3056	5144	10706	19984	18873	1601	0			7889
1995	5146	930	3666	2736	13194	12316	13969		2362	0	0	0	7025
1981–1988	1113	557	831	2351	3852	9101	6646	3714	304	0	34	27	

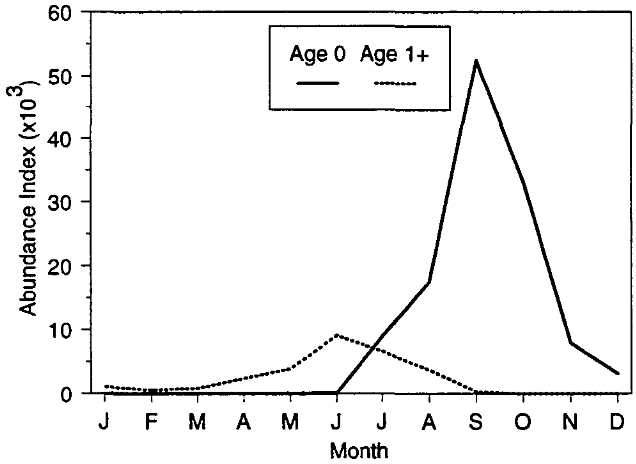

Figure 3 Seasonal abundance of plainfin midshipman captured in the otter trawl from 1980 to 1995

Seasonal Abundance

Age–0 plainfin midshipman were 1st collected in May, but only in 1989. They were more often first taken in June or July, although in 1980 and 1982 none were caught until August (see Table 1). On the average, abundance of age–0 fish peaked in September and declined sharply thereafter (Figure 3).

Age–1+ plainfin midshipman were either not collected or were not abundant from September to December (see Figure 3, see Table 2). Ninety-five percent of age–1+ fish collected in January and February and about 62% of those collected in March were small and newly recruited. On the average, age–1+ abundance peaked in June and declined sharply in fall (see Figure 3, see Table 2).

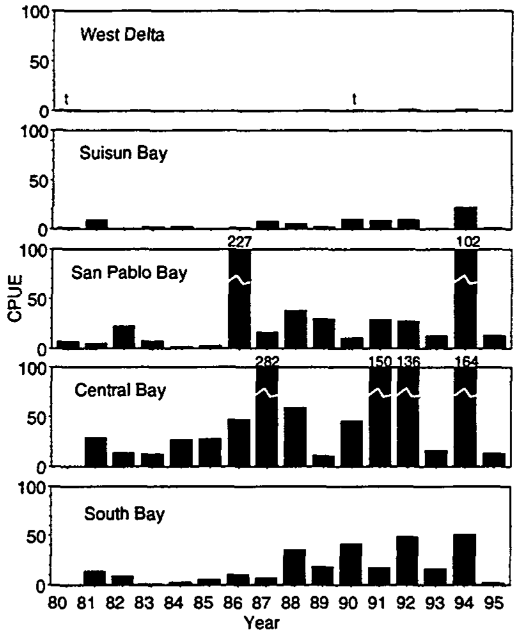

Figure 4 Annual distribution of age–0 plainfin midshipman captured in the otter trawl from 1980 to 1995. Data are mean CPUE for July to October by region. Numbers too small to show at this scale are indicated with a "t" (trace).

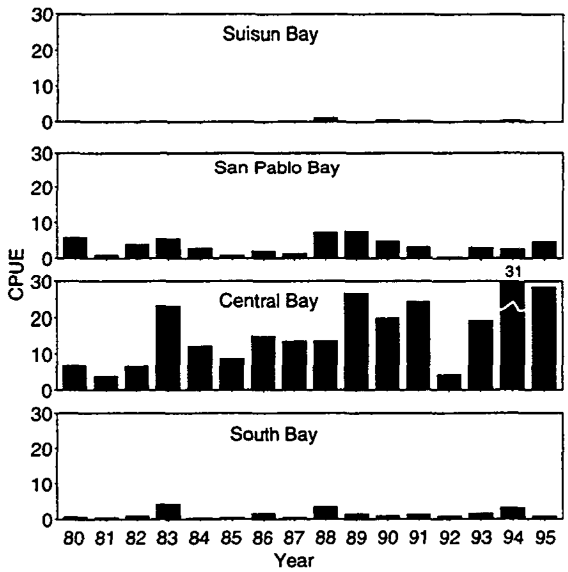

Figure 5 Annual distribution of age–1+ plainfin midshipman captured in the otter trawl from 1980 to 1995. Data are the mean CPUE for February to September by region.

Annual Distribution

Age–0 plainfin midshipman usually ranged from South to Suisun bays but the annual CPUE was generally highest in Central Bay and next highest in San Pablo Bay (Figure 4). In 1980, 1992, and 1994, a few age–0 fish were present in the west delta (too few to show in Figure 4). Age–1+ fish had a similar distribution but with an even stronger concentration in Central Bay (Figure 5). None were caught in the west delta.

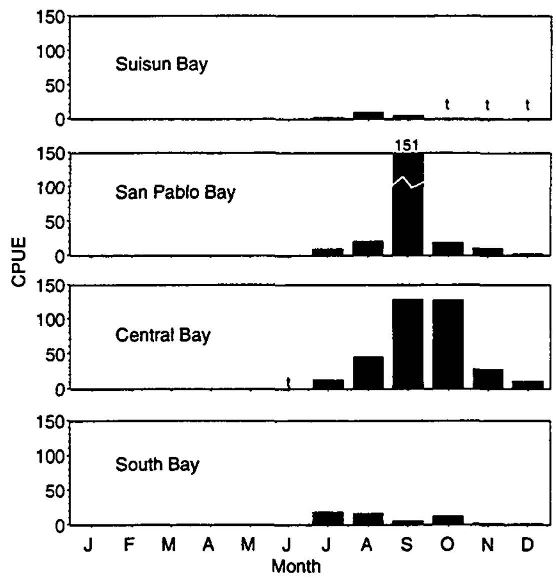

Figure 6 Seasonal distribution of age–0 plainfin midshipman captured in the otter trawl. Data are the mean CPUE by region for 1981 to 1988. Numbers too small to show at this scale are indicated with a "t" (trace).

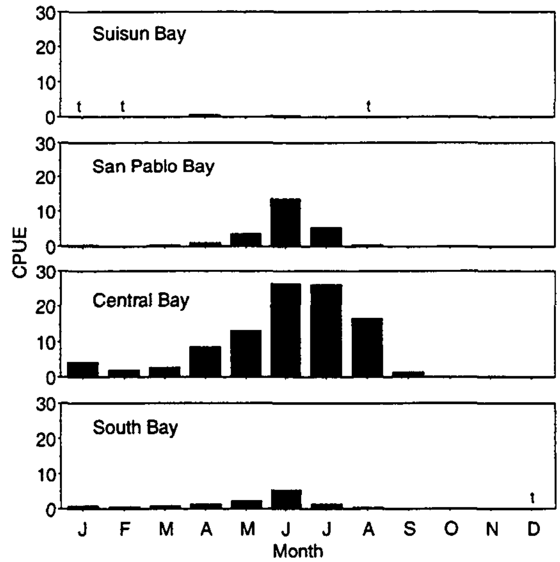

Figure 7 Seasonal distribution of age–1+ plainfin midshipman captured in the otter trawl. Data are the mean CPUE by region for 1981 to 1988. Numbers too small to show at this scale are indicated with a "t" (trace).

Seasonal Distribution

The average 1981–1988 seasonal distribution of age–0 plainfin midshipman showed that CPUE was highest in South Bay in July, in Central Bay in August, in San Pablo Bay in September, and again in Central Bay from October to December (Figure 6).

The CPUE of age–1+ plainfin midshipman was always higher in Central Bay than in other regions throughout the year (Figure 7). From January to March, the age–1+ fish were primarily new recruits and their distribution was proportionally similar to that of age–0 fish in December.

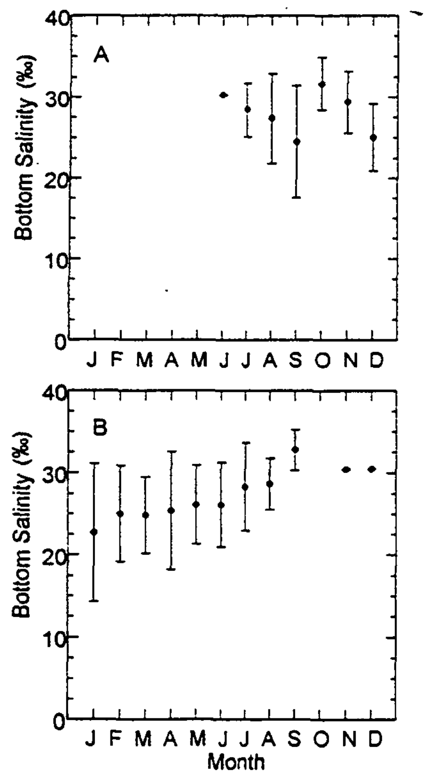

Figure 8 Seasonal salinity (‰) distribution (mean ±1 standard deviation) of (A) age–0 and (B) age–1+ plainfin midshipman captured in the otter trawl from 1981 to 1988

Salinity and Temperature

Although age–0 plainfin midshipman were found as far upstream as the west delta, both age groups occupied primarily salinities >15‰ (Figure 8). Age–0 fish were initially captured in the net in Central Bay at a salinity of about 30‰. As CPUE increased in other regions, mean salinity declined to about 24.5‰ in September. Rapid emigration from Suisun and San Pablo bays between September and October resulted in an abrupt increase in mean salinity to about 31‰. Fish congregated in Central and South bays in October before leaving the estuary. Mean salinity declined from October to December as fish emigrated from Central and South bays more rapidly than those that remained in San Pablo Bay, and as estuarine salinity declined.

In January, the few age–1+ plainfin midshipman collected were found in a wide range of salinities with a mean of about 23‰ (see Figure 8). Through March their salinity distribution narrowed and the mean increased slightly to about 25‰ as their geographic distribution shifted toward Central and South bays (see Figure 7). In April, as mature fish began entering the estuary in search of nest sites, their salinity distribution broadened slightly, but as the process continued through its peak in June the distribution stabilized around a mean salinity of about 26‰. After June, mean salinity climbed to almost 33‰ in September as fish immigrated to the coast.

Age–0 plainfin midshipman were found at the highest temperatures ($\bar{\chi}$ = 18 to 20 °C) and over the broadest temperature range in July and August as they first recruited to the net (Figure 9). From September through December mean temperature declined to just above 12 °C.

