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Changes in cover and use of Zostera marina habitat in Elkhorn Slough, California

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CHANGES IN COVER AND USE OF *ZOSTERA MARINA* HABITAT IN ELKHORN SLOUGH, CALIFORNIA

A Thesis
Presented to
The Faculty of Moss Landing Marine Labs
California State University Monterey Bay

In Partial Fulfillment
of the Requirements for the Degree
Master of Science

by
Nora Elaine Grant
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CALIFORNIA STATE UNIVERSITY MONTEREY BAY

The Undersigned Thesis Committee Approves the Thesis Titled

CHANGES IN COVER AND USE OF *ZOSTERA MARINA* HABITAT IN ELKHORN SLOUGH, CALIFORNIA

by
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ABSTRACT

CHANGES IN COVER AND USE OF *ZOSTERA MARINA* HABITAT IN ELKHORN SLOUGH, CALIFORNIA

by Nora E. Grant

Seagrasses provide an array of ecosystem services to the nearshore marine community. The goal of this study was to begin to determine the role of the seagrass, *Zostera marina,* in habitat provisioning within Elkhorn Slough, CA. Part one uses maps to assess variability in the spatial extent of *Zostera marina* in Elkhorn Slough over time and the potential of *Zostera* to provide a unique habitat to species assemblages within the slough. Part two examines habitat use within and among *Zostera,* algae and bare habitats in Elkhorn Slough by fishes and some mobile epibenthic invertebrates.

Zostera beds were mapped a total of six times; twice in 2007 and four times during 2008. Habitat use sampling was conducted from February 2008 to October 2008, split into the three sampling seasons winter, spring/summer, and fall. *Zostera*, algae and bare habitat were sampled each season using a 1-m^3 throw-trap and a stratified random design. Distribution, abundance and frequency of occurrence of species were compared across habitats and times using various metrics. Species distributions patterns indicated multiple potential habitat functions for *Zostera*. Species richness and diversity were highest in *Zostera* among the three habitats tested, and bare substrate was the most deplete of animals. Some species were exclusively found within *Zostera* while other species were distributed among all habitats. Trends in both size and abundance of particular fishes over time suggest *Zostera* beds provide nursery habitat within Elkhorn Slough.

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I would first like to thank my thesis advisory committee; Dr. Lara Ferry-Graham, Dr. Michael Graham and Dr. Gregor Cailliet, for their expertise, advice and encouragement during my time as a graduate student at Moss Landing Marine Labs (MLML). I feel very fortunate to have learned from and worked with the faculty and students of MLML who have provided me with an enthusiastic and passionate view of marine science.

This work would not have been completed without the help of generous volunteers and friends. I would especially like to thank the MLML BEERPIGS and Ecomorphology lab for all their help out in the field collecting data or testing gear, in the classroom studying or at the lab brainstorming and troubleshooting. I grateful to Kamille Hammerstrom and Kristin Green for their field sampling help as well. I would also like to thank the diving and small boats facility staff for providing boats and equipment and keeping us safe out on the water.

I would also like to acknowledge some awards and funding that contributed to this project; Friend's of Moss Landing Marine Labs Signe Lundstrom Memorial Scholarship (2007), The David and Lucile Packard Research and Travel Award (2008) and the Elkhorn Slough National Estuarine Research Reserve Student Conservation Research Award (2009). This work was approved and permitted by SJSU IACUC #0891.

Finally, I want to thank my family and friends for their emotional and financial support throughout my time in graduate school. I am especially grateful for my mother, and all she has taught me in my life. She always encouraged me to continue towards graduate school and to pursue marine science. Sadly, my mother passed away one year before I started school at MLML and in her honor I would like to dedicate my master's thesis work to her memory and a mother's love.

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BACKGROUND

Seagrasses can provide an array of ecosystem services to the nearshore marine community. They are considered "habitat-forming species" because they provide an upright structure in an otherwise two-dimensional environment (Orth et al., 1984; Jenkins at al., 1997; Pihl et al., 2006). The upright structures of seagrasses are used as habitat, refuge and nursery for many species, and the below-ground structures of roots and rhizomes support overall productivity as well as stabilize sediments (Green and Short, 2003). In addition to providing habitat, seagrasses also have the ability to physically modify the environment around them. Not only are they affected by ambient water flow they affect flows by creating waves and turbulence in the water around them (Koch et al., 2006).

Changes in flow characteristics mediate ecological processes that help to define the roles of seagrasses in the coastal environment (Fonseca and Koehl, 2006). Seagrasses are able to alter flow conditions within and around meadows due to the physical morphology of the plant itself, as well as influence the ecology of the surrounding habitat. Reduction of flow inside seagrass canopies is important because it can reduce turbidity and processes of erosion by providing increased deposition and retention of finer sediments within the seagrass bed (Green and Short, 2003). Studies have shown that current and flux reduction, shear stress at the canopy level and turbulence intensity are positively correlated with plant abundance (Gambi et al., 1990). In addition, bending of the shoot canopy has been implicated as a mechanism for re-direction of current flow and in-canopy reduction of current velocity (Fonseca et al., 1982).

Seagrasses play many important roles in estuarine ecosystems, namely as a food source, a habitat and provide sediment stabilization (Thorhaug, 1986). Seagrasses contribute to a large portion of total primary productivity of the ecosystem, creating a base for the food web and seagrass meadows enhance biodiversity and habitat diversity, improve water quality, as well as play a role in carbon and nutrient cycles of the environment (Hemminga and Duarte, 2000; Thayer et al., 1984). Seagrasses in estuaries are particularly vulnerable to contamination from anthropogenic sources, are currently threatened by natural and human-induced changes to habitats, and coastal development has led to decline or loss of populations (Moore and Short, 2006).

One of the most prominent and well-studied seagrasses both physically and biologically is the eelgrass, *Zostera marina*. *Zostera* species collectively have the widest latitudinal range of all seagrasses, from the tropics to the Arctic and Sub-Antarctic, and in the eastern Pacific, *Zostera marina* ranges from Baja California and the Sea of Cortez up to Alaska inhabiting the intertidal and subtidal zones of calm, shallow bays and estuaries (Moore and Short, 2006). Loss of *Zostera* populations has occurred in two large west coast estuaries; Puget Sound, Washington and San Francisco Bay, California, and losses are suspected at other sites (Wyllie-Echeverria and Ackerman, 2003). Studies suggest that an ecosystem level viewpoint of management of *Zostera* communities is required to adequately preserve the structure and function of the habitat (Thayer et al., 1984).

This study seeks to answer questions regarding use of *Zostera marina* as habitat by fishes and mobile epibenthic invertebrates in Elkhorn Slough, California. Research questions are divided into two sections. First, variability in the spatial extent of *Zostera* *marina* in Elkhorn Slough over time was examined to assess the seasonal and spatial potential of *Zostera* to provide a unique habitat to species assemblages within the slough. The second part examined habitat use of the *Zostera* in Elkhorn Slough by fishes and some mobile epibenthic invertebrates to better understand the ecological function of *Zostera* in Elkhorn Slough.

This project addressed five main questions: (1) Does the presence and spatial cover of *Zostera marina* in Elkhorn Slough change over time? (2) What fishes and invertebrate taxa are present in *Zostera*, algae and bare habitats? (3) Do species assemblages vary temporally over one year (seasonally)? (4) Do the fishes and invertebrates exclusively use *Zostera* as their habitat or can *Ulva* or other macroalgae provide the same habitat function as *Zostera?* (5) Is *Zostera* a potential nursery habitat for fishes in Elkhorn Slough?

PART 1. VARIABILITY IN SIZE AND SHAPE OF TWO *ZOSTERA MARINA* BEDS IN ELKHORN SLOUGH, CALIFORNIA

INTRODUCTION

This study took place in Elkhorn Slough, a coastal embayment and seasonal estuary located in the heart of Monterey Bay, central California. Elkhorn Slough was once a sluggish backwater with little oceanic influence until 1946 when the mouth of Moss Landing Harbor was created to accommodate commercial ship traffic (Browning et al., 1972). In 1983, a portion of marsh formerly used for a dairy pasture was re-opened to tidal flooding and dredged to two meters below mean lower low water (MLLW), increasing the volume of water exchanged per tidal cycle (Small, 1986). These acts of engineering transformed the slough from a depositional, fresh to brackish water estuarine environment to a tidal embayment dominated by erosion (Broenkow and Breaker, 2005). Tidal currents in the main channel have doubled in the past 30 years (Broenkow and Breaker, 2005) and the tidal prism has tripled over the past 40 years (Breaker et al., 2008). As erosion continues due to tidal forcing in an ebb-dominant system, the tidal prism and currents increase, leading to more erosion and loss of habitat; a process of positive feedback. Human-induced changes to the hydrographic regime of Elkhorn Slough have transformed this historically typical estuary into a tidal embayment with asymmetric tidal forcing, now classified as an ebb-dominant seasonal estuary.

Zostera marina in Elkhorn Slough was historically very abundant but has declined, as in most other locations, since the 1920’s (Van Dyke and Wasson, 2005). Restoration experiments using transplants suggested that *Zostera* populations require shallow depths (0-2 m MLLW) and moderate flows (10-30 cm sec^{-1}) (Zimmerman and

Caffrey, 2002). Interestingly, increased tidal flows within the slough may also have resulted in some positive effects on *Zostera.* Flood tides bring clear, cool ocean waters into the slough that are well mixed vertically, and residence times in the lower slough are short, resulting in full tidal exchange on an almost daily basis (Broenkow and Breaker, 2005). Recently, *Zostera* has been able to expand and recover about ten hectares of land (approximately 100,000 m^2) of the lower slough region (Zimmerman and Caffrey, 2002).

Aerial photo images of the lower reaches of Elkhorn Slough (1930-present) illustrate the trends in *Zostera* abundance in the lower slough over time (Fig. 1.1, photos and analysis courtesy of E. VanDyke, ESNERR). Delineating submerged aquatic vegetation form aerial photos (particularly black-and-white images) is challenging and confounded by a number of factors, namely tidal stage, water clarity and confusion with other vegetation types. For these reasons images from 13 different flights (1931, 1937, 1949, 1956, 1966, 1971, 1976, 1980, 1987, 1992, 2000, 2003 and 2005) were compiled into four time periods to generalize trends in *Zostera* abundance over time. Generalized results are presented for pre-harbor mouth opening (1931-1937), post-harbor mouth opening (1950-1970's), 1980-1990's and 2000-2005 (Fig. 1.1).

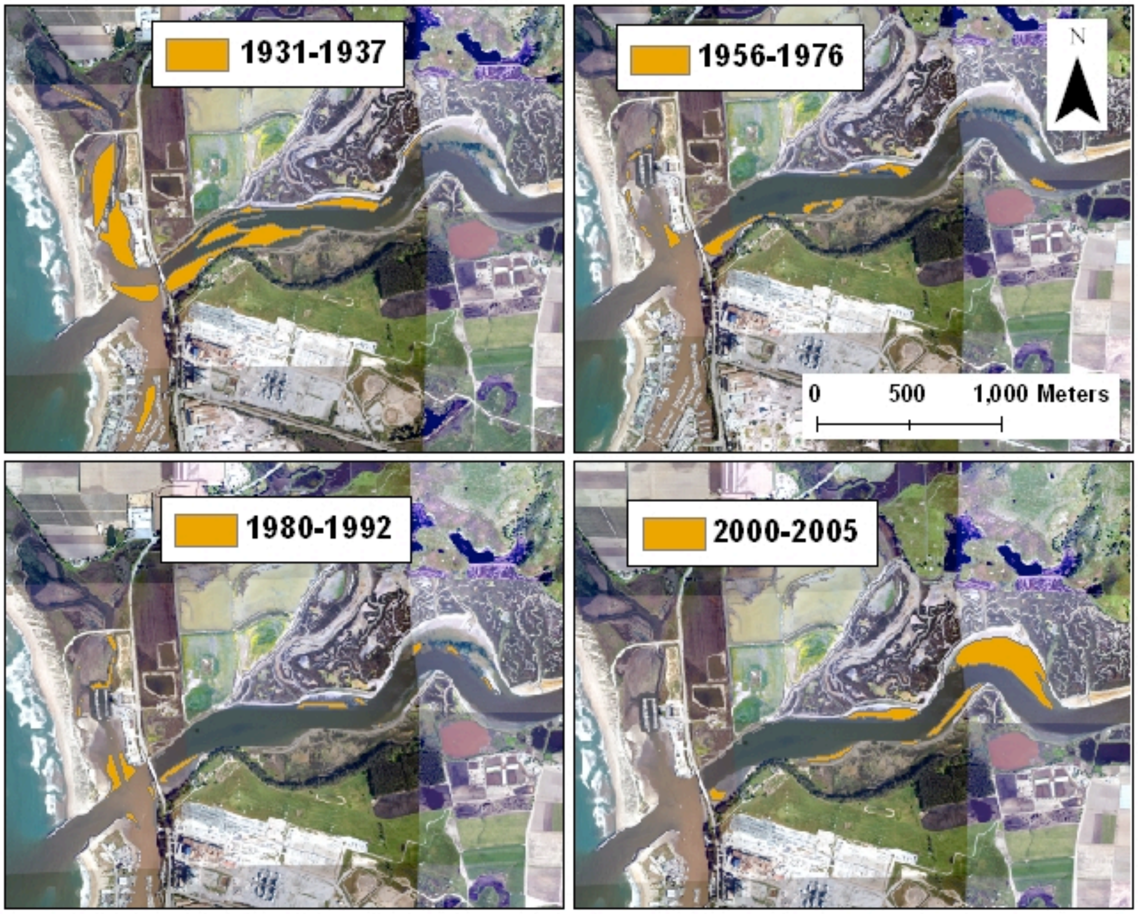

Figure 1.1. Historic aerial image analysis of *Zostera* abundance in the lower reaches Elkhorn Slough, 1931-2005 (E. VanDyke, ESNERR). 2005 CDFG aerial image used as background for reference.

Prior to the harbor mouth opening (1931-1937), *Zostera* was plentiful throughout much of the lower slough. During the 1950's through 1970's *Zostera* was relatively scarce in the slough, existing in scattered narrow bands along the north and south banks and sparse patches throughout the lower slough. Around 1980, *Zostera* had colonized an area called Seal Bend, about three kilometers up the slough, and by 1990 it was growing rapidly (Fig.1.1). By the 2000-2005 time period, the eastern beds had expanded and area was estimated to be 128,000 m^2, approximately half of the total area estimated before the harbor mouth was opened (Fig. 1.2).

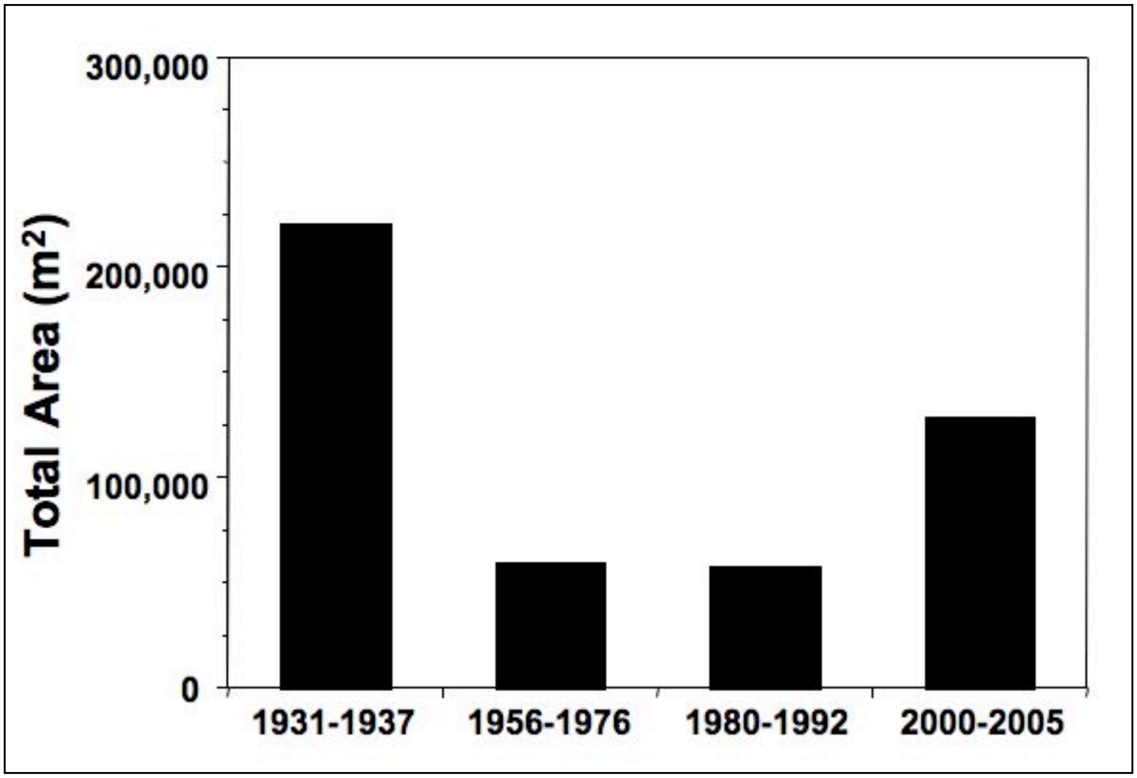

Figure 1.2. Total area (m^2) covered by *Zostera*, estimated from aerial photo images taken from 1931-2005, compiled into four main time periods.

If *Zostera* is expanding and re-colonizing the lower slough, while under erosional stress from tidal currents, it would be helpful to know if and how the plants are responding to short-term seasonal changes for future management and habitat restoration projects. The goal of this portion of the study was to assess the variability in the extent of the two main existing *Zostera* beds in the lower slough region over time, asking does the presence and spatial cover of *Zostera marina* in Elkhorn Slough change over time?

METHODS

Mapping

Using geographic information systems (ArcGIS) programs and digital analysis, changes in the spatial extent of the *Zostera* beds in Elkhorn Slough over time were examined to understand natural variability in *Zostera* bed cover and shape. A handheld global positioning system (GPS) unit was used to determine latitude and longitude points along the boundaries of existing *Zostera* beds in the slough. These points were plotted onto a bathymetry map of the slough with data provided by CSUMB Seafloor Mapping Lab. This map provided estimates of the distribution of *Zostera* relative to the depth contours of the slough. The map was also used to calculate area per bed (Fig. 1.3), providing a baseline estimate of how much *Zostera* was available as habitat to mobile species. *Zostera* beds were mapped at least once per season to track changes in the size and shape of the beds during seasonal habitat use sampling.

Bathymetry data for Elkhorn Slough was collected in 2003 by the CSUMB Seafloor Mapping Lab using a combination of multibeam sonar, single beam sonar and aerial photography. Bathymetric and sidescan data were collected aboard the R/V

MacGinnite using a Reson 8101 multibeam echosounder. Differential GPS position data were generated by a Trimble 4700 GPS with differential corrections provided by a Trimble ProBeacon receiver. Bathymetric data were post-processed using Coastal Oceanographics Hypax Max data collection and cleaning software and adjusted to MLLW using RTK tides collected during the survey. Slough depth contours for 2003 were symbolized with a blue scheme (darker being deeper) and classified into five depth classes based on natural breaks in the data.

Zostera beds were mapped from a boat using a handheld GPS unit (Garmin 76mapS). The datum used was GCS WGS 1984, projection is UTM Zone 10N, mapped in UTM coordinates to increase accuracy of the point data. Latitude and longitude coordinates along the edges of the beds were recorded every 5-10 m estimated visually from the boat, 93-575 points were collected each season to outline the *Zostera* beds for each map.

An aerial image from April 2005 (low tide was -0.2 m at 14:22; CDFG flight, E. Van Dyke image georeference and mosaic) provided a visual estimate of *Zostera* presence at the study site. The two study beds were named Seal Bend and LOBO (Fig 1.3). Polygons drawn around what appeared to be *Zostera* were used to estimate cover (m^2) of *Zostera* at Seal Bend and LOBO during spring 2005 and used as a baseline for comparisons of the seasonal estimates of *Zostera* bed cover. Waypoints were downloaded off the handheld GPS, imported into ArcMAP as UTM coordinates, and overlaid onto the map of 2003 depth contours. *Zostera* beds were outlined by connecting points into polygons using the snap to point feature and area per bed was calculated by ArcGIS (Fig. 1.4). Differences in the area and shape of the beds were compared over time.

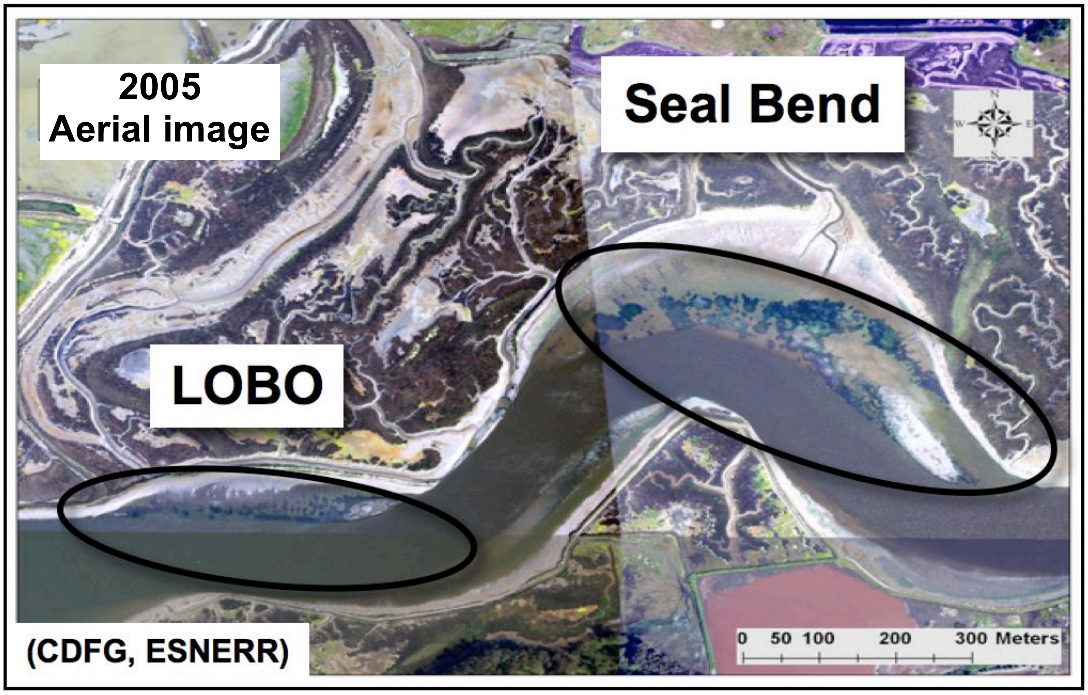

Figure 1.3. Aerial image of Elkhorn Slough (CDFG, 2005), circles indicate locations of Seal Bend and LOBO beds. *Zostera* cover was estimated from this image in ArcGIS as area (m^2) and used as a 'baseline' estimate of *Zostera* cover for comparison of bed size over time.

