CALIFORNIA
COOPERATIVE
OCEANIC
FISHERIES
INVESTIGATIONS

Reports

VOLUME 53
JANUARY 1 TO DECEMBER 31, 2012

Cooperating Agencies:

CALIFORNIA DEPARTMENT OF FISH AND GAME
UNIVERSITY OF CALIFORNIA, SCRIPPS INSTITUTION OF OCEANOGRAPHY
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION, NATIONAL MARINE FISHERIES SERVICE

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Printed and distributed December 2012, La Jolla, California
ISSN 0575-3317

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REPORTS, REVIEW, AND PUBLICATIONS

REPORT OF THE CALCOFI COMMITTEE 2011

CDFG HIGHLIGHTS

Marine Regulatory Changes

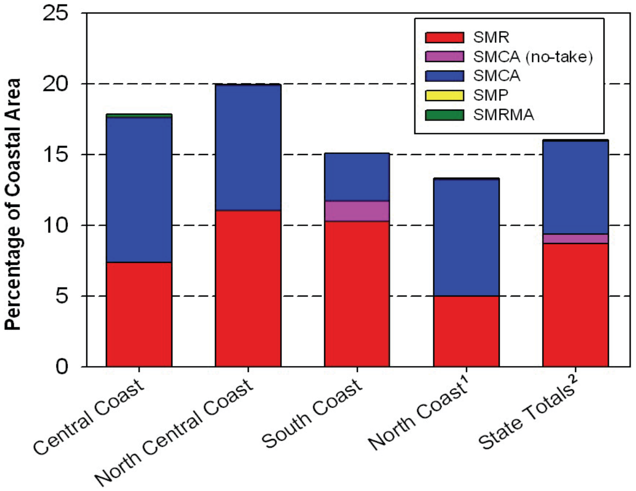
In 2011, the California Fish and Game Commission undertook 14 rule-making actions that addressed marine and anadromous species. The Commission adopted changes to commercial or sport fishing regulations that include ocean and inland salmon, herring, greenling, abalone, and Kellet's whelk.

Marine Life Protection Act

The Marine Life Protection Act (MLPA) mandates the re-examination and redesign of a network of Marine Protected Areas (MPAs) for California. The MLPA is being implemented in five planning regions encompassing the entire California coastline, including San Francisco Bay. In 2011, the goal for a statewide network of MPAs is nearing completion with the implementation of 29 MPAs in the central coast, 25 MPAs and seven special closures in the north central coast, and 50 MPAs (including those previously adopted in the northern Channel Islands) and two special closures in the south coast. Adoption for the 20 proposed MPAs and seven special closures in the north coast is expected summer 2012. Implementation of north coast MPAs and special closures will result in an improved statewide network comprised of 124 MPAs and 16 special closures covering approximately 848 square miles or 16% of state ocean waters. With regard to longer term management, in March 2011 CDFG convened the "Marine Protected Areas and Fisheries Integration Workshop" to elicit input from a broad range of scientists on fisheries management and MPAs. The CDFG continues to play a role in the long term monitoring efforts of MPAs through close affiliation with the California MPA Monitoring Enterprise and by pursuing a CDFG based subtidal monitoring program using scuba and ROV, as well as database management.

Ocean Protection Council

The Ocean Protection Council (OPC) approved a $990,000 grant to the nonprofit California Wildlife Foundation to support the Department's development of a spiny lobster Fishery Management Plan. The OPC is also working closely with California Sea Grant and CDFG to fund MLPA and baseline monitoring of the new network of MPAs in state waters.



[1] Based on MPAs in the north coast preferred alternative, and may be subject to change depending on the final north coast MPAs that are adopted.

[2] State totals include all MPAs in effect in the central coast, north central coast, and south coast regions and MPAs in the north coast preferred alternative under Commission consideration; they do not include existing MPAs in San Francisco Bay or special closures. Special closures were integrated into the MPA designation process and were used to provide further protections that would not otherwise be afforded by MPA designation within the same geographical location.

Coastal Pelagic Species

The market squid fishery had another banner year in which the harvest guideline was reached for the second year in a row. Staff participated in monitoring and tracking fishery landings to ensure a timely closure in response to the guidelines. Staff attended the second Sardine Otolith Workshop which resulted in plans to formalize the organization to further methods in CPS otolith research. CPS staff assisted with the Pacific mackerel stock assessment, where California Recreational Fishery Survey data was used for the first time as a fishery dependent index of abundance.

Aquaculture and Bay Management

The Aquaculture and Bay Management Project completed its annual monitoring and assessment activities for the San Francisco Bay commercial Pacific herring fishery for the 2011–12 season. The spawning biomass estimate for the 2011–12 season is 60,987 tons, well above the historical average (1978–79 season to the present) of 49,670 tons. Though the herring population has increased significantly since the historic 2008–09 season population low of 4,844 tons, the Department remains concerned about the low percentage of five- and six-year-old herring in the spawning population. Due to the ongoing age structure concerns, the Department will continue to recommend precautionary management principles for safeguarding the spawning population. As a result, for the 2012–13 season, the Department is recommending that the Fish and Game Commission adopt a conservative harvest rate of 5% of the 2011–12 spawning biomass. This would allow for a quota of 2,854 tons.

Invertebrate Fisheries Management

The Dungeness crab trap limit program was implemented in 2011 with the passage of SB 369. The Department was tasked with developing a set of rules to implement this tiered trap allocation system for the 2013 crab season. There will be seven tiers with the highest tier allocation set at 500 traps and a system of colored and numbered buoy tags used to identify vessels and their tier.

The Department and the FG Commission worked together to proactively manage the emerging Kellet's whelk fishery. New regulations were approved in 2011 that will set a total allowable catch and a closed season in the spring to protect spawning and egg-laying aggregations.

The stock assessment element of the spiny lobster fishery management plan was completed in 2011. The Department's Doug Neilson collaborated with Mexican fishery biologists in adapting their size-structured Fishery Simulation Model (FISMO), based on von Bertallanfy growth and Beverton-Holt recruitment, for southern California. In the model, the lobster stock was sustainable at present sport and commercial fishing levels.

An unprecedented die-off of marine invertebrates occurred coincident with a harmful algae bloom (aka red tide) along the Sonoma County coast in August, 2011. Significant numbers of red abalone, sea urchins and other invertebrate species were affected. At Fort Ross, red abalone populations are estimated to have been reduced by 30 percent, while at other Sonoma Co. sites such as Salt Point, mortality estimates ranged from 12 to 25 percent. The majority of dead abalone were found in depths <10m. The FG Commission issued an emergency closure of the red abalone fishery in Sonoma County closing the remainder of 2011 season.

Ocean Salmon

Ocean salmon fishing regulations were adopted that allowed for a fishing season, and inland salmon season regulations were adopted for the Central Valley, and Klamath and Trinity Rivers. This represents the first restoration of the traditional salmon fishery throughout California since major closures were enacted in 2008 and 2009 (for both ocean and inland waters) in which virtually no fishing was allowed because of low abundance forecasts and poor returns of fish to the Sacramento River Basin.

Groundfish

In 2011, the Groundfish Project prepared environmental documents for the 2013–14 federal biennial groundfish regulations for the Pacific Fishery Management Council including developing and analyzing regulatory options. California's representative on the Council's Scientific and Statistical Committee focused on Council-related discussions and reviews, including but not limited to: stock assessments, harvest specifications, essential fish habitat, and exempted fishing permits. At the state level, staff prepared regulation changes for greenlings, which went into effect in 2012, to provide increased harvest limits based on new information and increased federal limits. Lastly, staff prepared a manuscript submitted to Fish Bulletin that documents all of California's commercial historical landings from 1987–99. This paper completes the published information on commercial landings in California from 1916 to 2010.

The statewide total allowable catch for kelp greenling was increased from 37,600 pounds to 121,900 pounds with up to 55,400 pounds allowed for the commercial fishery and up to 66,500 pounds allowed to be taken recreationally. In the recreational fishery, the Greenling limit increased from two to ten fish.

California Recreational Fisheries Survey

The California Recreational Fisheries Survey (CRFS) and the Recreational Fisheries Data Project worked to transition California's saltwater sport angler intercept surveys to a California Department of Fish and Game program. In 2011 the projects jointly developed data entry and estimation programs for the commercial passenger fishing vessel (CPFV) mode of fishing, entered data that was collected dockside and onboard CPFVs, and produced estimates of total catch and effort. An independent review of CRFS sampling methods and estimation procedures was conducted by consultants hired by NOAA Fisheries' Marine Recreational Information Program.

The consultants concluded it is "a well-designed and executed program" and provided recommendations for improvements.

California Finfish Research and Management Project

The first statewide stock assessment for California halibut was completed by Dr. Maunder in 2011. Project staff provided data sets and worked with Dr. Maunder throughout the process and peer review. The stock assessment, Peer Review Panel Report and History of Fishery Regulations, were placed on the project web site in August 2011 (http://www.dfg.ca.gov/marine/sfmp/halibut-assessment.asp). The status of the halibut biomass north of Point Conception was relatively high with several recent recruitment events. Favorable environmental conditions appear to be driving recruitment and fishing was not considered to be a significant negative factor impacting biomass. South of Pt. Conception, the halibut population was estimated to be depleted at 14% of historic levels. The population was considered depleted at the start of the assessment period (1980) due to historic exploitation. Staff communicated the results of the stock assessment to the FG Commission as well as conducted three public workshops in southern California.

Preliminary results from a three year surf fish study consisting of 364 beach seine hauls at four southern California beaches indicate barred surfperch abundance has greatly declined since the 1950s, while leopard shark abundance has increased. Staff completed a report on barred sand bass spawning habitat characteristics at Huntington Flats during peak spawning season. It appears strong tidal fluxes and the development, persistence, and temperature of the thermocline may directly influence spawning aggregation formation. For more information see http://www.dfg.ca.gov/marine/scuba/index.asp.

SIO HIGHLIGHTS

This past year saw the Scripps CalCOFI program transition to NOAA funding through the new Cooperative Institute for Marine Ecosystems and Climate (CIMEC). Although this transition entailed a significant increase in the overhead rate charged for non-ship and equipment items, NOAA funding maintained the program at its current level of services, despite the difficult fiscal climate. The CalCOFI Committee views this as a strong endorsement of the program's value to the ocean science and management community.

Four CalCOFI cruises were carried out successfully over the last 12 months. A comprehensive range of ancillary measurements are now made on the cruises, funded by the California Current Ecosystem Long-Term Ecological Research Program (CCE LTER), the Southern California Coastal Ocean Observing Program (SCCOOS), the U.S. Navy, and private sources: enhanced coastal station coverage; the carbon cycle, including underway pCO_2, alkalinity, CO_2 and pH; particulate and dissolved carbon and nitrogen; bio-optical properties; phytoplankton community structure from HPLC, microscopy, and Advanced Laser Fluorescence (ALF); bacteria and picoautotrophs from flow cytometry; nano- and microheterotrophs from microscopy; mesozooplankton species groups and size composition from microscopy and Zooscan image analysis; micronekton from multifrequency acoustics and pelagic trawling; seabirds from visual observations; and marine mammals from passive acoustics and visual observations. These measurements, in addition to standard CalCOFI measurements of temperature, salinity, oxygen, nutrients, and chlorophyll with CTD and bottle measurement, primary production, zooplankton and ichthyoplankton, enables CalCOFI cruises to monitor physical processes, biogeochemical cycles and major ecological groups within the southern California Current. The CalCOFI Committee is committed to making these data sets available to marine research and management communities, in particular to nascent efforts to develop ecosystem-based management of the California Current.

NOAA HIGHLIGHTS

CalCOFI Ichthyoplankton Update

During the past year the SWFSC Ichthyoplankton Ecology laboratory continued to retroactively update identifications of fish eggs and larvae to current standards from 1951 to the present. Identification of Pacific whiting (hake) and jack and Pacific mackerel eggs collected in the oblique net samples are now complete from 1984 to the present, and identifications of all larvae have been updated from 1966 to the present.

We have identified market squid paralarvae from CalCOFI bongo samples since 1997 and from neuston samples dating back to1981. All cephalopod paralarvae have been identified since 2008. The presence or absence of jumbo squid paralarvae has been of interest in recent years; no ommastrephid paralarvae were collected in 2011, and none has been since the summer of 2008.