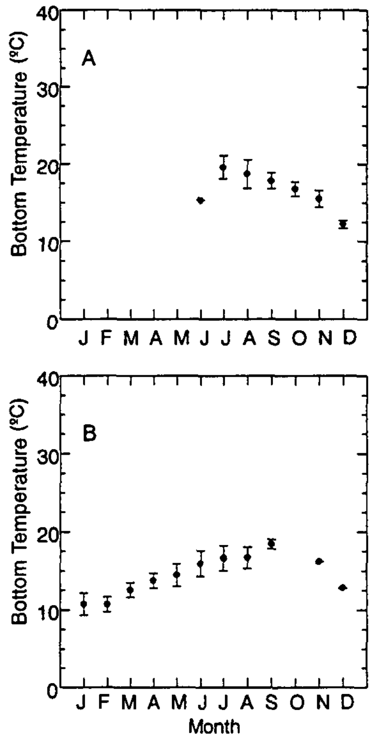

Figure 9 Seasonal temperature (°C) distribution (mean ±1 standard deviation) of (A) age–0 and (B) age–1+ plainfin midshipman captured in the otter trawl from 1981 to 1988

Age–1+ plainfin midshipman were collected from cool temperatures in January and February (mean temperature about 11 °C, see Figure 9). As abundance increased to a peak in June, mean temperature increased to about 16 °C. After June, age–1+ fish began to emigrate as estuarine temperatures continued to increase (see Salinity and Temperature chapter, Figure 12). The two processes counteracted each other and mean temperature rose only slightly through August. After August, temperature statistics were based upon few fish.

Discussion

The dates and locations of capture of age–1+ plainfin midshipman indicate that they used the estuary as a spawning ground. Age–1+ fish were collected from April through August, their reported spawning period (Wang 1986), and their distribution was similar to the subsequent distribution of age–0 fish. Furthermore, age–1+ fish were rare or absent from collections in the estuary during fall, and those collected before April were mostly newly recruited (that is, age 1). Thus, most older age–1+ fish were only in the estuary during their spawning season.

The seasonal pattern of abundance and the length-frequency distribution suggests that age–0 plainfin midshipman used the estuary as a nursery area, as did some younger age–1+ fish. Other age–0 fish appeared to emigrate out of the estuary in fall to return as young age–1+ the next spring. These young age–1+ fish remained in the estuary until August when a large decline in their abundance indicated they had emigrated to the ocean. The timing of this decline coincided with the decline and presumed emigration of older, possibly mature, fish.

Another indication that both age groups emigrated to the ocean was their seasonal shift in distribution. In fall, the abundance of age–0 fish in South and San Pablo bays declined as abundance increased in Central Bay, indicating a movement toward the Golden Gate. In November and December abundance dropped in Central Bay, suggesting that age–0 fish emigrated from the estuary. Age–1+ fish showed a similar pattern of movement but apparently emigrated in August and September.

The plainfin midshipman may mature and spawn in 1 year. However, the presence of age classes older than age 1, and the fact that most spawners are believed to die after spawning (Fitch and Lavenberg 1971), suggests that some age–1 fish do not spawn or that some spawners survive to spawn a 2nd time.

Although age–0 fish can tolerate freshwater (Wang 1986), few were collected in salinities <17‰. However, their salinity range would have been lower if the fish in their 1st winter of life that were found in low salinity water had been classified as age–0 instead of age–1+. Instead, inclusion of these young fish in the age–1+ group lowered the salinity range of the age–1+ fish.

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Summary

Kathryn Hieb and Kevin Fleming

The San Francisco Bay Study collected over 128 species of fishes, caridean shrimp, and *Cancer* crabs from 1980 to 1995, representing a large proportion of the estuary's macrofauna. Species not well sampled include those associated with rocky substrates, eel grass beds, and some shallow water habitats, such as tidal marshes, and also larger species that avoided our nets. Generally, the midwater trawl and beach seine were most effective in collecting age–0 fish; in addition to age–0 fish, the otter trawl was also effective in collecting shrimp and age–0 crabs. In the preceding chapters, we described estuarine use, including distributional patterns, abundance trends, and occurrence by salinity and temperature for the most commonly collected species. In this chapter, we provide an overview of the physical environment, occurrence by salinity and temperature, life history strategies or categories, timing and location of reproduction and rearing, and abundance trends.

Physical Environment

The environmental setting for the study period was far from "average." Alternating "wet" and "dry" or "critical" years bracketed a 6–year drought, one of the most severe of the century. The "wet" years included several years with very high outflow and the highest outflow year of the century (1983). In addition, sea surface temperatures were above average for much of the study period, with several sequential El Niño events. The largest El Niño event occurred in 1982–1983.

Physical factors that influence the estuary's biota can be broadly categorized as riverine, oceanic, or estuarine. Riverine factors are generally related to the magnitude and duration of freshwater outflow and include currents, sediment and nutrient inputs, temperature, and the amount and quality of upstream spawning and rearing habitat. The most important oceanic factors are nearshore surface currents, upwelling, and water temperature. Estuarine factors, including salinity, temperature, gravitational circulation, and tidal currents, are the result of the interaction of oceanic and riverine factors with estuarine bathymetry and geography. The gradations of shallow to deep water, open to structured habitats, and salt to fresh water combine to create a myriad of habitats. The estuarine habitat for each species expands and contracts as the physical environment changes on tidal, seasonal, annual, and even decadal scales.

Occurrence by Salinity and Temperature

The salinity and temperature gradations in the estuary, in conjunction with a species' salinity and temperature tolerance ranges, provide a good indication of the potential distribution of many species. In general, changes in salinity and temperature are as predictable as the seasons—increased precipitation and cool weather lead to lower salinities and temperatures in winter than summer. More specifically for the temperature gradient, the winter trend is for the lower estuary to be warmer than the upper estuary (Figures 1A and 1C), and the summer trend is for the lower estuary to be cooler than the upper estuary (Figures 1B and 1D).

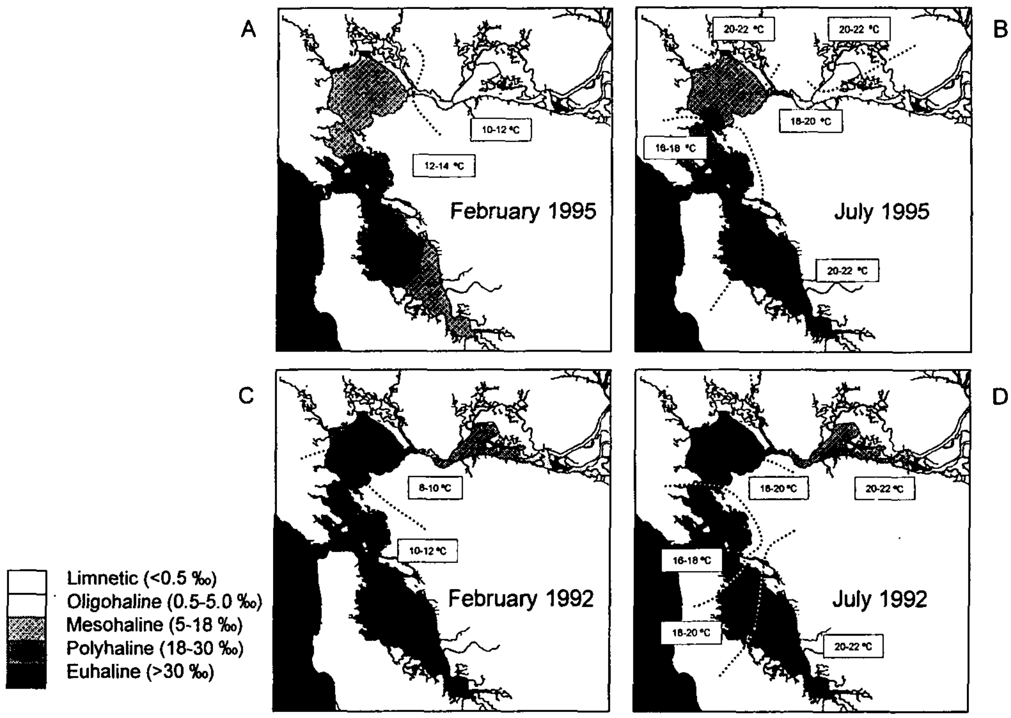

Figure 1 Isohalines and isotherms for winters and summers of "wet" (1995) and "dry" (1992) years: (A) February 1995, (B) July 1995, (C) February 1992, and (D) July 1992

The areas that fall within a species' salinity and temperature tolerances also vary from year to year, but interannual changes are not as predictable as seasonal changes. The factors affecting salinity and temperature are different; whereas salinity varies with outflow, temperature varies with outflow, weather, and ocean influences. In a high outflow year, such as 1995, the limnetic, oligohaline, and mesohaline zones increased and the euhaline zone decreased (see Figure 1A and 1B). In low outflow years, such as 1992, there was often no limnetic zone within the study area and the euhaline zone increased (see Figures 1C and 1D). Temperature was cooler in winters of high outflow years than low outflow years (see Figures 1A and 1C), but there were relatively little temperature differences in summer (see Figures 1B and 1D). Because there is no direct relationship between salinity and temperature, the boundaries of the thermal and salinity gradients do not consistently align; therefore, a species' distribution may be restricted by either or both of these variables.

To determine the general pattern of species occurrence by salinity and temperature, the mean salinity and temperature (±1 standard deviation) were plotted for the 54 most commonly collected species (Figures 2 and 3). The salinity plots form a sigmoid-shaped curve with inflection points between the limnetic and oligohaline salinities and the mesohaline and polyhaline salinities (see Figure 2). Most species were collected from polyhaline and euhaline salinities and only a few were limited to the limnetic or oligohaline regions. The low number of limnetic and oligohaline species is partially due to the concentration of stations downstream of the delta. Generally, the species found at the extreme ends of the salinity gradient (euhaline and limnetic) were collected from relatively narrow salinity ranges (small standard deviations), whereas those from primarily mesohaline salinities had wider salinity ranges (larger standard deviations). Many species with a wide salinity range are either anadromous or partially anadromous (for example, longfin smelt, chinook salmon, and American shad). Most of the others are catadromous, with some migrating long distances from their marine spawning areas to their low salinity nursery areas (for example, starry flounder and *Crangon franciscorum*).

