STATE OF CALIFORNIA
THE RESOURCES AGENCY
DEPARTMENT OF FISH AND GAME

FISH BULLETIN 174

THE CALIFORNIA HALIBUT, *Paralichthys californicus*, RESOURCE AND FISHERIES

Edited by

CHARLES W. HAUGEN

1990

survival of larval herring
Can. J. Fish. Aquat. Sci.

: growth and behavior of

DISTRIBUTION AND ABUNDANCE OF JUVENILE CALIFORNIA HALIBUT, *PARALICHTHYS CALIFORNICUS*, IN SHALLOW WATERS OF SAN DIEGO COUNTY

SHARON HENDRIX KRAMER [1]
University of California, San Diego
Scripps Institution of Oceanography A-008
La Jolla, CA 92093

and

Southwest Fisheries Science Center
National Marine Fisheries Service, NOAA
P.O. Box 271
La Jolla, CA 92038

ABSTRACT

The size-specific distribution and abundance of juvenile California halibut, *Paralichthys californicus*, were determined for bay and open-coast habitats using a random sampling design stratified by depth. The pattern of settlement differed over the two-year study. Halibut settled in the bays in 1987 and primarily on the open coast in 1988. Although there was settlement on the open coast in 1988, nearly all juveniles between 60 and 100 mm standard length (SL) were in the bays. This suggests that juveniles that settled on the open coast eventually moved into bays or died. The density of juvenile halibut was greatest in the bays with highest recorded densities in the shallow shoreline habitats where depth was $\leq$1 m. Nearly all juveniles $>$220 mm SL occurred on the open coast with movement of juveniles from the bays to the open coast beginning at about 140 mm SL. These results suggest that the bays are probably essential habitats for juvenile growth and survival.

INTRODUCTION

Processes used by flatfishes to select and settle in appropriate juvenile nursery areas are not known. The larvae of flatfishes that live on the continental shelf as adults are widely distributed over the shelf. The oldest and largest larvae are found closest to the area where settlement occurs (Weinstein et al. 1980; Barnett et al. 1984; Roper 1986; Boehlert and Mundy 1988).

Utilization of shallow water nursery areas by juvenile flatfishes is common (Edwards and Steele 1968; Weinstein et al. 1980; Roper and Jillett 1981; Poxton

[1] Present address: Australian Institute of Marine Science, PMB No. 3, Townsville, QLD 4810, Australia

et al. 1982; Krygier and Pearcy 1986; Rogers et al. 1989). Evolution of complex life histories involving the selection of specialized juvenile nursery areas suggests that these habitats present greater potential for increased fitness by increasing growth opportunities, decreasing the risk of mortality, or both (Werner and Gilliam 1984; Werner 1986). Density of individuals within these habitats reflects habitat preference with highest densities considered to be indicative of optimal habitats (Fretwell 1972).

California halibut, *Paralichthys californicus*, is a commercially important flatfish off southern California that utilizes embayments as nursery areas (Haaker 1975; Allen 1988). Adults inhabit coastal waters less than 100 m deep with greatest abundance at depths less than 30 m (Miller and Lea 1972; Allen 1982). Adults spawn throughout the year with peak spawning in spring (Lavenberg et al. 1986; Walker et al. 1987).

Eggs and larvae occur over the shelf with greatest densities in waters less than 75 m deep and within 6 km of shore (Frey 1971; Ahlstrom and Moser 1975; Gruber et al. 1982; Barnett et al. 1984; Lavenberg et al. 1986; Walker et al. 1987). California halibut have a relatively short pelagic larval stage, transforming and settling to the bottom at a smaller size (7.5–9.4 mm) than most coastal flatfish (Ahlstrom et al. 1984). The planktonic stage probably lasts less than one month; laboratory reared halibut begin to settle to the bottom 20 d after hatching when they are 7–8 mm standard length (SL) (Gadomski and Petersen 1988).

Newly settled and larger juvenile halibut are frequently taken in shallow water embayments (Haaker 1975; Allen 1988) but not on the open coast (Allen 1982; Plummer et al. 1983). However, nearly all of the sampling on the open coast has been at depths greater than 10 m and with mesh too large to catch newly settled halibut (Plummer et al. 1983; Allen 1988). In southern California, shallow coastal areas comprise a much larger fraction of the potential nursery habitat than do embayments. The objectives of this paper are to determine the extent of the dependency of juvenile halibut on embayments relative to shallow coastal habitats, and to describe the habitats where most juveniles are found and how habitat preference changes over time.

MATERIALS AND METHODS

Collections were taken with bottom trawls on the open coast and in bays to determine time and location of settlement and to estimate habitat-specific density and abundance of juvenile California halibut. I used a random sampling design stratified by depth. Open coast sampling areas were four blocks representing 40 naut mi of coastline; two blocks were adjacent to bays and two were distant from bays (Figure 1).

The two bays sampled were Mission Bay and Agua Hedionda Lagoon, each divided into blocks of similar habitat type, resulting in five blocks in Mission Bay and three in Agua Hedionda Lagoon (Figure 1). Blocks were numbered according to their distance from the opening of the bay; the lowest numbered block (1) was the farthest from the opening of the bay to the sea (Figure 1).

Sample locations were assigned randomly within three depth strata for each block. On the open coast, the depth strata sampled were: 5 m (near the first breaker line) to 8 m; 9–11 m; and the deepest stratum, 12–14 m. In bays, the

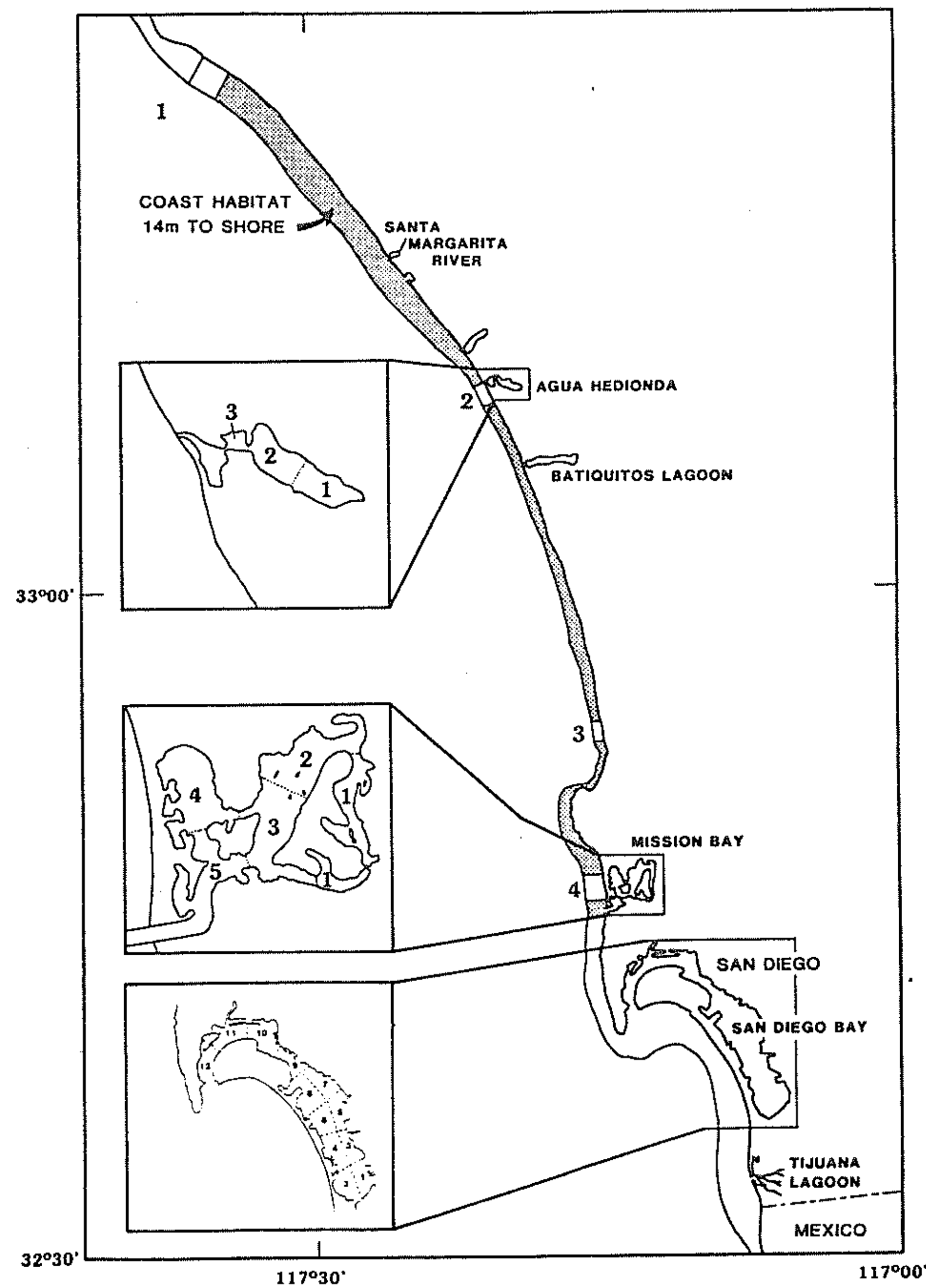

FIGURE 1. Map of location of sampling blocks. Open coast blocks are 1) San Onofre, 2) adjacent to Agua Hedionda Lagoon, 3) Torrey Pines, and 4) adjacent to Mission Bay. The two bays sampled are Agua Hedionda Lagoon and Mission Bay with sampling blocks denoted.

depth strata ranged from <1 m ("shoreline"); to 1–2 m ("open water," close to shore where it was possible to sample with a skiff); and to 2–4 m (near the center of the block). Three to four trawls were taken per depth stratum each month. Collections were taken monthly for 2 years beginning in September 1986 in Mission Bay and on the open coast and in March 1987 in Agua Hedionda Lagoon; last collections were taken in September 1988. Over 3300 collections were taken (Table 1).

TABLE 1. Total number of hauls using various gear types taken between September 1986 and September 1988 listed by block.

	Gear Type			
	1.6-m beam trawl	1.0-m beam trawl (by skiff)	1.0-m beam trawl (shore)	Seine
Sample Block				
Mission Bay				
block 1	0	134	60	83
block 2	59	136	64	80
block 3	72	144	62	78
block 4	68	143	60	70
block 5	65	192	64	74
Agua Hedionda Lagoon				
block 1	0	87	45	57
block 2	0	96	40	53
block 3	0	42	37	43
Open coast				
San Onofre	259			
Agua Hedionda	293			
Torrey Pines	267			
Mission Beach	277			

I used beam trawls lined with 3-mm mesh netting for all collections on the open coast and many of those in bays, since these trawls have a fixed mouth opening allowing quantitative assessment of fish density (Krygier and Pearcy 1986). Two trawls were used: a 1.6-m wide beam trawl fished from a small research vessel (15 m) and a 1-m wide beam trawl fished from a 6-m skiff or pulled by two people in shallow water ($\leq$1 m). Most bay sampling was conducted from the skiff with the 1-m beam trawl, and coastal collections were taken with the 1.6-m beam trawl (Table 1). Beam trawls were calibrated by comparing overlapping monthly samples taken in Mission Bay.