We collaborated with Ron Burton and his students at SIO on the development of a high-throughput system for molecular identification of ichthyoplankton. The ultimate aim of this project is to provide accurate, near real-time identifications of fish eggs, which often are difficult or impossible to identify to species using traditional morphological characters. When fully developed, this method will enable us to accurately identify the spawning locations of several taxa that are valuable to sport or commercial fisheries such as Pacific hake, Pacific mackerel, white seabass and California barracuda. These

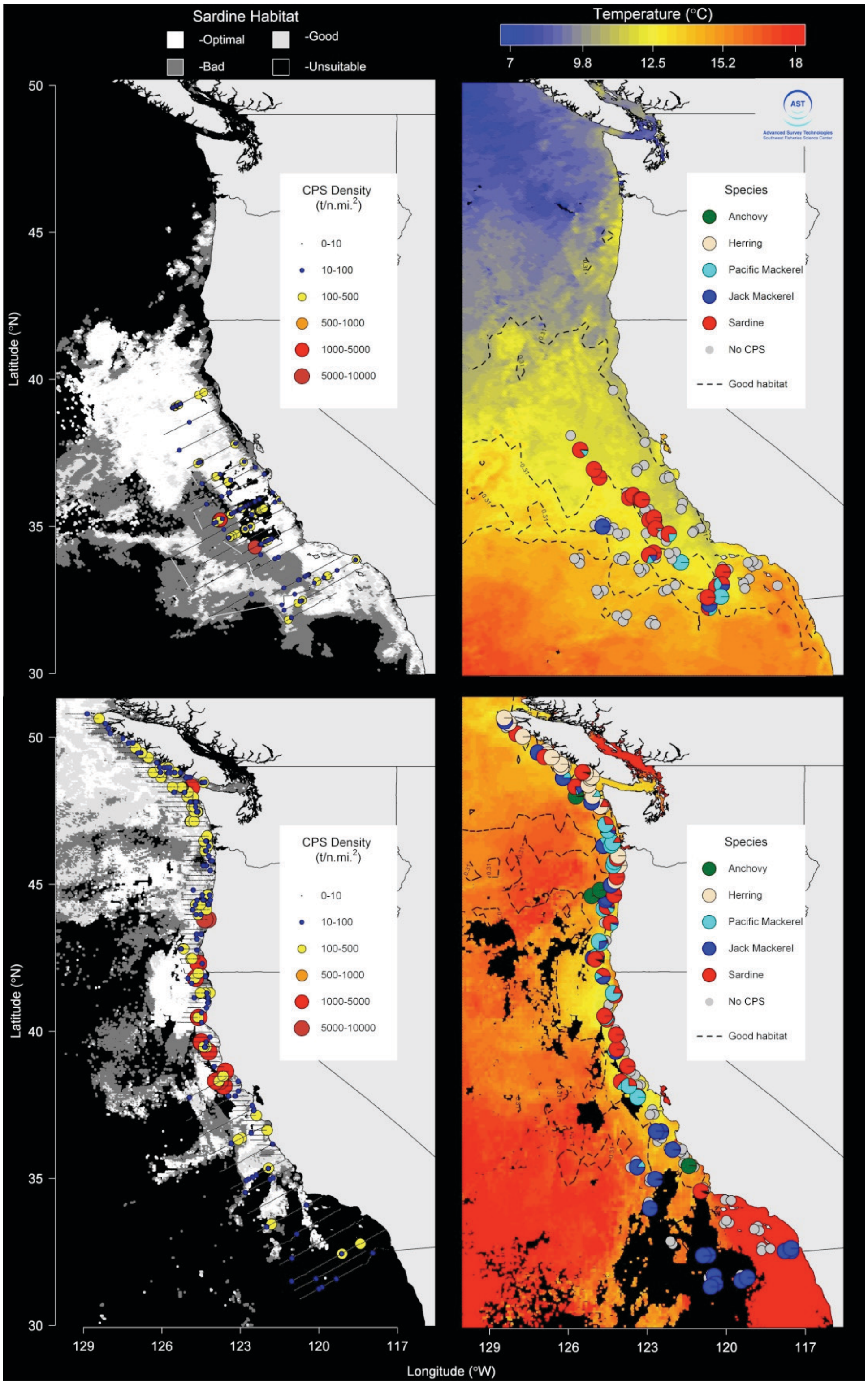


Figure 1. Mass densities of coastal pelagic fish species (CPS; left); and proportions of CPS in trawl catches (right) from the spring (top) and summer (bottom) Acoustic-Trawl-Method (ATM) surveys.

techniques will be applied to ethanol-preserved CalCOFI samples to develop a time series for eggs from 1997 to the present. During the past year we completed sorting eggs and larvae from ethanol-preserved samples from winter cruises in 2002, 2003, and 2005. We analyzed the larval fish assemblage from the winter CalCOFI cruises in 2002–04, which coincided with detailed sampling within the Cowcod Conservation Area (CCA), a marine reserve embedded within the core CalCOFI sample frame. We evaluated assemblage dynamics from both the relatively large (CalCOFI) and small (CCA) spatial scales and found that the larval fish assemblage changed significantly during a transition from La Niña (2002) to El Niño conditions (2003–04) at the smaller scale, but was relatively stable through time at the larger scale. A manuscript describing these results was published PLoS ONE (7:e33131).

We also collaborated with Nathalie Reyns and a graduate student from USD to evaluate dynamics of bocaccio larvae using samples from the 2002–04 CalCOFI and CCA cruises. Results of this work were published in Marine Ecology Progress Series (465:227–242).

To enhance understanding of how ichthyoplankton respond to environmental variability throughout the California Current system, we are analyzing CalCOFI data together with ichthyoplankton and environmental data collected between 1997 and the present in Oregon by Oregon State University and the NWFSC, and from Baja California by CICIMAR. In collaboration with Toby Auth and Ric Brodeur from Oregon, and Martin Hernandez-Rivas and coworkers from Mexico, we are preparing a manuscript describing these results and will give a talk on them at the 2012 CalCOFI meeting.

Spring and Summer Coastal Pelagic Species cruises

In Spring 2012 another coast-wide survey was conducted using two vessels (*Bell Shimada* and *Ocean Starr*), combining the CalCOFI with Coastal Pelagic Species (CPS) cruise. The spring CalCOFI was conducted aboard the *Bell Shimada*. The spring CalCOFI was plagued by poor weather this year, at times causing *Shimada* to take shelter when significant wave heights reached 4–5 m. Sampling on line 80 was badly affected by heavy weather, as evidenced by the zigzag cruise track. The cruise also started badly for *Ocean Starr* which was stuck in Seattle due to atrocious weather off Washington for almost 5 days. Due to the extensive delay, the *Ocean Starr* begin survey from Cape Mendocino rather than Cape Flattery. Data were collected on lines 50, 53, and 57 between Cape Mendocino and San Francisco, but the weather meant that most of leg one was used in transiting from Seattle to San Francisco. A few sardine were collected in trawls packed with heavy loads of gelatinous zooplankton, but the sardine were not reproductively active.

Four surface drifters were deployed from the *Ocean Starr* at station 93.53 in collaboration with Luca Centurioni's lab at SIO to track currents advecting eggs and larvae. Drifter data will be compared to modeled egg and larval drift derived from GCM and ROMS models outputs from SIO (Bruce Cornuelle and Art Miller's groups).

The second leg of the spring coast-wide ecosystem survey on *Shimada* sailed from San Diego on April 12. Due to low abundance of sardine eggs in the area offshore from the Southern California Bight, the survey lines were adjusted to focus on the central California coast. Egg counts from CUFES obtained anywhere this year are low. The trawl net, including the marine mammal excluder (MMED), was lost due to unknown causes on April 18. A replacement MMED for the spare trawl net was constructed aboard *Shimada* to avoid loss of survey time.

The second leg of the survey on *Ocean Starr* sailed from San Francisco on April 7 following repairs to the marine mammal excluder device and adjustment of the position of the trawl net roller. Trawls could then be retrieved more efficiently despite heavy catches of gelatinous zooplankton. The CTD unit on *Ocean Starr* malfunctioned but a replacement unit was obtained for leg three from the SWFSC Antarctic Division.

The spring coastwide ecosystem survey on *Shimada* ended on April 30 and on *Ocean Starr* ended on April 29. Both vessels returned to port in San Francisco. The final weekend brought more rough weather and some damage to the trawl on *Shimada*. Objectives of the survey in the region to the south of Cape Mendocino were generally achieved, despite a bad start due to mechanical problems experienced on *Shimada*, followed by poor weather that affected both vessels. As in 2010 and 2011, the sampling between Cape Mendocino and Cape Flattery did not meet planned objectives.

An even more extensive coastwide survey was conducted from these two vessels in summer 2012. *Ocean Starr* leg one (CalCOFI) sailed on July 2 with 4 SWFSC staff aboard (Dave Griffith, Amy Hays, Bryan Overcash, and Josiah Renfree). The cruise suffered delay due to cable problems on the CTD winch. The SIO CTD/rosette was recovered intact from deployment, with some difficulty. This occurred at the very beginning of the cruise causing the vessel to return from an inshore station on Tuesday evening and to moor in San Diego Bay. Repairs were completed and the summer CalCOFI leg sailed again on July 9, delayed by a week. *Ocean Starr* leg one (CalCOFI) ended in San Diego on Friday July 27 and the Coastal Pelagic Species part of the cruise sailed from San Diego on Monday July 30. The second generator required to operate winches failed on August 2, necessitating another return to San Diego for 24 hours. *Ocean Starr* legs two and three (CPS) then continued without incident. There were few fish eggs collected by CUFES, but occasionally there were modest numbers of jack mackerel, sanddabs, *Vinciguerria*, and possibly Dover sole. CUFES counts were dominated by pelagic squid eggs. Trawl catches were dominated by market squid of a variety of sizes, and an occasional catch of jack mackerel.

Ocean Starr arrived at Port Hueneme early on Wednesday August 29. Sam McClatchie and 11 SIO technicians, scientists, and students from Uwe Send's lab spent the next three days maintaining and redeploying subsurface moorings prior to returning to Port Hueneme for the start of the Island wake study. Despite quite rough weather, work proceeded to plan. The SIO group of Uwe Send has developed a new method for obtaining near-real-time data from subsurface moorings by using a spray glider to download the data from the mooring using an underwater acoustic link, and then rising to the surface to transmit the data from the glider via satellite to shore. The glider loiters at 500 m depth in between it's daily data delivery ascents, thereby saving batteries and permitting the glider to be on duty at the mooring for a full year.

Ocean Starr leg four (Island wake study) began on Sunday, September 2 after disembarquing 11 SIO mooring staff from Uwe Send's group following the 3-day mooring cruise. The goal of the Island wake study was to determine if juvenile fishes were associated with productivity hot spots around the Channel Islands. The cruise was a successful multidisciplinary collaboration between SWFSC (fisheries oceanography, ship operations, ichthyoplankton, and Advanced Survey Technology) and SIO (Marine Physical Lab, mooring group, drifter group, and marine mammal acoustics). Preliminary results revealed no juvenile fish hot spots. Instead we encountered a flatfish larva hot spot between Santa Cruz and Santa Rosa Island, and a remarkable concentration of blue, fin and humpback whales feeding to the west of Santa Rosa Island. The zooplankton were dominated by several species of salps. The glider resolved internal waves in the area to the west of the islands, and drifters showed eddying at several spatial scales in the wake from the Channel Islands.

The 2012 field season has been an extraordinary effort by the SWFSC ship operations team. Amy Hays spent 134 days at sea, Sue Manion spent 131 days, and Dave Griffith spent 121 days at sea.

Spring and Summer Acoustic-Trawl-Method Surveys

During both the spring and summer, the SWFSC conducted Acoustic-Trawl-Method (ATM) surveys for coastal pelagic fish species (CPS), e.g., sardine, jack and Pacific mackerel, anchovy, and herring. Sampling during spring was focused on the spawning aggregation of sardine, offshore between San Diego and San Francisco, California (CA); sampling during summer was focused nearshore between central CA and Vancouver Island (VI), Canada.