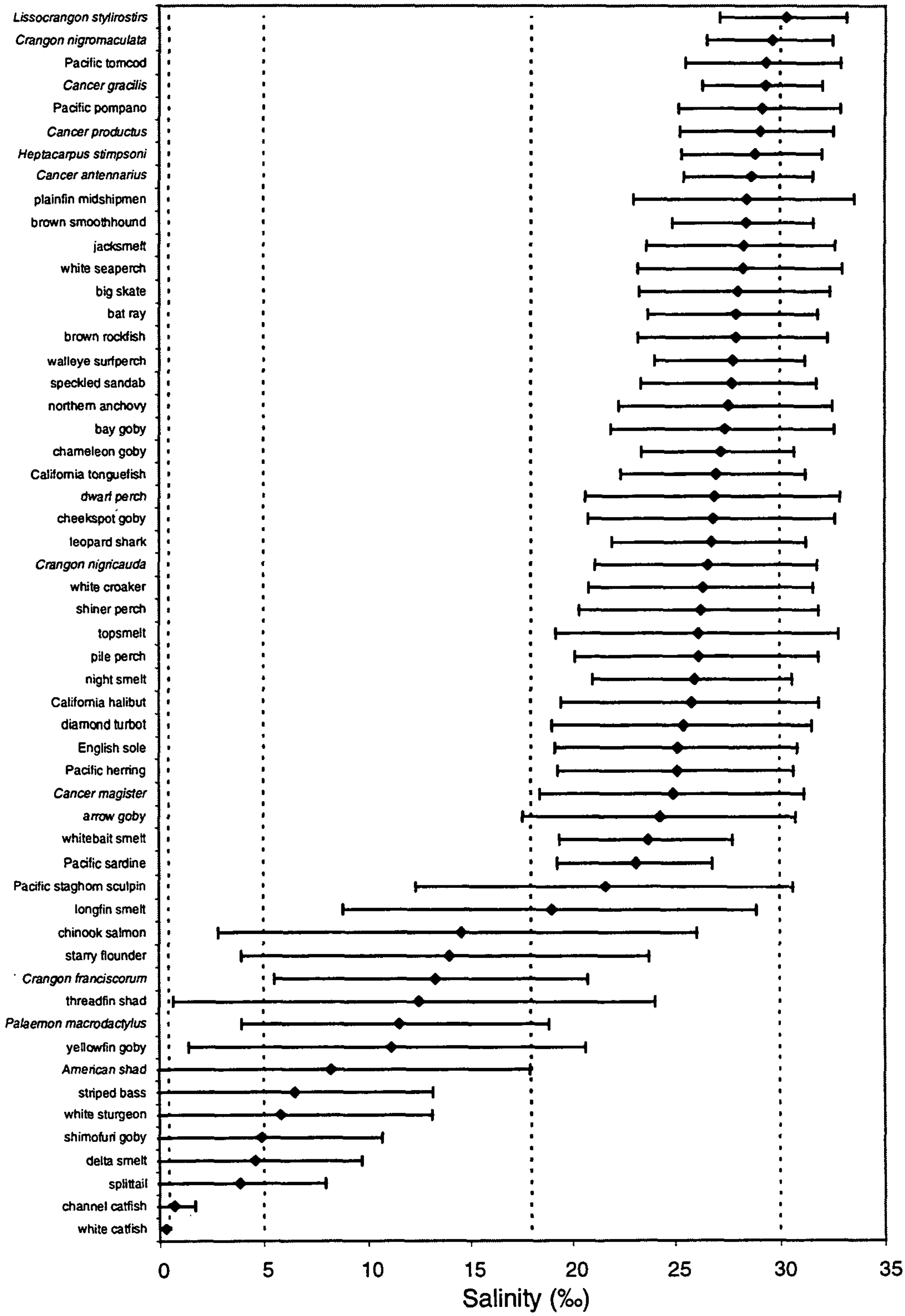

Figure 2 Mean salinity (‰) ±1 standard deviation for the 54 most commonly collected species of fishes, shrimps, and crabs. Data from beach seine for topsmelt, arrow goby, and dwarf perch, otter trawl for shrimps, crabs, and demersal fishes, and midwater trawl for pelagic fishes. CPUE weighted by surface salinity for beach seine, bottom salinity for otter trawl, and water column average salinity for midwater trawl. The vertical lines are the boundaries for the *Venice system of salinity classification.*

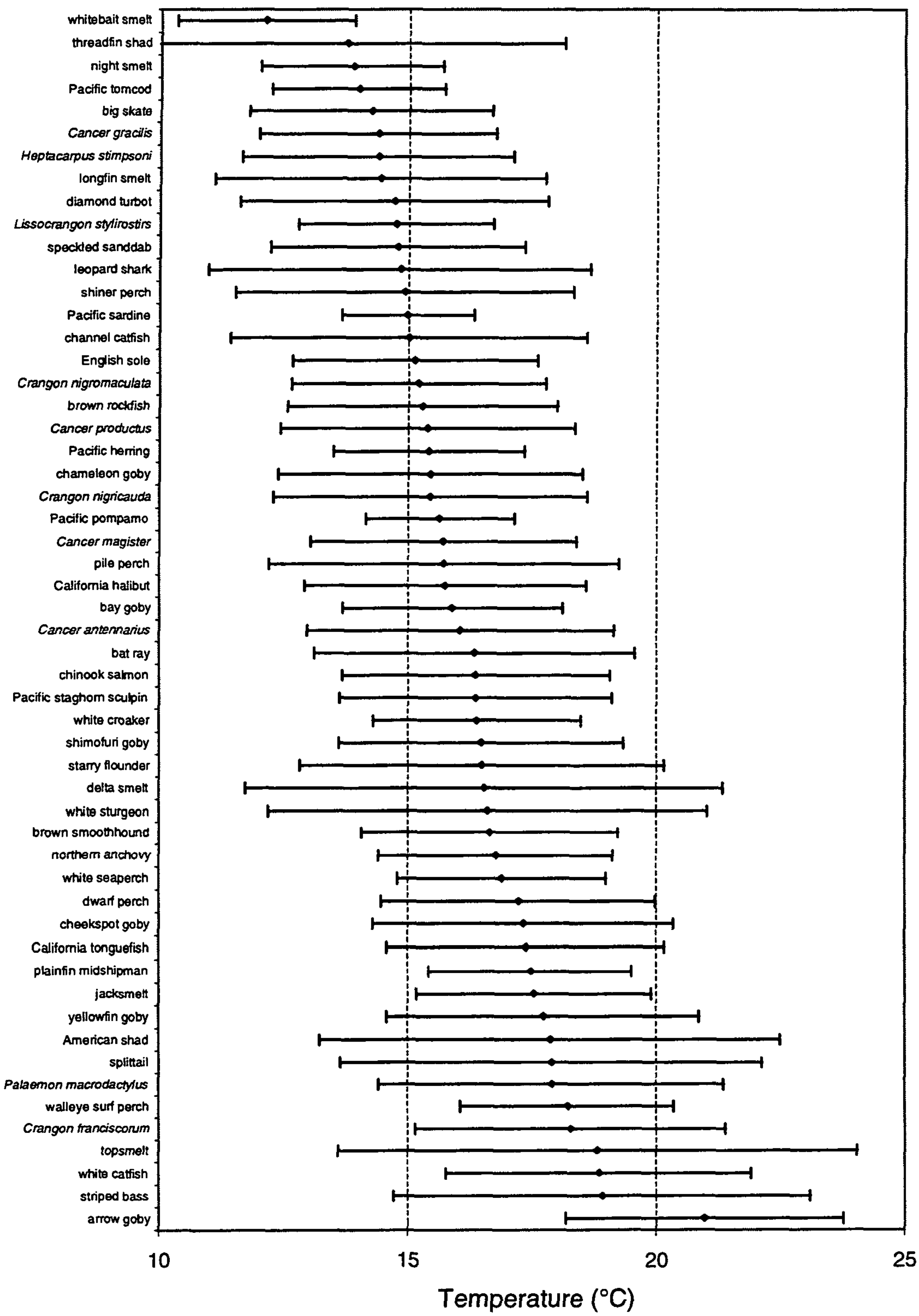

Figure 3 Mean temperature (°C) ±1 standard deviation for the 54 most commonly collected species of fishes, shrimps, and crabs. Data from beach seine for topsmelt, arrow goby, and dwarf perch, otter trawl for shrimps, crabs, and demersal fishes, and midwater trawl for pelagic fishes. CPUE weighted by surface temperature for beach seine, bottom temperature for otter trawl, and water column average temperature for midwater trawl.

The temperature plots form a continuous progression without sharp changes or break points (see Figure 3). Those species with the narrowest ranges (smallest standard deviations) are marine species that use the lower estuary opportunistically, including night smelt, Pacific tomcod, Pacific sardine, and Pacific pompano. Species with the widest temperature ranges (largest standard deviations) include anadromous species that rear in the estuary (for example, delta smelt, white sturgeon, splittail, striped bass, and American shad) and starry flounder, which migrate from the ocean to rear in the upper estuary. The exceptionally wide range for threadfin shad, a freshwater species, is probably an artifact of fish transported downstream of the delta by high outflow events some years.

Life History Strategies

Although the estuary's fishes, shrimps, and crabs have various life history strategies, they can be broadly categorized as either resident, seasonal, or anadromous (Table 1). Resident species generally spend their entire lives in the estuary and use several strategies to retain larvae in the estuary, including reproduction during low outflow periods, adhesive eggs, vertical migration of larvae, and partial anadromy. Many of the common residents inhabit shallow water and do not migrate extensively within the estuary (topsmelt, arrow goby, and dwarf perch), whereas others are partially anadromous (delta smelt) or partially catadromous (yellowfin goby and *Palaemon macrodactylus*).

Table 1 Categories of estuarine use for the most commonly collected species of fishes, shrimps, and crabs[a]

	Seasonal Inhabitants [b]			
Resident [c]	*Obligate Nursery [d]*	*Non-obligate Nursery [e]*	*Opportunist [f]*	*Anadromous*
Palaemon macrodactylus[g]	*Crangon franciscorum*	*Crangon nigromaculata*	*Lissocrangon stylirostris*	white sturgeon
Cancer gracilis	Pacific herring	*Crangon nigricauda*	big skate	American shad
delta smelt	jacksmelt	*Heptacarpus stimpsonii*	northern anchovy	chinook salmon
splittail	plainfin midshipman	*Cancer antennarius*	Pacific sardine	longfin smelt
topsmelt	pile perch	*Cancer magister*	threadfin shad[g]	striped bass[g]
dwarf perch	shiner perch	*Cancer antennarius*	night smelt	
Pacific staghorn sculpin	white seaperch	*Cancer productus*	whitebait smelt	
arrow goby	brown rockfish	brown smoothhound	white catfish[g]	
bay goby	starry flounder	leopard shark	channel catfish[g]	
chameleon goby[g]		bat ray	prickly sculpin	
cheekspot goby		white croaker	Pacific pompamo	
shimofuri goby[g]		walleye surfperch	Pacific tomcod	
yellowfin goby[g]		California halibut		
diamond turbot		California tonguefish		
		English sole		
		speckled sanddab		

[a] None of these categories are exclusive, but are meant to provide a basis for comparing general estuary use patterns.
[b] Seasonal = some life-stage found in the estuary or species found both in estuary and nearshore.
[c] Resident = most individuals usually complete their entire life cycle in the estuary.
[d] Obligate nursery = species that require the estuary as a nursery.
[e] Non-obligate nursery = species that use the estuary as an extension of nearshore coastal nursery.
[f] Opportunist = species that use the estuary as an extension of their nearshore distribution.
[g] Introduced species.

Seasonal species may spend an essential part of their life cycle in the estuary or opportunistically use the estuary. The most common life cycle use of the estuary is as a nursery area, either obligatory or non-obligatory. For obligate species, reproduction or rearing occurs almost exclusively within estuaries and year class success is largely dependent on estuarine conditions. Pacific herring, jacksmelt, and many surfperches are obligate species that immigrate to the estuary to reproduce. Note that all of these species have adhesive eggs or bear live young, characteristics that reduce loss of eggs and young from the estuary. Other estuarine obligates, such as the shrimp *Crangon franciscorum* and starry flounder, reproduce in the ocean and small juveniles or post-larvae immigrate to the estuary to rear. For the non-obligate nursery species, the portion of the year class that rears in the estuary may vary widely by year, and year class success is usually independent of estuarine conditions. Non-obligates species include those that reproduce in the ocean and enter the estuary as small juveniles, such as *Cancer magister*, brown rockfish, and English sole.