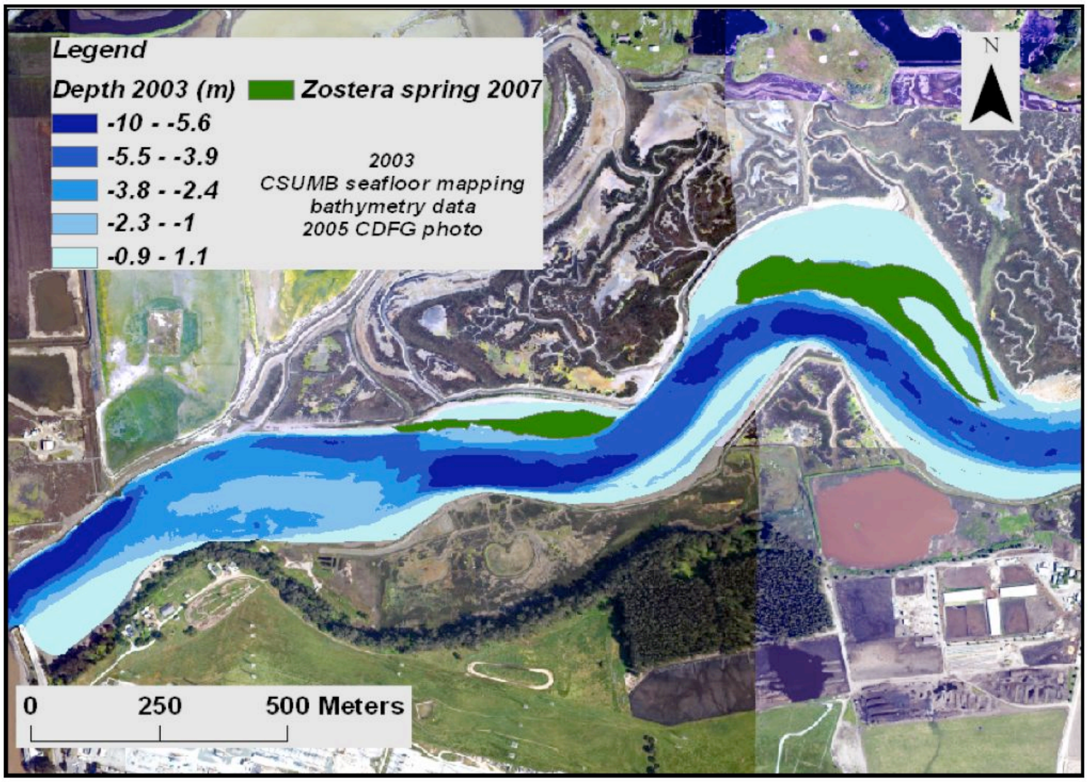

Figure 1.4. Aerial image (CDFG, 2005) with depth contours (CSUMB, 2003) and spring 2007 LOBO and Seal Bend *Zostera* beds outlined in green (polygons).

There was a bias in the data collection because turbidity, tide height, cloud cover and sun angle limited visibility of *Zostera* from the water's surface during each mapping event. Accuracy of the GPS unit was variable and dependent upon satellite reception, which ranged between two to four meters. Polygons drawn in the maps were the best estimate of *Zostera* bed size and shape based on these data collection methods.

Spring 2007 mapping was conducted May 4, 2007, using a canoe, and 93 GPS points were recorded over two hours during a 0.4-0.8 m rising tide. Fall 2007 mapping was conducted September 13, 2007 using a MLML Boston whaler research vessel, 189 GPS points were recorded during a 1.2-0.8 m ebb tide. Data for the Winter 2008 beds were recorded during two separate sampling events, both using the MLML Boston Whaler. On December 16, 2007, 36 GPS points were recorded during a 0.9-1.0 m rising tide and about a month later, January 16, 2008, during a slack low 0.2 m tide, 57 GPS points were recorded. Data from December and January were combined (93 points) to create the winter 2008 map and polygons. Data for spring 2008 were collected March 14, 2008, 306 GPS points were recorded from the R/V *Sloughboat* during a 0.3-(-0.1) m low tide. Summer 2008 beds were mapped July19, 2008, using a canoe, and 152 GPS points were recorded during a rising low tide from (-0.2)-0 m.

Fall 2008 beds were mapped from the R/V *Sloughboat* over two days, October 14-15, 2008. Two days were needed to collect these data because this was the most extensive mapping effort (578 GPS points) of the entire study. There were some *Zostera* patches that had gone un-mapped thus far because they were not within the main beds that were the focus of the study. For future reference these small patches were included in this final mapping event. Both days were mapped during an ebb tide and tide heights ranged between 0.5-(-0.1) m.

Data analysis

Tidal flow velocities the beds may have experienced were estimated for each sampling date using data from the MBARI LOBO mooring (LO1) near the study site. Flow velocity (cm/sec) was estimated using the change in surface elevation of the water over time multiplied by the ratio of the slough wetted surface area upstream of LO1 to the cross-sectional area at LO1 (Nidzieko, 2009). Velocity at L01 (U), can be related to the change in surface elevation as follows:

$$U = As/Ac \; dH/dt$$

As/Ac is the ratio of the slough wetted surface area upstream of L01 to the cross-sectional area at L01 and dH/dt is the change in surface elevation in units of m/s.

Correlations among average tide height (m) during mapping, time (days of study), flow velocity (cm/s) and total area (m^2) were performed to determine if any of these abiotic factors could be influencing estimates of *Zostera* area (m^2). Regressions were used to determine if estimates of *Zostera* area (m^2) were changing over the study period more than one would expect by random chance alone. Because tide height was correlated with estimates of *Zostera* area (m^2) the residuals were plotted to remove the effect of the tide to see how much variability in area was explained by time alone.

RESULTS

Estimates of area (m^2) per bed from the 2005 aerial image were 11,953 m^2 at the LOBO bed and 37,504 m^2 at the Seal Bend bed, totaling approximately 50,000 m^2 covered by *Zostera* (Table 1.1). Estimates of total *Zostera* cover ranged from 36,669 to 71,229 m^2 during the mapping study, but these numbers may have been confounded by tidal sampling bias. The lowest estimate of area was recorded during fall (September) 2007, which had the highest tide of any of the mapping events (Fig. 1.5). Spring (March), summer (July) and fall (October) 2008 were all mapped during a low tide of less than 0.5 m, and the resulting area estimates were not as variable as the earlier dates. From the estimates of bed size over time, total area covered by *Zostera* appeared stable and potentially increasing (Table 1.1). When analyzed on a per bed basis it appeared that the area of the LOBO bed decreased slightly over time while the area of the bed at Seal Bend increased (Table 1.1). Polygons used to estimate area per bed per season are shown in Figure 1.6 with depth contours from 2003.

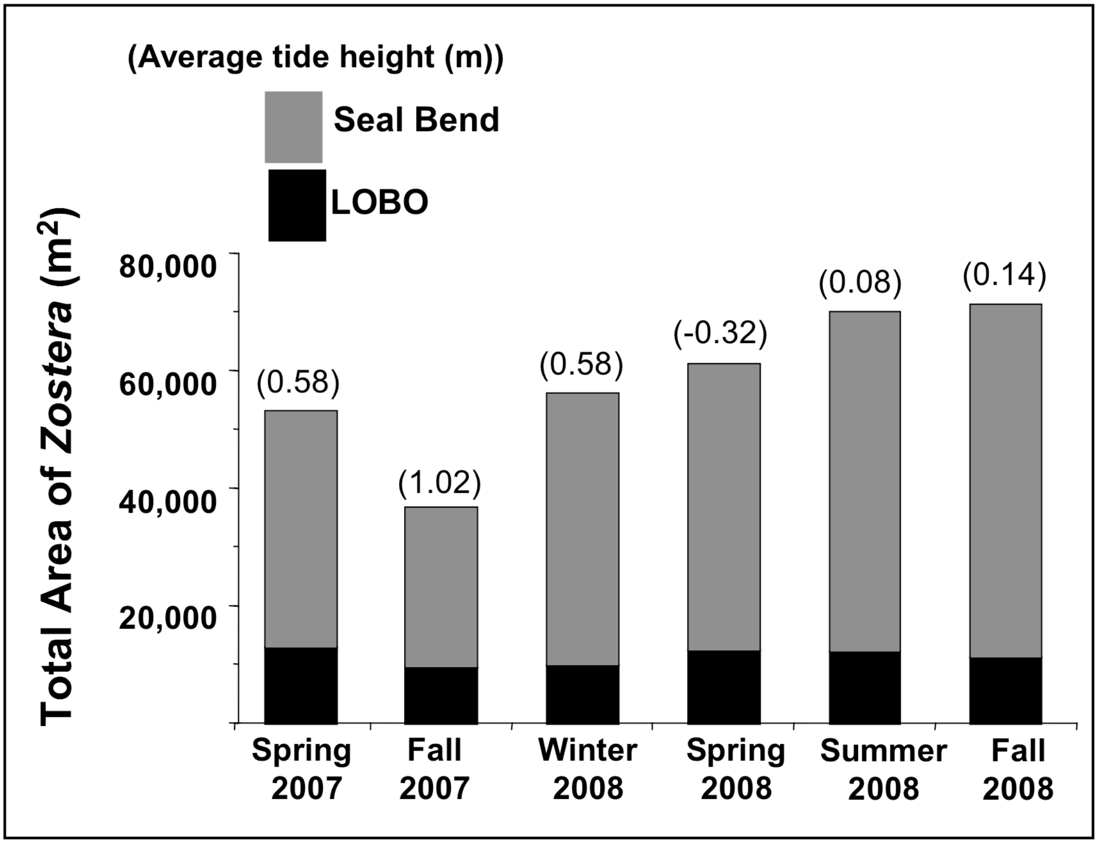

Figure 1.5. Estimated total combined area of *Zostera* (m^2) at Seal Bend and LOBO locations per season (Spring 2007- Fall 2008). Average tide height (m) during mapping event plotted on top of bars in parenthesis.

Table 1.1 Estimated area (m^2) of *Zostera* per season, spring 2005 area was estimated from an aerial image.

SEASON	AREA (m^2)		
	LOBO	Seal Bend	Total
Spring 2005*	11,953	37,504	49,457
Spring 2007	12,922	40,170	53,092
Fall 2007	9,521	27,148	36,669
Winter 2008	9,934	46,267	56,201
Spring 2008	13,405	50,572	63,977
Summer 2008	12,242	57,725	69,967
Fall 2008	11,273	59,956	71,229

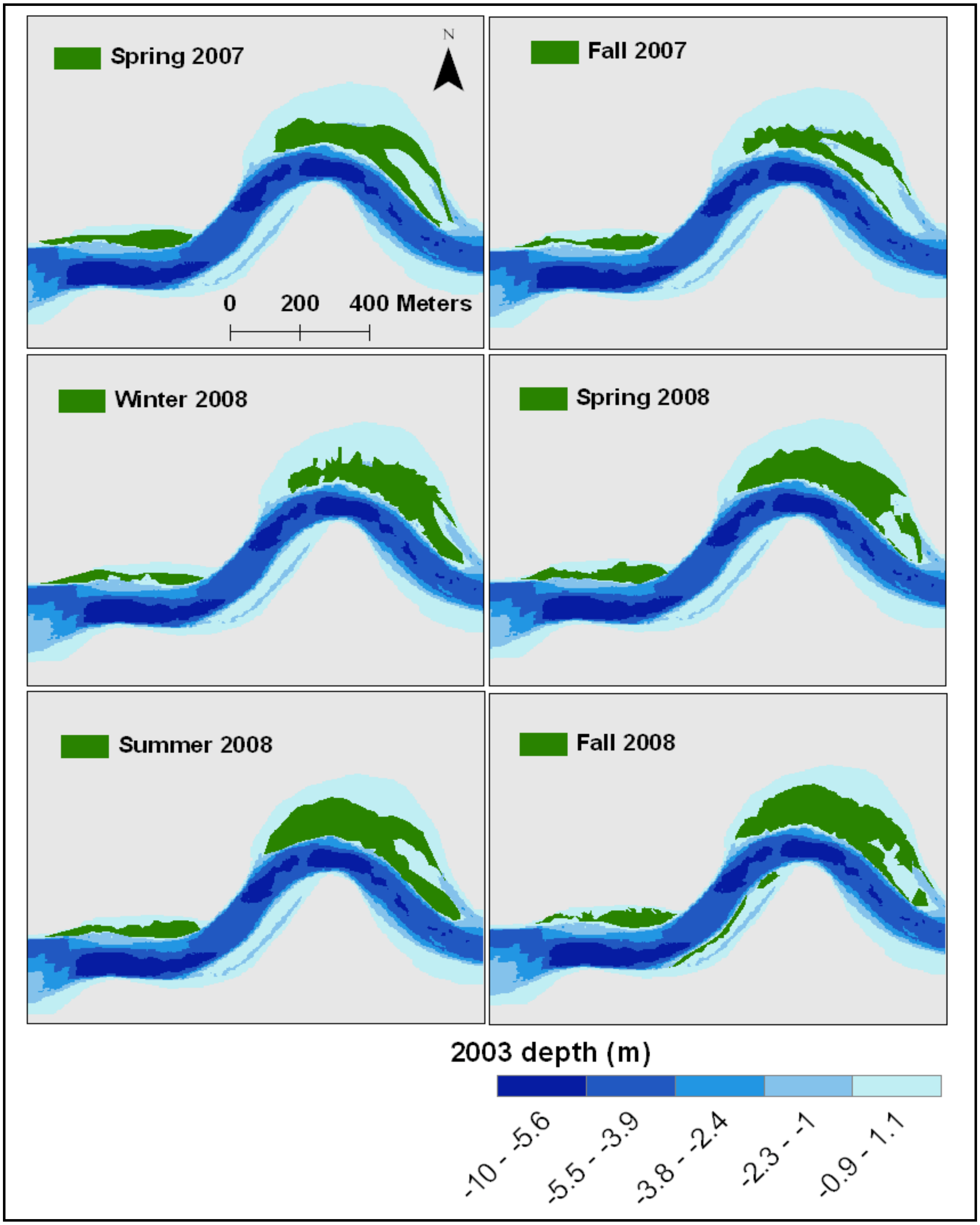

Figure 1.6. Maps indicating size and shape of LOBO and Seal Bend *Zostera* beds during the six mapping events overlaid onto CSUMB Seafloor Mapping Lab 2003 Elkhorn Slough depth contours.

Area of the LOBO bed during spring 2007 was estimated at 12,922 m^2 and Seal Bend was 40,170 m^2, totaling 53,092 m^2 (Table 1.1). This estimate of *Zostera* coverage was about 12,000 m^2 more than estimated visually from the 2005 aerial photo. Four months later, fall 2007, area of the LOBO bed was estimated to be 9,521m^2 and Seal Bend was 27,148 m^2, totaling 36,339 m^2 (Table 1.1). This was a marked decrease in area compared to the spring 2007 mapping, but was most likely due to the higher tide during the fall 2007 mapping.

From data collected during winter 2008 total area of *Zostera* was 56,201 m^2; 9,934 m^2 at LOBO and 46,267 m^2 at Seal Bend (Table 1.1). Estimates of coverage at the LOBO bed were similar to the previous season, but Seal Bend had increased by about 19,000m^2. This increase in area was most likely an artifact of tidal height and not due to temporal variability in the beds.

Spring 2008 total area of *Zostera* increased compared to winter 2008, and was estimated at 63,977 m^2. Area of both beds increased compared to the previous season as well, LOBO was 13,405 m^2 and Seal Bend was 50,572 m^2 (Table 1.1). Tidal height during this sampling event was the most similar to the 2005 aerial photo, and total area between spring 2005 and spring 2008 increased by approximately 14,500 m^2.

During summer 2008 total area of beds had increased by about 6,000 m^2, but area of LOBO had decreased from 13,405 m^2 to 12,242 m^2 and Seal Bend increased from 50,572 to 57,725 m^2 (Table 1.1). Tidal height during sampling events between spring and summer 2008 were similar, suggesting the change in area of these beds was real and influenced by seasonal growth patterns of the plants and not an artifact of sampling.

Estimates of total area of the main study beds during fall 2008 increased slightly from summer 2008, but only by about 1,200 m^2. Area of LOBO had decreased from to 12,242 m^2 to 11,273 m^2 and Seal Bend increased from 57,725 m^2 to 59,956 m^2 (Table 1.1). The smaller patches that were included in this mapping event were labeled as South Bank, Old Outfall and Eastern Corner (Fig. 1.7). Total area of these smaller patches was less than 9,000 m^2 (Table 1.2) and the shape of the patches varied from oval (Old Outfall) to thin strips (South Bank) (Fig. 1.7).

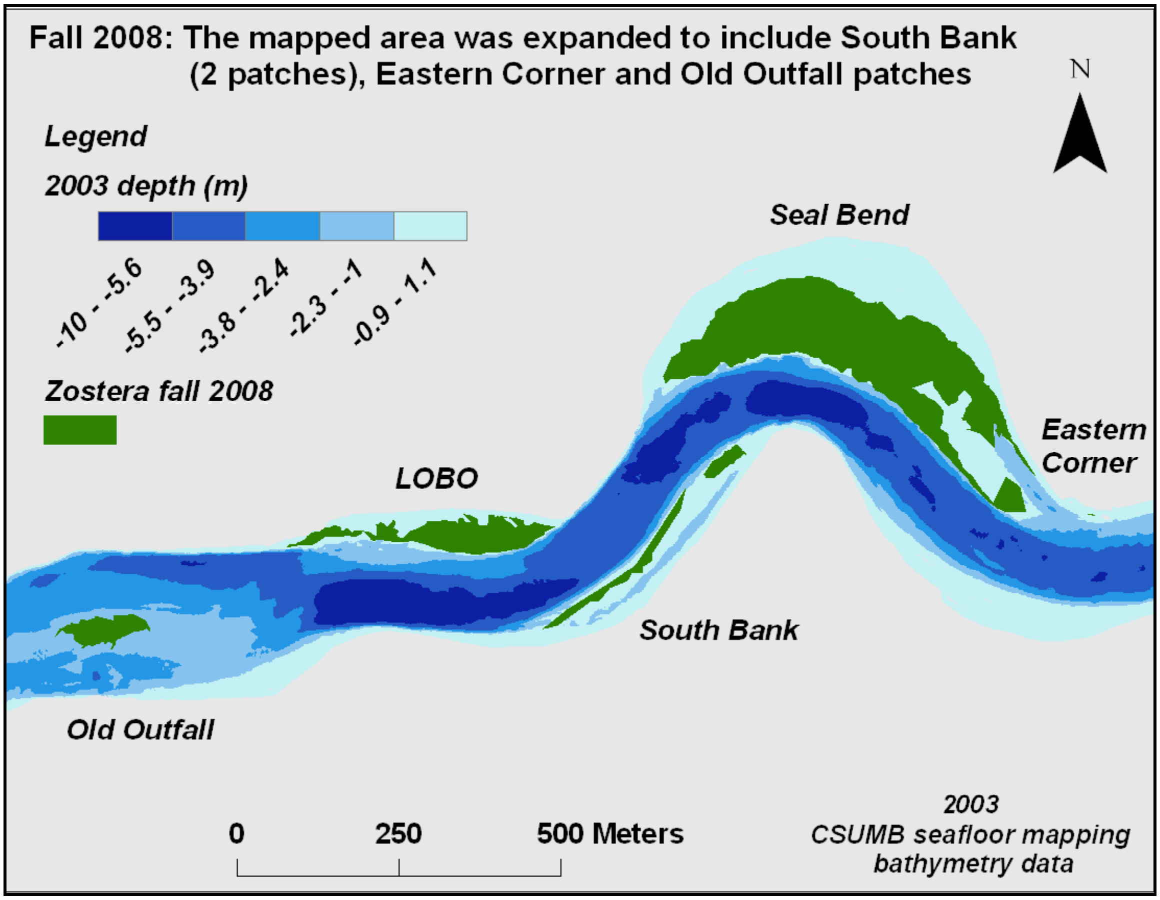

Figure 1.7. Map of fall 2008 extended mapping showing *Zostera* throughout the lower Elkhorn Slough region.

Table 1.2. Area (m^2) of each patch mapped during fall 2008.

PATCH	AREA (m^2) OF PATCH
Seal Bend	59,956
LOBO	11,273
South Bank (2)	4,621
Old Outfall	4,252
Eastern Corner	23
TOTAL	80,125

Average tide height (m) during sampling was significantly negatively correlated with total area of *Zostera* (m^2) (Fig. 1.8) and time had a significant positive correlation with total area of *Zostera* (Fig. 1.9). These patterns were consistent when the beds were analyzed separately therefore trends are discussed in terms of total area of *Zostera* mapped. The relationship of time on the residuals of total area with tide effect removed was not significant (R^2=0.24, p=0.31) (Fig. 1.10). This result indicated time was not able to explain the remaining variability in total area of *Zostera*, therefore time did not have an effect on area of *Zostera* different from random chance as measured in this study.

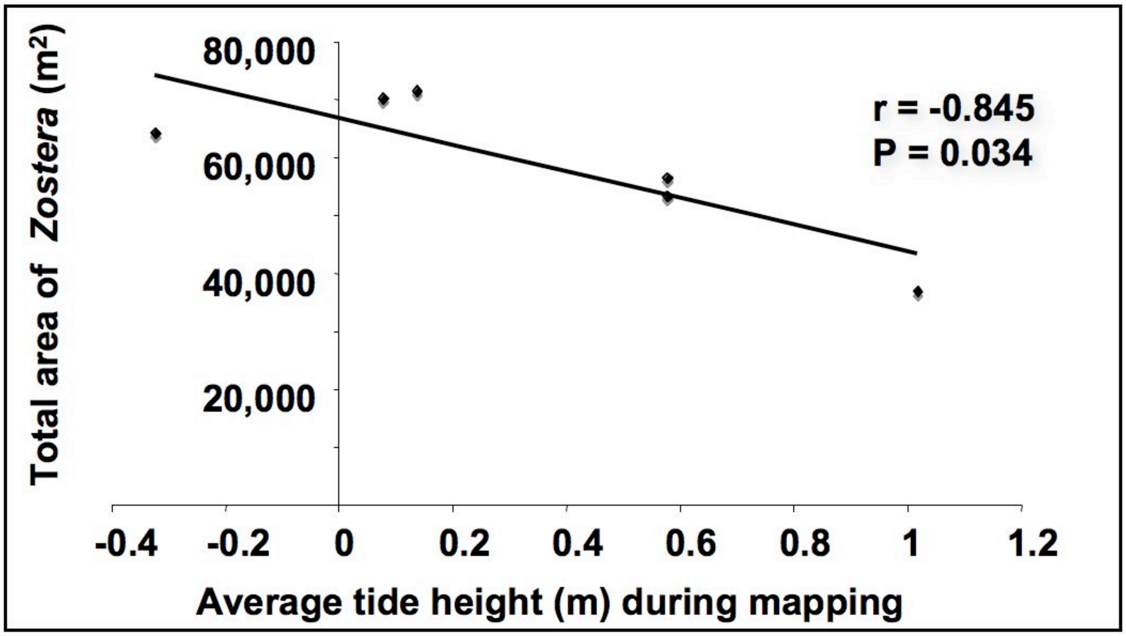

Figure 1.8. Plot of the result of correlation analysis of average tide height (m) during mapping events and total estimated area of *Zostera* (m^2).