The ATM uses ship-based, multiple-frequency echosounders to map the distributions of CPS; and trawl catches to apportion the echo energy to species and convert those values to animal densities. During daylight, from sunrise to sunset, multifrequency echosounders (38, 70, 120, and 200 kHz) were used to sample acoustic backscatter from CPS. During nighttime, surface trawls were used to identify the proportions of CPS and their lengths. The data were combined to estimate density-weighted fish-length distributions. This procedure resulted in maps of fish densities and estimates of their biomasses, by species and lengths (presented elsewhere).

The spring ATM survey was conducted from NOAA FSV *Bell M. Shimada* and chartered FV *Ocean Starr.* The ATM survey totaled 2,248 nmi of trackline spanning over 51,327 nmi^2 and the distribution of the northern stock of sardine predicted by a model of potential sardine habitat (fig. 1, top left). Sardine catches spanned the latitudinal extent of the survey, but were not found in the coastal region and the far offshore oceanic transects (fig. 1, top right).

The summer ATM survey was conducted from NOAA FSV *Bell M. Shimada* and chartered FV *Ocean Starr* off the west coasts of the USA and Vancouver Island, Canada: Leg I: 24 June–6 July; Leg II: 9–25 July; Leg III: 30 July–12 August; and Leg IV: 15–24 August. The ATM survey totaled 3,632 nmi of trackline spanning over 39,614 nmi^2 and the expected distribution of the northern stock of sardine (fig. 1, bottom left). Transects were spaced 10 nmi, generally, extending from 40 to 1500 m depths, to at least 35 nmi offshore.

During the summer ATM survey, the habitat in the Southern California Bight was unsuitable for the northern stock of sardine, and was bad during August off the west coast of VI (fig. 1, bottom left). CPS densities were low south of Monterey, higher from central CA to central Oregon (OR); and relatively uniform and low off Washington (WA) and VI. The region off northern CA and southern OR contained the largest concentration of CPS backscatter (fig. 1, bottom left). Jack mackerel were mostly offshore of southern and central CA; sardine were mostly between San Francisco and central OR; anchovy were patchy off central CA, central OR, and near the Strait of Juan de Fuca; and herring were offshore of WA and VI (fig. 1, bottom right).

Shark Surveys

The SWFSC's shark research group is responsible for collecting data to support the management of blue (*Prionace glauca*), shortfin mako (*Isurus oxyrinchus*), and common thresher sharks (*Alopias vulpinus*), all of which are common in off the U.S. West Coast and taken in regional fisheries, primarily as juveniles. Common thresher and mako sharks have the greatest commercial value and are also targeted by sport fishers. Although the blue shark has little market importance in the United States, it is a leading bycatch species in a number of U.S. fisheries and is targeted in Mexico. One of the primary methods used by NOAA Fisheries to collect data on the three species is fisheries independent surveys. These surveys provide catch data that allow us to track trends in abundance. Use of fisheries data alone for estimating population status is complicated by changes in regulations, fishing methods, and areas over time. The surveys also provide the opportunity to deploy conventional and electronic tags, obtain biological samples and conduct studies on age and growth.

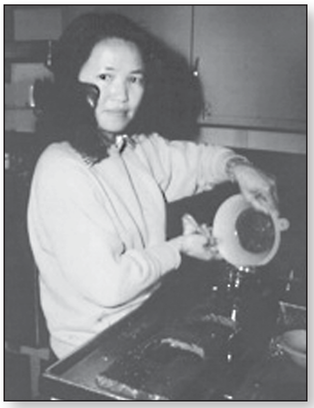
In June and July 2012, the SWFSC conducted its annual juvenile mako and blue shark abundance survey in the Southern California Bight. Working aboard FV *Ventura II*, the team of scientists and volunteers fished a total of twenty-eight survey sets with 5,592 hooks. Survey catch totaled 115 shortfin mako sharks, 26 blue sharks, 16 pelagic rays (*Pteroplatytrygon violacea*), and 4 opah (*Lampris guttatus*). The preliminary data indicate that the nominal survey catch rate was 0.535 per 100 hook-hours for shortfin mako and 0.150 per 100 hook-hours for blue sharks. The mako shark nominal CPUE was slightly higher than the previous year. However, there is a declining trend in nominal CPUE for both species over the time series of the survey.

Twenty eight additional longline sets and several hours of trolling each day were also conducted in areas beyond the survey sampling blocks for other highly migratory species life history studies. A total of 423 animals were caught during survey and ancillary sampling throughout the course of the cruise. Most animals were brought onboard and measured, tagged, and a DNA sample was collected before they were released. Spaghetti tags were released on 338 sharks for movement and stock structure data. A total of 387 DNA samples were collected, including samples from 254 shortfin mako, 92 blue shark, 29 opah, 9 pelagic rays and 3 common thresher. Opah is one species that has been caught in relatively high numbers in recent years. Fourteen opah were caught in 2011, sixteen in 2010, and eight in 2009. Prior to 2009, only one other opah had been recorded during a longline survey cruise. As opah are also one of the more commonly taken species in the swordfish drift gillnet fishery in recent years, the SWFSC has initiated a number of biological studies on opah including popoff tagging and respiratory physiology studies.

In September 2012, the SWFSC conducted its annual thresher shark nursery area survey in the Southern California Bight. Fifty nearshore longline sets were conducted aboard the FV *Outer Banks* over 18 days between Point Conception and the US/Mexico border. This survey continues an annual time-series started in 2006 tracking the relative abundance of thresher shark pups and juveniles (ages 0–2) in waters of less than 25 fm. The nominal catch rate for threshers was slightly down from 2011, the year with the highest catch rate for the time series so far. Nevertheless, over 260 threshers were caught tagged and released for movement and stock structure data, DNA samples were collected for genetic population studies, blood was collected from several animals for a collaborative study with NWFSC examining domoic acid levels, and a towed GPS positioning tag was released on a healthy threshers to examine detailed movement and migration patterns. Morphometric information and biological samples were collected from the few non-surviving animals in support of ongoing life history and feeding habits studies. Pacific mackerel were also collected for an ongoing reproductive maturity study.

The CalCOFI Committee
Tony Koslow, SIO
Laura Rogers-Bennett, CDFG
Sam McClatchie, NMFS

NANCY LO RETIRES AFTER 38 YEARS



Processing samples aboard the *R/V Jordan* in the early 1980's.

Nancy C. H. Lo retired from Southwest Fisheries Science Center, National Marine Fisheries Service at the end of 2011 after 38 years of working as a biometrician in marine fishery science. CalCOFI has no greater friend or advocate. After receiving her PhD in statistics from Oregon State University in 1972, she worked as a statistical method analyst with the California Department of Fish and Game (CDFG), Menlo Park, California from 1973–76. In 1976, she and her family moved to San Diego to join the Southwest Fisheries Science Center (SWFSC), National Marine Fisheries Service as the mathematical statistician in the Marine Mammal Division even though she had never heard of La Jolla and knew nothing about porpoises. In 1980, she transferred to the Coastal Fishery Division (presently the Fisheries Resources Division), where she remained for the rest of her career. The Fisheries Resources Division is the federal partner in the CalCOFI program. The Division has the responsibility of ensuring that the information collected by the CalCOFI surveys is in a form that can be used directly in the management of fishery stocks. Consequently much of her work was closely tied to CalCOFI, focusing on analysis of plankton survey data and quantification of new survey methodologies so that fish egg and larval data could be more effectively used to monitor the relative abundance of commercial species, and interpret their life history. Her research included application of statistical techniques to fishery and marine mammal biology: sampling schemes of fishery-independent sea surveys; estimation of biological parameters; and spawning biomass estimates, in particular using the daily egg production method (DEPM) for coastal pelagic species (CPS), which has been an input time series to the stock assessments of northern anchovy and Pacific sardine.

To improve survey efficiency, Nancy developed an adaptive allocation survey design for Pacific sardine DEPM-ichthyoplankton-trawl surveys, using the Continuous Underway Fish Egg Sampler (CUFES) developed by David Checkley. This design requires only a fraction of the ichthyoplankton tows that would be required by the traditional fixed-station design to achieve the same precision of the estimates of parameters used in the DEPM spawning biomass. Data from CUFES provide an instant spatial map of CPS eggs during the survey.

In addition to DEPM spawning biomass of CPS, she collaborated with other scientists to estimate vital rates of anchovy and sardines: mortality, growth rates of each life stage, fecundity rates, and to evaluate the sensitivities of changes in vital rates on the population growth of anchovy and sardines using the stage-specific matrix model. She strongly believes that through the vision of CalCOFI and it's founding ecosystem and oceanographic principles, the CPS populations of the California Current are now monitored to prevent population collapses, like Pacific sardines in the late 1950s, that led to the formation of CalCOFI. Nancy Lo had also constructed long time series of daily larval production for other species, like hake and Pacific mackerel.

At the SWFSC, laboratory experiments have been conducted for CPS, primarily for anchovy and sardine prior to the 1990s. Nancy developed automation procedures for temperature-dependent stage-to-age and yolk-sac larval growth for anchovy based on data collected from laboratory experiments conducted in 1981. These new methodologies attracted international attention, particularly in countries where monitoring sardines and anchovy stocks had a high priority. This stage-to-age model is now being used and/or modified for sardine and anchovy in other parts of the world, e.g., Korea, Mexico, Peru, Chile, Australia, Spain, Portugal, and Greece. Lo also found that the early larvae of anchovy do not have constant instantaneous mortality rates. As a result, the exponential survival curve was not applicable and an age-dependent survival curve has since been used.

Nancy explored methods other than plankton-based surveys for monitoring the relative abundance of fishes. In 1995, working with Jim Churnside and John Hunter, she explored the feasibility of an aerial survey using lidar (light detecting and ranging) by developing a model to evaluate such a survey approach. She also developed time series data from aerial surveys from com-

Nancy Lo on the balcony of the original SWFSC building in 2012.

mercial spotter pilot logbooks for anchovy, sardine, and Pacific mackerel to construct long time series of relative abundance from 1963-early 2000s. This survey was not statistically designed but has been very useful as a population index. Another area of survey science where Nancy made major contributions was the rescue of long-term time series. Such work involves extending present time series accurately into the past through all the changes in equipment, methodology, and survey pattern that inevitably occur, e.g., extrusion and avoidance of fish eggs and larvae for bongo nets which replaced the 1-m ring nets used by CalCOFI surveys prior to 1978.

Nancy has consistently demonstrated that fishery-independent ichthyoplankton surveys like the CalCOFI surveys are a treasure of information, often on topics that were not part of the original goals, and she has been an advocate and leader over the years to promote the CalCOFI approach worldwide, e.g., the around-Taiwan ichthyoplankton surveys (aka TaiCOFI) from 2003–present, DEPM sardine and anchovy surveys from 1996–2006 in Chile, the ichthyoplankton survey in Ireland in early 2000s, and the Korea-U.S. ichthyoplankon sea surveys (KISS) from 2004–08.

While the CalCOFI ichthyoplankton survey is one of the longest time series in the world, budget reductions have resulted in reductions of areal coverage from central or southern Baja California through central or northern California from 1951–84 to only southern California since then, and a reduction in sampling frequency from monthly to quarterly after 1984. Luckily, the IMECOCAL (Investigaciones Mexicanas de la Corriente de California) survey has been conducted quarterly since October 1997, similar to the current CalCOFI survey schedule and covers the area from the U.S.-Mexican border to Punta Eugenia. Data from IMECOCAL will fill some gaps of the current CalCOFI data. Regardless, the time series from the CalCOFI survey can serve as indices of abundance of fish populations.

Nancy indicated that retirement was a hard decision. She will miss her statistical applications to fishery problems and interactions with staff members of SWFSC and scientists around the world. In addition, she noted she will miss the white-water, oceanfront office that has been her home for over 30 years. However, she feels strongly about passing the baton to the younger generation to carry out projects with new statistical approaches to long-standing fisheries problems. Nancy's greatest contribution will always remain her integrity and fierce defense of quality science as embodied in the CalCOFI program. She has been a role model and an inspiration to several generations of young scientists. As Nancy once noted, being an Asian woman working in statistics and fisheries science, she is an outlier in every respect, and it is the outlier that has the disproportionate influence in most analyses! Nancy will be greatly missed by the CalCOFI community.