Opportunists use the estuary as an extension of their usual habitat; for these species, use of the estuary is not critical for their survival. Many coastal species are opportunists and under favorable conditions some, such as the northern anchovy, reproduce, rear, and forage in the estuary, whereas others (big skate and Pacific pompano) use the estuary primarily for foraging. Several freshwater species, such as white catfish and threadfin shad, are also opportunists; their abundance in the estuary is a function of salinity and increases in high outflow years.

Anadromous species reproduce in freshwater and rear in higher salinities, including the ocean. Some, such as longfin smelt and striped bass, rear in the mesohaline and polyhaline areas of the estuary and include individuals that may never enter the ocean. Others, such as chinook salmon and American shad, use the estuary primarily as a migration corridor.

Reproduction and Rearing

Estuaries are well known as important nurseries for fishes and invertebrates throughout the world. Although larvae and juveniles of many species were collected all year in the San Francisco Estuary, all species had a peak reproduction period (Table 2).

Most of the species that reproduce in the ocean do so in winter and early spring, before the onset of upwelling. This strategy results in retention of larvae near the coast, and most importantly, near the mouths of estuaries. Included in this group are starry flounder, English sole, brown rockfish, the *Cancer* crabs, and *Crangon* shrimp. Notable exceptions include speckled sanddab, which spawn during upwelling, and California halibut, which, in the northern portion of their range, apparently spawn in fall, when ocean temperatures reach their seasonal maxima.

The majority of the anadromous species also reproduce in late winter and spring, when water temperatures are increasing, freshwater flows transport eggs and larvae to downstream nursery areas, and phytoplankton and zooplankton blooms usually occur. Included in this group are longfin smelt and American shad.

For coastal species that enter the estuary to spawn or pup, the reproductive period ranges from winter through summer. As mentioned above, all of these species have a mechanism for retention of their eggs or young in the estuary. Pacific herring and jacksmelt, which have pelagic larvae, spawn in winter or late spring. The live-bearing surfperches and elasmobranchs give birth in late spring and summer, whereas plainfin midshipman, which are nest builders, reproduce in summer.

Table 2 Salinity, location, and timing of peak larval hatching or pupping for the most commonly collected species of fishes, shrimps, and crabs. ♦ indicates peak, + indicates lesser amount of hatching or pupping.

Species	Salinity: Limnetic (0-0.5 ‰)	Oligohaline (0.5 - 5 ‰)	Mesohaline (5 - 18 ‰)	Polyhaline (18 -30 ‰)	Euhaline (>30 ‰)	Location: Rivers and Streams	Delta	Suisun Bay	San Pablo Bay	Central Bay	South Bay	Ocean
white croaker				♦	♦				+	♦	+	♦
starry flounder					♦					+		♦
English sole					♦							♦
Pacific staghorn sculpin			♦	♦					♦	♦	♦	+
Pacific herring				♦	+				+	♦	♦	+
longfin smelt	♦	+				♦	♦	+				
brown rockfish					♦							♦
Pacific tomcod					♦							♦
yellowfin goby			+	♦				+	♦	+	♦	
Pacific sardine					♦							♦
prickly sculpin	♦	+				♦	♦	+				
white sturgeon	♦					♦						
jacksmelt				♦	♦				♦	♦	♦	
Pacific pompano					♦							♦
splittail	♦	+				♦	♦	+				
arrow goby				+	♦				+	♦	♦	
delta smelt	♦	♦				♦	♦	+				
striped bass	♦					♦	♦					
plainfin midshipman				♦	♦				♦	♦	♦	
threadfin shad	♦					♦						
inland silverside	♦	♦				♦	♦	♦	+			
chameleon goby				♦	♦					+	♦	
California tonguefish					♦							♦
speckled sanddab					♦							♦
topsmelt				♦	♦				+	+	♦	
American shad	♦					♦						
cheekspot goby				♦	♦				♦	♦	♦	
northern anchovy			+	♦	♦				♦	♦	♦	♦
bay goby				♦	♦				♦	♦	♦	
California halibut					♦					♦		♦
diamond turbot				♦	♦				♦	♦	♦	+
chinook salmon (fall run)	♦					♦						

Species	Peak hatching or pupping: JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
white croaker	♦	♦	♦	♦	+				+	+	+	♦
starry flounder	♦	♦	♦	+				+	+	+	+	♦
English sole	♦	♦	♦	+	+						+	♦
Pacific staghorn sculpin	♦	♦	♦	+							+	+
Pacific herring	♦	♦	♦	+								+
longfin smelt	♦	♦	♦	♦	+							+
brown rockfish	♦	♦	♦	+								
Pacific tomcod	♦	♦	♦	♦	+	+						
yellowfin goby	+	♦	♦	♦	+	+	+					
Pacific sardine	♦	♦	♦	♦	♦	♦	♦	♦	♦			
prickly sculpin		♦	♦	♦	♦							
white sturgeon		+	♦	♦	♦							
jacksmelt		+	♦	♦	♦	♦	♦	+				
Pacific pompano			♦	♦	♦	♦						
splittail			+	♦	♦	+						
arrow goby				♦	♦	♦	♦	+				
delta smelt				♦	♦	♦	+					
striped bass				+	♦	♦	+					
plainfin midshipman				+	♦	♦	♦	♦	♦	+		
threadfin shad					♦	♦	♦	+				
inland silverside					♦	♦	♦	♦				
chameleon goby					♦	♦	♦	♦	♦			
California tonguefish					♦	♦	♦	♦	♦	♦		
speckled sanddab				+	+	♦	♦	♦	♦	+		
topsmelt					+	♦	♦	♦	+			
American shad					+	♦	♦	♦	+			
cheekspot goby						♦	♦	♦	♦	♦		
northern anchovy				+	+	+	♦	♦	♦	+		
bay goby						+	♦	♦	♦	♦	♦	+
California halibut	+	+	+				+		♦	♦	♦	+
diamond turbot				+	+	+	+	+	♦	♦	♦	+
chinook salmon (fall run)										♦	♦	♦

Table 2 (Continued) Salinity, location, and timing of peak larval hatching or pupping for the most commonly collected species of fishes, shrimps, and crabs. ♦ indicates peak, + indicates lesser amount of hatching or pupping.

	Salinity					Location							Period hatching or pupping											
	Limnetic (0-0.5 ‰)	Oligohaline (0.5 - 5 ‰)	Mesohaline (5 - 18 ‰)	Polyhaline (18 -30 ‰)	Euhaline (>30 ‰)	Rivers and Streams	Delta	Suisun Bay	San Pablo Bay	Central Bay	South Bay	Ocean	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Live bearers																								
dwarf perch				♦	♦				♦	♦	♦	♦				♦	♦	♦	♦	♦				
walleye surfperch				♦	♦					♦	♦	♦					♦	♦						
shiner perch				♦	♦				♦	♦	♦	♦					♦	♦	♦					
pile perch				♦	♦				+	♦	♦	♦					♦	♦	♦					
white seaperch				♦	♦					♦	♦	♦					♦	♦	♦	♦				
leopard shark				♦	♦				+	♦	♦	♦			+	♦	♦	+						
brown smoothhound				♦	♦				+	♦	♦	♦				♦	♦	♦	+	+				
big skate				♦	♦				+	♦	+	♦		+	+	+	+	♦	♦					
bat ray				♦	♦				+	♦	♦	♦				+	+	♦	♦	♦	+			
Invertebrates																								
Heptacarpus stimpsonii					♦					♦	♦	+	♦	♦	+			+	+	+			+	♦
Crangon franciscorum				♦	♦				+	♦	♦	♦	♦	♦	♦	♦	+	♦	♦	+				
Crangon nigricauda				+	♦				+	♦	♦	♦	♦	♦	♦	♦	+	+	♦	♦	♦	+		
Lissocrangon stylirostris					♦							♦	+	♦	♦	♦	♦	+						
Crangon nigromaculata					♦					♦		♦	+	♦	♦	♦	♦	♦	+	+	+			
Palaemon macrodactylus		♦	♦					♦	♦								+	♦	♦	♦	+			
Cancer magister					♦							♦	♦	♦	♦	♦	+							+
Cancer productus					♦					♦		♦	+	♦	♦	♦	♦	♦	+				+	+
Cancer gracilus				♦	♦					♦		♦	+	♦	♦	♦	♦	♦	+					
Cancer antennarius					♦					♦		♦	+	♦	♦	♦	♦	♦	♦	+				+

Resident species also reproduce over a relatively long period, although most of their larvae hatch in late spring and summer. Included in this group are delta smelt, arrow goby, topsmelt, and cheekspot goby. Winter spawning residents include staghorn sculpin and yellowfin goby, whereas bay goby and diamond turbot are residents that primarily reproduce in late summer and fall.

The duration of estuarine rearing varies widely—species may rear in the estuary for only a few months (for example, walleye surfperch) to several years (for example, starry flounder and brown rockfish). Most rearing is from late spring through early fall (Table 3); the late fall and winter spawners rear earlier than the spring and summer spawners. For some ocean species, there is a long interval between larval hatching and estuarine use. For example, California tonguefish and speckled sanddab have long pelagic phases and months pass between larval hatching and settlement or immigration of juveniles. Some species emigrate from the estuary well before maturity (for example, English sole), whereas others emigrate at or after maturity (for example, *Cancer magister* and brown rockfish).

The nursery area is often not the same as the spawning or pupping location for many of the species that immigrate to the estuary to reproduce and some of the residents (see Table 3). For example, Pacific herring spawn in polyhaline and euhaline salinities (see Table 2) but rear in mesohaline and polyhaline areas (see Table 3). Yellowfin goby, which are partially catadromous, spawn in mesohaline and polyhaline salinities (see Table 2) but rear in oligohaline and mesohaline areas (see Table 3).

Concurrent with the migration to lower salinities to rear, juveniles of most species move to warmer, shallow water. As they mature, larger juveniles migrate to deeper, cooler, more saline water. Many species begin emigrating from their upstream rearing areas or from the estuary in late summer or early fall, when water temperatures reach their seasonal maxima. Thus, there is a common temperature pattern associated with growth. For most species, temperature initially increases and then decreases with size. This pattern is due to ontogentic changes in temperature tolerances coupled with the seasonal temperature cycle.

Abundance Trends

Many estuarine species had similar abundance trends (Table 4) and these trends were often related to physical factors. Although species can be grouped by abundance trends, these groups may oversimplify our conception of the mechanisms controlling abundance. For example, the species whose abundance increased with outflow (see Table 4) generally benefited from the increased area or volume of oligohaline and mesohaline nursery habitat in high outflow years (CDFG 1992). But for some species, such as longfin smelt, this positive response to outflow may be partially due to increased transport of larvae from upstream spawning areas to nursery areas. For species that reproduce in the ocean, such as starry flounder and *Crangon franciscorum*, increased abundance may be also a result of increased transport of larger larvae and juveniles into the estuary by gravitational currents or increased immigration of juveniles in response to some cue present in "estuarine" waters.