Trawls were fitted with a wheel and revolution counter to determine the distance travelled by the trawl on the bottom (Krygier and Horton 1975). Tow speed was approximately 1.5 knots; duration was 5 min in bays and 10 min on the coast. Tows were taken during daylight hours. No collections were made on the open coast in November 1987 or by skiff in bays in December 1987.

A 1-m by 6-m beach seine with 3-mm mesh was also used in shallow water (depth $\leq$ 1 m). The beach seine was pulled parallel to shore along a measured distance of 20–50 m while maintaining a constant mouth opening (a 4-m line was stretched between the brails).

All flatfishes taken in trawls and seines were measured (standard length in mm) and the station depth, surface and bottom temperatures, and salinity (bays only) recorded. Salinity was not taken on the open coast because the refractometer was accurate to only 1 ppt.

To describe the relationship between size and density of halibut and habitat type, halibut were grouped by 20-mm length classes for all analyses. These are denoted as follows: "20" refers to fish $\leq$20 mm; "40" refers to fish 21–40 mm; continuing up to ">220" which refers to all halibut >220 mm. Densities are in number of halibut per hectare. Analysis of variance (ANOVA) with an accepted significance level of $P \leq 0.05$ was used to analyze the data except where noted.

The area of each block or habitat type was calculated by digitizing navigation charts or maps. Only areas designated as "fine grey sand" or "sand" on coastal charts were used in the area estimates.

The largest bay in southern California, San Diego Bay, is about 5 mi south of the study area and is severely modified by dredging and pollution (Figure 1). For purposes of comparison, San Diego Bay was sampled in July 1988 and results compared to Mission Bay and Agua Hedionda Lagoon.

Gear Comparison

To compare the catch of California halibut taken in the 1.6-m beam trawl, the 1.0-m beam trawl, or the beach seine, it was necessary to weight the data for differences in the selectivity between these gear types. To compute the weighting coefficients, I used the densities of California halibut in 20-mm length classes when hauls using more than one type of gear were taken in the same block. The 1.6-m beam trawl and 1.0-m beam trawl densities were compared over the common trawling stations sampled within a 1-week period in Mission Bay (blocks 2-5). The 1.0-m beam trawl and 4.0-m beach seine densities were compared by sampling over common areas (shoreline areas in both Agua Hedionda Lagoon and Mission Bay) and were sampled on the same day.

Weighting coefficients and their variances were determined using a three-way ANOVA (Sokal and Rohlf 1981). I corrected all density (number of halibut/hectare) and abundance estimates of California halibut for the differences in gear efficiency by weighting the mean density and variance for each length class where significant differences in catchability were found. The weighted mean density (number/hectare) was calculated as

$$d_w = (d_1 + g d_2) / (1 + g)$$

where d_1=unweighted density, d_2=weighted density, and g=weighting coefficient.

Estimated variance of the weighted mean d_w was calculated as

$$V(d_w) = V(d_1) + g^2 V(d_2) + d_2^2 V(g) + V(g)V(d_2)$$

where $V(d_1)$ = variance of unweighted density, $V(d_2)$ = variance of weighted density, and $V(g)$ = variance of weighting coefficient. Variance estimates were underestimated because the covariance terms were not included. Resampling techniques to estimate variance were impractical because of the large size of the database.

In addition to the beam trawl and beach seine, a catch comparison was also made between the 1.6-m beam trawl and a standard otter trawl (foot rope length 7.5 m with 1.3-cm stretch mesh cod-end liner; Mearns and Allen 1978) in San Diego Bay in June and July 1988. This otter trawl has been used extensively in studies of southern California shallow water habitats, whereas the beam trawl had never been used before. Estimation of weighting coefficients for the otter trawl provides information on the upper size limits of halibut captured by the beam trawl. Weighting coefficients were determined for 50-mm length classes by summing the total catch over the total area sampled for each gear type.

RESULTS
Description of Habitats

Open Coast

The southern California shelf is relatively steep and narrow with an average width of 6.5 km (Emery 1960) throughout the region sampled, compared to the shelf along the east coast of the U.S. which averages 100 km (Emery 1960). Only 10–20% of the Pacific coast consists of estuaries and lagoons compared to 80–90% on the Atlantic coast (Emery 1967). Although narrow, the southern California shelf is a much larger fraction (89%) of the shallow water habitat (depth ≤ 14 m) than bays, which are relatively few and small (11%; Table 2).

On the shallow open coast (depth ≤ 14 m), temperatures were coldest in the winter and spring, with highest temperatures in the fall (Figure 2). Dense accumulations of drift algae in shallow water outside the surf line were common on the bottom after large storms or high surf events.

Bays

The two bays sampled, Mission Bay and Agua Hedionda Lagoon, are open to the ocean throughout the year. Salinity in the bays was about the same as seawater (annual mean salinity at the Scripps Institution of Oceanography pier was 33.48 ppt in 1986 and 33.47 ppt in 1987) except during heavy rainfall when runoff decreased salinity to as low as 26 ppt (Figure 3). The occasional declines in salinity were short in duration and were most marked in the blocks that were farthest from the entrance to the sea.

The shoreline habitat (depth ≤ 1 m) of bays was the most variable in temperature and salinity and was strongly affected by runoff (Figure 3). Eelgrass, *Zostera* sp., beds bound the outer edge of the shoreline habitat and the bottom is composed of sand or sandy mud.

TABLE 2. Estimated area of sample blocks in hectares.

Bays	Sample Block Number 1	2	3	4	5	Sum	Percent
Mission Bay							
Open water	79.5	121.7	159.0	139.5	116.3	615.9	8.2
Shoreline	21.4	17.5	22.8	20.8	9.3	91.8	1.2
Agua Hedionda Lagoon							
Open water	31.5	40.6	5.6			77.7	1.0
Shoreline	3.5	5.3	1.5			10.3	0.1

Open Coast	Depth Stratum Shallow	Mid	Deep	Sum	Percent
Mission Beach	205.0	236.2	230.4	671.6	9.0
Torrey Pines	86.8	123.2	107.4	317.4	4.2
Agua Hedionda	95.5	249.8	203.8	549.1	7.3
San Onofre	424.2	842.5	646.4	1913.0	25.5
Intervening habitat	738.9	1271.6	1237.2	3247.7	43.3

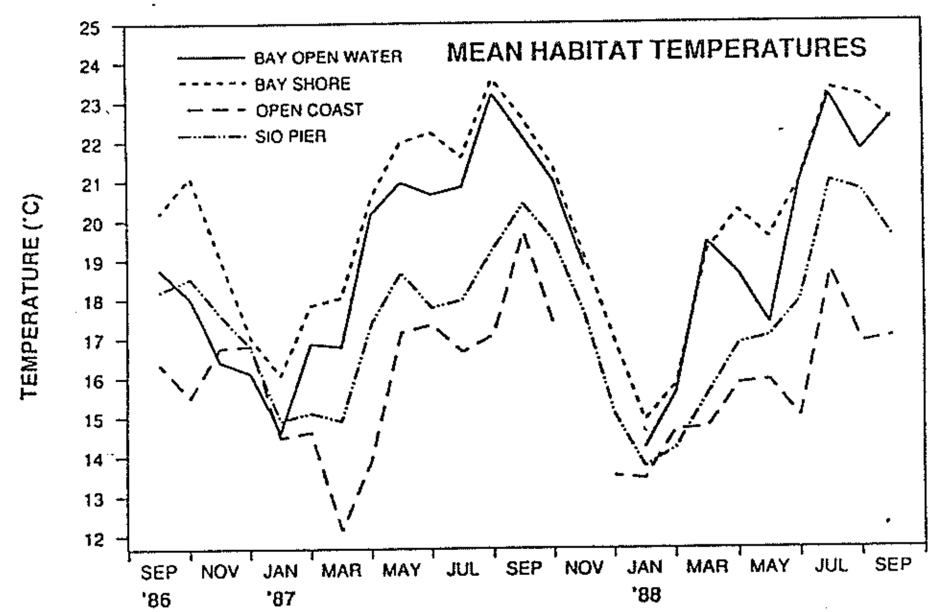

FIGURE 2. Monthly mean temperature (°C) of each habitat type.

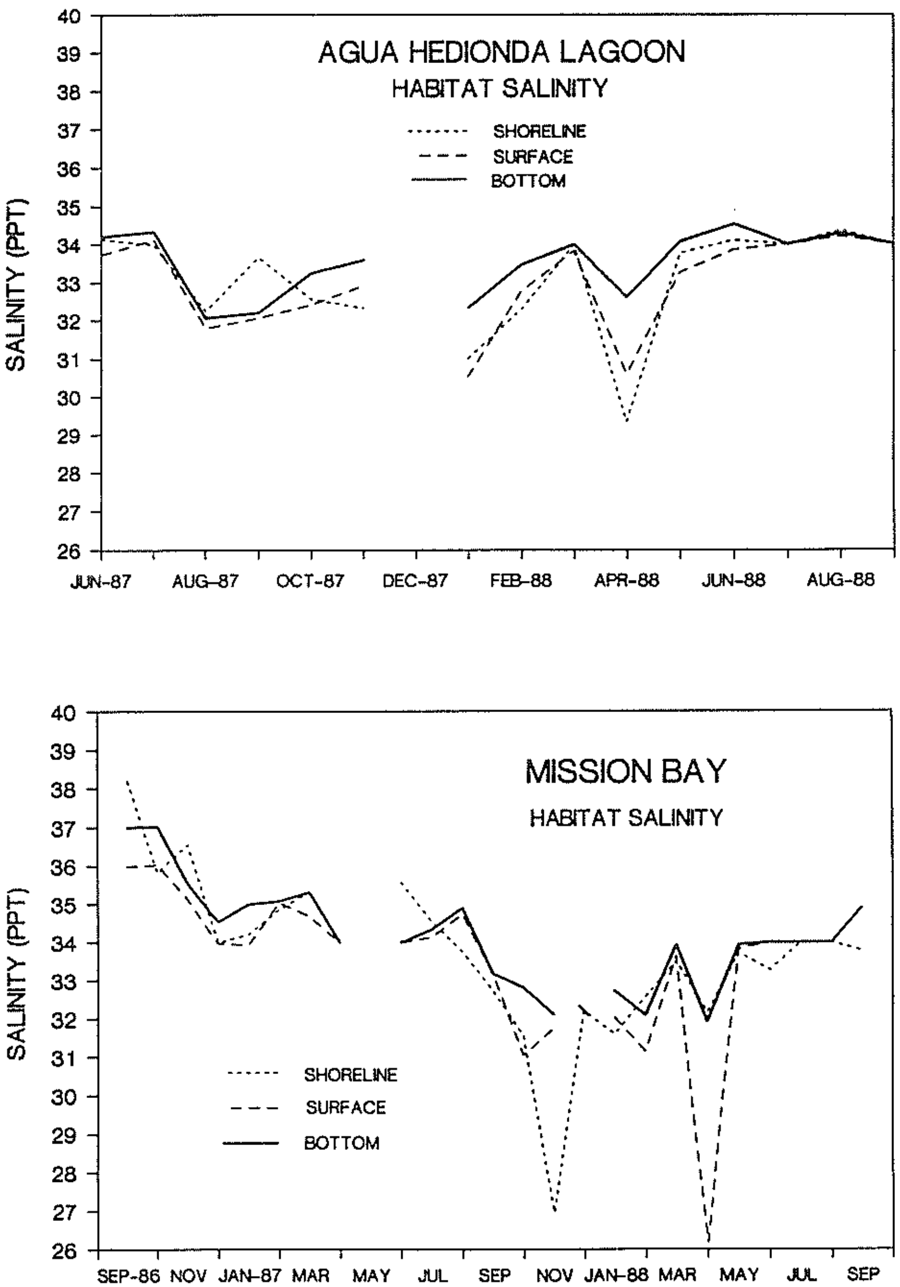

FIGURE 3. Salinity (ppt) in Agua Hedionda Lagoon and Mission Bay by habitat type.