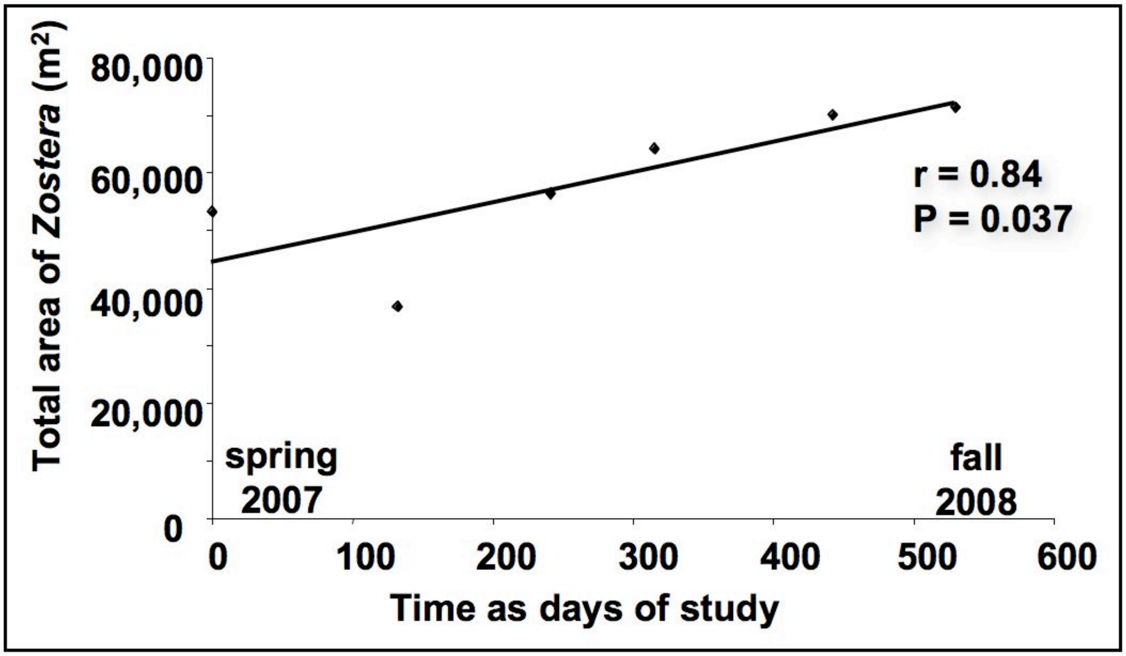

Figure 1.9. Plot of the result of correlation analysis of time (days of study) and total estimated area of *Zostera* (m^2).

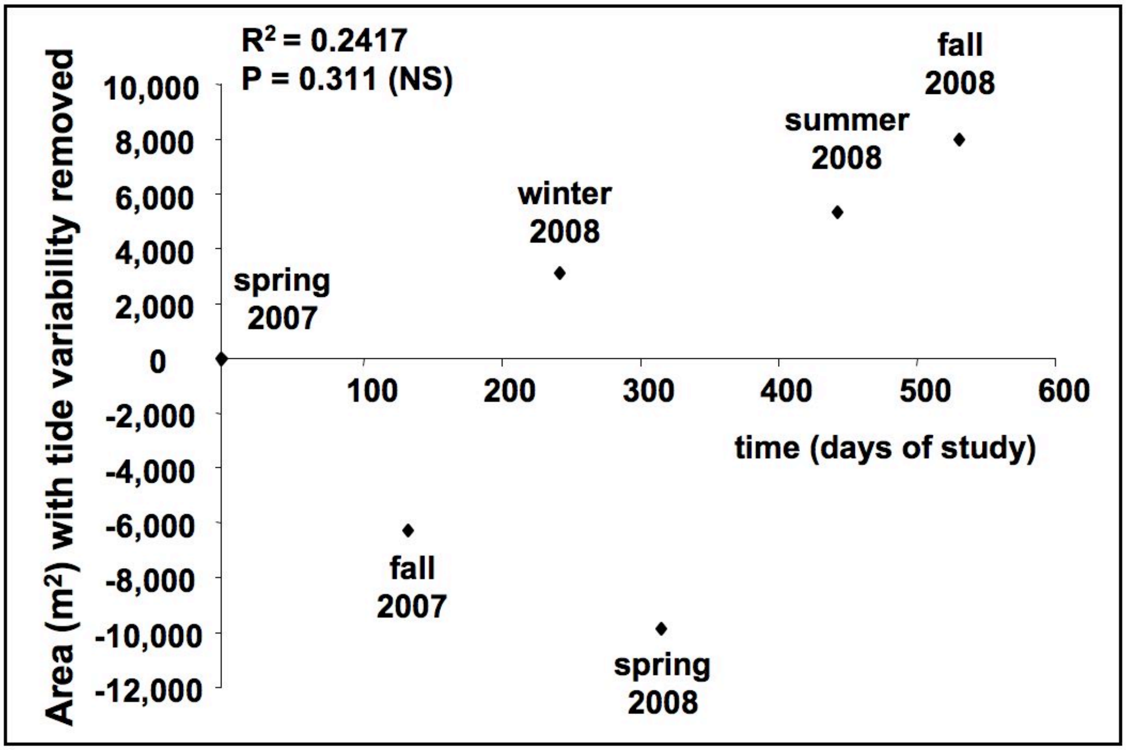

Figure 1.10. Result of regression analysis of time (days of study) on residuals of total area of *Zostera* (to remove variability in estimates of area due to tide height during mapping). There was not a significant effect of time on total area of *Zostera* (R^2=0.2417, P=0.311), the change in area of *Zostera* over the study period was not different from random chance alone.

DISCUSSION

The shape and area of the Seal Bend and LOBO beds varied over time, and *Zostera* was found mainly in shallower depths (less than 3 meters) along the north bank of Elkhorn Slough. Due to inconsistency in the tide level during data collection, changes in area of the beds were likely confounded by tidal height bias of the edge point data. During the course of the mapping study it became apparent that tide height could be biasing the map data. At the time of spring 2008 data collection a brief test to calibrate area estimates with tidal height was performed. The northern edge of the Seal Bend bed was mapped (west to east) during the ebb tide then that same edge was redone going the other direction (east to west), about 30 minutes after the tide receded. The map that resulted from the points collected indicated the edge of the bed had shifted north, making the bed larger, confirming a tidal height-bed area estimate co-variation.

This test demonstrated that as the tide receded, more *Zostera* was visible from the surface making the edge of the bed easier to distinguish, which resulted in a more accurate estimate of bed area. Tide is an important factor to consider when estimating change in surface area of *Zostera* over time because exposure of *Zostera* will change with tidal height. Additionally, the distribution of *Zostera* may be limited by tidal exposure, and tidal range (height) changes seasonally in Elkhorn Slough (Breaker et al., 2008).

Though there was some error in the data collection methods and artifacts from visually estimating area of *Zostera* from the surface of the water and aerial photos, it appeared that *Zostera* coverage was stable and the population is potentially expanding it’s range in the lower reaches of Elkhorn Slough. Data from March through October 2008 were collected during similar tidal heights and it appeared that the LOBO bed was decreasing in size and the Seal Bend bed was expanding.

Along the outer edge (towards the middle of the main channel) of the LOBO bed personal observations indicated that the main channel was continuing to erode towards the northern bank. Along that edge of the bed the *Zostera* root-rhizome mat was clinging to the edge of the channel and there is a steep drop off where the root-rhizomes do not exist. *Zostera* may be holding the remaining sediment down, but over time erosional forces of tidal currents in the main channel may be too strong and that edge of the bed will be undercut and fragment into smaller patches. But when there is erosion there also may be deposition, and thus the small bed towards the Hwy. 1 Bridge, near the old outfall, was persistent and potentially getting bigger.

CONCLUSION

Large-scale erosion events that changed the hydrographic regime of Elkhorn Slough appear to have shaped the current *Zostera* distribution in the lower slough, but the population seems to be resilient. These plants may have the ability to stabilize sediments in areas of erosion, but are still susceptible to tidal scour. Estimates of *Zostera* area were correlated with tide height during mapping and time, but the regression of area (with tide effect removed) and time was not significant. From the data collected, I was not able to detect a difference in total area of *Zostera* over the course of the study, and the plants do not appear to have a seasonal growth pattern.

Tidal height during mapping was important for obtaining consistent and accurate estimates of *Zostera* cover. There was either more *Zostera* exposed at lower tides, increasing the accuracy of the estimated area, or my mapping technique improved over time and estimates of area over time became more precise with each map event. Summer and fall 2008, the last two mapping events, had the highest estimates of area and were sampled at an average tide height of less than 0.25 m, but there was not enough replication to say if the change in area over time was different from random chance alone.

As tidal erosion continues in the lower reaches of Elkhorn Slough, the amount of habitat available to *Zostera* will change in response to the intense erosional pressures of tidal currents. Personal observations in the field suggest *Zostera* is subject to erosional pressures but also helps to functionally combat erosion due to the root-rhizome complex and flow dampening properties of upright shoots. Understanding current directions, flow velocities, substrate composition and erosional forces within Elkhorn Slough is imperative to predicting future habitat availability for *Zostera*, future expansion or fragmentation of beds, as well as restoration potential for *Zostera.*

Organisms using *Zostera* as habitat will be affected by changes to *Zostera* habitat caused by tidal erosion and the subsequent response of the *Zostera* plants to erosion (lack of submerged vegetation, increased flow velocities). I predict the LOBO bed will be slowly undercut and fragmented along the edge closest to the main channel, but the small bed at the old outfall will expand and persist over time. The larger bed at Seal Bend is being scoured along the edge closest to the main channel but the topography of the bend creates an eddy that may protect the bed from extensive erosion. Small patches along the southern side of the channel near Seal Bend also have potential for persistence and expansion along that bank.

PART 2. USE OF *ZOSTERA MARINA* HABITAT BY FISHES AND MOBILE EPIBENTHIC INVERTEBRATES IN ELKHORN SLOUGH, CALIFORNIA

INTRODUCTION

There are four types of fishes inhabiting central California estuaries, freshwater or brackish species, estuary residents, partial residents and marine migrants (Allen et al., 2006). The freshwater or brackish species have the ability to tolerate salinity changes, estuarine residents complete their entire life cycle within the estuary, partial residents occupy the estuary for a portion of the life history such as breeding or feeding, and finally the marine migrants spend most of their time in the near-shore environment but enter the estuary on an opportunistic basis (Allen et al., 2006). Elkhorn Slough is important to several species of fishes as spawning and nursery grounds, as well as the permanent home for resident species (Yoklavich et al., 1991; Barry et al., 1996).

The fish assemblage of Elkhorn Slough is traditionally broken into these same four groups: 1) freshwater associated fishes (three-spined stickleback, shad, mosquito fish, striped bass, prickly sculpin); 2) permanent residents (bay pipefish, Pacific staghorn sculpin, black surfperch, gobies); 3) partial residents (smelt, shiner and white surfperch, leopard shark, bat rays); and 4) marine migrants or slough opportunists that use Elkhorn Slough for spawning or nursery grounds (flatfishes, anchovy, herring, cabezon) (Yoklavich et al., 1991; 2002).

The fish assemblage of Elkhorn Slough exhibits seasonal changes that can be observed in all life stages of the fishes found there (Yoklavich et al., 2002). In the summer, there is a peak in abundance and diversity as juveniles and reproductively active adults enter the slough and locally spawned larvae grow into juveniles and become large enough to be caught in sampling nets (Yoklavich et al., 1991; Cailliet et al., 1977).

During fall, abundance and diversity decline when the partial resident and immigrant fishes leave the slough for winter. There are two seasonal assemblages of fish larvae, summer/fall and winter/spring, and two spatial assemblages, inland and near-ocean waters (Yoklavich et al., 1992). The mid-slough species composition represents a transition zone between upper and lower slough larval groups, suggesting the tidal prism and water circulation patterns of the slough may assist in retaining fish in a particular area where they were born, enhancing nursery function (Yoklavich et al., 1992; 2002).

Elkhorn Slough has been reported as a nursery for a number of fish species (Small, 1986; Brown, 2003; Carlisle and Starr, 2009). A study done following a marsh restoration during the early 1980's found that gravid shiner surfperch entered the marsh in May, gave birth, and left by June (Small, 1986). Pacific staghorn sculpin young entered the marsh habitat during winter, grew to adult size and left by fall (Small, 1986). A study done on a commercially valuable flatfish, the English sole, found using otolith microchemistry that the slough was contributing a higher proportion of recruits to the near-shore environment (Brown, 2003; 2006). A study using radio telemetry tracking of leopard sharks suggested the sharks use shallow areas of Elkhorn Slough as nursery habitat (Carlisle and Starr, 2009).

The role of *Zostera* as habitat within Elkhorn slough is unknown. In a study done in an estuary in New Jersey, *Zostera* was deemed superior habitat when compared to macroalgae *(Ulva)* and adjacent bare substrate (Sogard and Able, 1991). The vegetated habitats (*Zostera* and *Ulva*) supported higher densities of fishes and decapod crustaceans than the un-vegetated bare habitat, *Zostera* generally had higher densities of taxa than

Ulva and was not ephemeral like *Ulva* (Sogard and Able, 1991). Another study found survival of juvenile fish and invertebrates was significantly higher in seagrasses than unstructured habitats, but when compared to other structured habitats such as oyster reefs and kelp beds, it was suggested that the structure of the habitat, rather than type of structure might be providing the important (in this case nursery) function (Heck et al., 2003). Thus, there are many habitat functions that the *Zostera* may be providing within Elkhorn Slough: a seasonal refuge for migratory species or a permanent home to resident species, nursery habitat, food resources or a refuge from flow in a tidally driven system.

The concept of *Zostera* providing nursery habitat within Elkhorn Slough for some species, as well as Elkhorn Slough as a whole providing nursery habitat for other species, requires clarification. Habitat is generally where an animal lives and is bounded by a physical parameter (Minello et al., 2003) but can also be the place where a population of that species (or life stage) lives at any particular time (Odum, 1971), and can be involved with a shift in development or ontogeny of an organism. Habitats can be considered nurseries if there is a concentration of juvenile stages feeding and growing there; and nurseries are one of the main four habitat functions of estuaries (Allen et al., 2006). The concept of nursery habitat is hard to define but can be stated more specifically as a habitat that has a greater contribution to the production of recruits to adult populations than other habitats where juveniles occur (Beck et al., 2001). The production of recruits can be a result of enhanced density, growth and survival within that habitat and then subsequent movement into adult habitats (recruitment).

The goal of this part of the study was to address habitat utilization of *Zostera marina* in Elkhorn Slough and was structured into four sections as follows:

I. SPECIES HABITAT ASSOCIATIONS
II. TEMPORAL VARIATION OF SPECIES ASSEMBLAGES
III. EXCLUSIVE HABITAT USE
IV. NURSERY HABITAT FOR FISHES

A series of questions herein addressed potential habitat functions of *Zostera* within Elkhorn Slough. I investigated species-habitat associations by comparing the distribution and total abundance of a fishes and mobile invertebrates within *Zostera*, algae and bare habitats for an entire year (2008) and asked, what taxa occupy *Zostera,* bare and algae habitats? Additionally, I examined temporal variability in species assemblages among habitats, and specifically asked whether abundance of common species within each habitat changed over time? I examined the possibility of exclusive habitat use of *Zostera* by the most abundant species sampled across all habitats, asking whether the fishes and invertebrates exclusively use *Zostera* as habitat or if macroalgae can provide the same habitat function as *Zostera*.

Finally, I explored the potential nursery function of *Zostera* within Elkhorn Slough by looking at three questions: First, what is the distribution and abundance of juvenile and adult fishes across habitats? Second, does the distribution and abundance of juvenile and adult fishes vary over time? Third, case studies of four species that each displayed patterns of individual size distributions across space and time are presented in support of *Zostera* providing a nursery habitat; specifically, how does standard length change over time per species?

METHODS

Habitat use sampling

Sampling shallow vegetated estuary habitats can be challenging, and many types of sampling gear have variability in catch efficiency (Rozas and Minello, 1997). Throw traps provide relatively accurate estimates of fish density, size and community structure across a range of environmental conditions (Jordan et al., 1997) and are particularly useful in studies comparing different shallow estuarine habitats (Rozas and Minello, 1997). The visibility in Elkhorn slough is not conducive to visual fish counts on SCUBA, and the species inhabiting *Zostera* are small and cryptic. Sampling done with trawl nets or seines would clog the net and tear the *Zostera* out of the soft sediments, destroying the habitat. Therefore, a 1-m^3 throw-trap designed and tested in pilot studies was used to collect fish and invertebrate species in order to answer the questions outlined above.

The 1-m^3 throw-trap consisted of a frame and net. The frame was built out of ½" diameter PVC pipe with small holes drilled through the frame to facilitate sinking and weighted by pieces of steel bars within the frame. A 1-m^3 net sewn out of 4 mm mesh fish net fabric was tied to all corners of the frame. The net was closed on the top, open at the bottom with chain attached along perimeter of the net and there were two drawstrings at the base of opposite corners The trap was dropped over the side of the boat, sank down, and captured whatever it enveloped as it sank. Divers untied the net from the frame and pulled the drawstrings shut at opposite corners at the level of the substrate. The chain acted like a rake along the benthos to reduce chances of escape out the sides of the net. The PVC frame had depth markers on all sides and depth of the top of the net per trap was recorded for calculation of density estimates (# of individuals/m^3) of each species or taxa.

Elkhorn Slough can be characterized as having three distinct seasons; spring/summer, fall and winter (Caffrey, 2002). During the spring/summer season (April through August), strong winds lead to upwelling and coastal fog. During fall (September through November) offshore winds diminish and conditions are calm, dry and warm. The winter season (December through March) is rainy and cold, with December and January receiving the most rainfall, lowest temperatures and shortest day length of the year (Caffrey, 2002).

Sampling effort, therefore, was distributed throughout the year to capture these seasons in two-month blocks, and sampling bouts were separated by two months. Distribution of sampling effort into two months blocks ensured that data within a 'season' was equal or closer in time than data between seasons. The three habitats sampled over the course of the year were *Zostera*, algae and bare substrate, though algal habitat was not present during the winter sampling block. This sampling scheme was also able to capture the natural variability in the system by sampling all oceanographic phases of the Elkhorn Slough during the year.

At least 50 traps were collected each sampling season, half in *Zostera* and the other half in non-*Zostera* habitats. Algae and bare habitats were combined and considered non-*Zostera* habitat because algal habitat was not present during winter, and during the spring/summer and fall sampling it was unknown from the surface if a non-*Zostera* trap contained algae. A total of 177 traps were sampled for the entire year across all habitats. Winter sampling was completed during February and March, with 39 traps in *Zostera* and 38 traps on bare substrate. Summer sampling took place during July and the numbers of traps sampled were 25, 15 and 10 for *Zostera*, algae and bare habitats, respectively. Fall sampling was completed during October, and the numbers of traps sampled were 25, 13 and 12 for *Zostera*, algae and bare habitats respectively.

Throw-trap sample sites were chosen from an area of Elkhorn Slough with two existing *Zostera* beds, each comprised of a mosaic of patches of various sizes (Part 1). A random stratified sampling design was used avoiding edges of the habitat interface. Using the maps created in Part 1, a large polygon was traced around the most shallow depth contour of the area of each bed. Random GPS points were generated within each polygon, and 75% of the points were chosen from Seal Bend and 25% from the LOBO bed to ensure sampling was proportional to area of *Zostera*. Upon navigation to each random GPS point the exact trap location was chosen on site in order to ensure there was one meter of continuous habitat on all sides of the trap to avoid confounding factors of edge effects (Tanner, 2005). All trap locations for 2008 are shown below with the outline of the fall 2008 *Zostera* beds (Fig. 2.1). Trap locations per habitat during each sampling season are shown in Figures 2.2, 2.3 and 2.4 with the corresponding *Zostera* bed outline for each season.

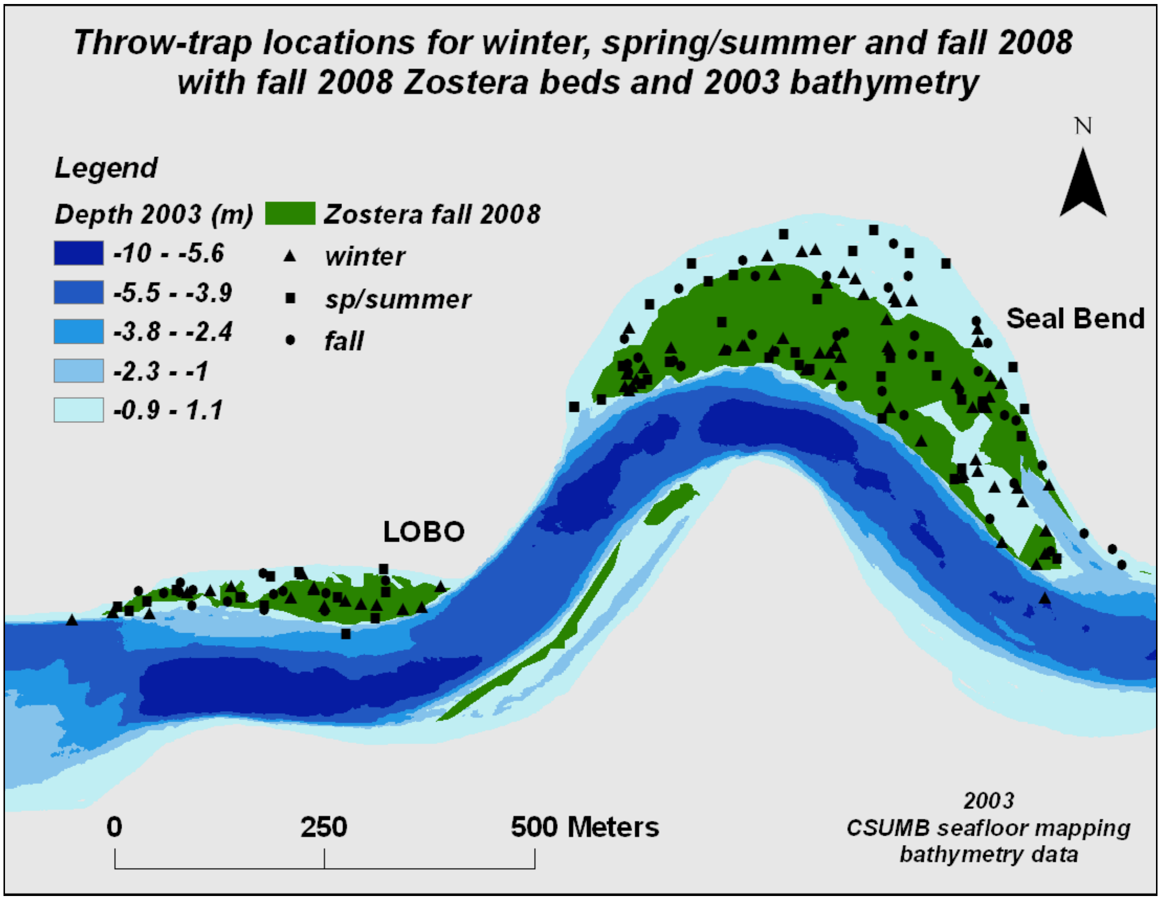

Figure 2.1. Throw-trap locations for winter, spring/summer and fall 2008 habitat sampling overlaid on the fall 2008 Seal Bend and LOBO *Zostera* beds (green), with 2003 depth contours (blue) (CSUMB).