Table 3 Salinity, location, and timing of juvenile rearing (age-0) for the most commonly collected species of fishes, shrimps, and crabs. ♦ indicates peak, + indicates lesser amount of rearing.

	Salinity					Location							Peak occurrence in estuary											
Species	Limnetic (0-0.5 ‰)	Oligohaline (0.5 - 5 ‰)	Mesohaline (5 - 18 ‰)	Polyhaline (18 -30 ‰)	Euhaline (>30 ‰)	Rivers and Streams	Delta	Suisun Bay	San Pablo Bay	Central Bay	South Bay	Ocean	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
bay goby				♦	♦				+	♦	♦		♦	♦	♦	♦	♦	♦	+				+	+
Pacific staghorn sculpin	+	+	♦	♦			+	+	♦	♦	+			♦	♦	♦	♦	♦	♦	♦	♦			
California halibut				♦	♦				+	♦	♦	♦	+	+	♦	♦	♦	♦					♦	♦
Pacific herring			♦	♦					♦	♦	♦				+	♦	♦	♦	♦	+	+			
jacksmelt				♦	♦				♦	♦	♦				+	♦	♦	♦	♦	♦	♦	♦	+	+
English sole			+	♦	♦				♦	♦	+	♦			+	♦	♦	♦	♦	♦	♦	♦	+	+
prickly sculpin	♦	♦	+			♦	♦	+								♦	♦	♦	+	+				
speckled sanddab				♦	♦				+	♦	♦		+			♦	♦	♦	♦	+			+	+
chinook salmon (fall run)	♦	♦	♦	♦	+	♦	♦	♦	♦	♦		♦				+	♦	♦	+					
northern anchovy			♦	♦	♦				♦	♦	♦					+	♦	♦	♦	♦	+	+		
longfin smelt		+	♦	♦	+		+	♦	♦	♦	+					+	♦	♦	♦	♦	♦	♦	+	+
splittail	♦	♦	+			♦	♦	+					+	+		+	♦	♦	♦	♦	♦	♦	+	+
white sturgeon	♦	♦	+				♦	♦	+				+	+		+	♦	♦	♦	♦	♦	♦	+	+
diamond turbot				♦	♦					♦	♦					+	♦	♦	♦	+	+			
Pacific pompano					♦					♦		♦				+	♦	♦	♦	♦	+	+		
white croaker				♦	♦				♦	♦	♦	♦					♦	♦	♦	+				
inland silverside	♦	♦	+			♦	♦	♦	+								♦	♦	♦	♦				
arrow goby				+	♦				+	♦	♦						♦	♦	♦	♦	+	+		
American shad	♦	♦	♦				♦	♦									+	♦	♦	♦	♦	+	+	
yellowfin goby	+	♦	♦				♦	♦	+		+						+	♦	♦	♦	♦	+	+	+
starry flounder	♦	♦	♦	+			♦	♦	♦	+	+	♦					+	♦	♦	♦	♦	♦	+	+
brown rockfish				+	♦				+	♦	+						+	♦	♦	♦	♦	♦	♦	♦
striped bass	♦	♦	+				♦	♦	♦		+		+	+	+		+	♦	♦	♦	♦	♦	♦	♦
California tonguefish				♦	♦				+	♦	♦							♦	♦	♦	♦	♦	+	+
threadfin shad	♦	♦	+				♦	+										♦	♦	♦	♦	♦	+	+
cheekspot goby				♦	♦				♦	♦	♦						+	+	♦	♦	♦	♦		
cheekspot goby				♦	♦				♦	♦	♦						+	+	♦	♦	♦	♦	+	+
delta smelt	♦	♦	+				♦	♦	+									+	♦	♦	♦	♦	♦	♦
topsmelt				♦	♦				+	♦	♦								♦	♦	♦	♦	+	+
plainfin midshipman				♦	♦				♦	♦	+								+	♦	♦	♦	+	
chameleon goby				♦	♦					+	♦									+	♦	♦	♦	♦
Pacific tomcod				♦	♦				+	♦										+	+	♦	♦	♦

Table 3 (Continued) Salinity, location, and timing of juvenile rearing (age-0) for the most commonly collected species of fishes, shrimps, and crabs. ♦ indicates peak, + indicates lesser amount of rearing.

	Salinity					Location							Peak occurance in estuary											
	Limnetic (0-0.5 ‰)	Oligohaline (0.5 - 5 ‰)	Mesohaline (5 - 18 ‰)	Polyhaline (18 -30 ‰)	Euhaline (>30 ‰)	Rivers and Streams	Delta	Suisun Bay	San Pablo Bay	Central Bay	South Bay	Ocean	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Live bearers																								
white seaperch				♦	♦				+	♦	♦						+	♦	♦	♦	+	+		
walleye surfperch				♦	♦				+	♦	♦	♦					+	♦	♦	♦				
shiner perch				♦	♦			+	♦	♦	♦						♦	♦	♦	♦	♦	♦	+	+
pile perch				♦	♦				+	♦	♦	♦						+	♦	♦	+	+	+	+
dwarf perch				♦	♦				+	♦	♦	♦					♦	♦	♦	♦	+	+		
leopard shark				+	♦				+	♦	♦	♦			+	♦	♦	♦	♦	♦	♦	♦	+	+
brown smoothhound				+	♦				+	♦	♦	♦				+	♦	♦	♦	♦	+	+		
big skate				+	♦				+	♦	♦	♦		+	+	+	♦	♦	♦	♦	♦	+		
bat ray				+	♦				+	♦	♦	♦					+	+	♦	♦	♦	♦	+	+
Invertebrates																								
Crangon franciscorum		+	♦	+			+	♦	♦	+	+					+	♦	♦	♦	♦	+	+	+	
Heptacarpus stimpsoni				♦	♦				+	♦	♦	+	+				♦	♦	♦	♦				+
Crangon nigricauda			+	♦	♦			+	♦	♦	♦	+	+	+			♦	♦	♦	♦	+			+
Crangon nigromaculata				+	♦				+	♦	+	♦					♦	♦	♦	♦	♦			
Lissocrangon stylirostris					♦					♦		♦				+	+	♦	♦	♦	+	+		
Palaemon macrodactylus	+	♦	♦				♦	♦	+		+							+	♦	♦	♦	♦	+	+
Cancer gracilis				♦	♦	♦			+	♦	+	♦	♦	♦		+	♦	♦	♦	♦		♦	♦	♦
Cancer magister			+	♦	♦			+	♦	♦	+	♦	+			+	♦	♦	♦	♦	♦	♦	♦	♦
Cancer productus				♦	♦				+	♦	+	♦	+			+	+	♦	♦	♦	+	+	+	+
Cancer antennarius				♦	♦				+	♦	♦	♦							+	♦	♦	♦	♦	+

Table 4 General categories in abundance trends for the most commonly collected fishes, shrimps, and crabs considered in this report[a]

Increased in high outflow years	*Increased during warm water events*	*Decreased during warm water events*	*Increased in the mid-1980s*	*Increased in the 1990s*	*Decreased through the mid-1980s and 1990s*
Crangon franciscorum	*Crangon nigromaculata*	*Cancer magister*	*Crangon nigricauda*	*Crangon nigromaculata*	delta smelt
longfin smelt	Pacific sardine	Pacific herring	brown smoothhound	*Heptacarpus stimpsonii*	jacksmelt
American shad	northern anchovy	northern anchovy	leopard shark	*Cancer antennarius*	barred perch
Pacific herring[b]	white croaker	starry flounder	bat ray	*Cancer gracilis*	pile perch
yellowfin goby	California halibut		white croaker	*Cancer productus*	shiner perch
starry flounder[b]	California tonguefish		bay goby	Pacific pompano	walleye surfperch
	diamond turbot		plainfin midshipman	chameleon goby	white seaperch
			California halibut		
			diamond turbot		
			speckled sanddab		

[a] Species common only in the beach seine were excluded, as this gear was used only through January 1987.
[b] In high outflow years, indices were lower in the 1990s than in the 1980s.

Above average ocean temperatures apparently resulted in increased abundance of a group of species that includes the shrimp *Crangon nigromaculata*, Pacific sardine, white croaker, and California halibut (see Table 4). The latitudinal distribution of these species is usually centered to the south of the estuary, and increased abundance may be due to a northerly movement of juveniles and adults with warm water. Also, several of these species, including California halibut, may have more successful local reproduction during warm water periods, as higher temperatures may stimulate maturation of gonads and increase fertilization, embryonic survival, and larval survival rates. Abundance of some species may have increased after a series of warm water events. Therefore, the frequency and duration of warm water events, as well as the magnitude, may be important factors.

Abundance of *Cancer magister*, Pacific herring, northern anchovy, and starry flounder decreased with increased ocean temperatures (see Table 4). With the exception of northern anchovy, the San Francisco Estuary is near the southern limit of these species' ranges. The observed abundance decreases may be due to a northward movement of a population or subpopulation during warm water events. Warm water events may also retard maturation of gonads and decrease fertilization, embryonic survival, and larval survival rates (for example, *Cancer magister* and Pacific herring).

In the mid-1980s, abundance of a number of species increased, including the shrimp *Crangon nigricauda*, white croaker, bay goby, and speckled sanddab (see Table 4). Although several factors probably contributed to this trend, increased area with euhaline and polyhaline salinities during the 1987–1992 drought was probably most important. During the drought, several species, including bay goby and *Crangon nigricauda*, had protracted spawning and multiple cohorts. This led to the hypothesis that higher salinities present all year in the estuary enhanced nursery conditions for many species within this group. However, abundance of some species, including white croaker and California halibut, increased prior to the onset of the drought. These initial abundance increases may have been in response to the 1986–1987 El Niño; favorable estuarine conditions associated with the drought then contributed to continued high abundance.

In the 1990s, a group of species including the rock crabs (*Cancer antennarius* and *C. productus*), the shrimp *Crangon nigromaculata*, and the chameleon goby, increased in abundance (see Table 4). All of these species inhabit euhaline and polyhaline areas of the estuary. Ocean temperatures were usually above average from 1992 to 1996 (see chapter 3, Figure 11), and the abundance of several of these species increased somewhat during previous warm water events. However, freshwater outflow was relatively high in 1995 and 1996, which leads us to ask how these "marine" species may have sustained high abundance through this period. We are not certain of the mechanisms that resulted in increased abundance.

The last group of species, including the surfperches, jacksmelt, and delta smelt, is notable for decreasing abundance as of the mid-1980s (see Table 4). Although the initial year of the decline varied, none of these species recovered to previous levels in the 1990s. The decline in delta smelt abundance may be due to several factors, including entrapment zone location, reverse flows, and food abundance (Sweetnam and Stevens 1993). Likewise, the decline of the remaining species in this group has not been attributed to a single factor, although overharvest by sport anglers has been proposed for the surfperches (see chapter 13).