REVIEW OF SELECTED CALIFORNIA FISHERIES FOR 2011: OCEAN SALMON, CALIFORNIA SHEEPHEAD, CALIFORNIA HALIBUT, LONGNOSE SKATE, PETRALE SOLE, CALIFORNIA SPINY LOBSTER, DUNGENESS CRAB, GARIBALDI, WHITE SHARK, AND ALGAL BLOOMS

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SUMMARY

In 2011, commercial fisheries landed an estimated 184,825 metric tons (t) of fish and invertebrates from California ocean waters (fig. 1). This represents a decrease of nearly 7% from the 197,956 t landed in 2010, an increase of 15% from the 160,615 t landed in 2009, and a 27% decline from the peak landings of 252,568 t observed in 2000. The preliminary ex-vessel economic value of commercial landings in 2011 was nearly $198 million, which continued the increasing trend in value of California fisheries since 2008, with a 13% increase from the $175 million in 2010, a 37% increase from the $144 million in 2009, and a 37% increase from the $145 million in 1999 which was, until 2010, the highest value observed in the last decade.

Four of the top five volume and valued fisheries were represented by invertebrates in 2011. California market squid remained the largest volume and highest value fishery in the state with 121,555 t landed and an ex-vessel value of more than $68.5 million (table 1). Although this represents a decrease from the nearly 130,000 t landed in 2010 with an ex-vessel value of approximately $73.8 million, 2011 was the second year in a row that the commercial fishery was closed due to the catch limit being reached before the end of the fishing season. In 2011 the fishery was closed on November 18, one month earlier than the December 17 closure in 2010. It is thought that cooler water along the West Coast has provided good squid spawning conditions and an increase in abundance throughout the state. Pacific sardine was the second highest volume fishery with 27,714 t, but only seventh highest in ex-vessel value at $5.4 million. The other top five volume fisheries were Dungeness crab at 9,344 t, red sea urchin at 5,213 t, and pink shrimp at 3,345 t. The other top five valued fisheries were Dungeness crab at $51.5 million, sablefish at $15.1 million, California spiny lobster at $12.9 million, and red sea urchin at $8.1 million.

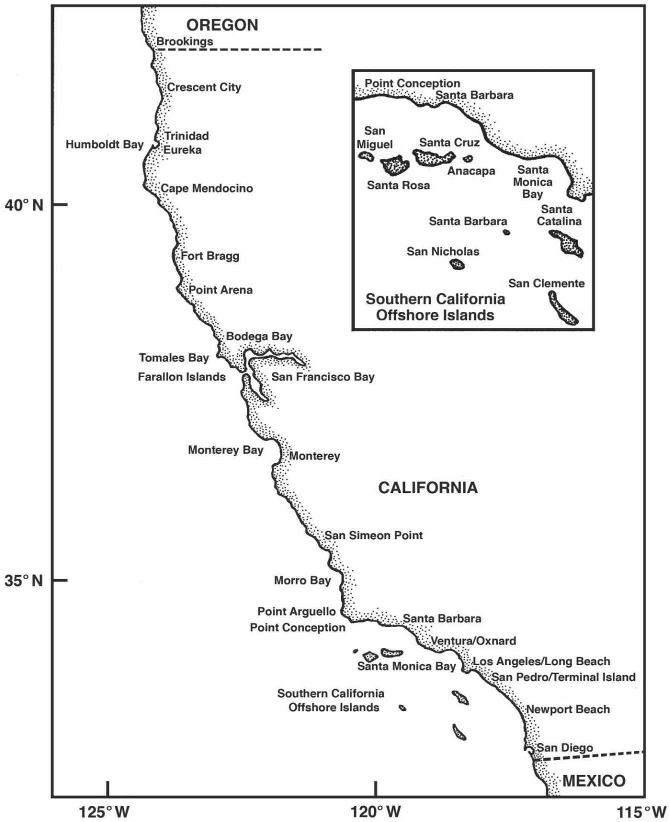

Figure 1. California ports and fishing areas.

In 2011, California ocean salmon fisheries were less constrained than in 2010 due to an increase in the forecasted ocean abundance of Sacramento River fall Chinook (SRFC), which support 80%–90% of California's ocean salmon fisheries. Commercial fisheries had 369 days open to fishing in 2011 compared to 70 days during the 2010 season. Total 2011 commercial landings were estimated at 69,800 Chinook salmon (448 t) with an ex-vessel value of $5.1 million. Recreational fisheries had 209 more days open than in 2010, for a season total of 709 days. An estimated 49,000 Chinook were landed in 2011 compared to 14,800 Chinook in 2010. The commercial and recreational numbers continued to show an increasing trend in landings since major closures were enacted in 2008 and 2009 after the lowest recorded landings in 2006 and 2007, respectively. During fall 2011, record numbers of SRFC and Klamath River fall Chinook (KRFC) jack salmon (age-2 fish) returned to spawn in the Central Valley and Klamath-Trinity basins, respectively. These returns, combined with other relevant

TABLE 1
Landings of Coastal Pelagic Species in California (metric tons)

Year	Pacific sardine	Northern anchovy	Pacific mackerel	Jack mackerel	Unspecified mackerel	Pacific herring	Herring roe	Market squid	Total
1977	2	101,132	3,316	47,615		5,286		12,811	170,163
1978	1	11,439	8,241	34,349	48	4,473		17,145	75,696
1979	51	48,880	22,404	21,548	301	4,257		19,982	117,424
1980	21	42,946	25,739	24,181	56	8,061		15,385	116,389
1981	34	52,308	35,257	17,778	132	5,961		23,510	134,980
1982	2	42,150	17,667	19,618	18,398	10,604		16,308	124,747
1983	1	4,427	17,812	9,829	23,659	8,024		1,824	65,576
1984	1	2,889	26,043	9,149	18,038	3,847		564	60,532
1985	6	1,626	18,149	6,876	19,624	7,984		10,275	64,540
1986	388	1,535	22,095	4,777	25,995	7,658		21,278	83,727
1987	439	1,390	26,941	8,020	19,783	8,420		19,984	84,978
1988	1,188	1,478	30,127	5,068	20,736	8,641		37,233	104,471
1989	837	2,449	21,067	10,746	26,661	9,296		40,893	111,950
1990	1,664	3,208	31,077	3,223	9,039	7,436		28,447	84,094
1991	7,587	4,014	31,680	1,693	339	7,347		37,389	90,048
1992	17,950	1,124	18,574	1,209	3	6,319		13,110	58,289
1993	15,346	1,958	11,798	1,673		3,846	0	42,722	77,345
1994	11,644	1,789	10,008	2,704	0	77	2,874	55,508	84,603
1995	40,328	1,886	8,625	1,728		3	4,664	72,433	129,667
1996	32,559	4,421	9,597	2,178	4	249	5,162	80,784	134,954
1997	43,246	5,718	18,398	1,160	1	0	9,147	70,387	148,057
1998	42,956	1,457	20,515	824		0	2,009	2,895	70,656
1999	59,493	5,179	8,688	953	0		2,279	91,950	168,542
2000	53,612	11,754	21,916	1,269	0	26	3,450	118,816	210,843
2001	51,894	19,277	6,925	3,624	1	0	2,768	86,385	170,873
2002	58,354	4,643	3,367	1,006	2	0	3,324	72,920	143,615
2003	34,732	1,676	3,999	156	0	34	1,808	45,061	87,467
2004	44,305	6,793	3,570	1,027	0	60	1,581	41,026	98,362
2005	34,633	11,182	3,244	199		219	136	58,391	108,005
2006	46,577	12,791	5,891	1,167	0	37	694	49,159	116,316
2007	80,981	10,390	5,018	630	1	336	261	49,474	147,091
2008	57,806	14,285	3,530	274	0	131	626	38,101	114,754
2009	37,578	2,668	5,079	119	1	74	460	92,338	138,317
2010	33,658	1,026	2,056	310	0			129,904	166,954
2011	27,714	2,601	1,357	80	453		1,566	121,555	155,326

Data Source: Commercial Fisheries Information System (CFIS)

data, were used to forecast the largest ocean abundance (approximately 2.5 million Chinook) estimated for management purposes since the early 1980s.

California sheephead support both commercial and recreational fisheries, and are one of the 19 species managed under the Nearshore Fishery Management Plan. In 2011, commercial landings for California sheephead were 29.7 t, 33% lower than the average annual landings of 44.2 t from 2000 to 2011, with an ex-vessel value of over $311,000. Recreational landings data showed 31,422 California sheephead were landed by Commercial Passenger Fishing Vessels (CPFVs). That is higher than the decade's average of 25,883 and the highest CPFV landings reported since 2002.

Total commercial landings for California halibut in 2011 were 200 t, a 17% decrease from 2010 landings. Preliminary data for the recreational fishery showed a 41% decrease from 2010 with an estimated 117 t (25,000 fish) of halibut landed. In 2011, the Department contracted for the first statewide stock assessment of California halibut, with separate estimates for areas north and south of Point Conception. The period assessed was 1971–2010. The status of the halibut biomass north of Point Conception was relatively high with several recent recruitment events. Favorable environmental conditions appear to be driving recruitment and fishing was not considered to be a significant factor impacting biomass. South of Point Conception, the halibut population was estimated to be depleted at 14% of historic levels. An independent peer-review panel concluded that the results were acceptable for use in management decisions, but required additional sampling to be conducted to improve the next assessment, which the Department plans to conduct in 2016.

California's commercial groundfish harvest for 2011 was 7,205 t, a 28% decrease from 2010 (table 2). However, the fishery once again saw an increase of the ex-vessel value over 2010 values. In 2011 the Groundfish Fishery Management Plan's (FMP) Trawl Rationalization and Individual Fishing Quota Program was implemented, which sets trawl allocation limits in combination with 100% observer coverage to help ensure all trawl-

TABLE 2

California commercial groundfish landings (in metric tons) and ex-vessel value in 2011 with comparisons to 2010. The top six species by weight for the flatfishes and rockfishes are represented in the table.

	2011		2010		% change from 2010 (t)	% change from 2010 ($)
	Harvest (t)	Value ($)	Harvest (t)	Value ($)		
Flatfishes						
Dover sole	2,412	$2,258,482	2,622	$1,798,113	–8	26
Petrale sole	174	$553,556	213	$557,412	–18	–1
Arrowtooth flounder	86	$19,670	68	$14,921	26	32
Rex sole	68	$53,181	55	$43,385	24	22
Sanddabs	51	$99,392	56	$91,722	–9	8
English sole	19	$17,298	24	$21,091	–21	–18
Other flatfishes	36	$78,584	33	$60,601	9	30
Total Flatfishes	2,846	$3,080,163	3,071	$2,587,246	–7	19
Rockfishes						
Chilipepper	293	$412,552	342	$457,029	–14	–10
Blackgill rockfish	126	$356,725	96	$247,963	31	44
Group slope rockfish	59	$82,304	78	$108,166	–24	–24
Gopher rockfish	30	$460,099	28	$412,792	7	11
Brown rockfish	29	$382,574	27	$336,953	7	13
Black rockfish	27	$108,939	53	$219,347	–49	–50
Other rockfishes	82	$741,689	88	$982,306	–7	–24
Overfished species						
Bocaccio	8	$18,183	4	$9,299	100	95
Canary rockfish	0.33	$456	0.44	$637	–25	–28
Cowcod	0.01	$17	0.03	$132	–67	–87
Darkblotched rockfish	3	$6,301	17	$21,750	–82	–71
Pacific ocean perch	0.07	$63	0.04	$47	75	34
Widow rockfish	1	$2,189	10	$8,937	–90	–75
Yelloweye rockfish	0	$0	0	$8	—	—
Total Rockfishes	658	$2,572,091	781	$2,516,817	–16	2
Roundfishes						
Sablefish	2,406	$15,119,335	2,449	$11,501,299	–2	31
Pacific whiting	5	$234	2,427	$694,248	–100	–100
Lingcod	33	$144,337	47	$173,276	–30	–17
Cabezon	32	$384,929	23	$266,032	39	45
Kelp greenling	2	$28,864	2	$22,154	0	30
Total Roundfishes	2,478	$15,677,699	4,947	$12,657,009	–50	24
Scorpionfish, California	5	$38,307	3	$26,734	67	43
Sharks & unsp. skates	39	$31,972	35	$28,834	10	10
Longnose skate	171	$129,556	142	$48,829	17	62
Thornyheads	921	$3,072,533	1,026	$2,957,617	–10	4
Other groundfish	87	$41,654	95	$44,453	–8	–6
Total Groundfish	7,205	$24,643,975	9,960	$20,818,711	–28	18

Data Source: CFIS (CMASTR) Extraction Date: 06-27-2012

caught groundfish species stay within established catch limits. The federal groundfish trawl individual fishing quota program allowed fishermen to trade their Pacific whiting quotas for sablefish quotas, which led to a drastic decline in Pacific whiting landings. Sablefish landings remained about the same but the ex-vessel value increased nearly $4 million, as many fishermen switched from trawl to longline gear which commands a higher price per pound. Longnose skate were removed from the "Other Fish" complex to be separately managed with a preliminary preferred Annual Catch Limit (formerly referred to as the optimum yield) set at approximately 2,000 t for the 2011 and 2012 regulatory cycle. Petrale sole experienced significant changes to the fishery due to restricted fishing regulations as a result of stock decline, and landings dropped to the lowest on record since 1931.