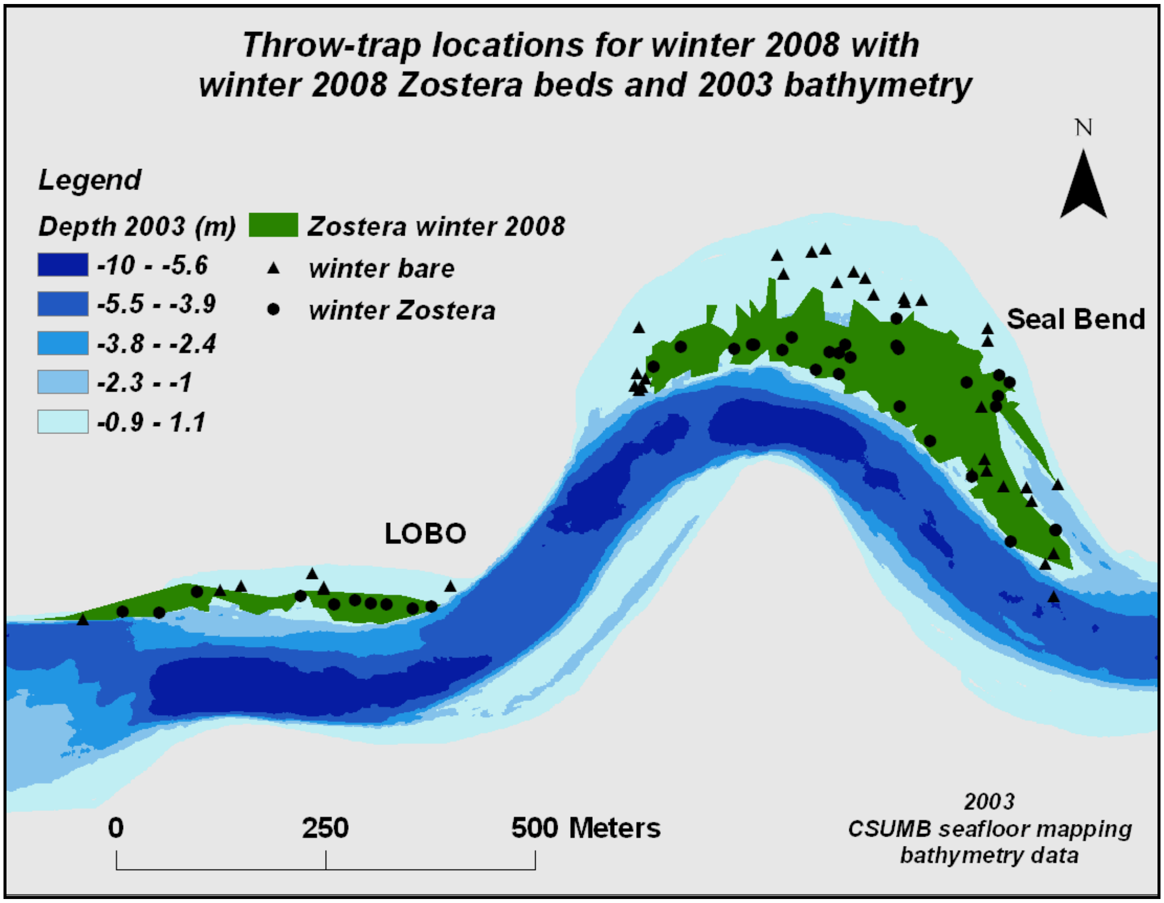

Figure 2.2. Throw-trap locations during winter 2008 for *Zostera* and bare habitats overlaid onto the *Zostera* bed outline during winter 2008 with 2003 depth contours (CSUMB).

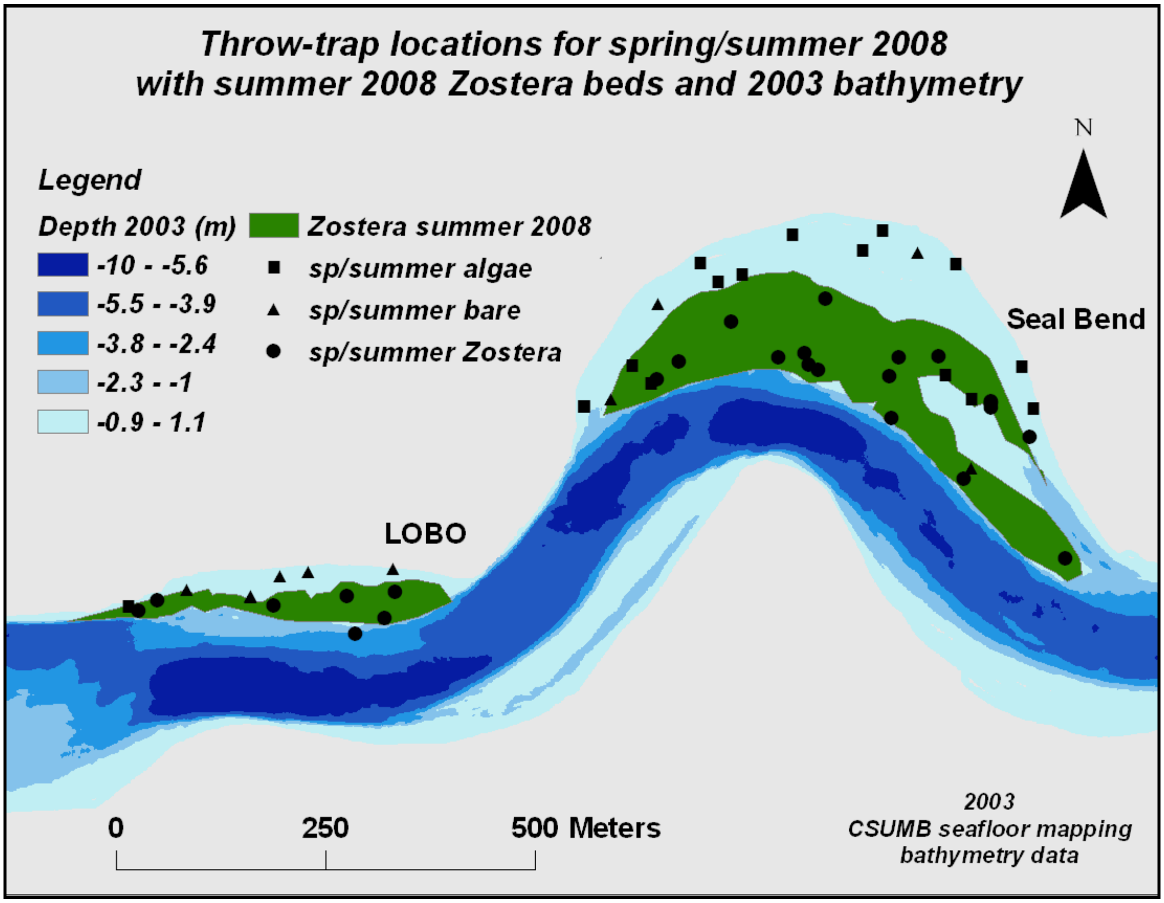

Figure 2.3. Throw-trap locations during spring/summer for *Zostera,* algae and bare habitats overlaid onto the *Zostera* bed outline during summer 2008 with 2003 depth contours (CSUMB).

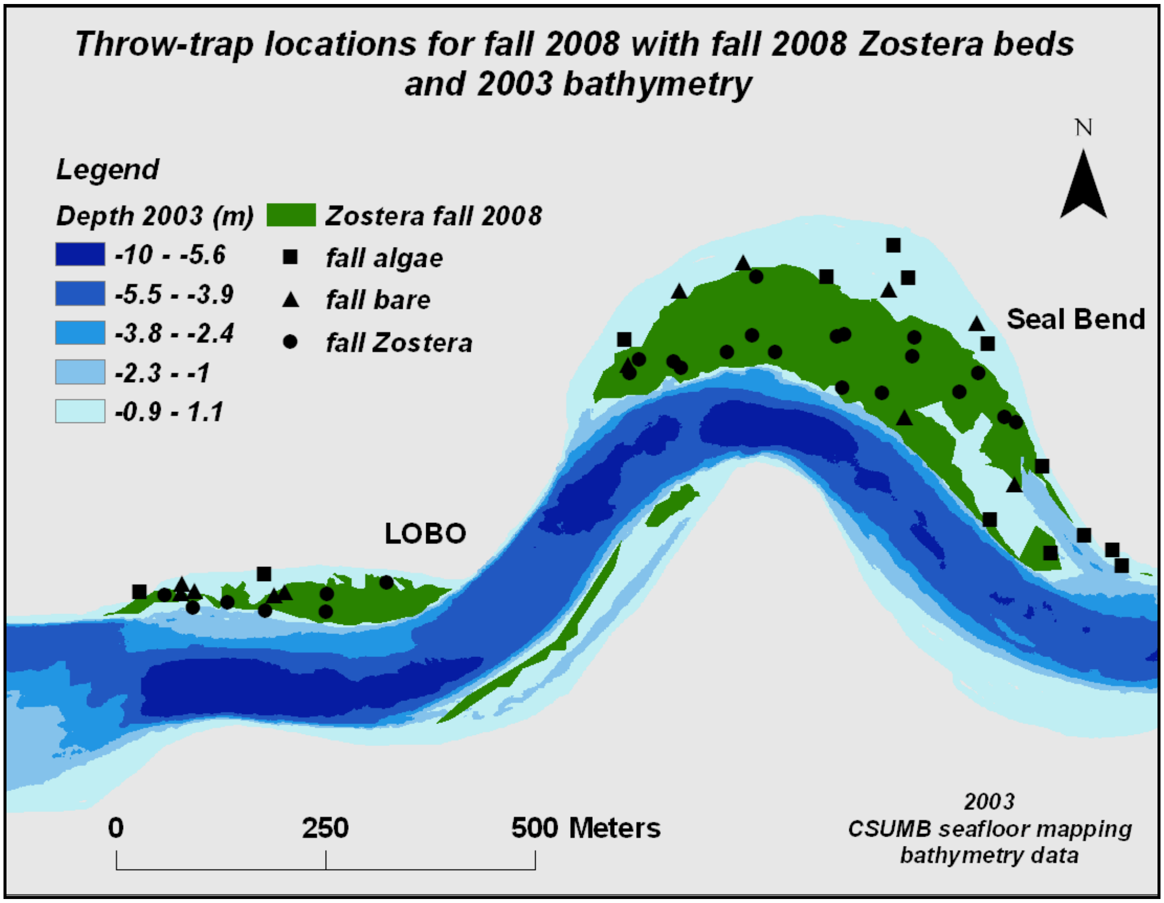

Figure 2.4. Throw-trap locations during fall 2008 for *Zostera,* algae and bare habitats overlaid onto the *Zostera* bed outline during fall 2008 and 2003 depth contours (CSUMB).

Daily tidal variation in Elkhorn Slough can range up to 1.7 meters (Broenkow and Breaker, 2005) therefore sampling effort was constrained to tidal heights in which the throw-trap could be used in 0.5-2.0 meter deep waters. Due to the number of samples required for each habitat and logistical restraints of sampling in Elkhorn Slough, tidal phase (ebb or flood) and time of day could not be controlled experimentally. Throw-trap sampling effort per day was stratified across the entire study site based on the random GPS points chosen in ArcMAP to minimize sampling artifacts and confounding factors.

Specimens from each throw-trap sample were identified to species or functional group and counted. All fishes were measured to standard length (mm), and after counting and measuring all animals were released back into their habitat unharmed. If field identification was not possible, animals were euthanized or transported live back to MLML's aquarium facility for identification. These animals were used as voucher specimen collections, donated to other student projects or added to the museum teaching collection. This work was permitted by SJSU IACUC protocol #0891.

Zostera, algae (when present) and bare habitats were sampled on the same day to test exclusive use of *Zostera* habitat by fishes and invertebrates, with the sampling design as stated above. All types of algae caught in the throw-trap net when sampling non-*Zostera* habitat were collected, identified and quantified (wet weight (g)) to determine if there was a dominant algal habitat-type. Each algae sample was spun dry in a 'salad spinner' and weighed to the nearest gram to obtain the wet weight of algae per trap. Algal samples were identified to the level of genus, and compared within and across seasons using mean wet weight (g) per genus.

To address the potential nursery function of *Zostera* the standard length (mm) of each fish caught was recorded and compared to literature values of size at maturity (Appendix II.). Literature values of size at maturity were used to classify individuals into age classes for comparisons of adult and juvenile distributions in space and time. Distribution and abundance of juvenile and adult fishes were used to answer specific questions regarding habitat use patterns.

Data analysis

I. SPECIES-HABITAT ASSOCIATIONS

Total abundance of fishes and invertebrates per habitat per season were plotted and compared to determine which taxa comprised the species assemblages within each habitat and if species distributions changed over time. Invertebrate species that occurred in low abundances were combined to make functional species groups for further analysis of species assemblage dynamics. The 'crab' group consisted of kelp crab (*Pugettia producta),* cancer crabs *(Cancer sp*.) and shore crabs (*Pachygrapsus crassipes)* and 'nudibranchs' consisted of *Melabe leonine*, *Hermissenda crassicornis* and *Dendrontus* species.

II. TEMPORAL VARIATION OF SPECIES ASSEMBLAGES

Total abundances (number of individuals present) of each species or group within each habitat were compared across sampling seasons (winter, spring/summer and fall). Spatial and temporal variability of species distributions were examined using mean density (#/m^3) estimates calculated by extrapolating to trap depth (m). Mean densities (#/m^3 +/- MSE) of common species were plotted for the each season to visualize species distributions and variation in the data. Due to the variability in habitat presence (no algae in winter) over the year, patchy species distributions within and among habitats as well as high variability of mean density values, ANOVA tests were not appropriate for this analysis.

Species assemblages among habitats and sampling seasons were compared using diversity and similarity metrics. Assemblage diversity was examined using three different components; species richness (S), heterogeneity (H') and evenness (J'). Species richness (S) is simply the total number of species observed per habitat. Heterogeneity (H') was measured using the Shannon-Weiner function (Krebs, 1989). A larger H' value means there is more uncertainty in your prediction of the next species and H' generally increases with the number of species in an assemblage. Evenness (J') takes H' divided by the natural log of the number of species to quantify how evenly the species are spread across the habitat. When all species have equal abundances evenness is maximal.

Assemblage overlap was compared among habitat pairs using the simplified Morisita's index of overlap (Krebs, 1989) for all 24 species of fishes and invertebrates sampled in this study. Habitat pairs were compared across the entire year and sampling seasons. For comparisons of algae habitat to either *Zostera* or bare habitats only the spring/summer and fall seasons of data were used because algae habitat was not sampled during winter. Comparisons of assemblage overlap between *Zostera* and bare habitats were done using all three seasons of data.

III. EXCLUSIVE HABITAT USE

Species which occurred in more than one habitat and more than one sampling season were analyzed using contingency tables and chi-square (χ^2) statistical tests to determine if habitat utilization differed; i.e. species were not independently distributed in space and time. Frequency of occurrence of taxa per habitat and time were compared and those taxa found in more than one habitat at a total frequency greater than ten were analyzed. Contingency tables were arranged with habitats as columns (*Zostera*, algae and bare) and time as rows (winter, spring/summer and fall) for each species.

To ensure the sample size was appropriate for these statistical tests (3x3 contingency tables, four degrees of freedom) a power analysis using G*power 3 was performed. The test determined that 90% statistical power would be attained to detect a medium effect size (f=0.3) at an alpha level of 0.1 with a total sample size of 177 (Faul et al., 2007). This was an ecological study and there were other factors that could have influenced habitat use by species therefore an alpha level of 0.1 was chosen to increase the likelihood of detecting a difference between habitats as well as allow more variability in this system. Alpha and Beta were held constant (0.1 each), so the chance of type I or type II error was equal.

Average expected cell frequencies (total observations/# cells in table) were calculated for each species as an a-priori test of power to detect a difference for tables with small frequencies (Zar, 1999). Requiring an average expected frequency to be at least six was less restrictive than requiring that each cell frequency be at least five, which was helpful for comparing the species which occurred across habitats in high and low frequencies (Zar, 1999).

For each table, expected frequencies per cell were calculated by multiplying the row total by column total, then dividing by the grand total. For the winter season the row total was divided between *Zostera* and bare habitats because algae was not available as habitat during that time. The null hypothesis for each species was that there was no difference in the frequency of occurrence across habitats and times. Each species χ^2 statistic was compared to the critical value at alpha level 0.1 for the appropriate degrees of freedom for that table (Zar, 1999. Appendix 12, Table B.1.).

The critical value for one species of fish, arrow goby *(Clevelandia ios),* had to be calculated rather than taken from a table to compensate for the conservative bias of χ^2 following the formula given in Lawal and Upton (1984). For this species only an alpha level of 0.05 was used instead of 0.1 because the critical value had to be calculated (Lawal and Upton, 1984).

$$\text{critical value}_{(\alpha=0.05)} = 1 - \frac{1}{n}(1 - d^{-1/2})$$

$$d = (\# \, rows - 1) * (\# \, columns - 1)$$

$$n = \text{total observations}$$

IV. NURSERY HABITAT FOR FISHES

To assess the potential for *Zostera* to be a nursery habitat for fishes within Elkhorn Slough the proportion of juveniles and adults of each species were compared across habitats and time. Fishes were classified into juvenile and adult size classes based on literature values of size at maturity (Appendix II.). If *Zostera* were providing a nursery habitat within the slough there would be more juveniles found within *Zostera* compared to the other habitats.

Case studies among four different fish species examined standard length (mm) over time within habitats. Changes in abundance, size and habitat use were compared for Pacific staghorn sculpin and bay pipefish *(Leptocottus armatus* and *Syngnathus leptorhynchus,* respectively; both are slough residents), three-spined sticklebacks (*Gasterosteus aculeatus;* a brackish species) and shiner surfperch *(Cymatogaster aggregata*; a partial resident). Each case suggested a unique pattern of *Zostera* providing nursery habitat within Elkhorn Slough.

RESULTS

I. SPECIES-HABITAT ASSOCIATIONS

Three genera of algae (*Ulva sp., Gracilariopsis sp.* and *Cladophora sp.*) comprised the algal habitat assemblage during summer and fall. *Ulva sp.* was a green alga comprised of a thin sheet-like blade, *Gracilariopsis sp.* was a red fleshy alga with a cylindrical spaghetti-like shape and *Cladophora sp.* was a filamentous green alga. *Ulva sp.* was the dominant alga present, the most algae traps contained *Ulva sp.* and mean wet weight (g) was constant summer to fall (Fig. 2.5). Wet weight of algae per trap during summer and fall sampling was plotted on the sampling map in Figure 2.6.

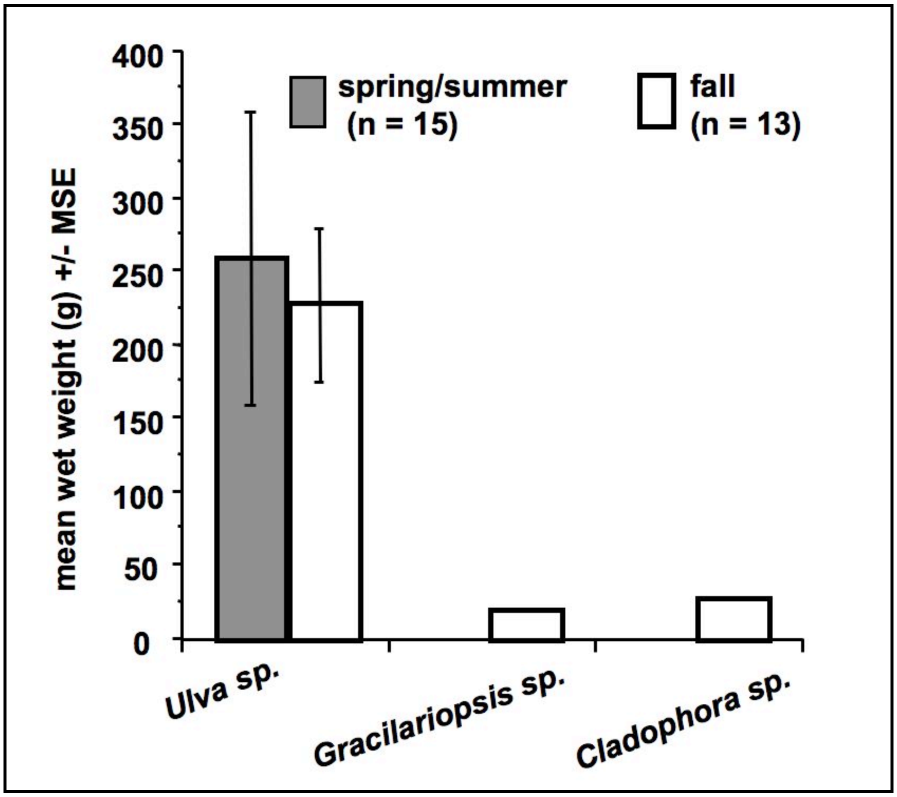

Figure 2.5. Mean wet weight (g) (+/- MSE) of algal genera sampled during spring/summer and fall 2008. *Ulva sp.* was the dominant habitat-forming alga during both times.