For many species, especially seasonal inhabitants, physical factors associated with the ocean or the rivers at least partially control abundance. Abundance of most species that rear in oligohaline salinities increased with freshwater outflow. In contrast, abundance of several species that rear in polyhaline and euhaline salinities increased in low outflow years, but most did so during the prolonged 1987–1992 drought rather than during single low outflow years. Many species responded to increased ocean temperatures. This is not surprising, as the San Francisco Estuary is situated in the transitional zone between the subtropical fauna (Point Conception south) and the cold water fauna (Cape Blanco north), and contains species from both faunas (Parrish and others 1981).

The San Francisco Bay Study has increased our understanding and appreciation of the complexity of the estuary. There are still many gaps in our knowledge, including a definition of critical life stages and the factors affecting these stages. We will continue our attempts to differentiate between causal and covarying factors. To do this, we will need to augment the study's data with other data sources when possible, and propose directions for improved monitoring and future research. The better we understand the mechanisms that regulate species' abundance, whether natural or anthropogenic, the better prepared we will be to manage the estuary's resources in future years.

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Appendix A

Appendix Table A Total catch, percent of total catch, and annual catch of fishes collected with the beach seine from 1980 to 1987. All months sampled are included (only August to December in 1980 and January in 1987).

			Year							
Common Name	*Total*	*%*	*80*	*81*	*82*	*83*	*84*	*85*	*86*	*87*
topsmelt	30210	31.76	3460	2261	3025	4408	6873	5677	4346	160
jacksmelt	13083	13.76	64	281	900	3388	1997	918	5503	32
northern anchovy	12995	13.66	287	3537	1990	4864	865	341	1108	3
Pacific herring	11335	11.92	0	21	1685	112	204	4663	4650	0
striped bass	5358	5.63	93	1299	169	2295	555	32	909	6
inland silverside	4811	5.06	216	642	262	270	2442	531	443	5
yellowfin goby	3778	3.97	128	182	276	136	221	44	2791	0
arrow goby	3395	3.57	53	1046	158	472	301	102	1260	3
Pacific staghorn sculpin	2783	2.93	22	327	615	117	577	771	272	82
shiner perch	1794	1.89	319	427	125	268	153	214	288	0
dwarf perch	1081	1.14	254	282	111	65	97	99	173	0
threespine stickleback	860	0.90	64	97	94	316	149	20	114	6
threadfin shad	634	0.67	8	10	13	573	18	1	10	1
chinook salmon	474	0.50	0	84	56	104	21	19	190	0
bay pipefish	454	0.48	62	105	25	29	66	37	130	0
surf smelt	290	0.30	4	29	150	19	36	48	4	0
walleye surfperch	269	0.28	50	35	10	95	7	12	60	0
splittail	255	0.27	0	5	77	120	9	3	41	0
English sole	214	0.22	15	26	50	1	27	7	87	1
delta smelt	115	0.12	8	11	3	75	12	0	6	0
longfin smelt	101	0.11	21	30	26	20	4	0	0	0
starry flounder	98	0.10	14	6	7	12	23	7	29	0
cheekspot goby	94	0.10	0	9	3	2	2	18	59	1
western mosquitofish	71	0.07	0	6	19	27	2	3	13	1
American shad	69	0.07	3	2	12	43	4	0	5	0
rainwater killifish	66	0.07	17	13	5	6	5	13	7	0
Sacramento squawfish	64	0.07	11	14	2	16	12	2	7	0
white croaker	62	0.07	0	0	2	3	3	22	32	0
bay goby	56	0.06	9	17	17	11	0	0	1	1
tule perch	49	0.05	2	29	1	2	1	13	1	0
barred surfperch	32	0.03	6	2	0	9	1	4	10	0
diamond turbot	23	0.02	1	3	1	3	4	6	5	0

Appendix Table A (Continued) Total catch, percent of total catch, and annual catch of fishes collected with the beach seine from 1980 to 1987. All months sampled are included (only August to December in 1980 and January in 1987).

			Year							
Common Name	*Total*	*%*	*80*	*81*	*82*	*83*	*84*	*85*	*86*	*87*
pile perch	19	0.02	2	2	0	4	6	4	1	0
chameleon goby	16	0.02	0	0	0	0	2	4	10	0
black perch	14	0.01	1	8	1	0	3	0	1	0
California halibut	11	0.01	0	0	0	0	6	4	1	0
plainfin midshipman	8	0.01	0	0	0	0	0	0	8	0
Pacific sand lance	6	0.01	0	0	0	0	0	6	0	0
bat ray	5	0.01	0	0	1	2	2	0	0	0
brown rockfish	5	0.01	1	1	3	0	0	0	0	0
night smelt	5	0.01	0	1	0	4	0	0	0	0
penpoint gunnel	5	0.01	0	5	0	0	0	0	0	0
steelhead trout	5	0.01	0	0	1	0	2	1	1	0
sand sole	4	>0.01	2	0	0	0	0	2	0	0
longjaw mudsucker	3	>0.01	0	0	0	2	1	0	0	0
prickly sculpin	3	>0.01	0	0	1	0	0	0	2	0
rubberlip seaperch	3	>0.01	1	0	0	0	0	0	2	0
speckled sanddab	3	>0.01	1	0	1	1	0	0	0	0
white seaperch	3	>0.01	0	1	0	0	0	2	0	0
common carp	2	>0.01	0	1	0	1	0	0	0	0
hitch	2	>0.01	0	0	0	2	0	0	0	0
saddleback gunnel	2	>0.01	0	0	0	0	0	0	2	0
striped kelpfish	2	>0.01	0	2	0	0	0	0	0	0
white catfish	2	>0.01	0	0	0	2	0	0	0	0
bigscale logperch	1	>0.01	0	0	0	0	0	0	1	0
bonehead sculpin	1	>0.01	1	0	0	0	0	0	0	0
channel catfish	1	>0.01	0	0	0	1	0	0	0	0
fluffy sculpin	1	>0.01	0	0	1	0	0	0	0	0
golden shiner	1	>0.01	0	0	0	0	0	0	1	0
largemouth bass	1	>0.01	0	0	0	1	0	0	0	0
Pacific sardine	1	>0.01	0	0	0	0	0	0	1	0
Sacramento blackfish	1	>0.01	0	0	0	1	0	0	0	0
shimofuri goby	1	>0.01	0	0	0	0	1	0	0	0
silver surfperch	1	>0.01	0	0	0	0	0	0	1	0
striped mullet	1	>0.01	0	0	0	1	0	0	0	0
unidentified sunfishes	1	>0.01	0	0	0	1	0	0	0	0
white crappie	1	>0.01	0	0	0	0	0	0	1	0
Total Catch	95114		5200	10859	9898	17904	14714	13650	22587	302

Appendix B

Appendix Table B Total catch, percent of total catch, and annual catch of fishes collected with the midwater trawl from 1980 to 1985. All months and stations sampled are included.

			Year															
Common Name	*Total*	*%*	*80*	*81*	*82*	*83*	*84*	*85*	*86*	*87*	*88*	*89*	*90*	*91*	*92*	*93*	*94*	*95*
northern anchovy	1845740	89.35	54042	94925	129876	63335	171188	90565	117998	112775	88127	95334	79186	93201	246395	241672	69296	97825
Pacific herring	80988	3.92	9283	1576	17571	937	4929	6957	11319	3373	6103	6181	691	1188	1194	6679	667	2340
longfin smelt	54130	2.62	7177	2987	20153	8357	1996	1412	1559	1375	821	314	119	121	55	303	239	7142
striped bass	19850	0.96	819	1730	4063	3180	1914	371	2207	486	560	269	276	430	854	2174	84	433
white croaker	11665	0.56	470	70	27	163	379	127	687	394	2840	1593	827	509	826	2254	175	324
jacksmelt	10716	0.52	206	1046	486	505	1107	2746	702	673	757	498	483	517	283	303	107	297
shiner perch	8273	0.40	396	1147	790	302	320	825	725	639	1152	393	336	362	316	449	51	70
plainfin midshipman	6315	0.31	45	30	77	1036	72	171	361	993	1169	485	534	242	931	91	10	68
American shad	6258	0.30	161	323	1247	519	274	110	162	118	181	101	240	171	186	871	7	1587
topsmelt	4906	0.24	124	68	120	384	61	1689	89	1685	164	15	19	12	8	67	11	390
yellowfin goby	2528	0.12	175	37	171	36	195	11	320	91	36	41	14	4	87	1142	4	164
chinook salmon	1866	0.09	34	39	142	96	55	79	161	60	66	91	104	281	218	170	5	265
threadfin shad	1630	0.08	36	28	29	219	47	16	33	34	26	12	6	0	46	672	4	422
Pacific pompano	1604	0.08	10	97	52	20	2	0	4	75	93	76	174	183	427	191	40	160
delta smelt	1598	0.08	201	307	170	219	107	37	103	44	30	14	28	60	81	56	58	83
Pacific sardine	1521	0.07	0	0	0	0	1	0	1	1	12	1	2	2	0	111	225	1165
bay goby	1123	0.05	60	13	73	13	27	5	52	53	184	337	112	92	48	23	0	31
English sole	838	0.04	17	22	2	11	3	10	94	1	170	61	30	390	2	18	2	5
walleye surfperch	749	0.04	37	203	72	22	78	40	29	67	44	42	29	21	25	26	1	13
Pacific staghorn sculpin	547	0.03	20	22	55	23	21	16	74	7	81	107	18	31	18	23	2	29
splittail	434	0.02	9	15	49	35	33	9	65	26	9	6	7	7	4	32	0	128
starry flounder	402	0.02	106	29	61	48	37	8	18	12	25	11	7	4	3	13	0	20
bat ray	365	0.02	24	23	10	8	11	12	11	17	75	26	29	28	42	16	22	11
white sturgeon	204	0.01	16	9	13	23	41	11	10	22	18	7	11	9	7	4	0	3
brown smoothhound	198	0.01	2	4	0	1	4	1	7	14	80	22	22	15	16	5	4	1
night smelt	183	0.01	159	1	0	0	0	0	0	0	0	0	1	1	4	14	1	2
channel catfish	114	0.01	0	0	0	0	0	0	0	0	0	0	0	0	3	89	16	6
speckled sanddab	92	>0.01	4	0	2	1	0	0	5	2	23	28	1	7	6	7	0	6

Appendix Table B (Continued) Total catch, percent of total catch, and annual catch of fishes collected with the midwater trawl from 1980 to 1985. All months and stations sampled are included.