California spiny lobster commercial landings increased 7% in 2011 with 340 t landed, and also set a new record high ex-vessel value of $12.9 million which exceeded the fisheries previous highest record ex-vessel value in 2010 of $11.3 million. Based on results from the Department's lobster stock assessment, which was completed in 2011 and independently reviewed, the current levels of commercial and recreational fishing are considered to be sustainable.

Dungeness crab had a record-breaking season for statewide landings, totaling 12,493 t, and landings in the central area totaled 8,666 t which were more than twice the 3,826 t caught in the northern area. Landings in the central management area have not exceeded 3,000 t since the late 1950s and this record season for the area was more than five times the catch of 1,539 t from the previous season. New legislation was passed in 2011 that will impose trap limits on Dungeness crab permit holders by the 2013–14 season. Once established, permit holders will be grouped into one of seven tiers, based on their total catch from a prescribed, consecutive 5-season period. Permit holders will also be required to purchase a biennial trap permit along with Department-issued trap tags for each trap in their tier.

Historically, garibaldi supported a minor commercial fishery for Los Angeles fish markets and also a commercial marine aquaria trade which targeted both adult and juvenile fish. There has never been a significant sport fishery. Garibaldi was designated California's state marine fish in 1995, and a prohibition on all commercial take was implemented. There has been a prohibition on recreational take of garibaldi since 1953.

The great white shark has historically interacted with several California commercial fisheries; most often with the set gill net and other entangling net fisheries. In the 1980s, as seabird and marine mammal mortalities associated with these nearshore fisheries increased and the target species populations declined, regulations were put in place to restrict these fisheries. This indirectly protected white sharks, especially in the vulnerable pupping grounds of the Southern California Bight. In 1994, two significant regulations went into effect that supported a rebuilding of the white shark population in California waters. The first was the Marine Resources Protection Act of 1990, which banned entangling nets in state waters. The second was Title 14, CCR, §28.06 and FGC §8599, which prohibits take of white sharks except under Fish and Game permits for scientific or educational purposes.

Marine phytoplankton are microscopic, single-celled plants that live in the ocean. With over 5,000 species of phytoplankton, less than 10% undergo periods of explosive population growth due to favorable environmental conditions. These instances are called algal blooms and they typically support fisheries and ocean productivity. However, some species of phytoplankton can produce toxins and when they bloom can create harmful algal blooms (HABs) which create numerous management considerations for the health and safety of humans and marine animal populations. Federal and state agencies, along with public-private partnerships, are working to establish predictive models for HAB occurrences and improve response time for affected marine resources.

Ocean Salmon

Ocean salmon fisheries in California primarily target Chinook salmon (*Oncorhynchus tshawytscha*). The retention of coho salmon (*O. kisutch*) has been prohibited in the commercial and recreational fisheries since 1993 and 1996, respectively. Pink salmon (*O. gorbuscha*) are taken occasionally in the fisheries, primarily in odd-numbered years. Each season, the Pacific Fisheries Management Council (PFMC) and the Fish and Game Commission (Commission) regulate California's ocean salmon fisheries to meet the conservation objectives for Klamath River fall Chinook (KRFC) and Sacramento River fall Chinook (SRFC) stocks as described in the Salmon Fishery Management Plan (FMP). In addition, the fisheries must meet the National Marine Fisheries Service (NMFS) Endangered Species Act (ESA) consultation standards for listed stocks, including Sacramento River winter Chinook (endangered), Central Valley spring Chinook (threatened), California coastal Chinook (threatened), Central California coast coho (endangered), and Southern Oregon/Northern California coho stocks (threatened).

In 2011, California ocean salmon fisheries were primarily constrained by the NMFS consultation standards for threatened California coastal Chinook which limit the KRFC age-4 ocean harvest rate to a maximum of 16%. Fishing in San Francisco and Monterey-south port areas was open May 1 through September 30 with several short-term closures occurring during June, July, and August. The Fort Bragg port area was open July 23 through September 30 (closed July 28 and August 29–30) while the Crescent City/Eureka port area (Klamath Management Zone; KMZ) had two quota fisheries—13 days open in July (1,400 Chinook quota) and 2 days open in August (880 Chinook quota).

Commercial fisheries in the four major port areas (Crescent City/Eureka, Fort Bragg, San Francisco, and Monterey-south) had 369 days open to fishing in 2011 compared to 70 days open during the 2010 season. An estimated 69,800 Chinook salmon (448 t) were landed during the 2011 commercial season (fig. 2). The average weight per fish was 6.45 kg (14.2 lbs). The average price was $11.37/kg ($5.17/lb). The total ex-vessel value of the fishery in 2011 was estimated to be $5.1 million. Total commercial effort was estimated to be 6,900 days fished in 2011.

The 2011 recreational fishing season increased 209 days compared to the 2010 season, for a season total of 709 days (days open in each of four management areas combined). The recreational fishery opened in Fort Bragg, San Francisco, and Monterey-south port areas on April 2 while the KMZ area opened on May 14. All fisheries remained open through the summer until closing on various dates in September and October. An estimated 49,000 Chinook were landed in 2011 compared to 14,800 salmon in 2010 (fig. 3). There was an estimated 91,100 angler days in 2011 compared to 48,700

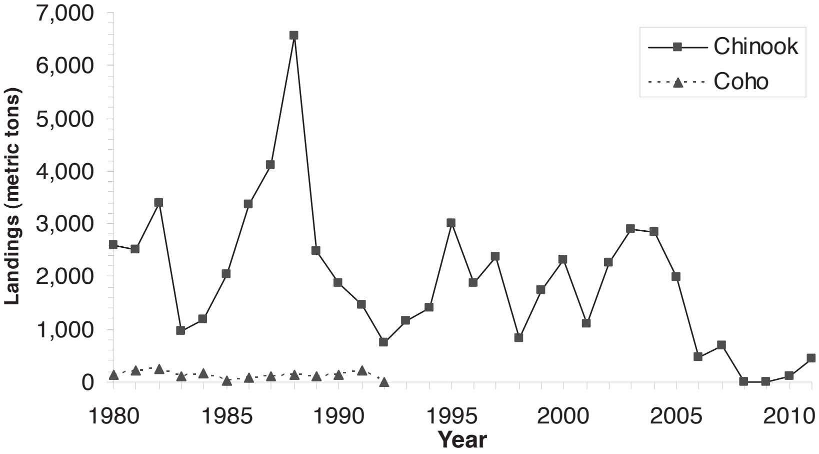

Figure 2. California commercial landings of ocean salmon, 1980–2011. Note: Commercial fishery landings of coho salmon (*Oncorhynchus kisutch*) have been prohibited since 1993 to protect ESA-listed California coastal coho salmon stocks.

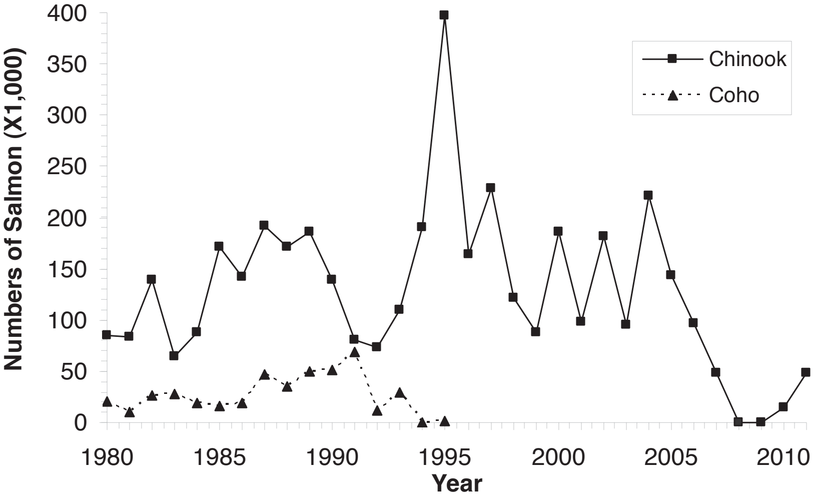

Figure 3. California recreational landings of ocean salmon, 1980–2011. Note: Recreational fishery landings of coho salmon (*Oncorhynchus kisutch*) have been prohibited since 1996 to protect ESA-listed California coastal coho salmon stocks.

angler days in 2010. The bag and possession limit was two salmon per day of any species except coho and anglers were required to use no more than two single-point, single-shank barbless hooks when fishing for salmon. The minimum size limit was 610 mm (24 in.) total length (TL) to protect the generally smaller-sized ESA-listed endangered Sacramento River winter Chinook. Approximately 300 coho were landed illegally during 2011, presumably by anglers who misidentified their salmon as Chinook.

During fall 2011, record numbers of Sacramento River fall Chinook (SRFC) and Klamath River fall Chinook (KRFC) jack salmon (age-2 fish) returned to spawn in the Central Valley and Klamath-Trinity basins, respectively. These returns, combined with other relevant data, were used to forecast the largest ocean abundance (approximately 2.5 million Chinook) estimated for management purposes since the early 1980s. As a result, California ocean sport and commercial salmon fishing opportunities in 2012 were greatly increased compared to recent seasons. Although all FMP conservation objectives were met, a few fishery constraints (e.g., increased size limit, 22-day June commercial closure) were still enacted specifically to protect ESA-listed salmon stocks.

California Sheephead

California sheephead (*Semicossphus pulcher*) are a hermaphroditic species, maturing first as female and may transition to become male later in life. Currently, there is both a commercial and a recreational fishery for sheephead. The commercial fishery targets smaller, plate size individuals for a live-fish market while the recreational

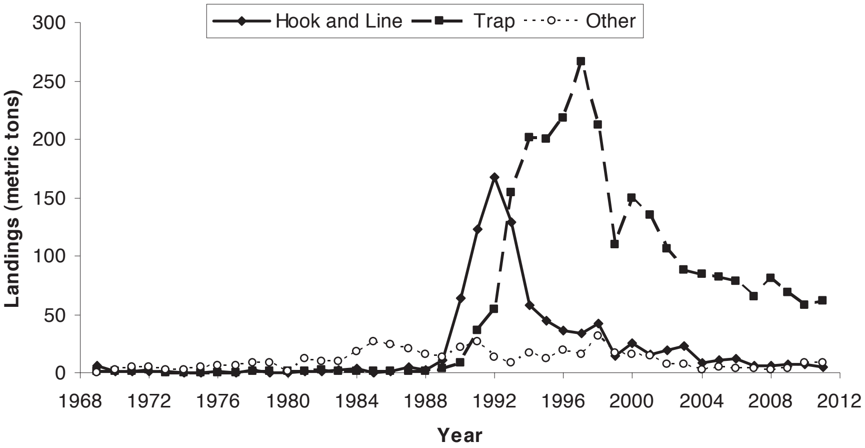

Figure 4. California sheephead (*Semicossyphus pulcher*) commercial landings by gear, 1969–2011.