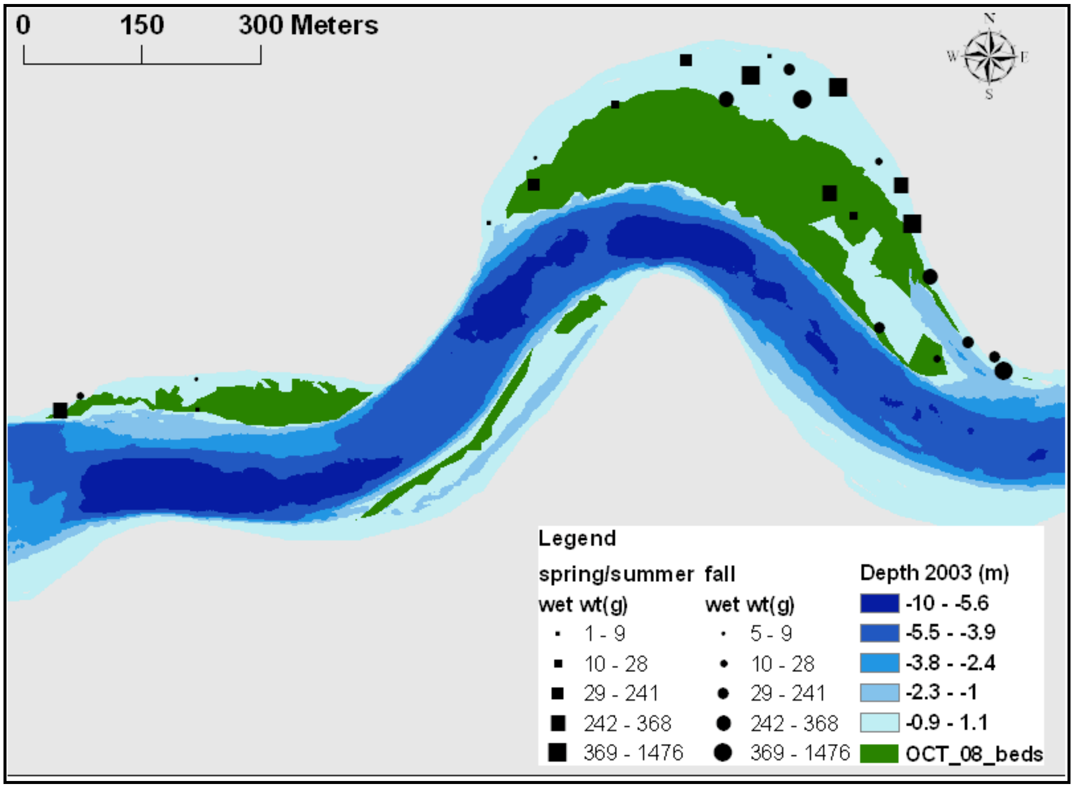

Figure 2.6. Wet weight of algae (g) per trap sampled during spring/summer and fall 2008 overlaid onto fall 2008 *Zostera* beds and 2003 depth contours (CSUMB).

There were more fishes present within *Zostera*, and abundances were greater within *Zostera*. Within non-*Zostera* habitats, when algae habitat was present, abundances were greater in algae than bare habitat. Some fishes were found within only one habitat while others were distributed across more than one habitat (Table 2.1). The most common fish species sampled during this study were arrow goby *(Clevelandia ios),* bay pipefish *(Syngnathus leptorhynchus),* shiner surfperch (*Cymatogaster aggregata)*, three-spined stickleback (*Gasterosteus aculeatus)* and Pacific staghorn sculpin *(Leptocottus armatus)*.

Pacific staghorn sculpins and arrow gobies were distributed among all habitats. Arrow gobies were the only fish that were more abundant in non-*Zostera* habitats and abundance was higher in algae than bare habitat (Table 2.1). Three-spined sticklebacks and bay pipefish were among the most abundant species within *Zostera*, and were exclusive to *Zostera* habitat (Table 2.1). Shiner surfperch were more abundant within *Zostera*, although some were found in algae habitat, none were found in bare habitat (Table 2.1).

Table 2.1. Total abundance of (A) adult and (J) juvenile fishes sampled within *Zostera*, algae and bare habitats during each sampling season (winter, spring/summer and fall) and during the entire study (Total).

FISHES		**WINTER**		**SPRING/ SUMMER**			**FALL**			**TOTAL**		
(A) = adult **(J) = juvenile**												
Common name	**Latin name**	***ZOSTERA***	**BARE**	***ZOSTERA***	**ALGAE**	**BARE**	***ZOSTERA***	**ALGAE**	**BARE**	***ZOSTERA***	**ALGAE**	**BARE**
(A) Arrow goby	*Clevelandia ios*	2	1	2	27	4	4	48	2	8	75	7
(J) Pacific staghorn sculpin	*Leptocottus armatus*	102	29	24	8	1	3	0	0	129	8	30
(A) Bay pipefish	*Syngnathus leptorhynchus*	4	0	2	0	0	12	0	0	18	0	0
(J) Bay pipefish	*Syngnathus leptorhynchus*	5	0	0	0	0	2	0	0	7	0	0
(A) Shiner surfperch	*Cymatogaster aggregata*	0	0	3	0	0	0	0	0	3	0	0
(J) Shiner surfperch	*Cymatogaster aggregata*	0	0	57	0	0	1	4	0	58	4	0
(J) Black surfperch	*Embiotoca jacksoni*	0	0	2	0	0	1	0	0	3	0	0
(J) Dwarf surfperch	*Micrometrus minimus*	0	0	1	0	0	0	0	0	1	0	0
(A) Three-spined stickleback	*Gasterosteus aculeatus*	0	0	2	0	0	6	0	0	8	0	0
(J) Three-spined stickleback	*Gasterosteus aculeatus*	0	0	39	0	0	86	0	0	125	0	0
(A) Kelpfish	*Gibbonsia sp.*	0	0	0	0	0	1	0	0	1	0	0
(J) Kelpfish	*Gibbonsia sp.*	0	0	1	0	0	0	0	0	1	0	0
(J) Plainfin midshipman	*Porichthys notatus*	0	0	0	0	0	1	0	0	1	0	0
(J) KGB rockfish	*Sebastes sp.*	0	0	1	0	0	0	0	0	1	0	0
(J) Butter sole	*Isopsetta isolepis*	0	5	0	0	0	0	0	0	0	0	5
(J) English sole	*Parophrys vetulus*	0	0	2	0	1	0	0	0	2	0	1
(J) Speckled sanddab	*Citharichthys stigmaeus*	2	1	0	0	0	0	0	0	2	0	1
(J) Starry flounder	*Platichthys stellatus*	0	1	0	0	0	0	0	0	0	0	1
(J) Topsmelt	*Atherinops affinis*	0	0	0	0	0	0	0	1	0	0	1

Invertebrate abundances were greater within *Zostera* than within non-*Zostera* habitats (Table 2.2). When algae habitat was present invertebrate abundances were higher within algae than in bare habitat. The most common groups of invertebrates were the shrimp-like crustaceans*; Crangon sp. (C. nigricauda* and *C. nigromaculata)* and grass shrimp (*Hippolyte californiensis),* isopods; *Idotea sp. (I. resecata and I. wosnesenskii),* and an opisthobranch*;* Taylor's sea hare *(Phyllaplysia taylori)*. Total abundances of mobile epibenthic invertebrate species for the year were much higher than total abundances of fishes and there were no invertebrates that were exclusive to *Zostera* habitat (Table 2.2). Invertebrates that were present but found in low abundance among habitats were brachyuran crabs (*Puggetia producta, Cancer sp.* and *Pachygrapsis crassipes)*, hermit crabs *(Pagarus sp.)*, snails *(Lacuna porrecta* and *Lacuna unifasciata),* and nudibranchs *(Melabe leonine, Hermissenda crassicornis,* and *Dendronotus sp.)* (Table 2.2).

Almost one quarter (23%) of all traps sampled for the year were empty, but the percentages of empty traps per habitat differed among the three habitats sampled. Over the entire sampling period, 7% of *Zostera* traps were empty (6/89), 53% of bare traps were empty (32/60), and 11% of algae traps were empty (3/28). The highest number of empty traps occurred within bare habitat during winter (Table 2.2), making it the most depauperate habitat.

Table 2.2. Total abundance of mobile epibenthic invertebrates sampled within each habitat during each sampling season and for the entire study. Number of traps sampled per habitat per time and total number of empty traps per habitat per time noted below species abundances.

INVERTEBRATES		**WINTER**		**SPRING/ SUMMER**			**FALL**			**TOTAL 2008**		
Common name (family or subfamily)	**Latin name**	***ZOSTERA***	**BARE**	***ZOSTERA***	**ALGAE**	**BARE**	***ZOSTERA***	**ALGAE**	**BARE**	***ZOSTERA***	**ALGAE**	**BARE**
Grass shrimp (Hippolytidae)	*Hippolyte californiensis*	167	9	228	44	1	642	224	14	1037	268	24
Crangon sp. (Crangonidae)	*C. nigricauda, C. nigromaculata*	16	2	0	0	0	1	4	5	17	4	7
Idotea sp. (Isopoda)	*I. resecata, I. wonesenskii*	36	5	405	13	1	195	7	16	636	20	22
Amphipoda	*Amphipod sp.*	5	0	1	5	0	3	71		9	76	0
Brachyuran crabs	*Pugettia producta, Cancer sp., Pachygrapsis sp.*	0	0	1	6		5	13	0	6	19	0
Hermit crabs	*Pagarus sp.*	0	0	0	0	0	4	2	0	4	2	0
Taylor's sea hare	*Phyllaplysia taylori*	33	0	448	8	0	240	38	0	721	46	0
Nudibranchs	*Hermissenda crassicornis, Melabe leonine, Dendronotus sp.*		1	0	0	0	3	0	0	3	0	1
Snails (Lacunidae)	*Lacuna sp.*	1		7	3		1	2	0	9	5	0
No. traps sampled		**39**	**38**	**25**	**15**	**10**	**25**	**13**	**12**	**89**	**28**	**60**
No. empty traps		**5**	**21**	**0**	**2**	**5**	**1**	**1**	**6**	**6**	**3**	**32**

II. TEMPORAL VARIATION OF ASSEMBLAGES

Species distributions and abundances within and among habitats changed over time. Bay pipefish were exclusive to *Zostera,* present during all times and were most abundant during fall (Fig. 2.7). Three-spined sticklebacks were also exclusive to *Zostera* and most abundant during fall, but not present in any of the habitats sampled during winter (Fig. 2.7). Other fishes that occurred in low abundance but exclusively in *Zostera* habitat were black surfperch (*Embiotoca jacksoni*) and kelpfish *(Gibbonsia sp.)* during spring/summer and fall, dwarf surfperch *(Micrometrus minimus)* and kelp-gopher-black and-yellow complex (KGB) juvenile rockfish *(Sebastes sp.)* during spring/summer only, and plainfin midshipman *(Porichthys notatus)* during fall (Fig. 2.7).

Pacific staghorn sculpin abundance declined over time across habitats but they were present in *Zostera* during all times and most abundant within *Zostera* compared to algae and bare; whereas none were found in algae nor bare habitats during fall (Fig. 2.7). Arrow gobies were the most abundant fish within algae habitat, and abundance within algae increased over time (Fig. 2.7). Arrow gobies live inside burrows in the mud (Hart, 1973) so it is likely they would utilize non-*Zostera* habitat more readily because there is more mud available to burrow into. During times when algae was present as habitat (summer and fall) arrow goby abundance was much higher in algae than abundance in either *Zostera* or bare habitats (Fig. 2.7). Shiner surfperch were found only in *Zostera* and algae, were more abundant in *Zostera* than algae and were present during only spring/summer and fall (Fig. 2.7). Only one topsmelt *(Atherinops affinis)* was caught for the whole year in bare habitat during fall (Fig. 2.7).

Four species of flatfishes were sampled in this study. Butter sole *(Isopsetta isolepis)* and starry flounder *(Platichthys stellatus)* were found in bare habitat only and during winter only. Speckled sanddab *(Citharichthys stigmaeus)* and English sole *(Parophrys vetulus)* and were distributed between *Zostera* and bare habitats, speckled sanddab were found during winter and English sole during spring/summer (Fig. 2.7). No flatfishes were found in any of the habitats during fall.

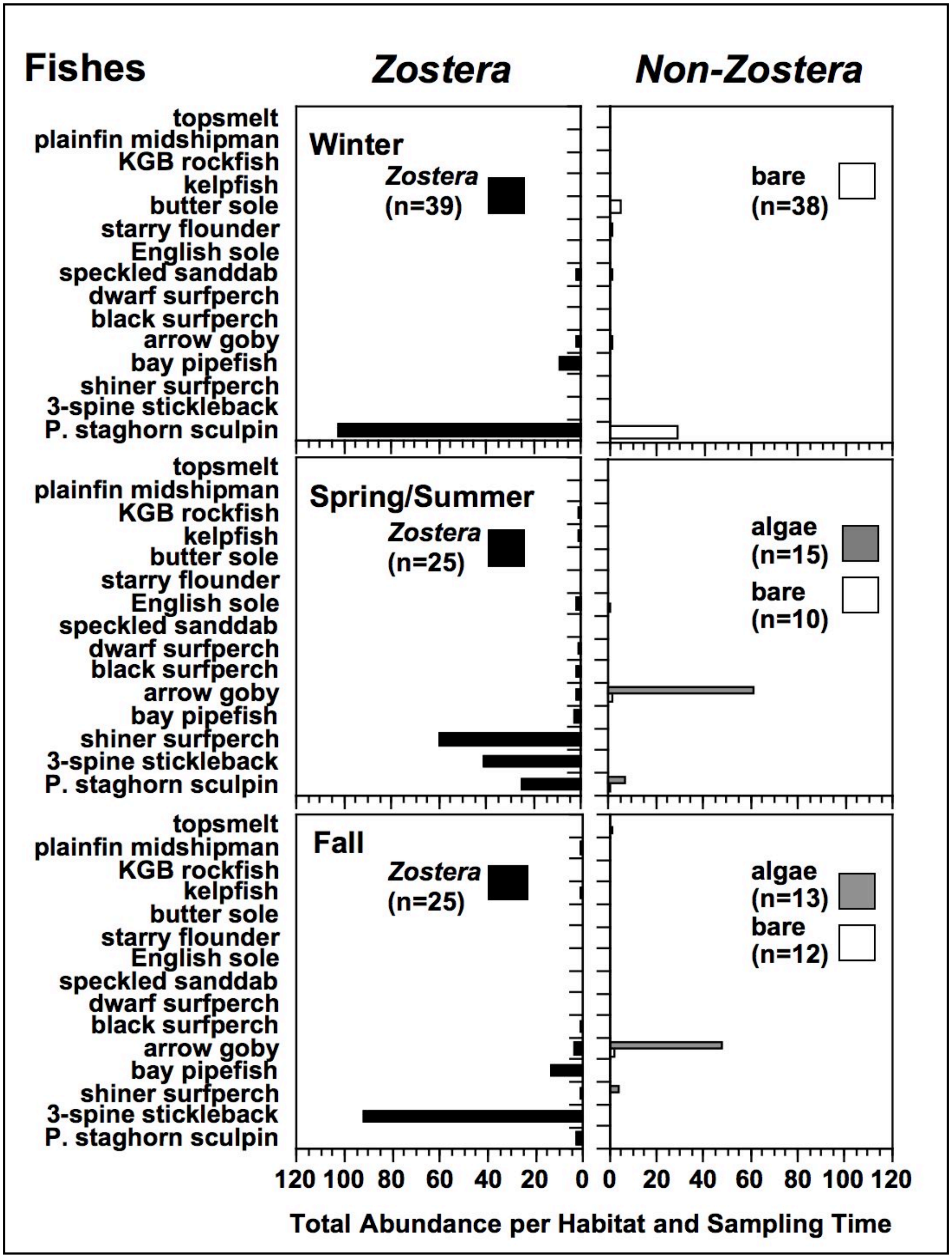

Figure 2.7. Total abundance of fishes per habitat during winter, spring/summer and fall 2008 sampling periods. Number of traps per habitat per time is noted in parenthesis.

Abundance of mobile epibenthic invertebrates changed across habitats over time. Grass shrimp were present during all times, were always most abundant within *Zostera*, and abundance increased over time (Fig. 2.8). Abundance of grass shrimp within *Zostera* during fall was about three times higher than abundance during winter and spring/summer. Among the non-*Zostera* habitats, grass shrimp abundance was greater within algae than on bare substrate, and abundance was greatest during fall.

Taylor's sea hare were present within *Zostera* during all times as well as within algae when algal habitat was present (spring/summer and fall), but never found in bare. Abundance of Taylor's sea hare within *Zostera* was lowest during winter, highest during summer and intermediate during fall (Fig. 2.8). Between spring/summer and fall abundance of Taylor's sea hare within algae increased (Fig. 2.8).

Idotea sp. were present in all habitats during all sampling times and most abundant within *Zostera*. Abundance of *Idotea sp.* was lowest during winter, highest during spring/summer, and intermediate during fall. Abundance of *Idotea sp.* within algae declined between spring/summer and fall and during fall abundance on bare substrate was greater than within algae (Fig. 2.8).

Amphipoda were present during all times but only in *Zostera* and algae habitats, and were most abundant within algae. Amphipoda were present in *Zostera* in low abundance across all times and were more abundant in algae during fall than during summer (Fig. 2.8). *Crangon sp.* were present only during winter and fall, and were distributed across all habitats in low abundance. The highest abundance of *Crangon sp.* occurred within *Zostera* during winter (Fig. 2.8).

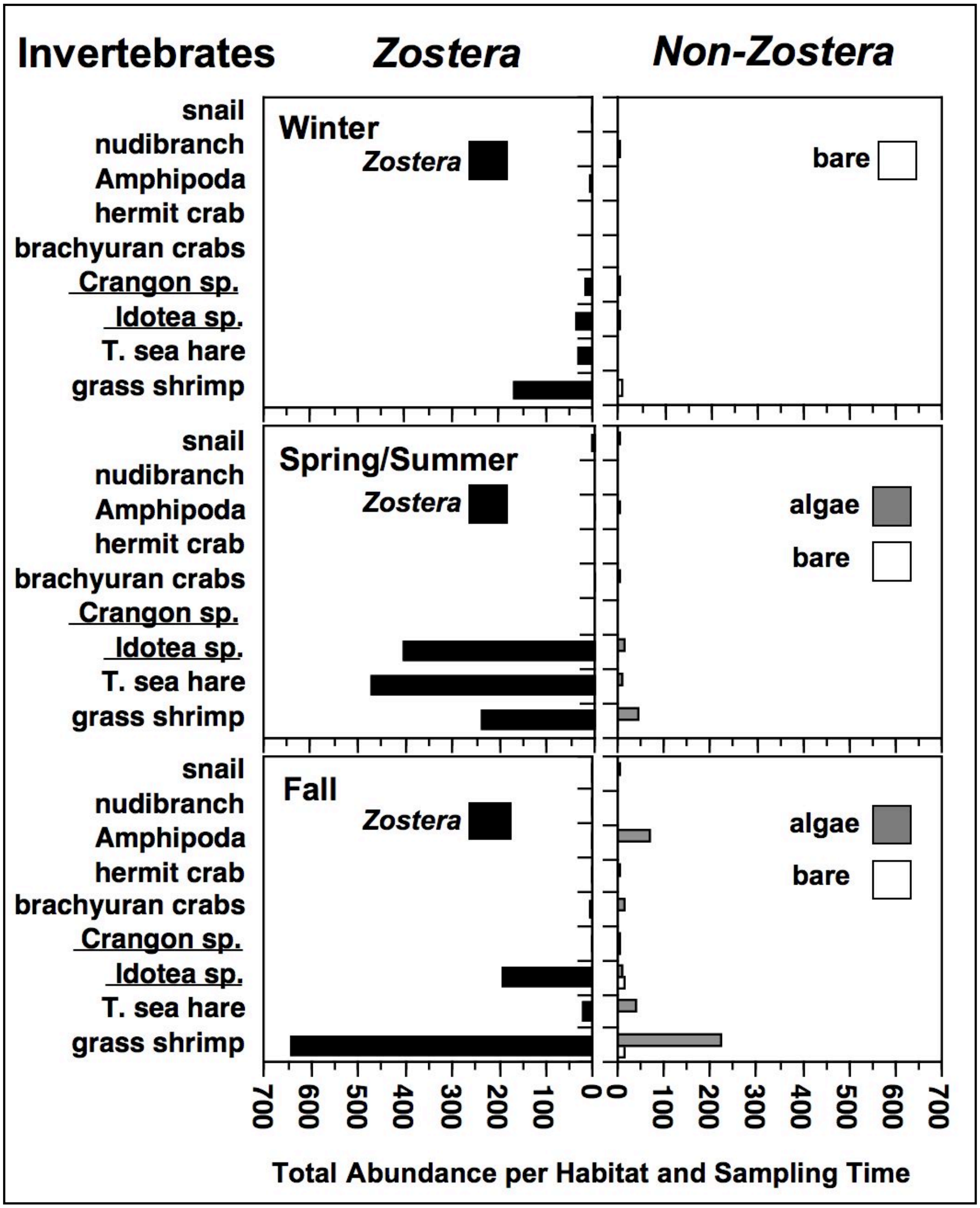

Figure 2.8. Total abundance of mobile epibenthic invertebrates per habitat during winter, spring/summer and fall 2008 sampling periods. Sample size per habitat noted in Fig. 2.7.

Brachyuran crabs and hermit crabs were present during spring/summer and fall. Brachyuran crabs were more abundant within algae habitat and hermit crabs were more abundant in *Zostera* habitat (Table 2.2). Snails were present during all times, never found in bare habitat and were more abundant within *Zostera* than within algae habitat (Table 2.2). Nudibranchs were found in bare habitat during winter and during fall within *Zostera* but were most abundant within *Zostera* during fall (Table 2.2).

Similar to patterns in abundance, mean densities (#/m^3) of invertebrates were generally higher than fishes and both changed over time (Fig. 2.9). Densities were generally higher within *Zostera* than in algae or bare habitats, but estimates of mean density had high variability due to patchy species distributions (Fig 2.9). Arrow gobies were the exception to this pattern and mean densities were highest in algae habitat.

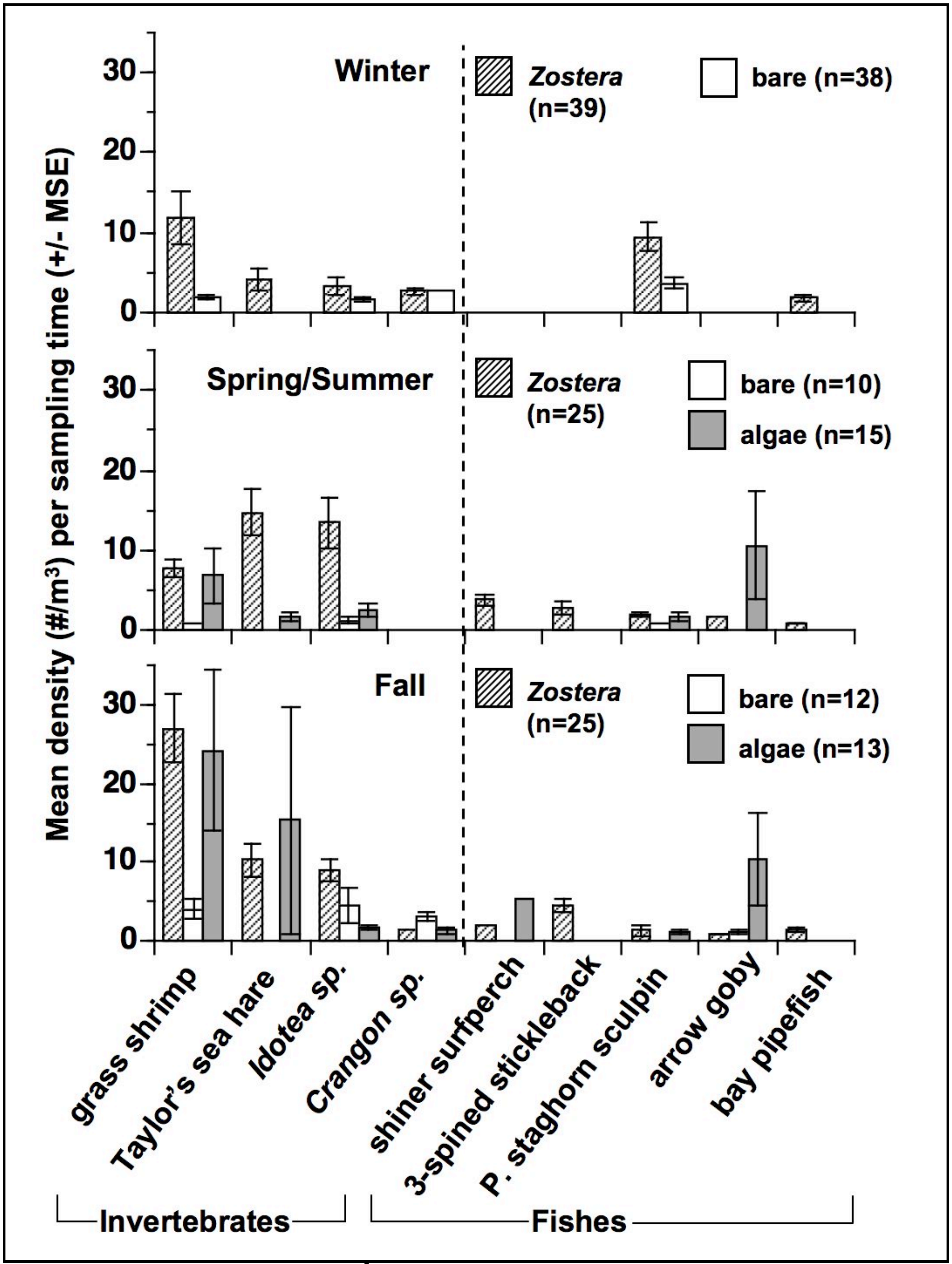

Figure 2.9. Mean densities (#/m^3 +/- MSE) of common invertebrates and fishes within *Zostera,* algae and bare habitats during winter, spring/summer and fall 2008 sampling periods. Sample size per habitat per time is noted in parenthesis.