Agua Hedionda Lagoon and Mission Bay differ in shape and in the extent of anthropogenic modification. The mouth of Agua Hedionda Lagoon is extended by short jetties into coastal water <4 m deep and surf breaks across the opening. The outermost section of the lagoon is used by the Encina power plant for intake of cooling water and is dredged yearly to prevent filling by sand. The back part of the lagoon, with depths of less than 3 m, is not dredged. Mission Bay is a harbor with large jetties extending out to deeper coastal water (about 10 m) and the entrance and most of the bay is dredged to depth of at least 4 m. There are several other embayments in the study area, but they were closed by sand bars nearly all year and are much smaller than Agua Hedionda Lagoon.

Habitat types within the bays varied with the distance from the opening. The shallow coastal sediments are composed of sand with coarsest grain size found in shallow sediments exposed to waves and strong currents (Emery 1960). Measured grain sizes at the entrance to Mission Bay were 236 μm (Dexter 1983). Tidal currents deposit sands at the entrance to bays, but farther into bays, as circulation decreases, sediments of smaller grain sizes accumulate (Warme et al. 1976). Measurements taken in Mission Bay indicate that grain size remains fairly large (up to 160 μm) as far as 2 km into the bay in the channels with strong tidal currents (Dexter 1983). Runoff into bays deposits silts and clays (<60 μm) which remain in areas with low circulation (Warme et al. 1976).

In the outer portions of bays where tidal circulation was strong, the bottom was usually dominated by eelgrass beds which represented a significant proportion of the bottom habitat in bays (nearly 25% in Agua Hedionda Lagoon; Bradshaw et al. 1976). The distribution of eelgrass is limited to areas in bays where the bottom substrate is stable and water is sufficiently clear for photosynthesis. Eelgrass beds were found in Mission Bay in blocks 2 through 5 and in Agua Hedionda Lagoon in blocks 2, 3, and the westernmost portion of block 1.

Farther into bays, the areas with poor circulation were dominated by invertebrate fauna including colonial bryozoans and sponges (Tetillidae). These areas included block 1 in Agua Hedionda Lagoon and blocks 1 and 2 in Mission Bay (Figure 1).

Gear Comparison

Interaction between gear type and block was usually not significant. Density calculated from the catch taken in the 1.6-m beam trawl was similar to that taken in the 1.0-m beam trawl when halibut were less than 80 mm, but for halibut >80 mm they were significantly different (Table 3). The larger 1.6-m beam trawl captured more halibut >80 mm than did the 1.0-m beam trawl.

Densities obtained by the 1.0-m beam trawl and 4.0-m beach seine were significantly different for the 40-, 60-, and 100-mm length classes (Table 3). The beach seine was a less effective sampler than the beam trawl; the 1.0-m beam trawl captured more halibut in all cases.

Comparison of the 1.6-m beam trawl and the 7.5-m otter trawl indicate that the beam trawl captured more small halibut (≤200 mm) per unit area than did the otter trawl, but the otter trawl captured more large halibut (>200 mm) per unit area than did the 1.6-m beam trawl (Table 3).

TABLE 3. Gear weighting coefficients and their variances by length class. Coefficients determined by 3-way ANOVA between gear types, blocks, and month of sample on density for each length class. Correction terms are given for length classes with significant gear effects ($P \leq 0.05$).

Conversion of 1.0-m beam trawl data for open-water habitat tows.

Length class	Correction term	Variance
80	2.779	0.112
120	4.905	0.182
140	8.262	0.470
160	7.606	0.532
180	6.807	0.438
200	3.949	0.129
220	1.885	0.020

Conversion of beach seine data for shoreline habitat tows.

Length class	Correction term	Variance
40	12.371	1.000
60	13.136	1.452
100	4.156	0.143

Weighting coefficient based on the estimated density by length class obtained from trawls taken in San Diego Bay for the 1.6-m beam trawl and 7.5-m otter trawl. Coefficient is the ratio of the estimated density from the otter trawl/density from 1.6-m beam trawl.

Length class	1.6-m beam trawl	Otter trawl	Coefficient
<50 mm	9.202	0	
51–100	6.135	0.114	0.019
101–150	2.045	0.303	0.148
151–200	5.112	1.706	0.334
201–250	1.022	1.555	1.520
250–300	0	0.455	
>300	0	0.189	

Temporal and Spatial Variation in Halibut Density

Catch Variability in Time and Space

Density of halibut is variable in both space and time. I tested for differences in variability in space and time using ANOVA on only three size classes—the smallest (≤ 20 mm), an intermediate length (141–160 mm), and a larger length class (201–220 mm)—assuming that the results obtained for these length classes applied to intermediate length classes. Significant differences in density by month and by block were found for all length classes with no significant difference found for the effect of year on the density of the smallest (≤ 20 mm) and largest (201–220 mm) length classes (Table 4). Although density was highly variable, it was necessary to combine data in time and space in order to establish important relationships.

TABLE 4. ANOVA of California halibut density on block, month, and year for three length classes: $\leq$ 20 mm, 141–160 mm, and 201–220 mm.

Source	Length class (mm)	Sum of squares	Mean square	F	df	P
Month	≤20	370978	33725	4.43	11, 3269	**
	141–160	12751	1159	2.89	11, 3269	**
	201–220	2911	265	2.03	11, 3269	*
Year	≤20	31907	15953	2.10	2, 3269	NS
	141–160	3140	1570	3.91	2, 3269	*
	201–220	300	150	1.15	2, 3269	NS
Block	≤20	373278	19646	2.58	19, 3269	**
	141–160	98749	5197	12.96	19, 3269	**
	201–220	17091	900	6.91	19, 3269	**
Error	≤20	24881588	7611			
	141–160	1310973	401			
	201–220	425523	130			

** $P<0.001$
* $P<0.05$
NS $P>0.05$

Distribution of Metamorphosing and Newly Settled Halibut

Distribution and abundance of late larval and early juvenile stages of halibut is indicative of preference and suitability of habitat for settlement. Metamorphosing halibut with eyes migrating were between 7 and 11 mm SL; by the time halibut were 12 mm long, eye migration was complete and the fish had acquired juvenile pigmentation patterns ("settlement").

Transforming stages of halibut were captured mostly on the open coast; few were taken in bays (Figure 4). Transforming halibut captured on the coast had larval pigmentation patterns (Ahlstrom et al. 1984) and incomplete eye migration. Almost all of the halibut captured in bays had juvenile pigmentation patterns and complete eye migration. All halibut ≤ 20 mm SL were considered "newly settled" in this study regardless of pigmentation or degree of eye migration.

Density of newly settled halibut differed in time and space over the 2 years of the study. In 1987, newly settled halibut were found primarily in the first and second quarters, while in 1988 most of the settlement occurred in the second and third quarters (Figure 5). Most of the halibut settled in bays in 1987, while in 1988 the greatest settlement occurred along the open coast (Figure 5).

The highest density of newly settled halibut encountered in the 2-year study was in the shallow (depth ≤ 1 m) shoreline habitat in 1987 with the highest mean density for Agua Hedionda Lagoon in March ($\bar{x}=368.9$/hectare, SD=556.9) and for Mission Bay in May ($\bar{x}=84.6$, SD=278.2; Figures 6 and 7). The inner block of Agua Hedionda Lagoon had the highest density of newly settled halibut in 1987 (March $\bar{x}=919$/hectare, SD=1373) and was significantly different from all other shoreline habitats ($F=2.29$, $P<0.001$). Water temperature in the shoreline habitat was warmer than the rest of the bay and the open coast in the time of year that newly settled halibut were found (Figure 2).

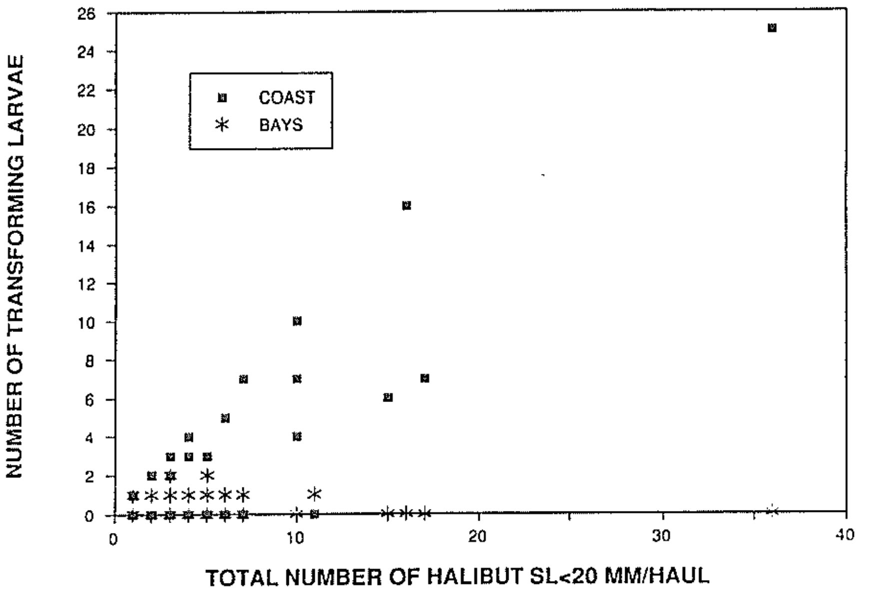

FIGURE 4. Number of transforming larvae of the total number of halibut in the 20-mm length class by haul for bay and open coast habitats.

In 1988, newly settled halibut were found along the open coast with highest densities occurring in the second and third quarters (Figure 5). During this time, the range in monthly mean density of halibut $\leq$20 mm was highest at Torrey Pines, between 5.9 and 171.3/hectare (SD=8.2 and 252.7, respectively), and lowest at San Onofre ($\bar{x}$=0 to 16.0, SD=22.8).

Significant differences in the density of newly settled halibut existed between the coastal blocks and between the depth strata within these blocks (ANOVA for blocks F=6.19; for depth F=7.06; $P<0.001$). The majority of the halibut settled in the shallowest strata, depth $\leq$8 m (Figure 8). The highest density occurred in the shallowest stratum (depth $\leq$8 m) at Torrey Pines (September $\bar{x}$=305.0/hectare, SD=278.0); this block is far from any continuously open bay (Figure 1).

Distribution of Juvenile Halibut

Distribution of juveniles by length class can be used to infer movement patterns and ontogenetic changes in habitat preference. Juveniles of 61–120 mm were taken in bays, while halibut >200 mm were taken mostly on the open coast (Figure 5). Overlap in relative frequency of length classes of halibut taken in bays and on the open coast indicates the timing of their movement out of bays and the length at which this occurs. Juveniles began to move out of bays to the open coast when they were 140 mm long and nearly all had migrated by the time they were 200 mm (Figure 5). Juveniles appeared to reach 200 mm in 9–12 months after they first settle to the bottom (Figure 5).