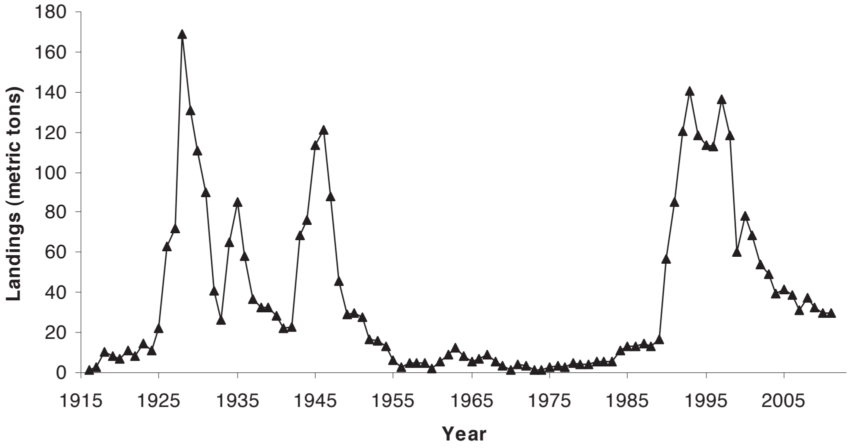

Figure 5. California sheephead (*Semicossyphus pulcher*) commercial landings by weight, 1916–2011.

fishery targets larger, trophy individuals. Most commercially caught sheephead are caught by trap but some are caught by hook and line and also by gill net and longline gear (fig. 4). Because sheephead are a sex-changing species, smaller individuals tend to be female while the largest individuals tend to be male making each of the fisheries both size and sex selective.

In 2011, commercial landings for sheephead were 29.7 t, 33% lower than the average annual landings of 44.2 t from 2000 to 2011 and 72% lower than the average annual landings in the 1990s (fig. 5). Landing receipt records show that the commercial fishery for sheephead has experienced two booms since 1916. During the 1925–51 boom, sheephead landings averaged 63.3 t per year and reached a historical high of 169.2 t in 1928. Then, commercial sheephead catch declined dramatically from 1952–89 averaging less than 7.3 t per year. The second boom began in 1990, initially driven by a live-fish fishery that began in the mid-1980s. The live-fish fishery primarily supplied the California Asian community at first but has since expanded and may supply other states and even other countries. Landings for sheephead increased nearly tenfold from 16.6 t in 1989 to almost 141 t in 1993 (fig. 5). After 1993, annual landings stayed above 113 t until 1999 when concern for the sustainability of the sheephead stock brought about regulatory changes in 1999 and 2001. These changes resulted in a steady decrease in landings since 2000. Since 1994, when landing receipts were first required to indicate the condition of fish sold at market, 87% of commercially caught sheephead were sold in a live condition. The value of the commercial fishery followed general trends in the catch data, peaking in the 1990s and decreasing over the last decade (fig. 6). In 2011, the ex-vessel value of the sheephead fishery was $311,135. In a contrasting trend, the market price for sheephead increased steadily since the second boom began in 1990.

Recreational fishers target large, trophy sheephead by spear and by hook and line; most sheephead are caught aboard Commercial Passenger Fishing Vessels (CPFVs). According to CPFV logbook data, the recreational sheephead fishery has also experienced a boom beginning in 1964 when average landings went from less than 15,000 fish (1936–63) to an annual average of almost

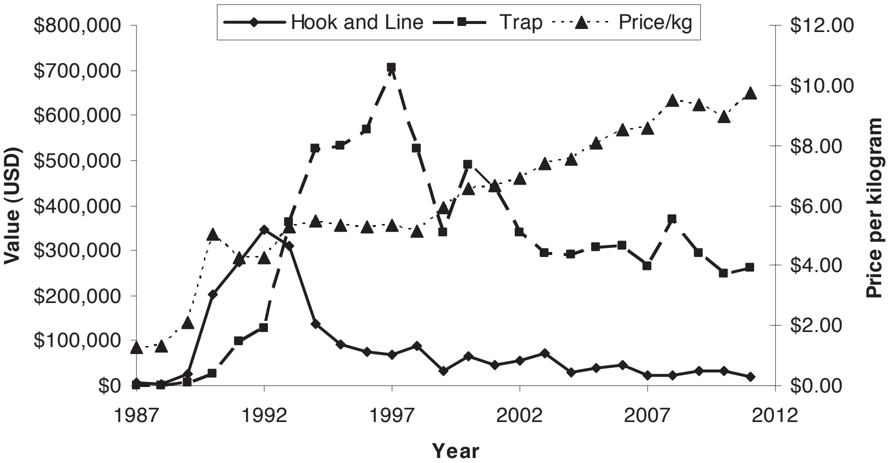

Figure 6. Total value of commercial California sheephead (*Semicossyphus pulcher*) hook-and-line and trap fisheries, and price per kilogram, 1987–2011.

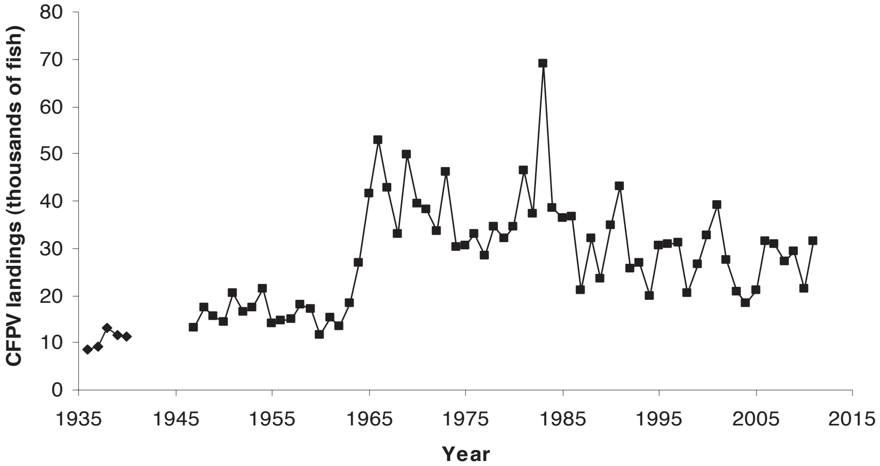

Figure 7. Recreational California sheephead (*Semicossyphus pulcher*) landings from Commercial Passenger Fishing Vessel (CPFV) logbooks, 1936–2011; no data for 1941–46.

39,000 fish (1964–86) (fig. 7). In the last 25 years, average annual landings have decreased to less than 28,000 sheephead per year, still almost twofold that of historical annual landings. In 2011, 31,422 sheephead were landed by CPFVs, higher than the decade's average of 25,883 and the highest CPFV landings reported since 2002. The decrease in recreational landings since the late 1980s may be in part due to increased competition for fish from the commercial fishery and the introduction of minimum size and bag limits in the early 2000s.

California sheephead are one of the 19 nearshore species managed under the Nearshore Fishery Management Plan (NFMP). The minimum size limit for commercially caught sheephead was first set in 1999 at 30.5 cm (12 in) total length (TL) but the size limit was then increased to 33 cm (13 in) in 2001. For the recreational fishery, a minimum size limit was first set in 2001 at 30.5 cm (12 in) TL and the bag limit was reduced from 10 fish to 5. Also in 2001, annual catch limits for sheephead based on optimum yield estimates were first set and the commercial fishery met those limits and closed early every year from 2001 to 2004 and also in 2007. To avoid closing the sheephead fisheries in mid-season, seasonal closures were implemented in both the commercial and recreational fisheries, and seasonal fishing restrictions remain today. The statewide total allowable catch for sheephead in 2011 is 93 t, 59 t allocated to the recreational fishery and 34 t allocated to the commercial fishery. The commercial live-fish trap fishery for sheephead is a restricted access fishery requiring permits.

A stock assessment of California sheephead conducted in 2004 estimated the stock was approximately 20% of the unfished level, well below the target level of 50% estimated as sustainable. Unfortunately, most of the biological data used in the stock assessment were collected before the booms in the fisheries that began in the 1980s and 1990s and before the effects of size limits and catch limits set between 1999 and 2001 could be fully observed. Data used in the stock assessment were also limited because they came from only a few southern California populations.

Recent studies show there is wide spatial variation in the demography and life history of sheephead populations in the Southern California Bight. New research indicates that sheephead in four southern populations (Santa Catalina Island, San Clemente Island, Palos Verdes, and Point Loma) attain smaller maximum sizes (for females and males), reach maturity, and undergo sexual transition at smaller sizes and younger ages than five northern populations (Santa Cruz Island, Santa Rosa Island, Anacapa Island, Santa Barbara Island, and San Nicolas Island). The growth rate of sheephead was also slower in the southern populations than in the northern populations.

As a sex-changing species, sheephead present a unique challenge for fisheries managers. For populations of sheephead in the most southern populations in California, the current minimum size limit of 30.5 cm (12 in) preserves some mature females and males allowing them to spawn at least once before they are recruited to the fishery; however, in the more northern populations, sheephead are still immature at 30.5 cm (12 in) and individuals may not get to spawn before they are recruited to the fishery. A new modeling study for sheephead made estimates of fishery yields under different minimum size limits. Models indicate that a statewide increase in the minimum size limit by at least 5 cm (2 in) would allow more individuals in northern populations to spawn at least once and may increase fishery yield by up to 15%. Models also highlight the potential for increasing fishery yield by dividing the management area into northern and southern management zones with unique size limits.

California Halibut

California halibut (halibut), (*Paralichthys californicus*) is an important flatfish species to the commercial and recreational fisheries in central and southern California. Halibut may be found in relatively shallow nearshore waters on the west coast of North America from Almejas Bay, Baja California Sur to the Quillayute River, Washington, with the species most common south of Bodega Bay, California. Individual fish can grow up to 1.5 m (5 ft) in total length (TL) and weigh as much as 32.7 kg (72 lbs). Halibut are sexually dimorphic with females growing at a faster rate compared to males of the same age. Female halibut will attain a larger size, and may become sexually mature between 5 and 6 years of age. Males do not grow as large as females and mature earlier, at 1 to 3 years of age. Fecundity is considered high with mature females producing up to one million eggs per spawning event. Successful recruitment is dependent upon favorable environmental conditions and availability of suitable nursery habitat.

In regard to the commercial fishery, halibut are harvested using three primary gears: trawl, hook and line, and set gill net. Over the past 30 years, from 1981 to 2011 (fig. 8), total annual landings of halibut peaked at 602.4 t with an ex-vessel value of $3.26 million in 1997, had a low of 176.3 t valued at $1.84 million in 2007, and averaged 438.3 t. Total landings for 2011 were 199.7 t with an ex-vessel value of $2.17 million. In 2011, the three principle gears comprised 99% of halibut landings. Trawl was the dominant gear in 2011, accounting for 49% of the total catch, followed by hook and line gear at 29% and set gill net at 21%.

Bottom trawls have produced more halibut landings than any other commercial gear type; landings have fluctuated from a high of 331.3 t in 1997 to a low of 71.9 t in 1985 (fig. 9). At the peak of the halibut trawl fishery (1997), 112 trawl vessels made at least one halibut landing. For this period, the year of lowest trawl landings (1985), 58 vessels made at least one halibut landing. In 2011, a total of 32 trawl vessels landed 98.8 t of halibut compared to 42 trawl vessels that landed 137.2 t in 2010. The San Francisco port complex received a majority (67%) of the landings in 2011, followed by the Santa Barbara port complex (27%), with Morro Bay accounting for 3% of the trawl catch. Directed trawling for halibut is by Department-issued permit only. Currently there are 43 permitted vessels, but not all actively fish. Vessels with a federal groundfish permit may take up to 68 kg (150 lb) of halibut incidentally per trip while fishing for groundfish.

Gill net landings generally have declined in the past 30 years, from a high of 421.7 t in 1985 to a low of 41.6 t in 2011. A series of depth restrictions, enacted to protect seabird and sea otter populations along the central California coast and prohibiting set net gear in 60 fm or less, greatly impacted the gill net fleet. This is evidenced by the lack of landings made north of Point Arguello since 2002. The gill net fishery now operates only in southern California, with the Santa Barbara port complex receiving 73% of 2011 landings, followed by the port complexes of San Diego (14%) and Los Angeles (13%). A limited-entry general gill net permit is required.

Annual landings reported by the hook and line fleet have fluctuated over the past three decades, ranging from a high of 94.4 t in 2003 to a low of 3.3 t in 1984. In 2011, 271 hook and line vessels landed 58.7 t statewide. The top two port complexes for hook and line landings were San Francisco (52%) and Santa Barbara (15% t). The hook and line fishery is open access; no special permit is required and only a commercial fishing license is needed.