Diversity of assemblages

Species richness for the entire year was greatest in *Zostera* habitat (21 species) and lower but constant across algae and bare habitats (11 species each) (Fig. 2.10). When broken into sampling season species richness within habitats varied over time. During each sampling season *Zostera* had the highest species richness among the three habitats sampled, species richness within *Zostera* was lowest during winter and greatest during fall (Fig. 2.10). Algal habitat was not present during winter, but when it was present as habitat, species richness was greater within algae than in bare habitat (Fig. 2.10). Algal habitat contained nine species during spring/summer and nine species during fall. Species richness within bare habitat changed over time; richness was greatest during winter (nine species) and declined during both spring/summer and fall (five species) (Fig. 2.10).

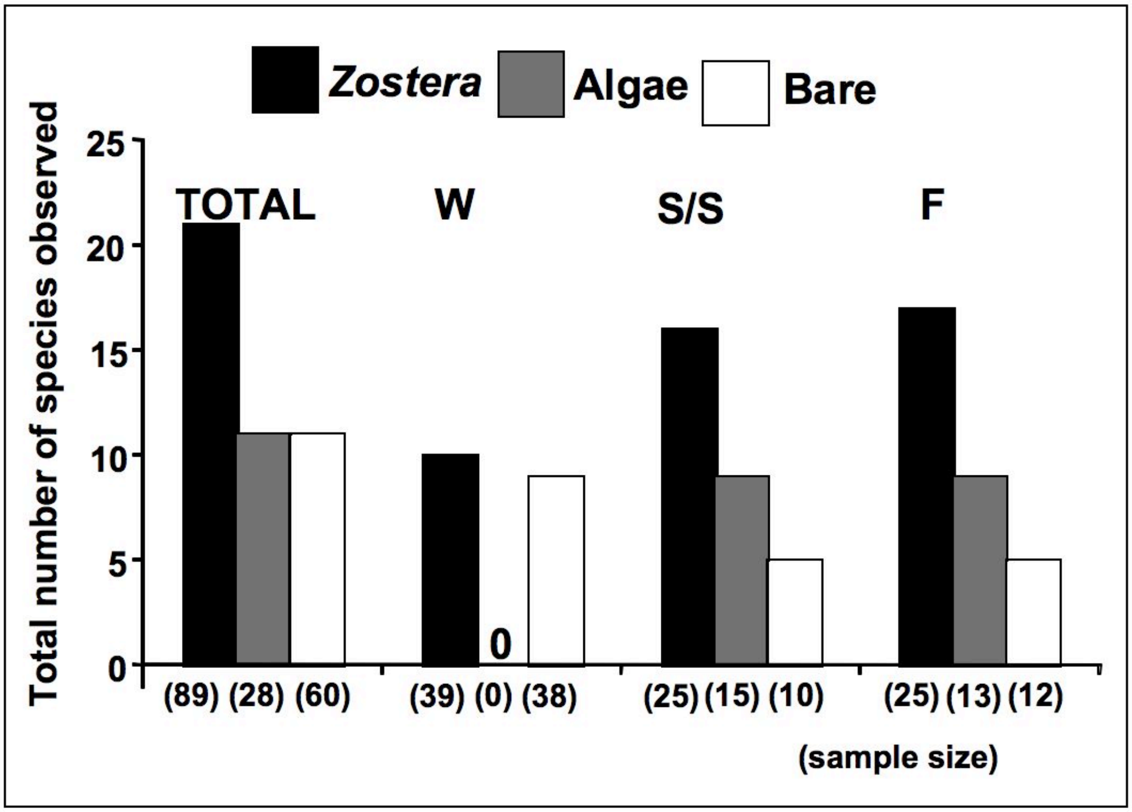

Figure 2.10. Species richness measured by total number of fish and invertebrate species observed within *Zostera*, algae and bare habitats during 2008 and per sampling period; W (winter), S/S (spring/summer) and F (fall). Sample size per time is noted in parenthesis below bars on the x-axis.

The *Zostera* assemblage had the highest heterogeneity (H') for the year but evenness (J') was similar among all three habitats (Table 2.3). When analyzed by sampling season, heterogeneity (H') and evenness (J') within *Zostera* declined over time (Table 2.3). The algae assemblage had higher heterogeneity (H') and evenness (J') than *Zostera* during both spring/summer and fall suggesting the assemblage was both more heterogenous and species were more evenly spread than within *Zostera* (Table 2.3). Of all three assemblages compared, the species assemblage of bare habitat had the highest evenness (J') values for the entire year and per season (Table 2.3).

Table 2.3. Diversity of assemblages within *Zostera,* algae and bare habitats measured using species richness (S), heterogeneity (H’) and evenness (J’) for the entire year (2008) and separated by sampling season.

H’=Shannon-Weiner for diversity $=\Sigma\, p_i\mathrm{Ln}p_i$ (0-5 range, higher>>more species)

J’=H’/Hmax for evenness (0-1 range, 1 being totally even)

Hmax=Ln(Species No.)

Habitat	**2008**			**winter**			**spring/summer**			**fall**		
	S	**H’**	**J’**	**S**	**H’**	**J’**	**S**	**H’**	**J’**	**S**	**H’**	**J’**
Zostera	21	2.19	0.72	10	1.51	0.66	16	1.48	0.54	17	1.34	0.47
algae	11	1.58	0.67	---	---	---	9	1.64	0.75	9	1.38	0.64
bare	11	1.72	0.74	9	1.49	0.68	5	1.56	0.97	5	1.20	0.74

Assemblage overlap of habitat pairs was about the same for the entire year but varied when broken into seasons (Table 2.4). For the entire year, *Zostera* and algae habitats had the most assemblage overlap of the three comparisons (C_H=0.72), while *Zostera* and bare habitats (C_H=0.66) and algae and bare habitats (C_H=0.67) were almost equal. *Zostera* and algae habitats also had the most assemblage overlap when comparisons were broken into sampling season, and the highest amount of overlap occurred during fall (C_H=0.88). *Zostera* and bare assemblages showed the highest value of overlap among seasons during fall (C_H=0.77), but the value of the overlap index was similar to winter (C_H=0.74). Interestingly, during spring/summer, algae and bare habitat assemblages had more overlap (C_H=0.84) than during fall (C_H=0.64), and the amount of overlap during spring/summer was similar to the amount of overlap of *Zostera* and algae assemblages during fall (C_H=0.88).

Table 2.4. Estimates of species assemblage overlap of *Zostera* and bare habitats, *Zostera* and algae habitats, and algae and bare habitats, using the simplified Morisita's index of overlap. Comparisons were done for the entire year and within sampling seasons (winter, spring/summer and fall).

Simplified Morisita's index of overlap (24 species) $C_H = 2*\sum pijpik/ \sum pij^2+\sum pik^2$				
Season **Habitat** **(# samples)**	**2008 total** ***Zostera* (89)** **algae (28)** **bare (60)**	**winter** ***Zostera* (39)** **bare (38)**	**spring/summer** ***Zostera* (25)** **algae (15)** **bare (10)**	**fall** ***Zostera* (25)** **algae (13)** **bare (12)**
***Zostera*-bare**	0.66	0.74	0.35	0.77
***Zostera*-algae**	0.72 (s/s, fall)	n/a	0.38	0.88
algae-bare	0.67 (s/s, fall)	n/a	0.84	0.64

III. EXCLUSIVE HABITAT USE

Invertebrates were not exclusive to any habitat. Some fishes were only found in *Zostera*, some were distributed across more than one habitat and some were only found in bare habitat. Fishes exclusive to *Zostera* were three-spined sticklebacks, bay pipefish, black surfperch, dwarf surfperch, kelpfish, kelp-gopher-black-and-yellow complex (KGB) rockfish, and plainfin midshipman (Fig. 2.11). Species found in more than one habitat were Pacific staghorn sculpin, shiner surfperch, arrow goby, English sole, and speckled sanddab (Fig. 2.11). Butter sole, starry flounder and topsmelt were only found in bare habitat (Fig. 2.11).

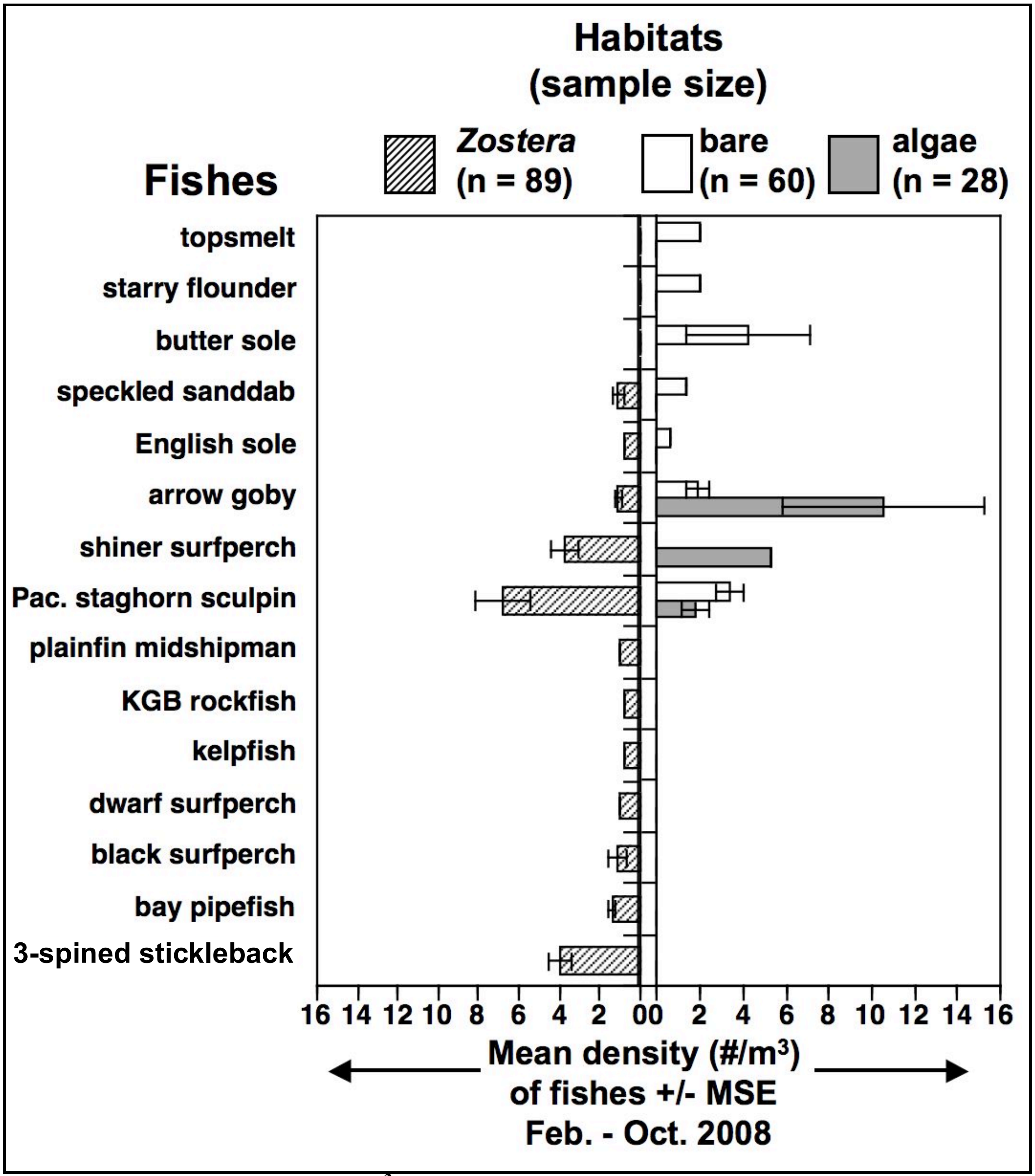

Figure 2.11. Mean density (#/m^3) of all fishes sampled within *Zostera*, bare and algae habitats during all seasons of 2008. Sample size per habitat type is noted in parenthesis.

In general, frequency of occurrence of invertebrates was higher than fishes across all habitats, and frequencies were higher in *Zostera* than algae and bare habitats (Fig. 2.12). Similar to the patterns of species abundance within habitats, when algae habitat was present, frequencies were greater within algae than in bare habitat (Fig. 2.12).

Pacific staghorn sculpin was more frequently found in *Zostera* during all times and frequencies were highest during winter (Fig. 2.12). Grass shrimp frequencies were higher in *Zostera* than in algae or bare habitat across times, but within *Zostera* frequencies did not vary much over time (Fig. 2.12). *Idotea sp.* were more frequently observed within *Zostera* than in algae or bare habitat across times, and frequency of occurrence within *Zostera* increased over time (Fig. 2.12). Arrow gobies were more frequently observed within algae habitat and were most frequent within algae during spring/summer (Fig. 2.12).

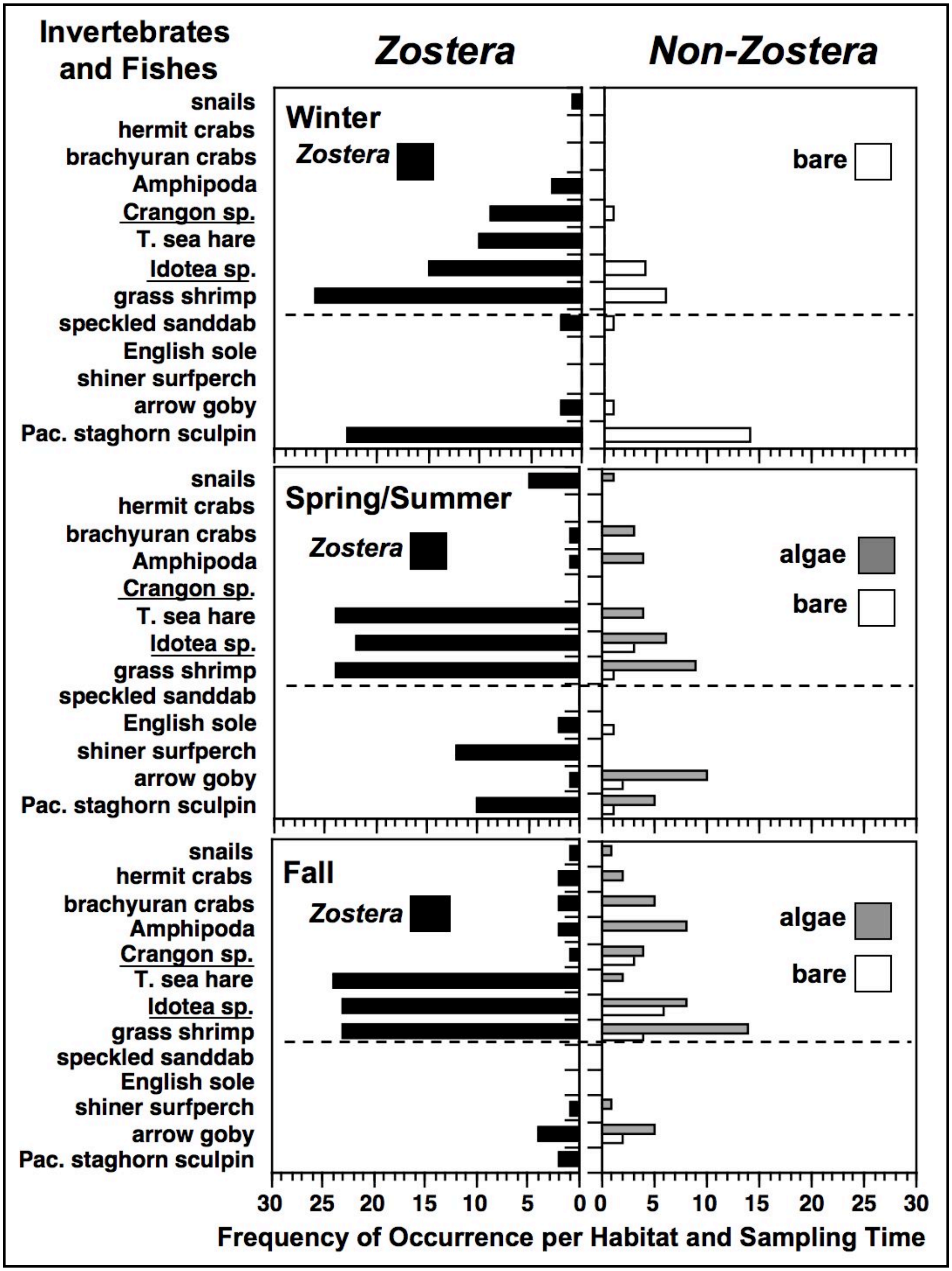

Figure 2.12. Frequency of occurrence (# of times observed within each habitat during each sampling time) of species found *Zostera*, algae and bare habitats during winter, spring/summer and fall 2008. Sample size per habitat per time noted in Fig. 2.9.

Some species distributed across habitats and time had observed frequencies different from expected by random chance. Of the species analyzed using a 3x3 contingency table, Pacific staghorn sculpin, grass shrimp and *Idotea sp.,* all had expected average cell frequencies greater than six, and observed frequencies were greater than expected, therefore the null hypothesis was rejected for all (Table 2.5).

Of all habitats and sampling times, *Crangon sp.* occurred most frequently in *Zostera* during winter, but during fall occurred more frequently in algae and bare habitats than within *Zostera* (Fig. 2.12). Average expected cell frequency was only two, but the test was still done and the null hypothesis was rejected (Table 2.5). From the data collected during this study it seems that *Crangon sp.* could be switching habitats over the course of the year.

Observed frequencies of three groups of invertebrates; amphipoda, Taylor's sea hare and brachyuran crabs, were not different from expected by random chance alone (Table 2.5). Interesting patterns of frequency of occurrence suggested amphipoda and brachyuran crabs were more frequent within algae habitat, and Taylor's sea hare was more frequently found within *Zostera* (Fig. 2.12). Though I was not able to reject the null hypothesis, I suspect there may have been too little data to detect a difference among habitats or times (Table 2.5).

Shiner surfperch had a total observed frequency greater than ten but did not occur frequently enough across habitats or times to do a test of independence (Fig. 2.12). Shiner surfperch were more frequently observed within *Zostera* habitat, and were most frequently observed during spring/summer with only one observation in algae habitat during fall (Fig. 2.12). Flatfishes found in both bare and *Zostera* habitat, speckled sanddab and English sole*,* were twice as frequent in *Zostera*, but frequencies were too low to test for independence of habitat use (Fig. 2.12). Hermit crabs and snails were also not sampled enough to test for independence of habitat use but they were more frequently observed on vegetated substrates, either *Zostera* or algae habitat (Fig. 2.12).

Table 2.5. Summary of species that were present in combinations of habitats across sampling seasons, contingency table format per species, and results of χ^2 tests of independence which tested exclusive habitat use.

Species	All times and all habitats	All habitats	All times	Other combinations	Contingency table format (R x C) Row=time Column=habitat	Result Ho: species are distributed independently of habitat and time, alpha=0.1
Arrow goby	X				3x3	Observed>expected
Grass shrimp	X				3x3	Observed >expected
Idotea sp.	X				3x3	Observed>expected
Pacific staghorn sculpin			X	*Zostera* only in fall	3x3	Observed>expected
Crangon sp.		X		winter and fall only	2x3	Observed>expected
Amphipoda			X	*Zostera* and algae only	3x2	Do not reject Ho
Taylor's sea hare			X	*Zostera* and algae only	3x2	Do not reject Ho
Brachyuran crabs				*Zostera* and bare; summer and fall only	2x2	Do not reject Ho

IV. NURSERY HABITAT FOR FISHES

Total abundance of fishes per habitat by age class

Most of the fishes sampled during this study were juveniles. Pacific staghorn sculpin were present only as juveniles and were most abundant in *Zostera* habitat (Fig. 2.13). Fishes present as both juveniles and adults were bay pipefish, shiner surfperch, three-spined stickleback and kelpfish, and were generally more abundant within *Zostera* (Fig. 2.13). Species exclusive to *Zostera* were bay pipefish (most abundant as adults), three-spined stickleback (most abundant as juveniles) and kelpfish which had only one juvenile and one adult sampled during the entire study. Within *Zostera,* abundance of juvenile shiner surfperch was greater than adults, but four juvenile shiner surfperch were sampled within algae habitat (Fig. 2.13). Arrow gobies were present only as adults and were most abundant in algae habitat (Fig. 2.13).

Species present as juveniles, exclusive to *Zostera,* but in low abundance were black surfperch, dwarf surfperch, plainfin midshipman, kelpfish, and KGB rockfish (Fig. 2.13). Juvenile fishes that occurred in habitats other than *Zostera* were mostly flatfishes. English sole and speckled sanddab juveniles were found on both bare habitat and within *Zostera* (Table 2.1). Other juvenile flatfishes, butter sole and starry flounder, as well as topsmelt juveniles were found only on bare habitat (Table 2.1).