Common Name	*Total*	*%*	*Year*															
			80	*81*	*82*	*83*	*84*	*85*	*86*	*87*	*88*	*89*	*90*	*91*	*92*	*93*	*94*	*95*
surf smelt	89	>0.01	7	12	19	9	2	1	2	0	1	2	18	4	12	0	0	0
whitebait smelt	80	>0.01	0	0	6	8	8	36	3	1	6	3	4	3	1	0	1	0
white catfish	76	>0.01	2	0	0	1	10	0	1	0	2	1	2	12	7	3	0	35
white seaperch	69	>0.01	10	23	3	3	1	1	1	13	6	6	1	0	1	0	0	0
threespine stickleback	65	>0.01	6	1	11	5	0	0	6	2	3	4	1	4	3	10	0	9
leopard shark	64	>0.01	1	3	2	1	1	1	2	3	19	11	5	4	6	1	3	1
shimofuri goby	60	>0.01	0	0	0	0	0	0	0	0	0	9	2	7	15	17	0	10
spiny dogfish	41	>0.01	2	1	0	1	2	1	1	1	7	6	4	11	2	2	0	0
common carp	33	>0.01	7	1	4	0	1	0	3	11	0	1	3	1	0	0	0	1
brown rockfish	28	>0.01	0	0	0	1	0	0	0	0	2	2	0	1	0	22	0	0
Pacific tomcod	27	>0.01	6	1	3	2	0	0	0	0	2	9	1	2	0	0	0	1
pile perch	27	>0.01	2	6	5	2	1	4	4	1	1	0	0	1	0	0	0	0
big skate	26	>0.01	0	6	0	0	0	0	0	1	13	1	0	1	0	2	2	0
steelhead trout	26	>0.01	4	0	2	2	0	1	1	0	0	2	0	1	3	6	1	3
lingcod	22	>0.01	1	0	2	1	2	3	1	2	8	2	0	0	0	0	0	0
California halibut	19	>0.01	1	1	0	0	0	0	0	0	1	0	0	0	0	7	3	6
bay pipefish	13	>0.01	1	2	0	1	0	1	2	2	1	2	0	0	0	1	0	0
chameleon goby	10	>0.01	0	0	0	1	0	1	0	0	3	2	0	1	1	0	0	1
Pacific lamprey	10	>0.01	1	1	2	2	0	1	2	0	0	1	0	0	0	0	0	0
California lizardfish	9	>0.01	0	0	0	2	0	0	0	0	1	0	0	0	6	0	0	0
diamond turbot	9	>0.01	1	1	3	0	0	0	0	0	1	0	0	0	1	1	1	0
green sturgeon	9	>0.01	1	1	4	0	0	0	0	0	0	1	0	1	0	1	0	0
river lamprey	8	>0.01	0	0	0	1	2	0	0	1	0	0	1	2	0	1	0	0
black rockfish	7	>0.01	0	0	0	0	0	0	0	0	7	0	0	0	0	0	0	0
jack mackerel	6	>0.01	0	0	0	0	0	0	0	0	0	0	0	0	0	6	0	0
rubberlip seaperch	6	>0.01	0	0	0	0	0	0	0	4	0	0	2	0	0	0	0	0
cheekspot goby	5	>0.01	0	0	0	0	0	0	0	0	1	0	1	1	1	1	0	0
queenfish	5	>0.01	0	0	0	0	0	0	0	1	0	0	1	1	1	0	1	0
sand sole	5	>0.01	1	0	0	2	0	0	0	2	0	0	0	0	0	0	0	0
unidentified rockfish	5	>0.01	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0
barred surfperch	4	>0.01	1	1	0	0	0	0	0	0	0	0	0	1	1	0	0	0

Appendix Table B (Continued) Total catch, percent of total catch, and annual catch of fishes collected with the midwater trawl from 1980 to 1985. All months and stations sampled are included.

Common Name	*Total*	*%*	*Year*															
			80	*81*	*82*	*83*	*84*	*85*	*86*	*87*	*88*	*89*	*90*	*91*	*92*	*93*	*94*	*95*
brown bullhead	4	>0.01	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pacific electric ray	4	>0.01	0	0	0	0	0	0	1	0	1	1	1	0	0	0	0	0
tule perch	4	>0.01	1	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1
California tonguefish	3	>0.01	0	0	0	1	0	0	0	0	1	0	0	0	1	0	0	0
inland silverside	3	>0.01	0	1	0	0	2	0	0	0	0	0	0	0	0	0	0	0
Sacramento squawfish	3	>0.01	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	1
bluegill	2	>0.01	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0
rainwater killifish	2	>0.01	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0
silver surfperch	2	>0.01	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
unidentified sunfishes	2	>0.01	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0
wakasagi	2	>0.01	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1
arrow goby	1	>0.01	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
black bullhead	1	>0.01	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
black crappie	1	>0.01	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
black perch	1	>0.01	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
bonehead sculpin	1	>0.01	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
calico surfperch	1	>0.01	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
chub mackerel	1	>0.01	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
coho salmon	1	>0.01	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
dwarf perch	1	>0.01	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
goldfish	1	>0.01	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
kelp greenling	1	>0.01	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
largemouth bass	1	>0.01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Pacific barracuda	1	>0.01	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Pacific sanddab	1	>0.01	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
prickly sculpin	1	>0.01	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
redtail surfperch	1	>0.01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Sacramento sucker	1	>0.01	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
showy snailfish	1	>0.01	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
thresher shark	1	>0.01	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Total Catch	2065750		73696	104816	175380	79544	182936	105281	136828	123084	102938	106133	83353	97948	252149	257559	71043	113062

Appendix C

Appendix Table C Total catch, percent of total catch, and annual catch of fishes collected with the otter trawl from 1980 to 1985. All months and stations sampled are included. Note: northern anchovy excluded.

			Year															
Common Name	*Total*	*%*	*80*	*81*	*82*	*83*	*84*	*85*	*86*	*87*	*88*	*89*	*90*	*91*	*92*	*93*	*94*	*95*
longfin smelt	44759	15.81	8009	1250	16289	7189	2656	1336	840	510	454	115	42	36	40	258	202	5533
bay goby	40540	14.32	782	464	1349	2346	1085	341	1725	1788	2703	3508	4001	9607	2950	3309	2153	2429
white croaker	34171	12.07	2320	339	339	607	1297	1320	2403	1648	2039	1399	2105	1901	3011	9366	2837	1240
striped bass	29026	10.25	1046	2173	2291	6619	3243	1693	1284	1145	742	686	552	1075	1842	1544	1787	1304
English sole	21969	7.76	2045	1382	1140	949	2385	2330	1088	449	1477	1364	613	1904	962	2873	487	521
speckled sanddab	21936	7.75	2564	204	681	546	258	449	945	1042	1521	1555	637	1348	1672	2827	3239	2448
shiner perch	20986	7.41	1490	1929	3159	1629	987	1791	2725	1405	2120	699	835	548	464	362	297	546
Pacific staghorn sculpin	15790	5.58	1063	261	1515	693	937	1201	2069	785	1120	1507	582	956	547	1082	444	1028
plainfin midshipman	13797	4.87	170	312	326	457	305	254	1554	1649	1049	614	985	1237	1166	609	2641	469
yellowfin goby	12428	4.39	843	189	370	324	863	102	1504	737	267	322	145	49	744	3733	385	1851
Pacific herring	4135	1.46	585	241	1029	73	91	244	90	76	285	892	136	25	39	12	180	137
starry flounder	4002	1.41	986	259	598	644	392	200	217	145	137	38	60	89	35	34	54	114
California tonguefish	2123	0.75	110	12	102	404	147	52	15	40	201	41	8	44	78	468	372	29
cheekspot goby	1769	0.62	0	7	11	29	20	8	40	16	44	40	348	105	227	188	423	263
white catfish	1484	0.52	20	7	12	292	42	8	9	7	0	7	0	6	40	2	634	398
brown smoothhound	1440	0.51	47	47	79	73	38	37	130	101	212	181	157	99	78	43	71	47
chameleon goby	1284	0.45	0	10	3	8	21	44	47	54	108	118	79	71	85	322	227	87
channel catfish	1264	0.45	0	1	1	29	13	9	36	43	2	2	1	18	16	578	211	304
brown rockfish	1260	0.44	93	73	27	42	121	49	42	55	61	8	28	64	55	237	211	94
Pacific tomcod	988	0.35	90	75	168	53	1	0	0	1	19	61	16	30	23	8	2	441
California halibut	708	0.25	7	8	9	7	21	32	30	29	18	8	26	42	62	222	107	80
walleye surfperch	520	0.18	27	184	91	37	21	16	39	27	28	7	11	17	6	5	3	1

Appendix Table C (Continued) Total catch, percent of total catch, and annual catch of fishes collected with the otter trawl from 1980 to 1985. All months and stations sampled are included. Note: northern anchovy excluded.

			Year															
Common Name	*Total*	*%*	*80*	*81*	*82*	*83*	*84*	*85*	*86*	*87*	*88*	*89*	*90*	*91*	*92*	*93*	*94*	*95*
leopard shark	443	0.16	53	25	59	47	20	3	22	10	50	40	24	14	14	14	23	25
bat ray	421	0.15	13	34	22	12	17	9	35	8	36	21	47	43	32	13	60	19
shimofuri goby	413	0.15	0	0	0	0	0	0	1	0	2	10	17	44	110	121	42	66
bay pipefish	412	0.15	19	8	7	9	7	28	32	27	13	5	15	13	46	37	52	94
delta smelt	410	0.14	78	71	42	48	10	8	16	5	7	1	10	5	13	24	46	26
white sturgeon	385	0.14	5	1	70	62	88	19	15	11	14	9	7	5	2	25	5	47
big skate	327	0.12	18	18	32	31	16	17	23	41	36	22	20	22	14	4	7	6
splittail	327	0.12	7	1	23	45	34	36	23	14	13	9	3	15	13	16	8	67
American shad	287	0.10	22	11	20	43	11	22	3	5	9	6	9	6	4	10	68	38
diamond turbot	250	0.09	18	9	11	9	9	9	7	11	13	8	20	20	18	37	35	16
tule perch	243	0.09	10	2	3	1	1	6	0	1	5	2	1	19	26	31	81	54
pile perch	218	0.08	29	34	38	34	9	19	19	1	21	8	4	1	0	1	0	0
whitebait smelt	193	0.07	0	0	59	98	9	10	2	3	3	1	8	0	0	0	0	0
barred surfperch	178	0.06	19	29	16	48	18	6	0	7	3	8	9	4	3	1	2	5
dwarf perch	153	0.05	14	31	50	27	5	0	3	1	11	5	2	1	0	0	2	1
spotted cusk-eel	140	0.05	0	0	0	0	3	4	8	47	21	2	2	2	9	16	20	6
white seaperch	137	0.05	16	35	12	10	24	5	9	7	5	3	6	0	0	1	4	0
threadfin shad	135	0.05	7	6	6	14	20	20	3	8	12	2	0	0	0	4	10	23
curlfin sole	122	0.04	1	1	3	6	3	7	1	2	1	2	3	3	14	34	21	20
river lamprey	119	0.04	0	0	0	10	10	8	10	5	13	12	7	4	7	8	5	20
prickly sculpin	111	0.04	2	0	8	23	8	0	8	0	0	0	0	0	4	15	7	36
jacksmelt	105	0.04	4	7	7	5	2	8	7	4	3	23	6	4	1	2	0	22
arrow goby	100	0.04	0	0	2	8	4	1	17	7	4	3	0	3	7	2	4	38
Pacific lamprey	98	0.03	7	38	8	9	4	1	13	1	3	3	0	0	0	0	5	6
showy snailfish	98	0.03	2	4	4	9	1	1	6	18	6	16	4	14	7	0	4	2
threespine stickleback	95	0.03	5	2	5	11	1	0	12	2	3	6	3	6	6	13	5	15
bigscale logperch	94	0.03	0	5	4	18	17	22	0	4	1	0	0	0	0	3	6	14
lingcod	89	0.03	11	9	1	1	37	13	0	1	3	1	0	5	0	6	0	1

Appendix Table C (Continued) Total catch, percent of total catch, and annual catch of fishes collected with the otter trawl from 1980 to 1985. All months and stations sampled are included. Note: northern anchovy excluded.