For the halibut commercial fishery, California Fish and Game Code §8392 requires a minimum size of 559

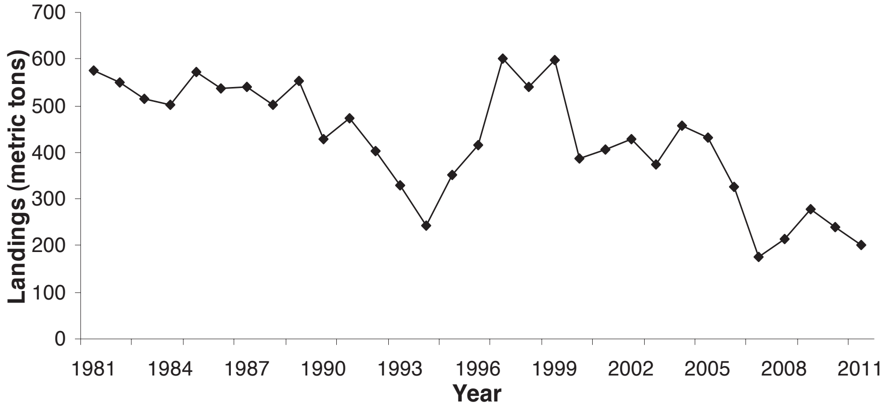

Figure 8. Statewide commercial ladings of California halibut (*Paralichthys californicus*) for 1981–2011.

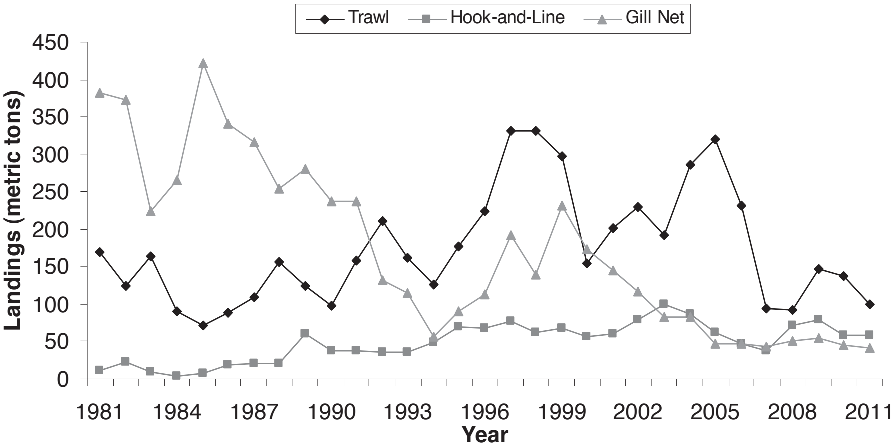

Figure 9. Catch comparison between the three principle commercial gears for California halibut (*Paralichthys californicus*), 1981–2011.

mm (22 in) TL for retention. This simple but effective statute was established in 1979. Various prohibitions on bottom trawling within state waters have been in effect since 1915 with some exceptions, one of these being the California Halibut Trawl Grounds (CHTG). Created in 1971, the CHTG by definition encompass an area one to three nautical miles from shore between Point Arguello (Santa Barbara County) and Point Mugu (Ventura County). The CHTG are closed to trawling from March 15 through June 15 and fishermen are required to use "Light Touch Trawl Gear" (Title 14 CCR §124(b)) with a minimum cod-end mesh size of 191 mm (7.5 in). In 2004, Senate Bill 1459 prohibited trawling in all state waters except those in the CHTG. The most notable closure, enforced since 2007, is the historical trawl area of Monterey Bay.

Recreational anglers target halibut from shore, private and rental skiffs, and party boats (Commercial Passenger Fishing Vessels or CPFVs) using hook and line gear. Some catch also occurs from scuba divers and free divers using spear guns or pole spears. From 1980 to 2004, the method for estimating recreational catch was the Marine Recreational Fisheries Statistical Survey (MRFSS). During this period, the highest estimated annual recreational catch was 1,062 t (337,000 fish) in 1995 and the lowest estimated annual catch was 122 t (40,000 fish) in 1984 (fig. 10). There are no MRFSS data available for 1990 through 1992. The predominant fishing mode for 1980 through 2004 was private/rental skiff, followed by CPFV. In 2004, the California Recreational Fisheries Survey (CRFS) replaced the MRFSS. CRFS and MRFSS data and estimates are not directly comparable because of differences in the estimation methodology. Preliminary data for the 2011 recreational fishery showed an estimated 117 t (25,000 fish) of halibut landed for all fishing modes statewide (fig. 11). CRFS data indicate that private and rental boats continued to be the primary mode within the recreational halibut fishery. Similar to the commercial fishery, a recreational halibut fishing regulation established in 1971 requires a minimum size of 559 mm (22 in) TL for retention. Each recreational angler is limited to five halibut per day south of Point Sur (Monterey County) and three halibut per day north of Point Sur.

In 2011, the Department contracted for the first state-

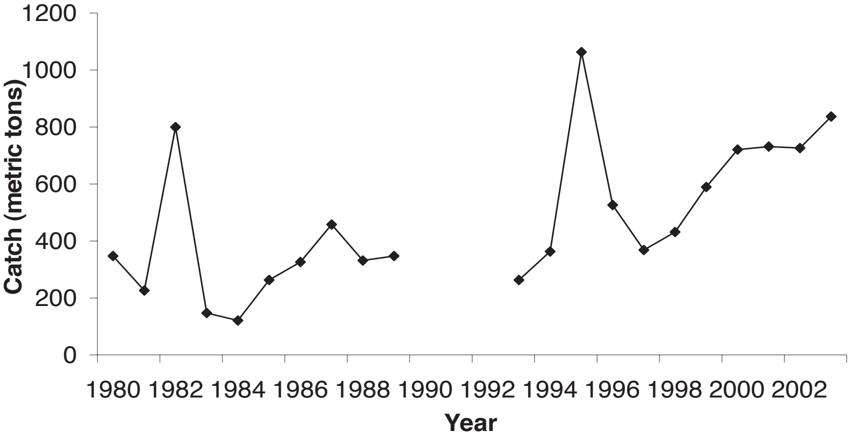

Figure 10. Marine Recreational Fisheries Statistical Survey (MRFSS) estimated recreational catch of California halibut (*Paralichthys californicus*), 1980–2003.

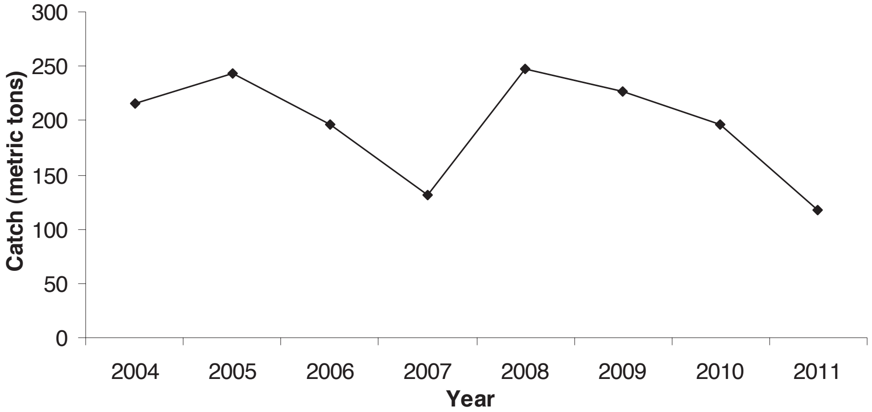

Figure 11. California Recreational Fisheries Survey (CRFS) estimated recreational catch of California halibut (*Paralichthys californicus*), 2004–11.

wide stock assessment of halibut, with separate estimates for areas north and south of Point Conception. The period assessed was 1971–2010. An independent peer-review panel concluded that the results were acceptable for use in management decisions, but required additional sampling to be conducted to improve the next assessment. It was recommended that the Department increase gender-specific sampling of the fished population, continue ageing studies, divide southern California into smaller sampling regions to increase precision in analysis, and examine the possible link between the north and south through larval abundance. After implementing these recommendations, the Department plans to conduct another assessment in 2016. In addition to the peer-review, Department staff conducted an evaluation of the stock assessment using methods to evaluate data-poor fisheries. None of the Department's findings were inconsistent with the results of the stock assessment.

The population status north of Point Conception was considered healthy, with a relatively high biomass associated with several recent recruitment events, especially in the San Francisco area. Favorable environmental conditions appear to be driving recruitment events and fishing was not thought to be a factor in controlling abundance.

South of Point Conception, the halibut population was estimated to be depressed to 14% of historic levels, characterized by a lack of significant recruitment during the past decade, but nevertheless the fishery appears to be sustainable at current levels of harvest. In general, flatfish are highly resilient marine finfish with high fecundity, and can respond relatively quickly to favorable environmental conditions with episodes of good recruitment. Southern California halibut stocks were considered depressed by the start of the evaluation period in 1971 due to sustained exploitation: the assessment found that the southern population was considered exploited since 1916. In response to the assessment, the Fish and Game Commission and the Department agreed that the best current course of action would be to increase monitoring of the fishery (both for catch level and total participation), investigate environmental bottlenecks, fill data gaps through fishery-independent survey work, and to revisit the assessment process in five years. The assessment did not take into account any potential benefits from a recently implemented series of Marine Protected Areas (MPA), especially those with halibut habitat. The new southern California MPA network, which became effective January 1, 2012, accounts for 14% of soft bottom halibut habitat in this region.

Ageing of halibut otoliths, using thin cross sections, continues at present by Department staff, and individuals greater than 15 years of age are rare in the sampled catch. The majority of halibut aged from fishery sampling have been in the 5- to 8-year old range; this is true for historic samples from the late 1980s as well as those aged from 2007 to 2011. A recent recreational state-record fish, weighing 30.5 kg (67.3 lbs), was aged at 23 years, which is somewhat less than the maximum recorded age of 30 years for this species.

Longnose Skate

The longnose skate (*Raja rhina*) fishery in California is exclusively commercial due to their deep water habitat, and plays a moderate role in the seafood industry. Only recently has longnose skate been tracked and monitored as an individual market category allowing for more in-depth information regarding market behavior and fishery trends.

Longnose skates are easily distinguishable from other skate species, although still occasionally reported on landing receipts as "unspecified skate." As a result of their large size and wingspan, historically it was a common practice for vessel crews to "wing" skates by removing the marketable pectoral fins and discarding the carcass in order to save space onboard rather than storing skates in a whole condition. This practice contributed to the difficulty of identifying and recording landings of skates by correct species. Since 2009, changes in management resulted in better information on longnose skate landings. First, regulatory sorting requirements were implemented requiring longnose skate to be separated. In addition, dockside sampling protocols were expanded to include sampling of all skate species, resulting in increased identification and separation of species. Also in 2009, existing regulatory authority was enforced to disallow the practice of "winging" in order to more accurately record species composition and estimate life history parameters. There was initial concern that landing large whole skates, in addition to mandatory sorting, would impose time and safety constraints on industry and port sampling staff that would prevent compliance and possibly encourage increased discarding at sea. Despite these concerns, landings are being separated; now the majority of receipts record the longnose skate market category rather than the unspecified skate category, and sampling information has been safely obtained from both market categories (fig.12). Accordingly, industry spends some extra time sorting, but overall landings have not been negatively impacted by this requirement. Smaller vessels were moderately impacted because they could not accommodate the onboard space necessary to separate and land longnose skate whole. However, these smaller vessels were rarely encountering skate species, so the overall amount of discard was negligible.

As a result of these changes, it is apparent that longnose skate is the dominant species of skate caught in California (fig. 12), while the other skate species are landed to a much lesser extent (fig. 13). Longnose skate are considered an incidental species within the groundfish fishery in that they have never been individually targeted in California waters. Instead, they are caught in the process of targeting other groundfish species with high market demand and value such as sablefish. Despite being taken incidentally, the commercial fishing industry has utilized longnose skate rather than discarding at sea, often at substantially lower market value than other more lucrative and targeted groundfish species. In 2010 and 2011, the median price for longnose skate was $0.40/lb. In 2010, total ex-vessel value was $48,829, with an average price of $0.07/kg ($0.16/lb). In 2011, 171 t was landed, and total ex-vessel value was $129,556 with an average price of $0.15/kg ($0.34/lb). The increase in ex-vessel value resulted from a combination of increased landings of longnose skate with a corresponding decline in the unspecified skate category, and likely changes in market demand.