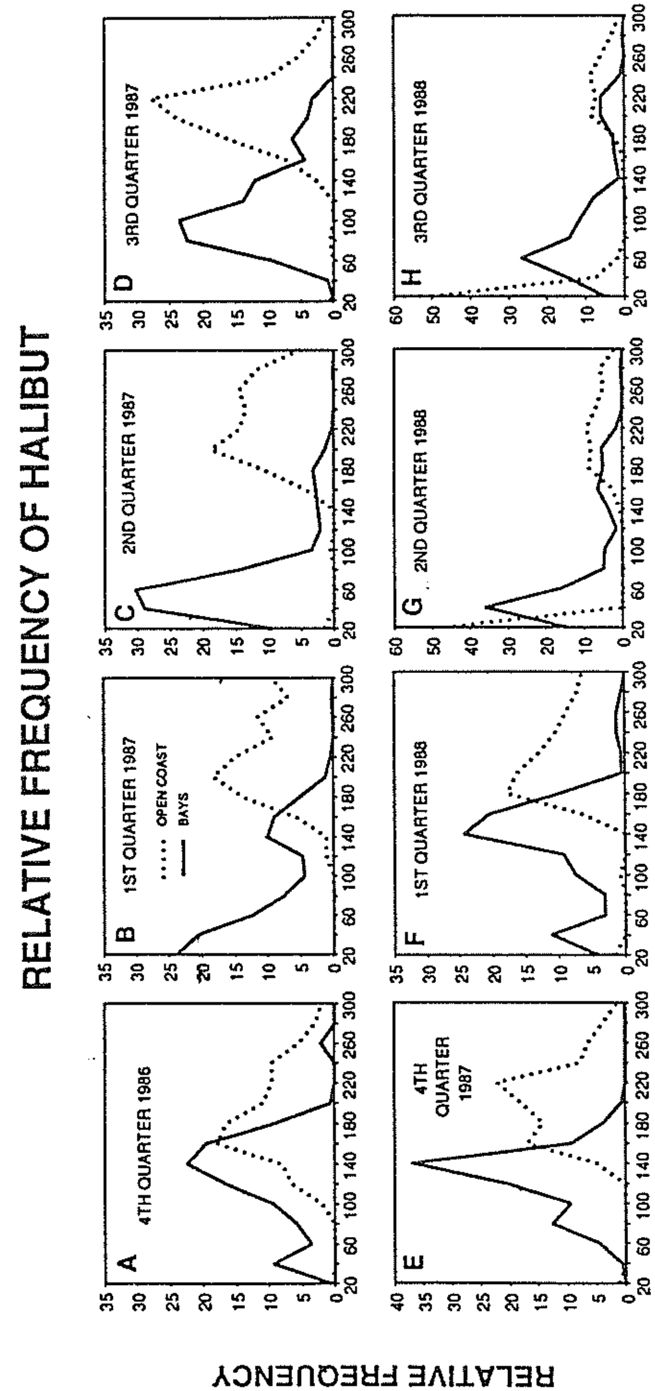

FIGURE 5. Relative frequency of halibut by habitat on the open coast and in bays by quarter. A. 4th quarter 1986; bay N=138, coast N=200. B. 1st quarter 1987; bay N=468, coast N=87. C. 2nd quarter 1987; bay N=806, coast N=186. D. 3rd quarter 1987; bay N=224, coast N=180. E. 4th quarter 1987; bay N=127, coast N=77. F. 1st quarter 1988; bay N=160, coast N=123. G. 2nd quarter 1988; bay N=335, coast N=162. H. 3rd quarter 1988; bay N=306, coast N=319.

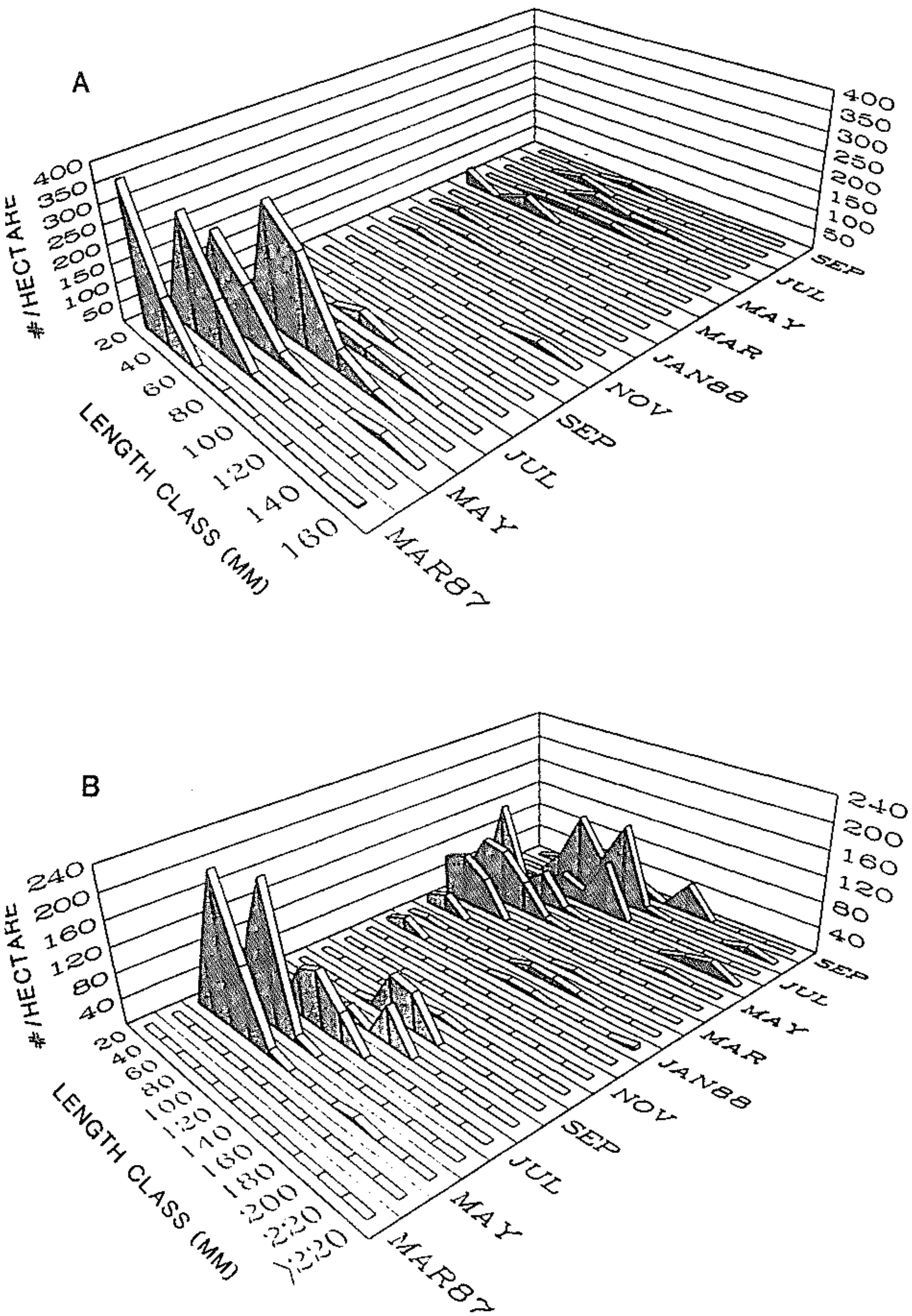

FIGURE 6. Density of halibut in Agua Hedionda Lagoon by habitat type: (a) shoreline, and (b) open water.

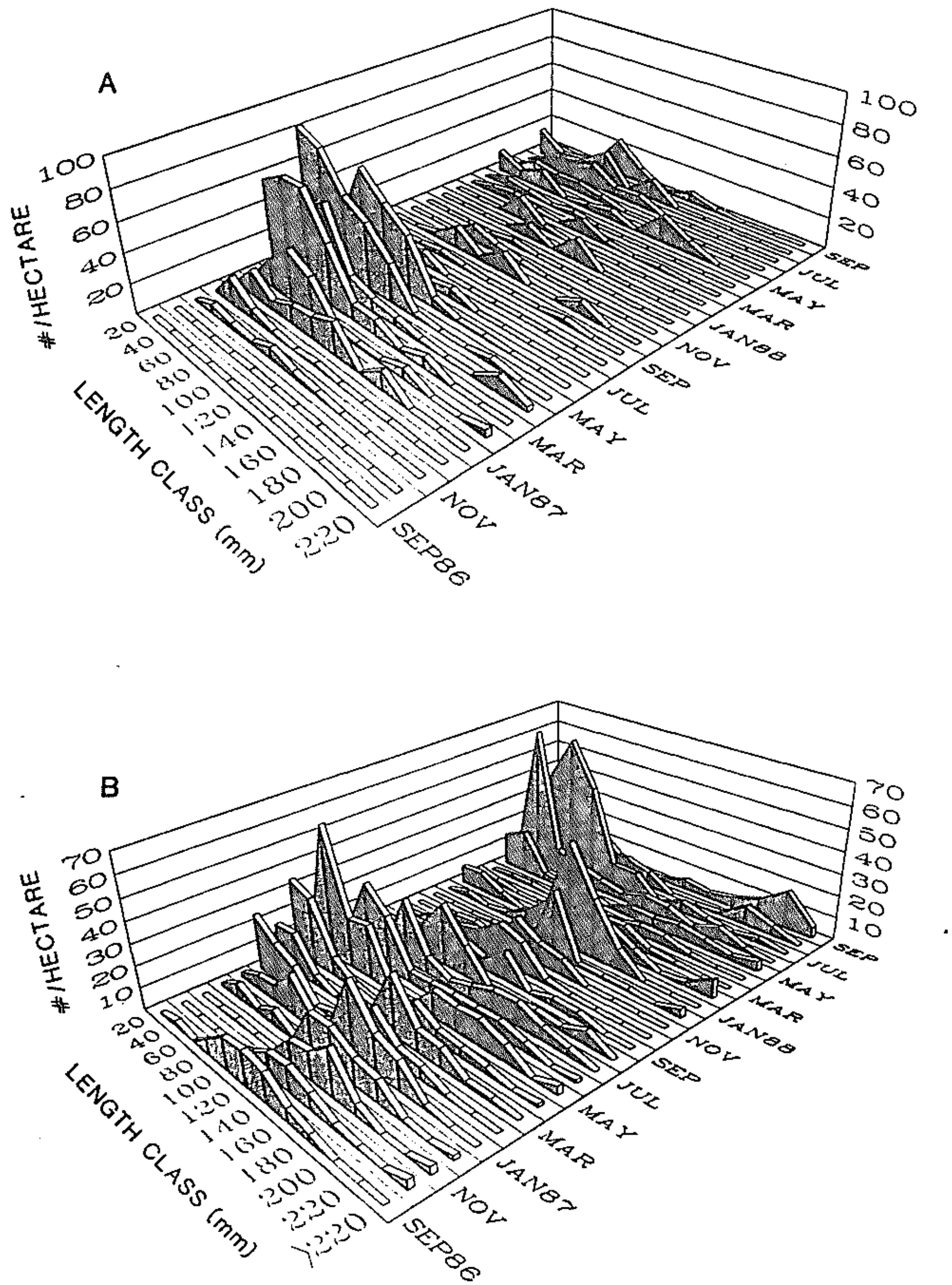

FIGURE 7. Density of halibut in Mission Bay by habitat type: (a) shoreline, and (b) open water.