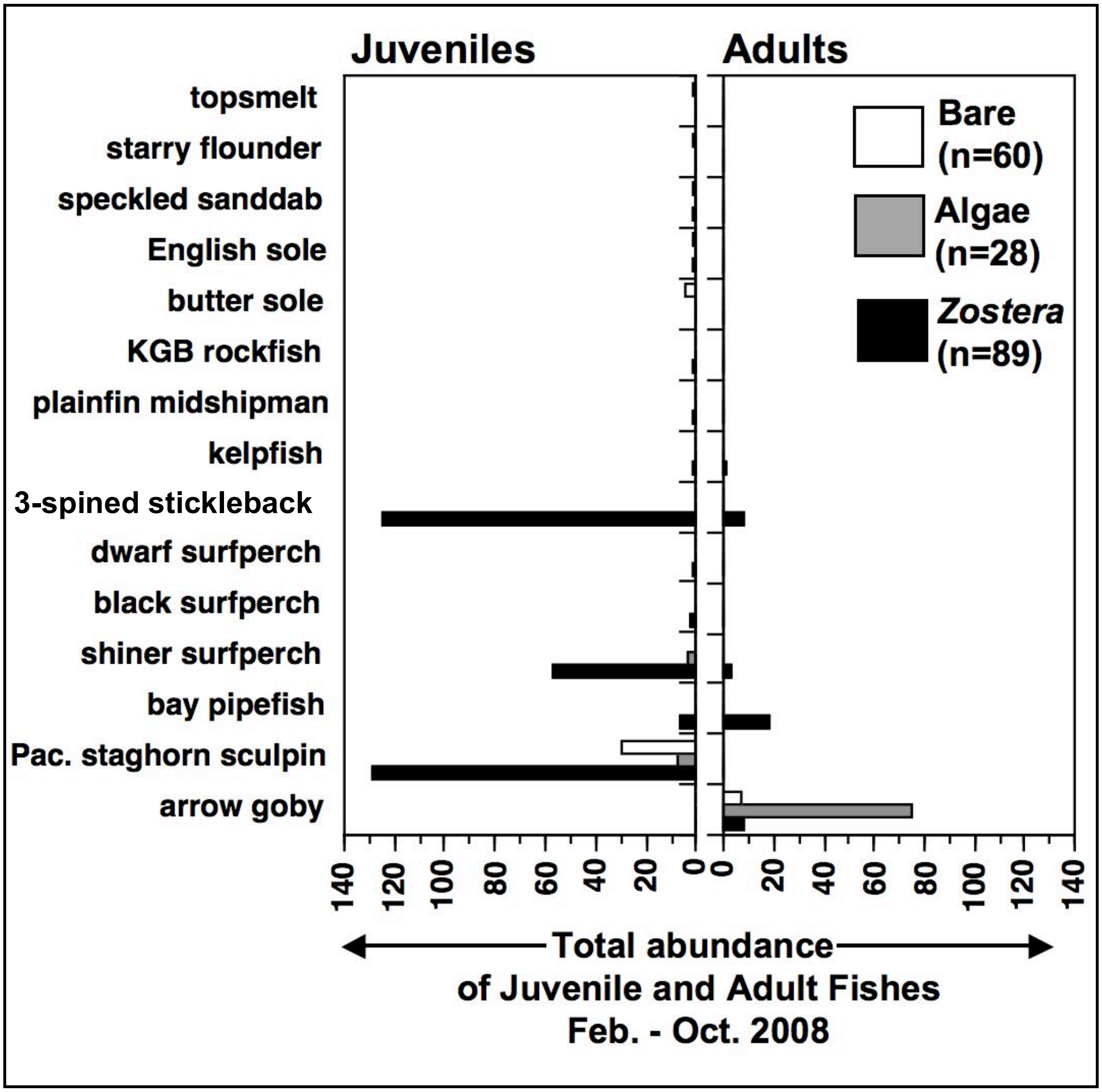

Figure 2.13. Total abundance of juvenile and adult fishes within *Zostera*, algae and bare habitats across all sampling seasons for 2008. Sample size per habitat type noted in parenthesis.

Temporal variability of juvenile and adult fishes within Zostera, algae and bare habitats

Many of the fishes sampled during this study occurred only as juveniles and were exclusive to *Zostera*, and overall total abundance of juvenile fishes was greater than abundance of adults (Fig. 2.14). Fishes that occurred as both adults and juveniles were shiner surfperch, bay pipefish*,* three-spined stickleback and kelpfish but they did not occur frequently enough or in habitats other than *Zostera* to do tests of independence.

Shiner surfperch were present as both adults and juveniles in *Zostera* during spring/summer, and during fall four juveniles were found in algae and there was just one juvenile within *Zostera* (Table 2.1). Juvenile shiner surfperch were more abundant during spring/summer than during fall (Fig. 2.14). Bay pipefish were present as juveniles during winter and fall, and adults occurred during all times (Fig. 2.14). Three-spined stickleback juveniles and adults were present during summer and fall, exclusive to *Zostera* habitat, and were most abundant during fall (Fig. 2.14).

Pacific staghorn sculpin were present as juveniles only, occurred across all habitats, and abundance decreased over time (Fig. 2.14). Abundance was greater within *Zostera* than within either algae or bare habitat during all times (Fig. 2.14). Among the non-*Zostera* habitats, Pacific staghorn sculpin were more abundant within algae habitat when it was present.

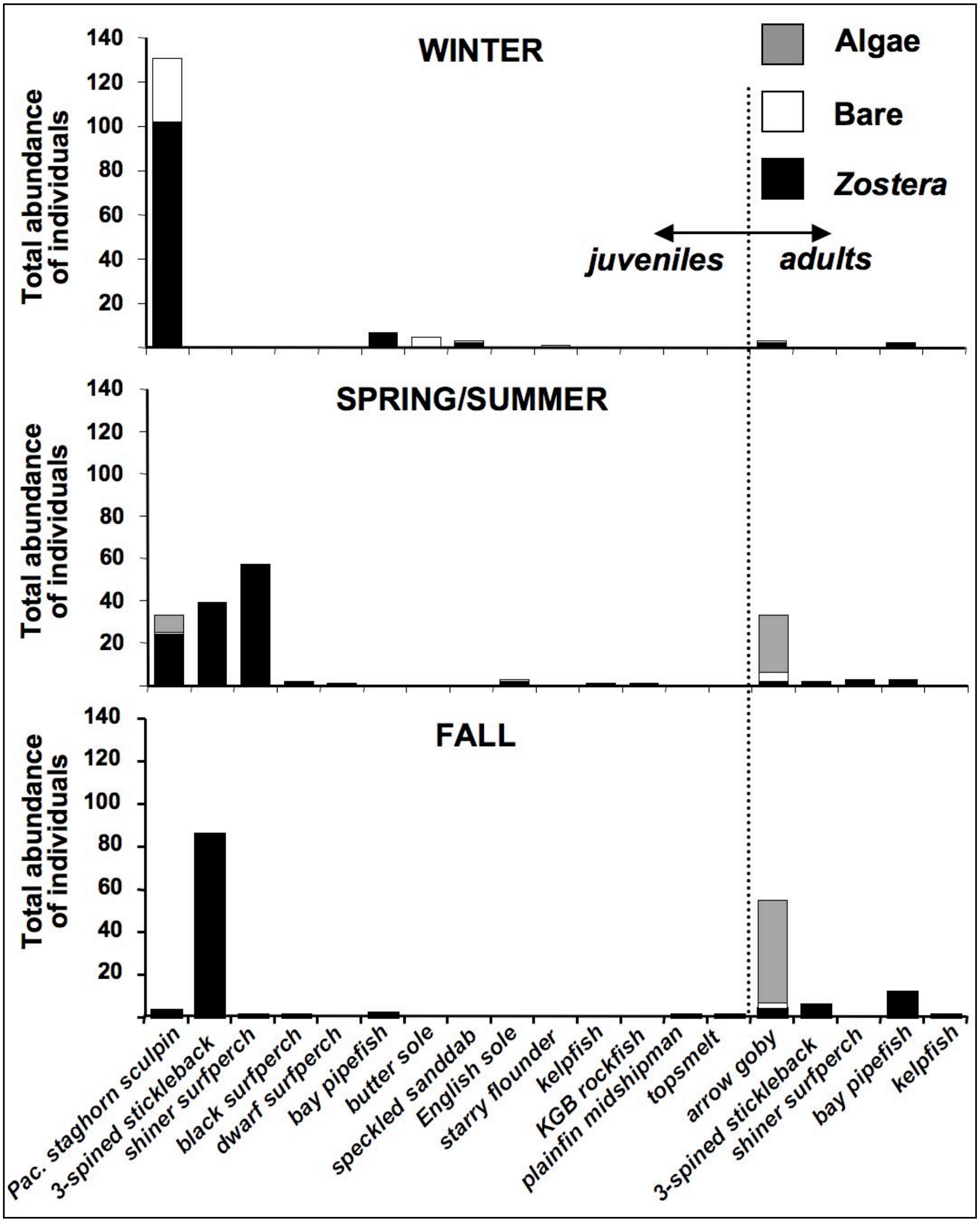

Figure 2.14. Total abundance (bars stacked by habitat) of adult and juvenile fishes within *Zostera*, algae and bare habitats during winter, spring/summer and fall 2008. Sample size per time: winter - *Zostera* (n=39), bare (n=38); spring/summer - *Zostera* (n=25), algae (n=15), bare (n=10); fall - *Zostera* (n=25), algae (n=13), bare (n=12).

Bay pipefish and arrow gobies were the only species that were more abundant as adults and this may be due to a sampling bias. Both of these species are potentially smaller than the mesh size of the net at early life stages and may have been small enough to escape through the mesh. Arrow gobies were the only adult fish found in all habitats, and abundance was greatest during fall within algae habitat (Fig. 2.14).

Case studies of potential nursery function of Zostera habitat

Pacific staghorn sculpin (Leptocottus armatus)

Pacific staghorn sculpins are considered an estuary resident species and there was a pattern of growth over time in all habitats (Fig. 2.15). Total abundance of Pacific staghorn sculpin juveniles was about three times greater within *Zostera* than in non-*Zostera* habitats for each sampling season (Fig. 2.15). The range in standard length (SL) for each season's group of juveniles was largest within *Zostera* than in algae and bare habitats (Fig. 2.15).

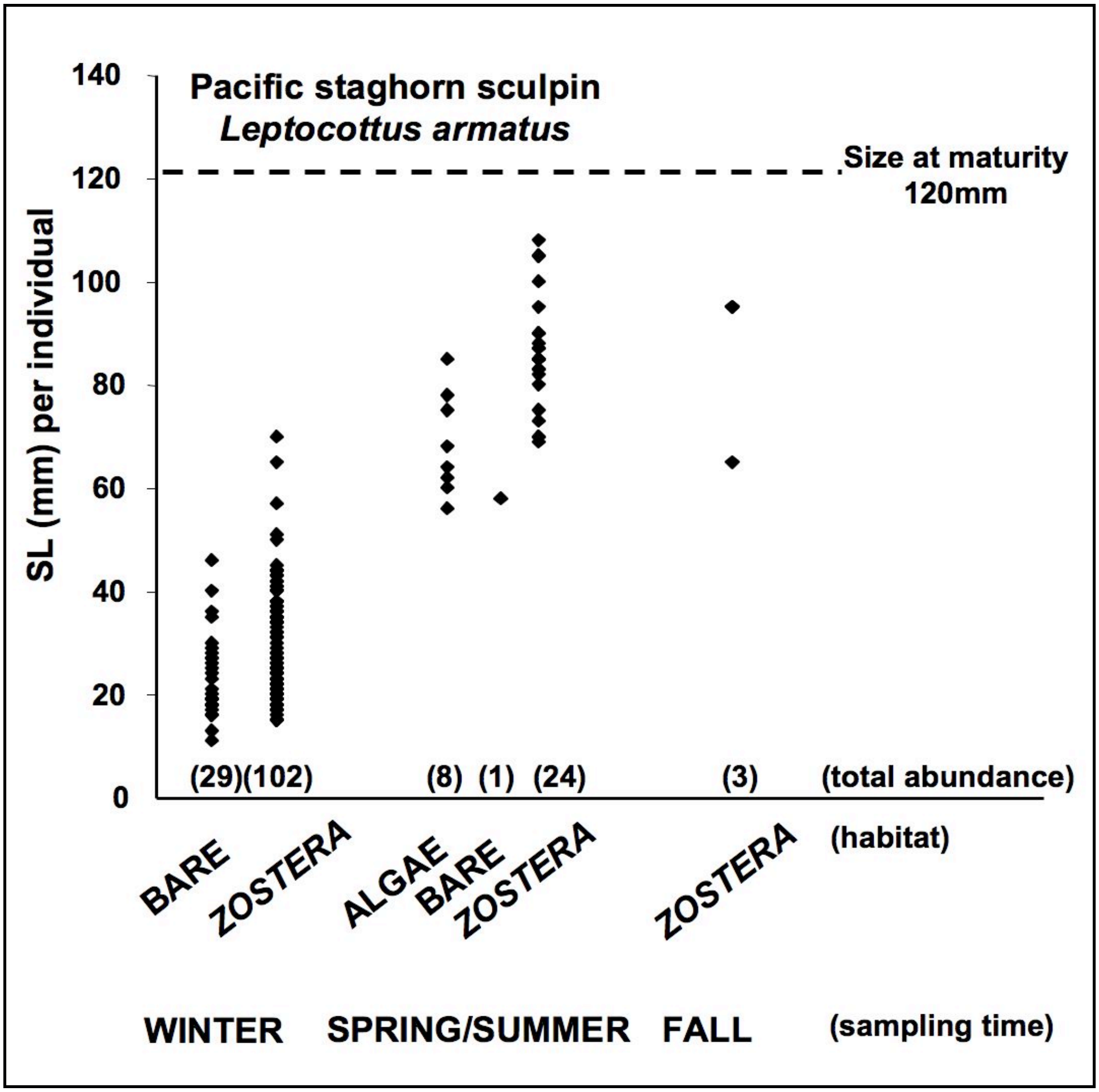

Figure 2.15. Size distribution (standard length (mm) per individual) of Pacific staghorn sculpin (*Leptocottus armatus)* juveniles (Jones, 1962) among habitats during winter, spring/summer and fall 2008. Total abundance of individuals is noted in parenthesis along the top of the x-axis.

Bay pipefish (Syngnathus leptorhynchus)

Bay pipefish are another estuary resident species but were exclusive to *Zostera,* present as both adults and juveniles, and abundances changed over time (Table 2.1). Bay pipefish were present throughout the year and were most abundant as adults within *Zostera* during the fall sampling period (Fig. 2.16). These fish are considered to be reproductive from February to October and mature at 100-120 mm long (Bayer, 1980). During winter the size range of individuals was 84-126 mm, during summer only two individuals were observed and were 217 mm and 220 mm each, and during fall sizes ranged 64-220 mm (Fig. 2.16). Juveniles were most abundant during winter and adults were most abundant during fall, and the largest individuals were sampled during summer (Fig. 2.16). No juveniles were observed during spring/summer and the smallest individuals were sampled during fall (Fig. 2.16).

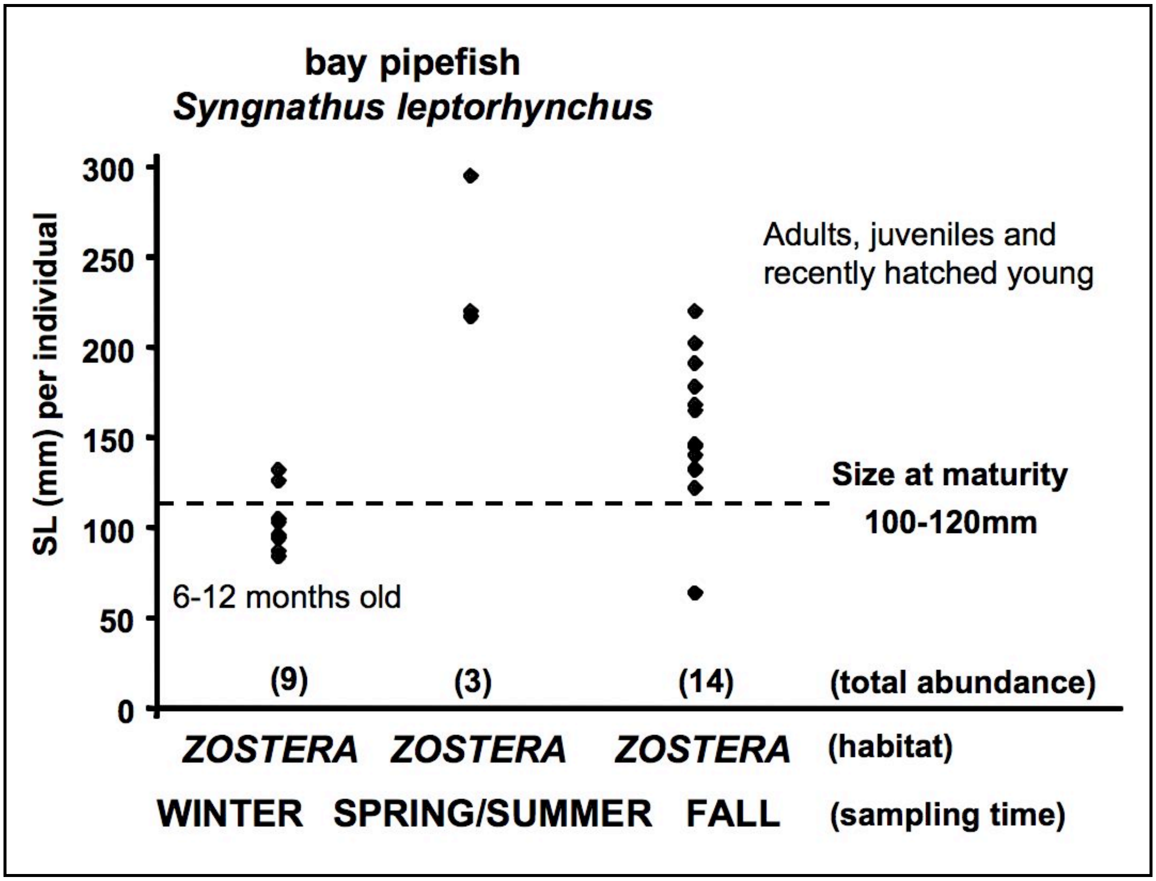

Figure 2.16. Size distribution (standard length (mm) per individual) of bay pipefish *(Syngnathus leptorhynchus)* within *Zostera*. during winter, spring/summer and fall 2008. Proposed life history stages noted next to data (Bayer, 1980). Total abundance of individuals is noted in parenthesis along the top of the x-axis.

Three-spined stickleback (Gasterosteus aculeatus)

Three-spined sticklebacks are a brackish water species that were found only in *Zostera*, and not present during winter. Abundance increased from spring/summer to fall and most fish were present as juveniles. The size range during spring/summer was lower than during fall, and juveniles were most abundant during both seasons (Fig. 2.17). During spring/summer, 39 juveniles ranged from 18-30 mm SL, and there were two adults observed, each near the size at maturity limit (35 mm SL) (Fig. 2.17). In the fall, juvenile abundance more than doubled to 86 fish, and sizes ranged from 22-36 mm SL (Fig. 2.17). Adult abundance during fall was higher than during spring/summer, six fish, and the range of sizes was 35-37 mm, which is still close to the size at maturity threshold.

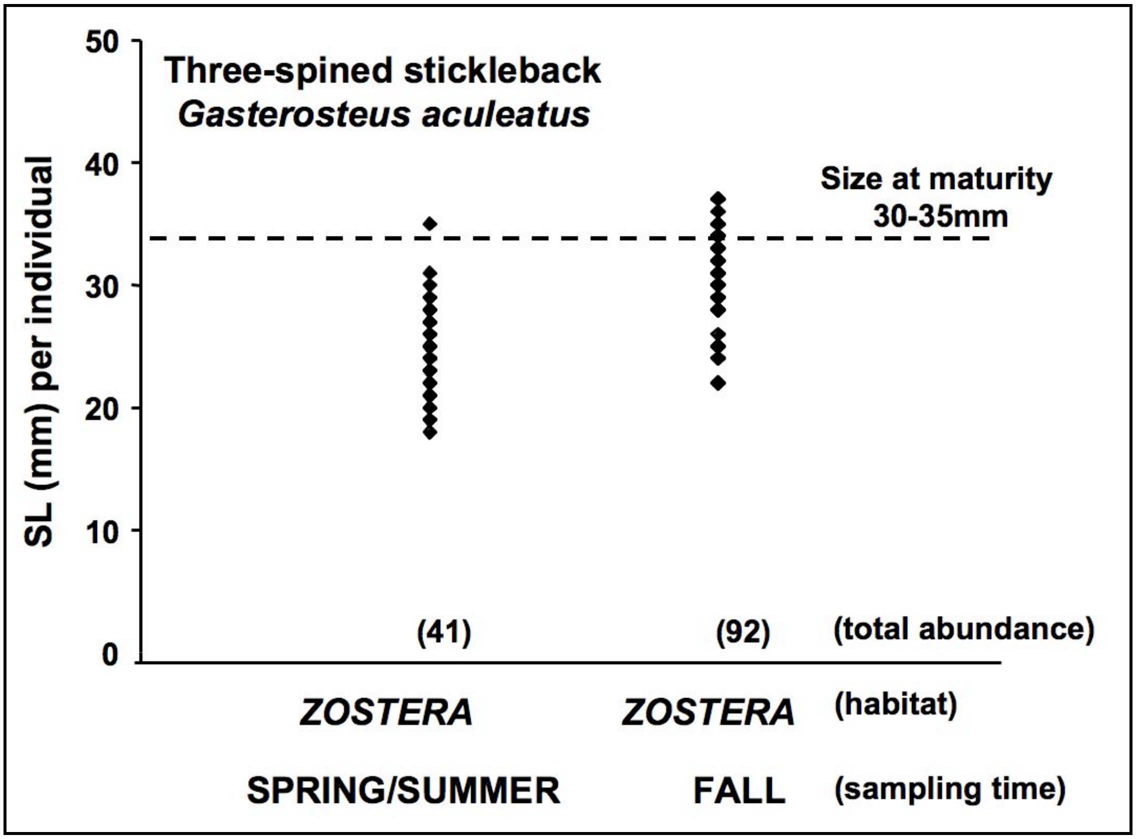

Figure 2.17. Size distribution (standard length (mm) per individual) of three-spined stickleback (*Gasterosteus aculeatus)* juveniles and adults (Wootton, 1976) within *Zostera* during spring/summer and fall 2008. Total abundance of individuals is noted in parenthesis along the top of the x-axis.

Shiner surfperch (Cymatogaster aggregata)

Shiner surfperch, a partial resident species, were present as both adults and juveniles, and were most abundant as juveniles within *Zostera* during spring/summer. Three adult fish were observed during spring/summer and the size range of the 57 juveniles captured within *Zostera* at this time was between 30-48 mm SL (Fig. 2.18). During fall, four juveniles were present within algae habitat and ranged from 38-41 mm, and one fish was found in *Zostera* that was a transitional size between juvenile and adult (Shaw, 1971) (Fig. 2.18). Other less abundant juvenile surfperches were black and dwarf surfperches, and were exclusive to *Zostera*. Black surfperch were caught during spring/summer and fall, but dwarf surfperch were only sampled during spring/summer (Table 2.1).