Common Name	Total	%	Year 80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95
bonehead sculpin	88	0.03	0	6	1	4	8	1	3	4	0	0	10	9	10	17	8	7
sand sole	73	0.03	3	1	2	7	6	5	6	8	2	2	1	3	7	11	3	6
black perch	69	0.02	0	13	2	4	12	4	1	1	5	5	3	1	4	4	7	3
chinook salmon	65	0.02	1	5	2	2	0	0	2	0	2	3	1	3	1	0	2	41
topsmelt	64	0.02	8	0	17	12	0	2	1	5	14	2	1	0	0	0	0	2
spiny dogfish	55	0.02	3	3	5	4	4	2	2	1	7	4	8	3	5	0	3	1
California lizardfish	43	0.02	0	0	0	12	1	0	0	0	4	0	0	0	25	1	0	0
green sturgeon	35	0.01	8	1	5	4	4	2	0	0	1	2	1	0	0	3	3	1
common carp	32	0.01	1	1	6	8	1	2	0	2	0	1	1	2	1	0	5	1
Pacific sanddab	25	0.01	3	0	1	11	1	3	0	0	3	1	0	0	0	2	0	0
night smelt	21	0.01	2	1	0	0	0	0	0	0	0	0	0	3	8	5	1	1
Pacific pompano	14	>0.01	1	0	0	0	0	0	0	0	1	1	1	1	8	1	0	0
unidentified rockfish	13	>0.01	4	4	0	0	1	0	0	0	3	0	0	0	1	0	0	0
surf smelt	12	>0.01	0	0	9	1	0	0	0	1	0	1	0	0	0	0	0	0
rubberlip seaperch	10	>0.01	1	3	1	0	2	0	0	0	1	1	0	0	0	0	0	1
pygmy poacher	7	>0.01	1	0	0	0	1	0	1	0	1	0	0	1	0	1	0	1
Pacific sand lance	5	>0.01	0	0	0	0	0	0	0	1	0	0	0	0	2	1	1	0
Sacramento squawfish	5	>0.01	1	0	1	2	0	0	0	0	0	0	0	0	0	0	0	1
saddleback gunnel	5	>0.01	2	0	0	0	0	0	0	2	0	0	1	0	0	0	0	0
Pacific sardine	4	>0.01	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3	0
silver surfperch	4	>0.01	2	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0
black rockfish	3	>0.01	0	0	0	0	0	0	1	0	2	0	0	0	0	0	0	0
bluegill	3	>0.01	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	2
brown Irish lord	3	>0.01	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0
inland silverside	3	>0.01	0	1	0	0	1	0	0	0	0	0	0	0	0	1	0	0
kelp greenling	3	>0.01	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	1

Appendix Table C (Continued) Total catch, percent of total catch, and annual catch of fishes collected with the otter trawl from 1980 to 1985. All months and stations sampled are included. Note: northern anchovy excluded.

			Year															
Common Name	*Total*	*%*	*80*	*81*	*82*	*83*	*84*	*85*	*86*	*87*	*88*	*89*	*90*	*91*	*92*	*93*	*94*	*95*
Pacific electric ray	3	>0.01	0	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0
redear sunfish	3	>0.01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
Sacramento sucker	3	>0.01	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0
rainbow seaperch	2	>0.01	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0
rainwater killifish	2	>0.01	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0
western mosquitofish	2	>0.01	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0
black crappie	1	>0.01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
blue rockfish	1	>0.01	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
C-O sole	1	>0.01	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
goldfish	1	>0.01	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
hornyhead turbot	1	>0.01	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
hybrid sole	1	>0.01	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
longjaw mudsucker	1	>0.01	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
onespot fringehead	1	>0.01	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
queenfish	1	>0.01	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
scalyhead sculpin	1	>0.01	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
sevengill shark	1	>0.01	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
spotfin surfperch	1	>0.01	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
tube-snout	1	>0.01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
unidentified flounders	1	>0.01	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
unidentified minnows	1	>0.01	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
unidentified snailfishes	1	>0.01	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
yellowtail rockfish	1	>0.01	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
Total Catch	283178		22699	9847	30156	23762	15376	11827	17144	12032	14969	13425	11624	19554	14564	28568	17527	20104

Appendix D

Appendix Table D Total catch, percent of total catch, and annual catch of yolk sac and post-yolk sac larval fishes collected with the plankton net from 1980 to 1989. All months and stations sampled are included (only January to May in 1989).

			Year									
Common Name	*Total*	*%*	*80*	*81*	*82*	*83*	*84*	*85*	*86*	*87*	*88*	*89*
Pacific herring	484049	34.08	25815	54641	210898	32167	9498	53612	40148	38329	9570	9371
northern anchovy	449642	31.66	11826	9882	2699	14019	6755	19273	23788	21123	340141	136
yellowfin goby	170571	12.01	12	5513	11492	2385	21748	39352	13832	42926	21270	12041
longfin smelt	68949	4.85	5993	91	5818	4517	7149	9662	9980	14732	6962	4045
unidentified smelts	61076	4.30	762	11509	38357	1165	5264	2431	1585	3		
arrow goby/ cheekspot goby	58146	4.09		6098	4333	4742	5326	4349	10536	3764	14204	4794
goby type II	48838	3.44	31720	17118								
striped bass	25700	1.81	4736	3019	4736	2779	1503	1013	5747	594	131	1442
bay goby	10364	0.73	888	1444	802	607	693	516	400	1023	3546	445
prickly sculpin	10009	0.70	773	545	1991	3134	1138	421	1047	515	158	287
white croaker	7851	0.55	1119	421	351	893	489	1290	1629	518	572	569
Pacific staghorn sculpin	5906	0.42	276	604	480	229	369	1244	1148	469	394	693
chameleon goby	5295	0.37	2	182	91	249	249	728	452	371	2514	457
jacksmelt	4593	0.32	514	1996	612	269	343	76	96	73	554	60
arrow goby	3051	0.21	7	6	3036	1		1				
threadfin shad	1998	0.14	13	194	797	649	233	104		3	5	
unidentified rockfish	491	0.03	56	45	96	81	27	34	63	30	30	29
English sole	422	0.03	27	1	277	45		26	7		12	27
cheekspot goby	406	0.03			406							
delta smelt	378	0.03	33	27	126	163	24					5
common carp	303	0.02	31	29	226	5	1					11
diamond turbot	268	0.02	49	25	7	54	14	45	23	13	36	2
topsmelt	268	0.02	16	164	22	21	6	17	20	2		
starry flounder	266	0.02	59	8	31	14	13	34	39	27	38	3
longjaw mudsucker	265	0.02	3	31	24	19	17	11	10	13	123	14
cabezon	133	>0.01	15	22	18	4	14	22	14	11	4	9
unidentified minnows	132	>0.01				1		108	15		8	

Appendix Table D (Continued) Total catch, percent of total catch, and annual catch of yolk sac and post-yolk sac larval fishes collected with the plankton net from 1980 to 1989. All months and stations sampled are included (only January to May in 1989).

			Year									
Common Name	*Total*	*%*	*80*	*81*	*82*	*83*	*84*	*85*	*86*	*87*	*88*	*89*
unidentified sunfishes	130	>0.01	4	2	1	24	3	39		3	48	6
unidentified gobies	93	>0.01				1	3	5	16	64	4	
bigscale logperch	84	>0.01	4	1	16	52	3	2	5	1		
California halibut	75	>0.01	2	1	1	44	8	7	6	1	5	
unidentified pricklebacks	75	>0.01	9	7	11	1	2	24	3	7	3	8
striped kelpfish	49	>0.01	21	18	6	3	1					
unidentified clinids	45	>0.01			2		8	14	4	10	4	3
unidentified sculpins	42	>0.01	8	4	3	3	8		2	4	3	7
American shad	37	>0.01			8	29						
unidentified fish	37	>0.01	6	5	3	5	1	4		2	4	7
bonehead sculpin	34	>0.01	15	12	4		1	1				1
unidentified flounders	30	>0.01	16	2	2			2		4		4
northern lampfish	25	>0.01	17		2	2		2	2			
splittail	25	>0.01	1		6	18						
lingcod	23	>0.01	3	2	9	6	1	1				1
sand sole	20	>0.01	3		7	2		4	1	1		2
onespot fringehead	15	>0.01	3		3	7	2					
kelp greenling	13	>0.01	2	4	1	3			2			1
threespine stickleback	13	>0.01	2		2	7				1	1	
Pacific tomcod	11	>0.01	9								1	1
unidentified clupeidae	10	>0.01	10									
bluegill	9	>0.01			9							
brown Irish lord	9	>0.01	9									
inland silverside	9	>0.01			4		3	2				
painted greenling	9	>0.01		1	5		1					2
red brotula	7	>0.01	3	1	2						1	

Appendix Table D (Continued) Total catch, percent of total catch, and annual catch of yolk sac and post-yolk sac larval fishes collected with the plankton net from 1980 to 1989. All months and stations sampled are included (only January to May in 1989).

			Year									
Common Name	*Total*	*%*	*80*	*81*	*82*	*83*	*84*	*85*	*86*	*87*	*88*	*89*
unidentified snailfishes	7	>0.01			4	1						2
Sacramento sucker	6	>0.01				4	2					
Sacramento squawfish	5	>0.01			5							
white sturgeon	5	>0.01	1			3			1			
plainfin midshipman	4	>0.01								1	3	
tidepool sculpin	4	>0.01		1	3							
blue lanternfish	3	>0.01			1		1				1	
Pacific hake	3	>0.01							3			
unidentified atherinids	3	>0.01							2			1
blackeye goby	2	>0.01		1		1						
surf smelt	2	>0.01	1						1			
unidentified poachers	2	>0.01							2			
brown rockfish	1	>0.01										1
hornyhead turbot	1	>0.01								1		
northern clingfish	1	>0.01	1									
Pacific argentine	1	>0.01					1					
Pacific blacksmelt	1	>0.01			1							
unidentified Citharichthys	1	>0.01							1			
Total Catch	1420351		84895	113677	287847	68428	60922	134476	110630	124639	400350	34487