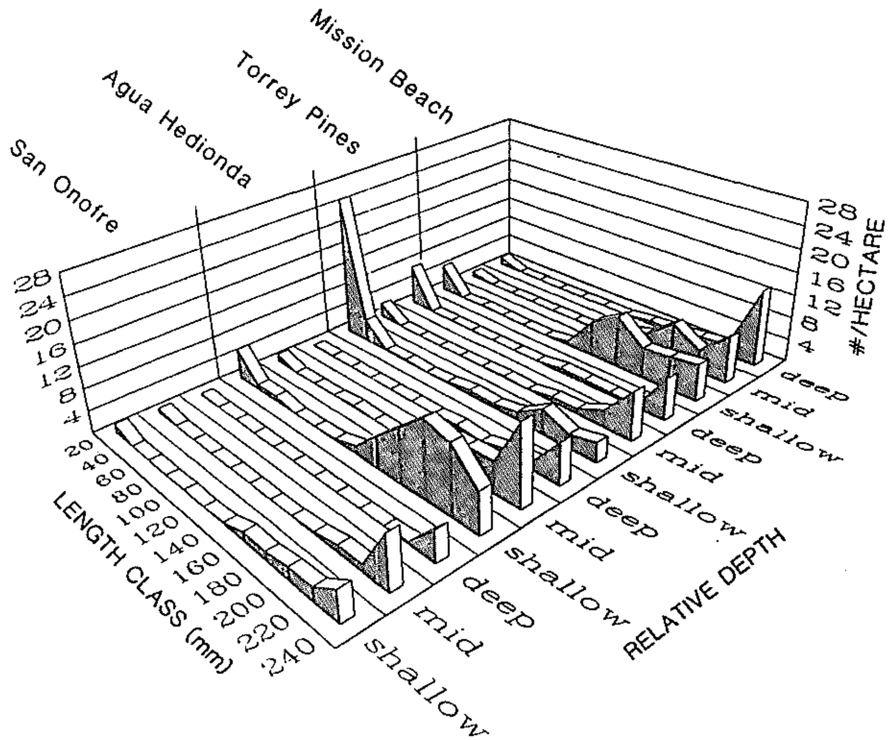

FIGURE 8. Mean density of halibut on the open coast by block and depth stratum. The three depth strata are "shallow" (5–8 m), "mid" (9–11 m), and "deep" (12–14 m). Densities are averaged over the entire sampling period.

Movement out of bays to the open coast was also indicated by the appearance on the coast of fish between 140–200 mm SL. This trend was most marked at the blocks adjacent to bays; small halibut (<200 mm) were prominent off Mission Bay and Agua Hedionda Lagoon (Figure 8). Density of halibut (140–220 mm) in the two blocks near bays was significantly different from the two blocks that had no open bay nearby (ANOVA, $P<0.001$; Figure 8). For example, the highest densities of all open coast juveniles in the 180-mm length class were at the blocks adjacent to Agua Hedionda Lagoon and Mission Bay ($\bar{x}_{AH}=9.7$/hectare, SD=18.0; $\bar{x}_{MB}=9.3$, SD=20.7), with lower densities at Torrey Pines and San Onofre ($\bar{x}_{TP}=1.6$, SD=6.5; $\bar{x}_{SO}=1.6$, SD=5.8; Figure 8).

Relationship Between Fish Size and Depth

Distribution of halibut was correlated with depth for the depths sampled. The relationship between standard length (mm) and depth of capture (m) was:

$$SL = 14.87 \times DEPTH + 48.19$$

(SE slope=0.29, $r^2=0.40$, $N=3898$; Figure 9).

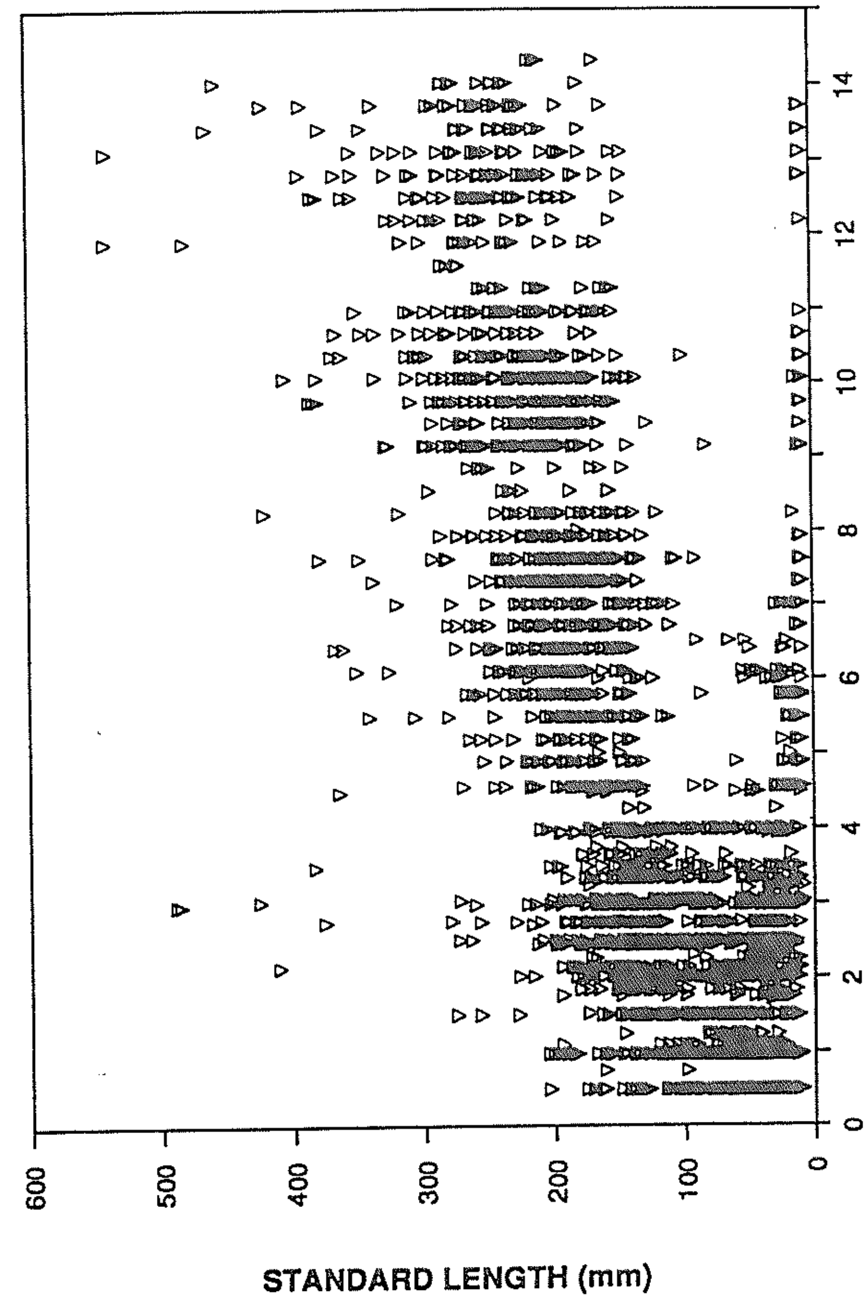

FIGURE 9. Length of halibut at depth of capture.

Several authors have noted that halibut segregate by size on the open coast with larger halibut found in deeper water (Allen 1982; Plummer et al. 1983). Segregation by size was also found in this study with small length classes found primarily in bays (Figure 5). Although newly settled halibut occur in shallower water on the open coast, most halibut between 40 and 100 mm are in embayment habitats.

Density of Juveniles Within Bays

Density of juveniles within bays differed with size and with time of year. Mission Bay and Agua Hedionda Lagoon had the highest densities of small juveniles (21–60 mm SL) found throughout the survey. Density in bays was as great as 10 times that occurring on the coast (Figures 6, 7, and 10). Both bays had high densities of halibut in the shoreline habitat in spring 1987 (highest monthly density of the 60-mm length class in Agua Hedionda Lagoon $\bar{x}=322.7$/hectare, SD=186.7; Mission Bay $\bar{x}=68.4$, SD=61.2) with fewer juveniles in this size range in 1988 (Agua Hedionda Lagoon $\bar{x}=38.7$, SD=39.0; Mission Bay $\bar{x}=13.1$, SD=12.4; Figures 6 and 7).

Of the open-water habitats, density of halibut in the 60-mm length class was highest in Agua Hedionda Lagoon ($\bar{x}_{1987}=$ 235.2/hectare, SD=237.9; $\bar{x}_{1988}=87.9$, SD=79.9) and lower in Mission Bay ($\bar{x}_{1987}=35.9$, SD=58.2; $\bar{x}_{1988}=64.0$, SD=86.7). No halibut in this length class were found on the open coast in 1987, but in 1988 the density at the Torrey Pines block was $\bar{x}=1.9$ (SD=6.4; Figure 10). While the shoreline habitat of bays appears to be important both as an initial settling area and as a nursery area for small juveniles, most juveniles greater than 100 mm did not remain in the shallow shoreline but occurred in the open-water habitat (Figures 6 and 7).

The greatest density of juveniles in the open-water habitat of Mission Bay was in blocks 2 and 3. For example, the highest density for the 141- to 160-mm length class from ANOVA (Table 4) was found in the open-water habitat of block 3 in Mission Bay, with a mean of 22.2/hectare (SE=3.6) and a maximum trawl density of 460.8/hectare. In these blocks the bottom was composed of sand and mud interspersed with eelgrass. In the summer and fall, invertebrates settled on the bottom in great abundance; often trawls would fill with either sponges (Tetillidae) or bryozoans (*Zoobotryon* sp.).

Larger juveniles also tended to occupy the open-water habitats in Agua Hedionda Lagoon (Figure 6). The greatest density of juveniles in open water in Agua Hedionda Lagoon was in blocks 1 and 2; these blocks had habitat types similar to blocks 2 and 3 in Mission Bay.

Abundance of Juveniles

Abundance of halibut in different nursery habitats is an indication of the potential production of the habitat. Abundance of juveniles in Mission Bay and Agua Hedionda Lagoon was calculated for open-water and shoreline habitats. In 1987, the shoreline habitats had the highest densities of juveniles <100 mm SL relative to all other habitats, but because the shoreline is a small area (about 1/7 of the total area of the bay) the standing stock of halibut is lower than in the open-water bay habitat (Figure 11).