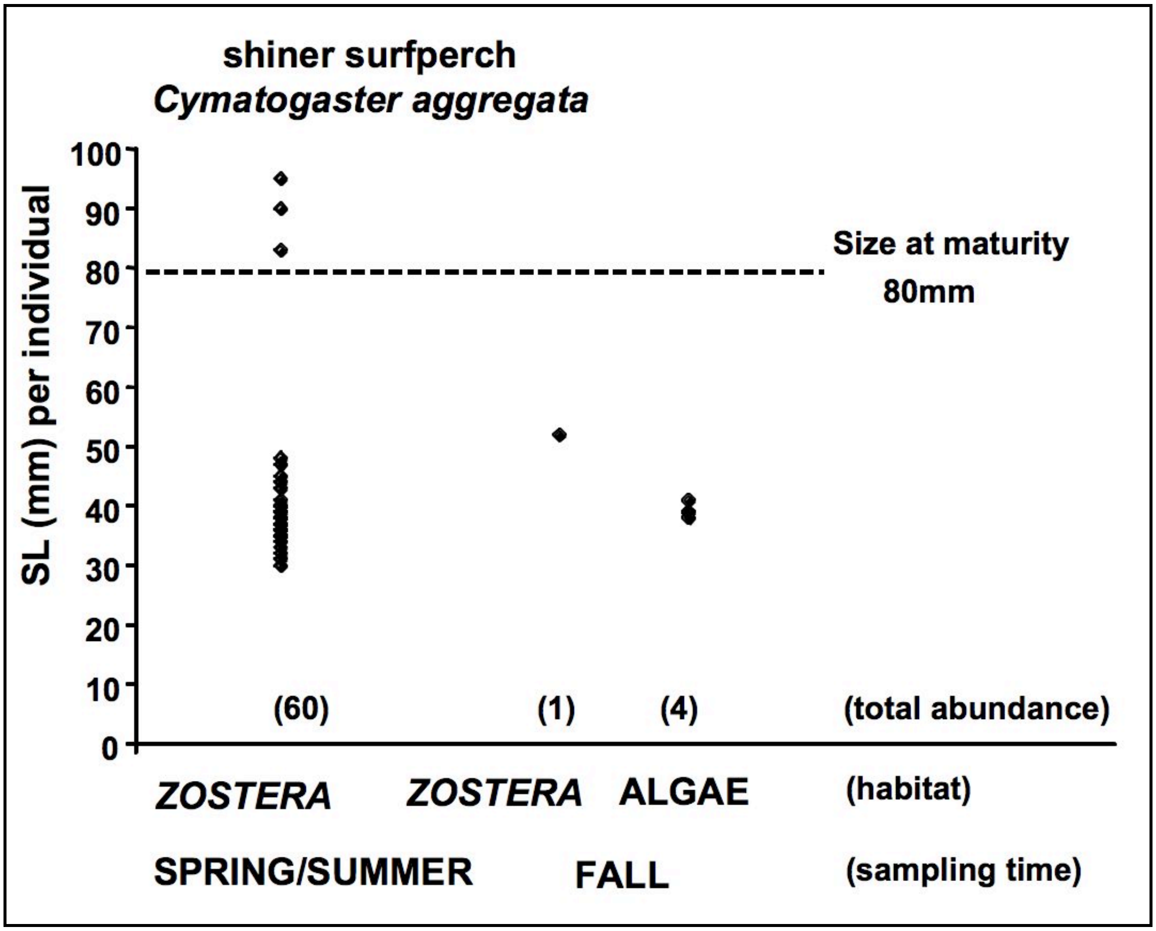

Figure 2.18. Size distribution (standard length (mm) per individual) of shiner surfperch (*Cymatogaster aggregata)* juveniles and adults (Shaw, 1971) within *Zostera* and algae habitats during spring/summer and fall 2008. Total abundance of individuals is noted in parenthesis along the top of the x-axis.

DISCUSSION

Species assemblages, habitat availability and habitat utilization varied over time within Elkhorn Slough. The majority of algal habitat was comprised of *Ulva sp.* and was ephemeral, not present during winter but present in summer and fall. All four classes of estuarine fishes (Allen et al., 2006) were sampled during this study and abundances varied over time. Fishes sampled over the course of this survey represented most of the groups that comprise the fish assemblage of Elkhorn Slough (Yoklavich et al., 1991; 2002).

Brackish/freshwater species were represented by three-spined sticklebacks, and occurred in greatest abundance during fall. Permanent slough residents (Pacific staghorn sculpin, bay pipefish*,* arrow goby and black surfperch), comprised the majority of individuals sampled for the entire study, and were present throughout the year. Pacific staghorn sculpins and arrow gobies were present in all habitats, but bay pipefish and black surfperch were only found in *Zostera*. The only partial resident species observed was shiner surfperch*,* which were present during spring/summer and fall, and distributed among *Zostera* and algae habitats. Marine or immigrant fishes were represented by flatfishes (butter sole, English sole, speckled sanddab and starry flounder)*,* which occurred during winter and spring/summer, but not during fall.

Similar to other studies, there was a peak in abundance and diversity of fishes during summer and a subsequent decline during fall and winter when partial residents and immigrant fishes leave the slough (Yoklavich et al., 2002). Most of the fishes observed during this study were juveniles and abundances were greater within *Zostera* than in other habitats. Namely, there were higher proportions of juvenile Pacific staghorn sculpin, three-spined stickleback and shiner surfperch within *Zostera.* It would be interesting use tagging, caging or tracking studies to test the nursery habitat hypothesis for *Zostera* habitat within Elkhorn Slough more rigorously in future studies.

Abundances of adult fishes varied across habitats, bay pipefish and arrow gobies were most abundant as adults. Bay pipefish were most abundant in *Zostera* and arrow gobies were only found as adults and were most frequently observed in algae habitat. This may have been due to a sampling bias because the mesh size of the net might have been large enough for very small recently hatched individuals of these species to escape.

Species summaries

Pacific staghorn sculpin (Leptocottus armatus)

Studies within Elkhorn Slough reported Pacific staghorn sculpin dominated the larval assemblage during winter and spring and are permanent residents within the slough (Yoklavich et al., 2002). During this study Pacific staghorn sculpin abundance varied in all habitats sampled and during all times of the year. Similar to the salt-marsh restoration survey twenty years ago (Small, 1987) at a nearby site, Pacific staghorn sculpin were most abundant during winter, grew to adult size and left the marsh in fall. During 2008, the same pattern was observed total abundance of juvenile Pacific staghorn sculpin was greatest during winter and declined over time, while fish grew to adult size. Though juveniles were distributed across habitats they were more abundant within *Zostera* than the other habitats sampled, which suggests *Zostera* plays a role as nursery habitat for this species. During fall large juveniles may be leaving the *Zostera*, moving into adult habitats in another region of the slough, moving into deeper waters or are a food resource for birds and other predators in the slough.

Bay pipefish (Syngnathus leptorhynchus)

Studies of pipefish in other estuaries from Oregon (Bayer, 1980) and Southern California (Herald, 1941) suggested the reproductive season for western pipefishes changes with latitude. A survey of an estuary in Oregon reported that the breeding season of bay pipefish spanned February-July, fish were most abundant during December-May with a peak in March and by June all sizes had declined and most individuals had emigrated up the estuary (Bayer, 1980). Reproduction can take place year round for southern ranges, with a peak from February-October (Herald, 1941). Bay pipefish are classified into age classes by size and are considered mature at 100-120 mm, individuals up to 130 mm are probably 6-12 months old and within two months of hatching individuals reach a size of about 70 mm (Bayer, 1980).

Bay pipefish observed during winter sampling, February and March, could have been individuals released as a late summer cohort and had been growing in *Zostera* for the past eight months and reached juvenile and young adult sizes (84-132 mm). During spring/summer sampling, July, only three individuals were observed and sizes ranged from 217-220 mm, in the size range of reproductive adult fish. Fish sampled during fall, October, spanned the entire range of size classes of adults, juveniles and recently hatched young. The size range of juveniles caught during October was consistent with a growth rate of 70 mm in two months, born during mid-to-late summer.

Bay pipefish were observed exclusively within *Zostera* habitat and are considered a permanent resident species. Patterns observed during this study indicated *Zostera* had an important and critical role as nursery habitat for bay pipefish within Elkhorn Slough. These fish were observed during all sampling times and appear to complete their entire life cycle within *Zostera*.

Abundance and size of bay pipefish over time within *Zostera* suggests adults breed during the winter and early spring and incubate their young until they are released during late summer. In the following fall and winter fish grow to adult sizes, adding to the resident population of bay pipefish within *Zostera.* This may be why only adults were observed during spring/summer sampling because the juveniles had not been released yet or recently hatched juveniles might have been too small during July to be sampled by the net.

Three-spined stickleback (Gasterosteus aculeatus)

Three-spined sticklebacks are a brackish or euryhaline fish distributed along the Pacific coast from Alaska to Baja California. They occur in fresh, brackish and saltwater restricted to coastal areas and most common in slow flowing backwaters, sheltered bays and harbors (Wootton, 1976). The breeding season lasts two-three months during spring or summer and they are non-reproductive for the rest of the year. Adult size ranges between 35-80 mm, maximum adult size can be 100 mm but is typically about 50 mm. During spring they migrate from over-wintering in the sea or move from deeper fresh waters into shallow ditches and backwaters for breeding grounds to build nests the males guard. When they hatch at 3-5 mm long it takes about 18 days to assume an adult-like form at 11 mm (Wootton, 1976). During fall they move back out to sea or to deeper waters, and live in schools when not breeding. Three-spined stickleback collected in *Zostera* beds in Denmark ate gammarids, other amphipods and isopods as the main food items. They are generally carnivorous and will feed on benthic, swimming or floating items, as well as eat their own eggs (Wootton, 1976).

Patterns of distribution and abundance of three-spined sticklebacks within Elkhorn Slough suggest these fish use *Zostera* as nursery habitat. *Zostera* provides a shallow refuge within the slough for them to build and guard nests of eggs, as well as providing habitat for food items to sustain the growing juveniles. No fish were present during winter in any of the habitats sampled suggesting adults and juveniles leave *Zostera* and move into deeper waters within the slough or to other habitats during winter. It is possible these fish are seeking out the brackish water habitats of the slough during the rainy winter season and moving into *Zostera* as nursery habitat during the later parts of the year. Algal habitat may not provide the sediment stabilization, shallow nesting habitat, reduction of flow or invertebrate assemblage that *Zostera* does and for these reasons *Zostera* is an important and valuable habitat for three-spined sticklebacks within Elkhorn Slough.

Shiner surfperch (Cymatogaster aggregata) and black surfperch (Embiotoca jacksoni)

Shiner surfperch are common in many habitats in Elkhorn Slough and are considered partial slough residents because they reproduce (generally during summer) and spend most of the time in the slough but then move to the ocean for some portion of the year (generally winter). This pattern was reflected in the data collected over 2008, adults and juveniles were not present during winter, but juveniles were abundant during spring/summer and some adults were caught during spring/summer. The literature values for different life history stages of shiner surfperch suggest that 50-80 mm is the transitional size from juvenile to adult and 80-120 mm is considered mature (Shaw, 1971). For this analysis, any fish less than 80 mm was considered a juvenile and greater than 80 mm was an adult. Adults observed during spring/summer were large enough (83-95 mm) to be mature at the time of sampling.

During summer, of the three adults sampled, the largest of the group (95 mm) was pregnant at the time of collection and gave birth to six fish after being brought back to the aquarium facility. During the fall sampling period only one fish was observed within *Zostera* and it was 52 mm SL, within the transitional size range from juvenile to adult. I think this individual was an older juvenile that had not reached maturity (80mm) and was still using the *Zostera* as nursery habitat before moving leaving the slough during winter.

Similar to shiner surfperch, black surfperch showed a pattern of growth over time within *Zostera*. During summer, sizes ranged between 75-84 mm for the two individuals sampled, and during fall one individual was observed at 105 mm. All individuals were classified as juveniles, less than one year old (Schmitt and Holbrook, 1984) based on size. Black surfperch are considered permanent slough residents, but no adults were observed within any of the habitats sampled. Black surfperch were observed as juveniles in low abundance within *Zostera*, but are potentially using *Zostera* as nursery habitat. Adult fish may live in deeper areas of *Zostera* that were unable to be sampled or in other habitats throughout Elkhorn Slough.

Arrow goby (Clevelandia ios)

Arrow gobies dominate the larval pool within Elkhorn Slough during summer and fall and are a permanent slough resident species (Yoklavich et al., 2002). During this study arrow gobies were observed most often in algae habitat, and were most abundant during fall. All individuals sampled were classified as adults based on standard length, but larvae and juveniles may have been present but too small to be caught in the net. Arrow gobies and amphipoda were the only taxa found most often in algae habitat, and there may be a correlation between these distributional patterns. A diet study done in the Tijuana Estuary in southern California found that the main food item of arrow gobies was copepods (85%IRI) but amphipods made up a portion of the diet (5% IRI) and arrow goby were preyed upon by Pacific staghorn sculpin (West et al., 2003). Perhaps amphipoda use algae as a food source and in turn become food for arrow gobies. In addition, algae may provide a refuge from predation by Pacific staghorn sculpins that bare habitat would not.

Flatfishes (butter sole, English sole, speckled sanddab, starry flounder)

Other research has shown that estuaries are important nursery habitat for English sole and speckled sanddab, and central California estuaries contribute more to the near-shore adult population than would be expected based on the area of available sandy habitats (Brown, 2003; 2006). All flatfishes sampled during this study were classified as juveniles based on standard length (Love, 1996; Ford, 1965; Pearson and Owen 1992; Orcutt, 1950) and occurred in low abundances (Fig. 2.7). Flatfishes were predominantly caught during winter and were distributed across both *Zostera* and bare habitats. Butter sole were the most abundant flatfish species and five individuals were observed in bare habitat during winter. One starry flounder was observed in bare habitat during winter. Of the species distributed across habitats, English sole and speckled sanddab, total abundance within *Zostera* was twice the abundance in bare habitat. *Zostera* may be providing a refuge for some individuals, but there was not enough data to conclude *Zostera* was specifically providing nursery habitat for flatfishes within Elkhorn Slough.

CONCLUSION

Species richness and heterogeneity were greatest within *Zostera* for the entire year. Richness within *Zostera* increased from winter to fall while heterogeneity and evenness declined. Algae and bare habitats had fewer species present but evenness was greater than within *Zostera* habitat. Of all habitats sampled bare habitat produced the greatest proportion of empty traps.

Patterns of species distributions among habitats and over time suggest habitat utilization differs throughout the lower slough region. Some fishes exclusively used *Zostera* as habitat but invertebrates were not exclusive to any habitat. Some fishes and invertebrates were distributed across habitats but were found to be more frequent within vegetated (*Zostera* or algae) habitats. No species were exclusive to ephemeral algae habitat, and no taxa were found more frequently in bare habitat than within *Zostera* or algae habitat. *Zostera* may provide nursery habitat within Elkhorn Slough for certain fish species. A high proportion of juvenile fishes were found within *Zostera*, mainly during the later part of the year.

Pacific staghorn sculpin potentially used *Zostera* as nursery habitat, over time size of individuals increased toward size at maturity and abundance decreased. This indicated fish were leaving *Zostera* and recruiting to adult habitats when they reached maturity, or they may be a diet item for larger fish and birds foraging within *Zostera*. Bay pipefish were exclusive to *Zostera*, and all life stages were found within *Zostera* throughout the year. Three-spined sticklebacks showed patterns in abundance and size that suggested use of *Zostera* as nursery habitat within the slough during spring/summer and fall coincident with a life history strategy that would favor *Zostera* as nursery habitat (Wootton, 1976). Shiner surfperch may also use *Zostera* as a nursery habitat during summer.

Flatfishes and burrowing fish utilized non-*Zostera* habitats, algae and bare habitats, more than *Zostera*. Elkhorn Slough is an important nursery for some flatfishes (Brown, 2003; 2006), and all were present as juveniles during the early part of 2008. Although patterns of habitat use by flatfish did not suggest *Zostera* plays a direct role as nursery habitat, the ecological role that *Zostera* plays in stabilizing sediments and combating erosion in Elkhorn Slough may be indirectly benefiting other flatfish nursery habitats within the slough. Arrow gobies were the only burrowing fish sampled in this study, and were most abundant within algae habitat. Algae habitat may be provide a refuge from predation as well as a food source for the arrow goby (amphipoda).

This study indicated *Zostera* was an important habitat for resident and migratory species of fishes as well as mobile invertebrates within Elkhorn Slough throughout the year. Habitat-modifying properties of *Zostera* potentially provided important physical and biological ecosystem services to the species assemblage of Elkhorn Slough, and I predict the Elkhorn Slough ecosystem would be less diverse and robust without the presence of *Zostera*.

SUMMARY

The *Zostera* population and distribution within the lower reaches of Elkhorn Slough may have been influenced by large-scale erosion events over the past 50 years, but the plants and beds are dynamic in response to environmental pressures and seem to be resilient over time. *Zostera* may be expanding and re-colonizing shallow areas of Elkhorn Slough. The amount of habitat available to *Zostera* is susceptible to erosion in the lower slough, and the *Zostera* population must be able to respond and adapt according to the changing hydrographic regimes. Organisms using *Zostera* as habitat may be negatively affected by changes to *Zostera* habitat caused by tidal erosion (lack of submerged vegetation, increased flow velocities), and algae or bare habitat would not provide the same ecosystem services as *Zostera.* If the *Zostera* population within the lower reaches of Elkhorn Slough is able to expand to recover suitable habitat, the species assemblage may benefit from ecosystem services provided by the seagrass.

The species assemblages changed over time in all habitats sampled during this study. Species distributions suggested *Zostera* was an important habitat for both permanent and migratory species of fish using Elkhorn Slough, and some of these species might rely on *Zostera* as nursery habitat. Most importantly, *Zostera* should be monitored and included in future studies of erosion and habitat change in Elkhorn Slough since the plant provides habitat for fish and invertebrates but is also susceptible to erosion and tidal scour.

APPENDIX I. SAMPLING CONDITIONS DURING *ZOSTERA* MAPPING EVENTS

map event	date	time	tide range (m)	tidal phase	change in surface elevation (m) at LO1	LO1 tidal flow velocity (cm/sec)	boat	time spent (hrs)	# of points
spring 2007	5/4/07	10-12:00	0.4-0.8	flood	0.69	23.4	canoe	2	93
fall 2007	9/13/07	14:00-15:40	1.2-0.8	ebb	0.84	28.5	whaler	1.75	189
winter 2007	12/16/07	11:15--12:27	0.9-1.0	flood	0.25	8.4	whaler	1	36
winter 2007	1/16/08	11:15-12:47	0.2-0.2	low	0.26	8.7	whaler	1.5	57
spring 2008	3/14/08	10:00-13:00	0.3-(-0.1)	low>flood	0.27	9.1	slough boat	3	306
summer 2008	7/19/2008	6:00-7:30	(-0.2)-0	low>flood	0.3	10.3	canoe	1.5	152
fall 2008	10/14/08	14:30-16:36	0.5-0	ebb>low	0.63	28.4	slough boat	2	303
fall 2008	10/15/08	15:37-17:45	0.4-(-0.1)	ebb>low	0.41	27.6	slough boat	2	275

APPENDIX II. FISHES: SIZE (mm) AT MATURITY

Species common name	Species latin name	Size at maturity (mm)	Reference
arrow goby	*Clevelandia ios*	18	Moser, G.H. 1996. The early stages of fishes in the CA current region. CALCOFI atlas No.33: 1217-1221.
Pacific staghorn sculpin	*Leptocottus armatus*	120	Jones, A.C. 1962. The biology of the euryhaline fish *Leptocottus armatus* Girard. University of California Publications in Zoology 67: 321-367.
bay pipefish	*Syngnathus leptorhynchus*	100	Bayer, R.D. 1980. Size, Seasonality and Sex Ratios of the Bay Pipefish (*Syngathus leptorhynchus*) in Oregon. Northwest Science Vol. 54:161-167.
shiner surfperch	*Cymatogaster aggregata*	<50 juvenile, 50-80 transitional, 80-120 adult	Shaw, E. 1971. Evidence of sexual maturation in young adult shiner perch, *Cymatogaster aggregata* Gibbons (Perciformes, Embiotocidae). American Museum Novitates 2479:1-10.
black surfperch	*Embiotoca jacksoni*	120	Schmitt, R.J. and S.J. Holbrook. 1984. Ontogeny of prey selection by black surfperch *Embiotoca jacksonii* (Pisces: Embiotocidae): the roles of fish morphology, foraging behavior, and patch selection. Marine Ecology Progress Series 18:225-239.
dwarf surfperch	*Micrometrus minimus*	50	Tarp, F. H. 1952. A revision of the family Embiotocidae (the surfperches). Calif. Div. Fish Game Fish Bull. 88. Bernardi G., and G. Bucciarelli. 1999. Molecular Phylogeny and Speciation of the Surfperches (Embiotocidae, Perciformes). Molecular Phylogenetics and Evolution. Vol. 13: 77-81.
three-spined stickleback	*Gasterosteus aculeatus*	30-35	Wootton, R.J. 1976. Biology of the Sticklebacks. Academic press, New York. 387p.
kelpfish	*Gibbonsia sp.*	240 max size	Milton Love-1996 ‘Probably more than you want to know about the fishes of the Pacific coast’ -there is no age and growth data on this species in

			particular but the giant kelpfish juveniles range from 50-80mm
plainfin midshipman	*Porichthys notatus*	Males-180, Females-140	Phillips, A.C. 1973. Age determination and growth rate studies of the northern midshipman (*Porichthys notatus* Girard). B.S. Thesis, University of Victoria. 41 p.
KGB (kelp-gopher-black-and-yellow complex) rockfish	*Sebastes sp.*	160	Coyer, J.A. 1979. The invertebrate assemblage associated with *Macrocystis pyrifera* and its utilization as a food source by kelp forest fishes. Ph.D. Thesis, University of Southern California. 364 p.
butter sole	*Isopsetta isolepis*	Males-102, Females-254	Milton Love-1996 'Probably more than you want to know about the fishes of the pacific coast'
speckled sanddab	*Citharichthys stigmaeus*	70	Ford, R.F. 1965. Distribution, population dynamics and behavior of a Bothid flatfish, *Citharichthys stigmaeus*. Ph.D. Thesis, University of California San Diego. 243 p.
English sole	*Parophrys vetulus*	250	Pearson, D.E. and S.L. Owen. 1992. English sole. In: W.S. Leet, C.M. Dewees, and C.W. Haugen (Editors), California's living marine resources and their utilization, p. 99-100. California Sea Grant Extension Program, Department of Wildlife and Fisheries Biology, University of California, Davis, California Sea Grant Extension Publication UCSGEP-92-12.
starry flounder	*Platichthys stellatus*	330	Orcutt, H.G. 1950. The life history of the starry flounder, *Platichthys stellatus (Pallas)*. State of California department of natural resources, division of fish and game bureau of marine fisheries. Fish bulletin No. 78
topsmelt	*Atherinops affinis*	100	Schultz, L.P. 1933. The age and growth of *Atherinops affinis oregonia* Jordon and Snyder and of other subspecies of baysmelt along the Pacific coast of the United States. University of Washington Publications in Biology 2(3): 45-102.

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