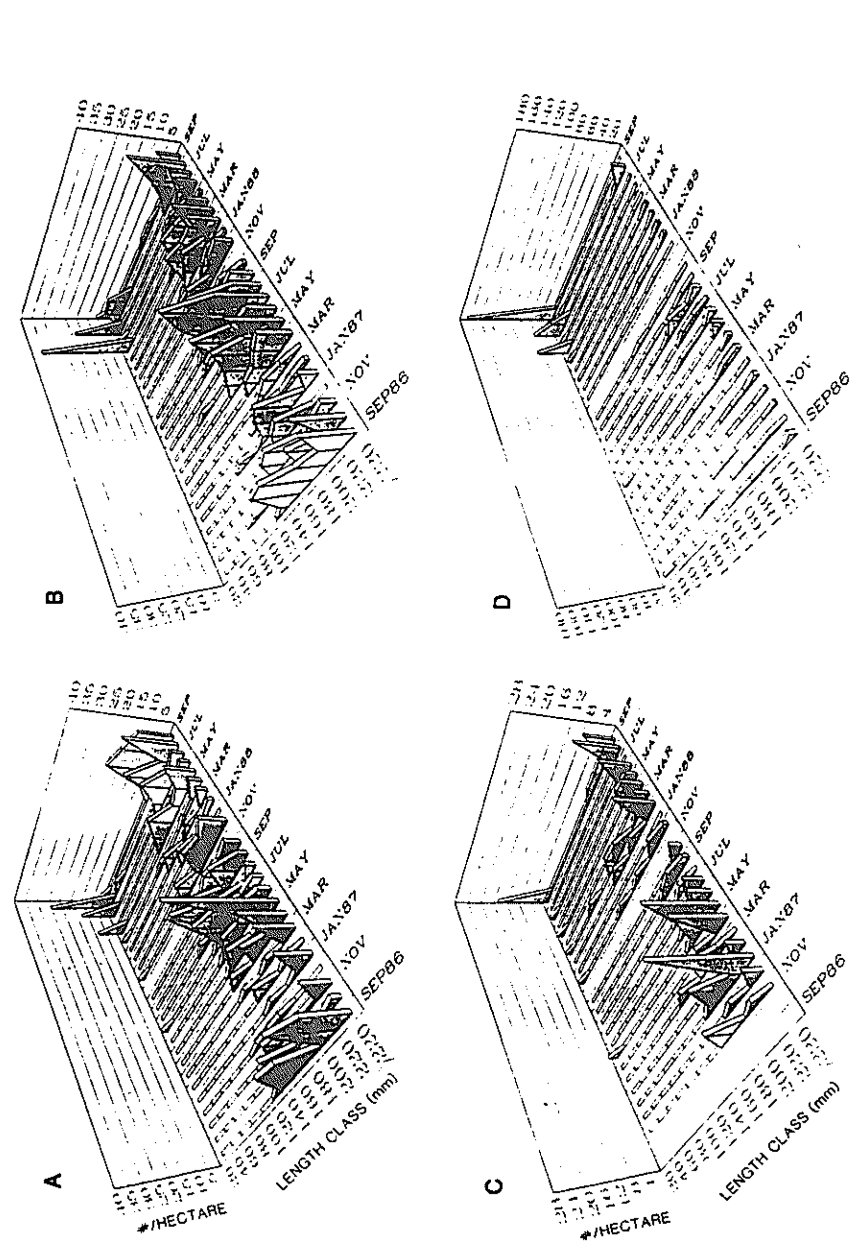

FIGURE 10. Density of halibut on the open coast by block. The blocks are (a) adjacent to Agua Hedionda Lagoon, (b) adjacent to Mission Bay, (c) San Onofre, and (d) Torrey Pines.

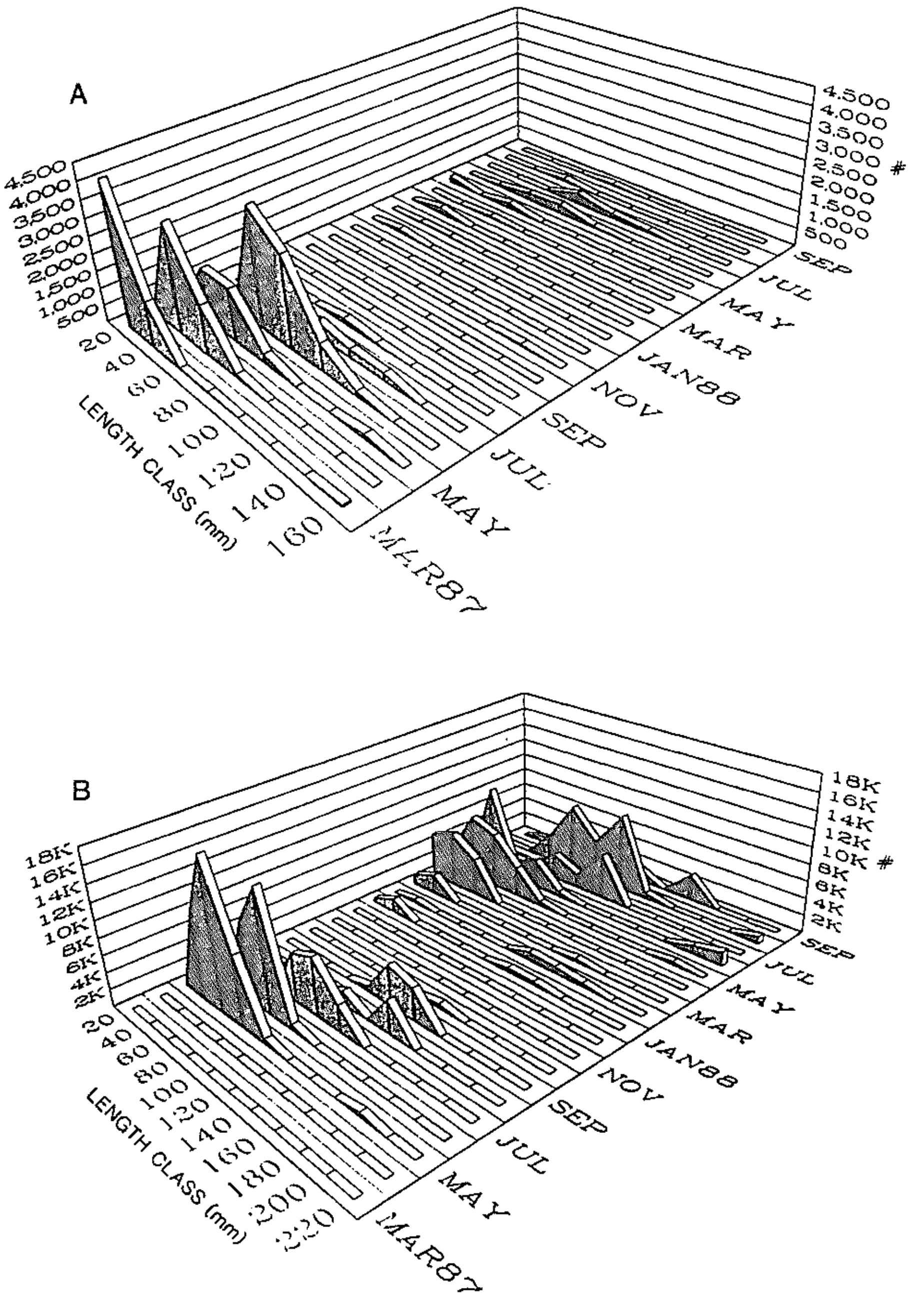

FIGURE 11. Abundance of halibut in Agua Hedionda Lagoon by habitat type: (a) shoreline, and (b) open water.

Abundance of newly settled halibut by habitat and month differed between the 2 years of sampling. In 1987, halibut ≤ 20 mm were most abundant in the open-water habitat of Mission Bay in April ($N=23,610$, SD=41,330) and less abundant in the shoreline habitat of Agua Hedionda Lagoon ($N=4,170$, SD=6,320; Figures 11 and 12). In contrast, newly settled halibut were least abundant in 1988 in both bays with the highest abundance in the Mission Bay open-water habitat in May ($N=12,210$, SD=42,500) and the lowest in Agua Hedionda Lagoon ($N=190$, SD=325; Figures 11 and 12). No settlement occurred on the open coast in 1987, but in 1988 there were 51,290 (SD=77,740) newly settled halibut in May and 92,260 (SD=137,690) in September (Figure 13).

The decline in number of halibut between the 20-mm and 60-mm length classes was greatest on the open coast with numbers dropping from several hundred thousand to nearly zero between May and September 1988 (Figure 13). Halibut settling on the open coast represented the largest standing stock of newly settled halibut (≤ 20 mm) observed in this study. However, few halibut of 40–60 mm were taken later in the year after the large settlement, and none had been found in 1987 (Figure 13). Although these length classes were relatively rare on the open coast, in Mission Bay the highest numbers of juveniles occurred in the 40-mm length class with peak abundance in June 1988 of 48,800 juveniles (2 SE=28,390; Figure 12b). By August, the 60-mm length class was most abundant with 25,740 estimated juveniles (2 SE=15,440; Figure 12b).

If halibut are dependent upon bays as nursery areas, then the numbers of halibut leaving bays should be greater than or equal to the numbers appearing on the coast for the length classes that overlap between the bay and the coastal habitats (Figure 5). Indeed, the abundance of halibut in the 140- to 200-mm length classes in Mission Bay was greater than the abundance on the open coast block adjacent to Mission Bay. In 1986, estimated abundance of 140–200 mm halibut in Mission Bay was 79,020 (2 SE=58,810) and 61,750 on the adjacent coastline (2 SE=60,930); estimated abundances in 1987 and 1988 in Mission Bay were 220,370 and 123,320 (2 SE=95,880 and 68,380, respectively) with adjacent coastal estimates of 152,090 and 89,610 (2 SE=95,410 and 53,580 respectively). For each year, the estimated abundance of halibut leaving bays is greater than the numbers found on the coast, suggesting that bays could account for the population of halibut found on the open coast.

The standing stock of juveniles <50 mm SL in San Diego Bay was 13,760 (2 SE=10,880). In comparison, the standing stock of juveniles <50 mm in Mission Bay was 22,080 (2 SE=18,600) and in Agua Hedionda was 10,190 (2 SE=10,190). Thus the standing stock of juveniles in San Diego Bay was less than that in Mission Bay, yet the area of Mission Bay is only about 1/5 of the area of San Diego Bay. The abundance of juveniles was much lower than in any of the other habitats surveyed during the same time period (Figures 11, 12, and 13), although the area of San Diego Bay is large (3615 hectares).

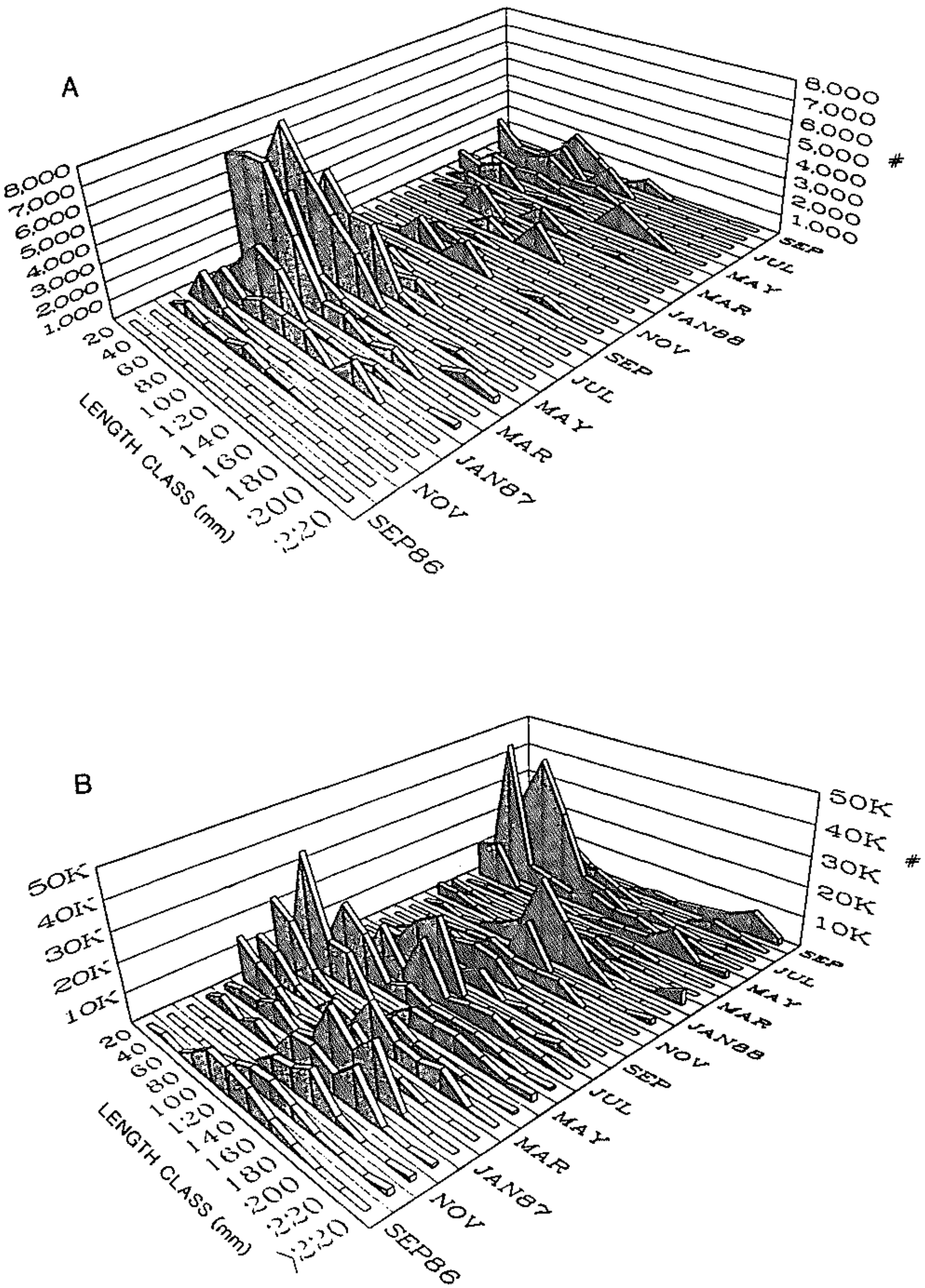

FIGURE 12. Abundance of halibut in Mission Bay by habitat type: (a) shoreline, and (b) open water.

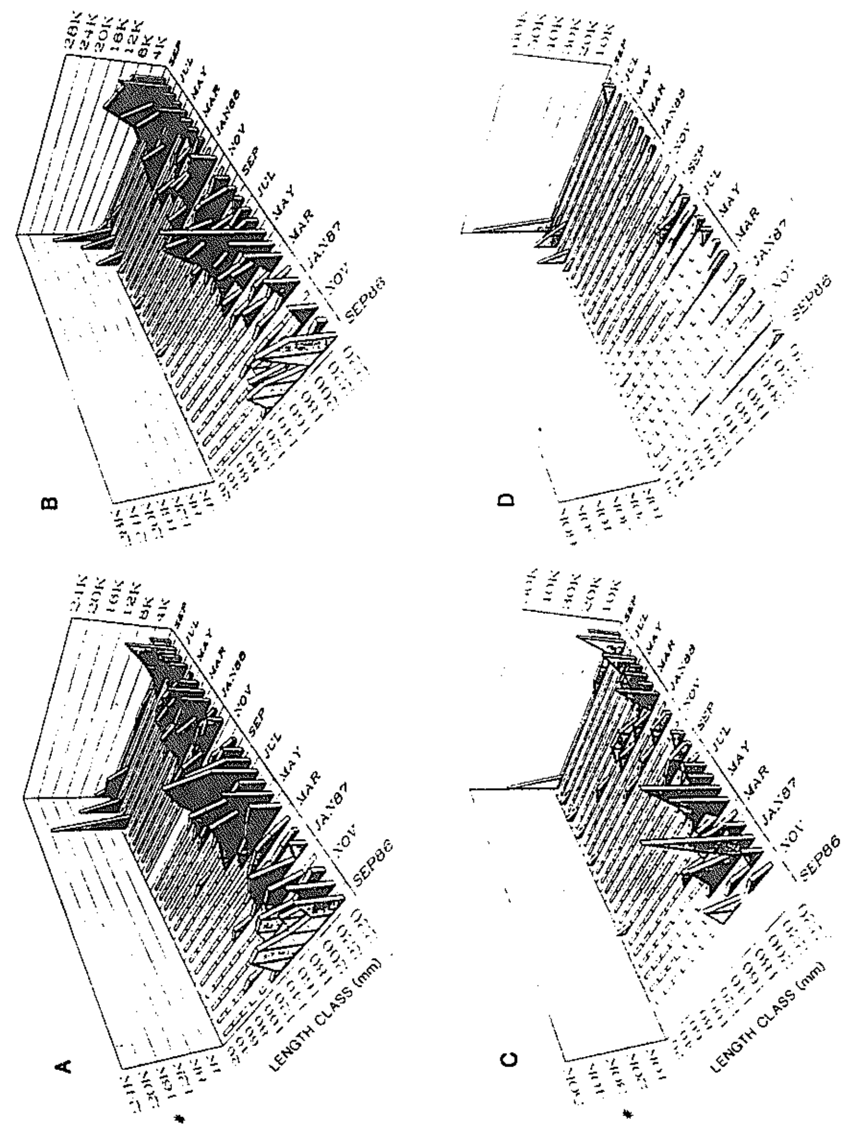

FIGURE 13. Abundance of halibut on the open coast by block. The blocks are (a) adjacent to Agua Hedionda Lagoon, (b) adjacent to Mission Bay, (c) San Onofre, and (d) Torrey Pines.

DISCUSSION

Adaptive Value of Bays

The advantages of utilizing bays as nursery areas include providing a productive habitat that enhances juvenile growth and increasing survival by separating juveniles from predators that include adults. Adult halibut are mainly piscivorous (Plummer et al. 1983) feeding mostly on northern anchovy, *Engraulis mordax*, and incidentally on other coastal species including flatfishes (Ford 1965).

This study indicates that bays probably produce enough juvenile halibut to maintain the population on the open coast (Figures 11, 12, and 13). Scanty existing information suggests that halibut can move considerable distances. Tagging data indicate that there is little movement of juvenile halibut within bays before emigration (Haaker 1975), but larger halibut (up to 22 inches) have been recovered up to 140 mi from the release point (Frey 1971). It seems possible that movement of halibut from bays could support the population of larger halibut found on the coast.

The estimated additional area of bay habitat in southern California, excluding the bays studied and Los Angeles Harbor, is at least 800 hectares which is close to the combined areas of Mission Bay and Agua Hedionda Lagoon (Horn and Allen 1976). If the estimates for the abundance of halibut at Mission Bay and Agua Hedionda Lagoon are doubled, this should approximate the potential number of halibut produced annually by bays in the Southern California Bight region. Using this estimate, over 400,000 halibut came from bays in 1987, and nearly 250,000 in 1988. The estimate of annual recruitment of age-1 halibut for California is between 0.45 and 1.0 million fish (Reed and MacCall 1988); the estimates of recruits from this survey and from Reed and MacCall (1988) are reasonably close considering the recruitment estimate is for the entire California coast.

The Fate of Newly Settled Halibut in Coastal Areas

The fate of newly settled juveniles from the open coast in 1988 is uncertain. There are several possible outcomes: 1) they dispersed to deeper coastal habitats; 2) they settled on the coast and were lost because of high mortality; or 3) they first settled on the coast and later move into bays.

It is not likely that juveniles moved to deeper water habitats on the coast, because small juveniles (20–40 mm SL) were found only on the shallowest open coast strata (depth <8 m). If the settlement of halibut on the open coast was lost due to high mortality, then bays must be able to account for the population. If newly settled juveniles migrated from the coast to bays, there should be far greater numbers of intermediate-size juveniles in the 40- to 60-mm length classes then in the smaller size classes (20–40 mm) in the bays.

In bays, there were always fewer halibut in the 20-mm length class than in the 40-mm length class (Figures 11 and 12). The first peak of newly settled halibut (20-mm length class) occurred on the coast in May 1988, and a strong peak in abundance of 40-mm length class juveniles appeared in bays in June (Figures 12 and 13). The lack of <20-mm halilbut in bays and the great decline in abundance of halibut from the 20-mm to the 40-mm length class on the coast suggests that at least some of the halibut in the 40-mm and larger length classes in bays may have been derived from halibut that had settled originally on the coast and then moved into bays as larger (>20-mm) juveniles. English sole (*Parophrys vetulus*) also settle in bays and along the open coast with subsequent movement into bays (Krygier and Pearcy 1986; Boehlert and Mundy 1987).

An Evolutionary Perspective

Complete dependence on bays as nursery areas by juvenile halibut is not likely, as the existence and quantity of bay and shallow water habitats in the Southern California Bight over time has not been predictable. Pliocene otoliths referred to as *P. californicus* have been reported (Fitch and Reimer 1967), and *Paralichthys antiquus* was described from the Miocene (David 1943). Miocene and Pliocene sea levels were considerably higher than present day levels resulting in the formation of many large, shallow, warm embayments along the southern California coast (Vedder and Howell 1979). California halibut evolved in these conditions, assuming that halibut have been in the region since at least the Miocene and that the species has always been shallow dwelling.

On the other hand, Pleistocene glaciation events resulted in dramatic changes with colder water temperatures and sea levels 100 m lower than those of present day (Emery 1967; Vedder and Howell 1979). Lowered sea levels would decrease the area of shelf habitat and perhaps decrease shallow embayment habitats as well. This might have resulted in a decline in the halibut population. In the last 3000 years, the sea level has been near present levels (Emery 1967).

Southern California bay habitats have been considered to be relatively unpredictable with bays open to the ocean only in seasons with high rainfall and closed to the ocean by formation of sand bars across their entrances (Zedler and Nordby 1986). Currently many of the smaller bays in southern California are open to the ocean only when dredged open by removal of the sand blocking the mouth (Warme et al. 1976). The extent of shallow water and bay habitat is additionally decreased by destruction and pollution of these habitats by man.

I conclude that shallow water habitats are utilized as nursery areas by juvenile halibut, and that the amount of available nursery habitat may limit the size of the halibut population. Bay habitats can support a greater density of juvenile halibut than the shallow open coast and are probably the optimal habitats for juvenile growth and survival. The ability to utilize both open coast and bays as nursery areas is an important adaptive strategy in a region where bay habitats can be unpredictable.

ACKNOWLEDGMENTS

This paper represents part of a dissertation submitted to University of California San Diego, Scripps Institution of Oceanography. The research was supported by funds provided by the Habitat Program of the National Marine Fisheries Service and by the Southwest Fisheries Science Center of the National Marine Fisheries Service. I thank John Hunter, Richard Rosenblatt, and Michael Mullin for their support and comments. Mike Davis, Steve Swailes, Kevin

George, Dennis Gruber, Darlene Pickett, David Moser, Wayne Kicklighter, Mark Drawbridge, and many others were invaluable in the field. Richard Charter and Carol Kimbrell provided technical guidance with analysis and management of the database. Roy Allen, Henry Orr, and Ken Raymond assisted in drafting figures. I also thank MBC Applied Environmental Sciences for their support during the preparation of this paper for publication and for the use of the R/V WESTWIND.

LITERATURE CITED

Allen, L.G. 1988. Recruitment, distribution, and feeding habits of young-of-the-year California halibut (*Paralichthys californicus*) in the vicinity of Alamitos Bay-Long Beach Harbor, California, 1983–1985. Bull. South. Calif. Acad. Sci. 87:19–30.

Allen, M.J. 1982. Functional structure of soft-bottom fish communities of the southern California shelf. Ph.D. Thesis, Univ. Calif. at San Diego. 577 p.

Ahlstrom, E.H., K. Amaoka, D.A. Hensley, H.G. Moser, and B.Y. Sumida. 1984. Pleuronectiformes: development. Pages 640–670 *in* H.G. Moser, W.J. Richards, D.M. Cohen, M.P. Fahay, A.W. Kendall, Jr., and S.L. Richardson, eds. Ontogeny and systematics of fishes. Amer. Soc. Ichthyol. Herpetol., Spec. Publ. No. 1.

Ahlstrom, E.H. and H.G. Moser. 1975. Distributional atlas of fish larvae in the California Current region: flatfishes, 1955–1960. Calif. Coop. Oceanic Fish. Invest. Atlas 23.

Barnett, A.M., A.E. Jahn, P.D. Sertic, and W. Watson. 1984. Distribution of ichthyoplankton off San Onofre, California, and methods for sampling very shallow coastal waters. Fish. Bull., U.S. 82:97–111.

Boehlert, G.W. and B.C. Mundy. 1987. Recruitment dynamics of metamorphosing English sole, *Parophrys vetulus*, to Yaquina Bay, Oregon. Estuarine Coast. Shelf Sci. 25:261–281.

Boehlert, G.W. and B.C. Mundy. 1988. Roles of behavioral and physical factors in larval and juvenile fish recruitment to estuarine nursery areas. Amer. Fish. Soc. Symp. 3:51–67.

Bradshaw, J., B. Browning, K. Smith, and J. Speth. 1976. The natural resources of Agua Hedionda Lagoon. Calif. Dept. Fish and Game, Coastal Wetland Series No.16. 110 p.

David, L.R. 1943. Miocene fishes of southern California. Geological Society of America. Spec. papers no. 43:1–181.

Dexter, D.M. 1983. Soft bottom infaunal communities in Mission Bay. Calif. Fish and Game 69:5–17.

Edwards, R.R. and J.H. Steele. 1968. The ecology of 0-group plaice and common dabs at Loch Ewe. 1. Population and food. Journal Exp. Mar. Biol. Ecol. 2:215–238.

Emery, K.O. 1960. The sea off southern California; a modern habitat of petroleum. John Wiley and Sons, New York. 366 p.

Emery, K.O. 1967. Estuaries and lagoons in relation to continental shelves. Pages 9–11 *in* G.H. Lauff, ed. Estuaries. Amer. Assoc. Adv. Sci. Publ. 83.

Fitch, J.E. and R.D. Reimer. 1967. Otoliths and other fish remains from a Long Beach, California, Pliocene deposit. Bull. South. Calif. Acad. Sci. 66:77–91.

Ford, R.F. 1965. Distribution, population dynamics, and behavior of a bothid flatfish, *Citharichthys stigmaeus*. Ph.D. thesis, Univ. Calif., San Diego. 243 p.

Fretwell, S. 1972. Populations in a seasonal environment. Princeton Univ. Press, NJ. 217 p.

Frey, H. 1971. California's living marine resources and their utilization. Calif. Dept. Fish and Game, Sacramento. 148 p.

Gadomski, D.M. and J.H. Petersen. 1988. Effects of food deprivation on the larvae of two flatfishes. Mar. Ecol. Prog. Ser. 44:103–111.

Gruber, D., E.H. Ahlstrom, and M.M. Mullin. 1982. Distribution of ichthyoplankton in the Southern California Bight. Calif. Coop. Oceanic Fish. Invest. Rep. 23:172–179.

Haaker, P.L. 1975. The biology of the California halibut, *Paralichthys californicus* (Ayres) in Anaheim Bay. Pages 137–151 *in* E.D. Lane and C.W. Hill, eds. The marine resources of Anaheim Bay. Calif. Dept. Fish and Game, Fish Bull. 165.

Horn, M.H. and L.G. Allen. 1976. Numbers of species and faunal resemblance of marine fishes in California bays and estuaries. Bull. So. Cal. Acad. Sci. 75:159–170.

Krygier, E.E. and H.F. Horton. 1975. Distribution, reproduction, and growth of *Crangon nigricauda* and *Crangon franciscorum* in Yaquina Bay, Oregon. Northwest Sci. 49:216–240.

Krygier, E.E. and W.G. Pearcy. 1986. The role of estuarine and offshore nursery areas for young English sole, *Parophrys vetulus* Girard, of Oregon. Fish. Bull., U.S. 84:119–132.

Lavenberg, R.J., G.E. McGowan, A.E. Jahn, J.H. Petersen, and T.C. Sciarrota. 1986. Abundance of southern California nearshore ichthyoplankton: 1979–1984. Calif. Coop. Oceanic Fish. Invest. Rep. 27:53–64.

Mearns, A.J. and M.J. Allen. 1978. Use of small otter trawls in coastal biological surveys. Corvallis Env. Res. Lab., Off. Res. Dev., U.S. Env. Prot. Agency, Corvallis, OR. EPA/600/3/78/083. 33 p.

Miller, D.L. and R.N. Lea. 1972. Guide to the coastal marine fishes of California. Calif. Dept. Fish and Game, Fish Bull. 157. 299 p.

Plummer, K.M., E.E. DeMartini, and D.A. Roberts. 1983. The feeding habits and distribution of juvenile-small adult California halibut (*Paralichthys californicus*) in coastal waters off northern San Diego county. Calif. Coop. Oceanic Fish. Invest. Rep. 24:194–201.

Poxten, M.G., A. Eleftheriou, and A.D. McIntyre. 1982. The population dynamics of 0-group flatfish on nursery grounds in the Clyde Sea area. Estuarine Coast. Shelf Sci. 14:265–282.

Reed, R.J. and A.D. MacCall. 1988. Changing the size limit: how it could affect California halibut fisheries. Calif. Coop. Oceanic Fish. Invest. Rep. 29:158–166.

Rogers, C.W., D.R. Gunderson, and D.A. Armstrong. 1989. Utilization of a Washington estuary by juvenile English sole, *Parophrys vetulus*. Fish. Bull., U.S. 86:823–831.

Roper, D.S. 1986. Occurrence and recruitment of fish larvae in a northern New Zealand estuary. Estuarine Coast. Shelf Sci. 22:705–717.

Roper, D.S. and J.B. Jillett. 1981. Seasonal occurrence and distribution of flatfish (Pisces: Pleuronectiformes) in inlets and shallow water along the Otago coast. New Zealand J. Mar. Freshwater Res. 15(1):1–13.

Sokal, R.R. and F.J. Rohlf. 1981. Biometry. 2nd ed. W.H. Freeman and Co., San Francisco, CA. 859 pp.

Vedder, J.G. and D.G. Howell. 1979. Topographic evolution of the southern California borderland during late Cenozoic time. Pages 7–31 *in* D.M. Power, ed. The California islands, proceedings of a multidisciplinary symposium. Santa Barbara Mus. Natl. Hist., Santa Barbara, CA.

Walker, H.J., Jr., W. Watson, and A.M. Barnett. 1987. Seasonal occurrence of larval fishes in the nearshore southern California bight off San Onofre, California. Estuarine Coast. Shelf Sci. 25:91–109.

Warme, J.E., L.A. Sanchez-Barreda, and K.T. Biddle. 1976. Sedimentary patterns and processes in west coast lagoons. Pages 167–181 *in* M. Wiley, ed. Estuarine processes, vol. 2. Circulation, sediments, and transfer of materials in the estuary. Academic Press, New York.

Weinstein, M.P., S.L. Weiss, R.G. Hodson, and L.R. Gerry. 1980. Retention of three taxa of postlarval fishes in an intensively flushed tidal estuary, Cape Fear River, North Carolina. Fish. Bull., U.S. 78:419–438.

Werner, E.E. 1986. Amphibian metamorphosis: growth rate, predation risk, and the optimal size at transformation. Am. Nat. 128:319–341.

Werner, E.E. and J.F. Gilliam. 1984. The ontogenetic niche and species interactions in size-structured populations. Ann. Rev. Ecol. Syst. 15:393–425.

Zedler, J.B. and C.S. Nordby. 1986. Ecology of Tijuana estuary, California: an estuarine profile. U.S. Fish Wildl. Serv. Biol. Rep. 85 (7.5). 104 p.

CALIFORNIA HALIBUT, *PARALICHTHYS CALIFORNICUS*, IN TODOS SANTOS BAY, BAJA CALIFORNIA, MEXICO.

M. GREGORY HAMMANN and A. ANGÉLICA RAMIREZ-GONZALEZ [1]
Centro de Investigación Cientifica y Educacion Superior de
Ensenada. (CICESE).
Apdo. Postal 2732,
Ensenada, B.C. Mexico.
(U.S. mailing: P.O. Box 439038-39, San Ysidro, CA 92143)

ABSTRACT

A total of 163 California halibut, *Paralichthys californicus*, was caught from nine trawl stations in Todos Santos Bay, Baja California, Mexico, from August 1986 to July 1987, representing 2.2% of the abundance of all species caught and 16.0% of the total biomass. Average monthly catches per trawl ranged from 0.33 to 2.44 individuals. Significantly more halibut were caught in 8 m than in deeper waters (2.97 halibut per trawl at 8 m versus 0.65 halibut per trawl at 25 m). Total length increased with depth, especially at the central and southern regions. Halibut of ages 1 and 2 years composed 85% of the total catches; in Punta Banda Estuary, halibut of age 0 dominated. The overall sex ratio was 1.0:2.2 F:M; juveniles (28% of the halibut caught) were not macroscopically sexable. Age 3 females were significantly larger than males of the same age; no differences were found between the size at age for ages 1 and 2 males and females. On the average, halibut in Todos Santos Bay grew 0.79 cm per month. No significant difference was found between the length-weight relationship of males and females. Combining our information from Punta Banda Estuary and the icthyoplankton in the bay, the following life cycle can be developed. After spawning, larvae that are transported into the bay settle and move into the estuary where they spend several months of their first year of life. Juveniles quickly leave the estuary during spring and spend the next 2 years of their life in the semiprotected but deeper waters of the bay. After 2 years, halibut begin to move offshore, out of the bay to the deeper waters of the continental platform. Todos Santos Bay and Punta Banda Estuary, therefore, may play an important role in the life history of the California halibut off the northern coast of Baja California.

INTRODUCTION

The California halibut, *Paralichthys californicus*, family Paralichthyidae, is a resource shared by both the United States and Mexico. It is the most valued

[1] Present address: Centro de Investigación de Quintana Roo, Apdo. Postal 424, Chetumál, Código Postal 77000, Quintana Roo, Mexico.