From 1990 to 2011, all skates species, which longnose skate likely comprised the majority, were almost exclusively caught with trawl gear (96% average) and minimal amounts were taken with hook and line and gill net gears. When market demand peaked from 1995 to 2001, an average of 75% of skates were landed in the northern California Crescent City and Eureka port complexes. In 2010 and 2011, there was a significant shift away from northern California and a majority of the landings came from Fort Bragg and central California (fig. 14). This was likely due to changes in the trawl fishery and market demand.

Historical landings in the commercial skate fishery in California have been documented by the California Department of Fish and Game (Department) since 1916. Despite historical record keeping, it has been difficult to determine what proportion of these landings were composed of longnose skate because the general "unspecified" skate category was used when recording landings rather than using individual market categories to distinguish between various skate species. In addition to longnose skate, the general "unspecified" skate category has also been composed of big skate (*Raja binoculata*), California skate (*Raja inornata*), shovelnose guitarfish (*Rhinobatos productus*), and thornback skate (*Platyrhinoidis triseriata*). These combined commercial skate landings

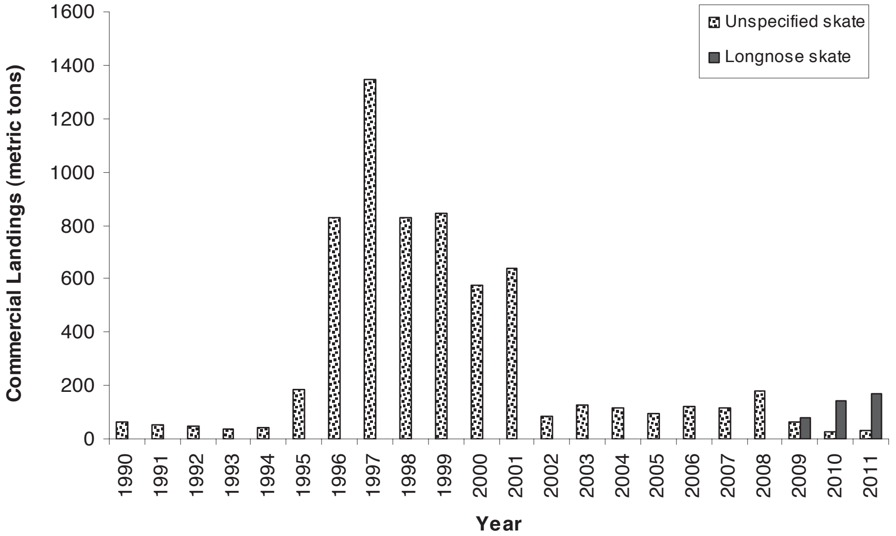

Figure 12. Longnose skate (*Raja rhina*) and unspecified skate commercial landings by species, 1990–2011.

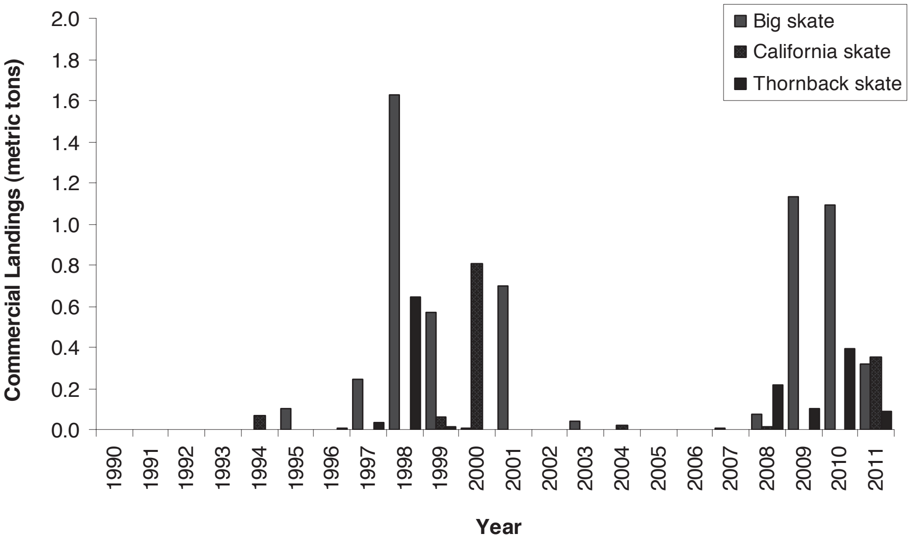

Figure 13. Big skate (*Raja binoculata*), California skate (*Raja inornata*), and thornback skate (*Platyrhinoidis triseriata*) commercial landings, 1990–2011.

varied widely in the past due to a combination of fluctuations in market demand and changes to fishing regulations. From 1916–89, the skate catch ranged from a low of 23 t in 1944 to a high of 286 t in 1981. Throughout the last two decades, landings of all skates peaked in 1997 at 1,315 t and an ex-vessel value of $575,000 (fig.15).

Stock Status and Management. In general, skates are vulnerable to overfishing due to sensitive life-history parameters such as slow growth, late age maturation, low fecundity, and relatively long life spans compared to other fishes. Because the cumulative landings equate to a significant fishery along the entire U.S. West Coast, the first longnose skate stock assessment was conducted in 2008. The results revealed a healthy West Coast stock estimated at 66% of the unfished spawning stock biomass. However, the assessment relied on critical assumptions regarding species composition of California's skate catch to estimate the longnose skate landings, which resulted in uncertainty in the model. Future research was recommended in order to reduce uncertainty in the population model for successive stock assessments. Reducing uncertainty in the model is imperative for the development of effective management measures to maintain a sustainable population in the future.

In 1982, longnose skate, big skate, and California skate were adopted as part of the federal Pacific Coast Groundfish Fishery Management Plan (Groundfish FMP). These skate species were managed in the "Other Fish" complex, which is an aggregate of species that are un-assessed and generally considered underutilized.

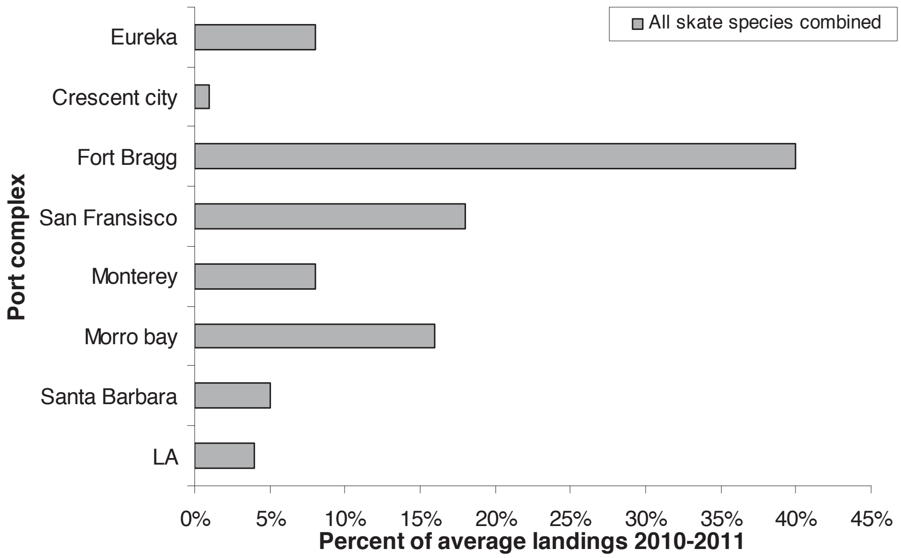

Figure 14. Skate, all species combined, percent of average commercial landings by port complex, 2010–11.

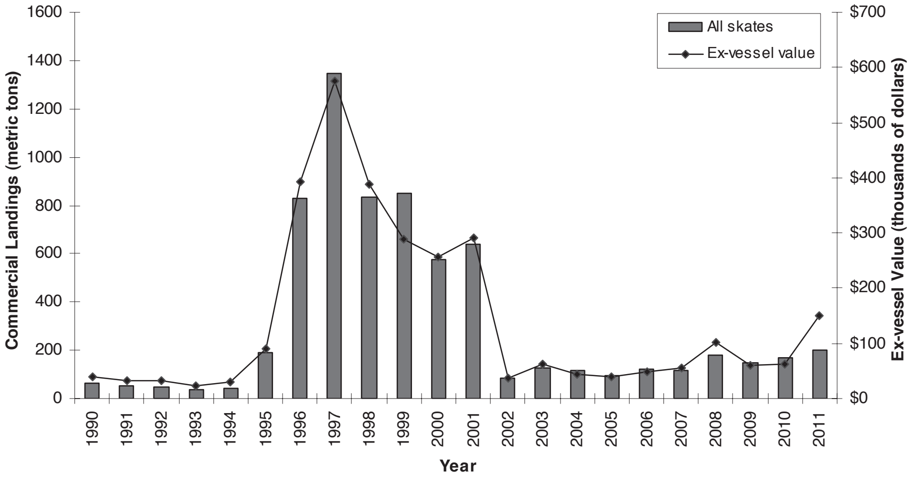

Figure 15. Skate commercial landings and value (all species combined), 1990–2011.

As a result of the healthy stock assessment outcome in 2008, adequate information was provided to set an optimum yield contribution for longnose skate of approximately 1,349 t to the "Other Fish" complex in 2009 and 2010. The Pacific Fishery Management Council (PFMC) decided on the mandatory sorting requirement for longnose skate beginning in 2009. The requirement was intended to provide more species-specific catch data to inform future stock assessments, which minimizes the need to take more precautionary management measures for the sake of protecting sensitive skate species. In addition, with the implementation of the Groundfish FMP's Trawl Rationalization and Individual Fishing Quota Program in 2011, all trawl fishing has 100% observer coverage and greater catch accounting, assuring further catch accuracy for all skates. It will not be necessary to reassess the stock for several years until sufficient new data can be collected to significantly inform the population model, due to the healthy outcome of the initial longnose skate assessment. The preliminary preferred Annual Catch Limit (formerly referred to as the optimum yield) for longnose skate was set at approximately 2,000 t for the 2011 and 2012 regulatory cycle and it was removed from the "Other Fish" complex to be separately managed.

Fish and Game Code Section §5508 requires that longnose skate be landed in whole condition (the fish cannot be dressed or cut). A conversion factor which calculates the weight of the whole fish based on the weight of the wings would be needed to remedy the necessity of landing longnose skate in whole condition.

Petrale Sole

Commercial Fishery. Petrale sole (*Eopsetta jordani*) is a larger flatfish found throughout the state of California and it is among the most valuable commercial flatfish

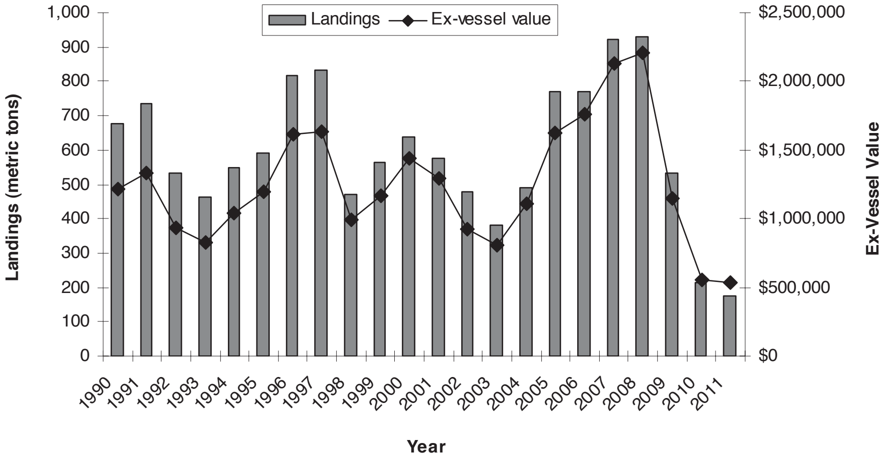

Figure 16. Petrale sole (*Eopsetta jordani*) commercial landings, all gear types combined, 1990–2011.

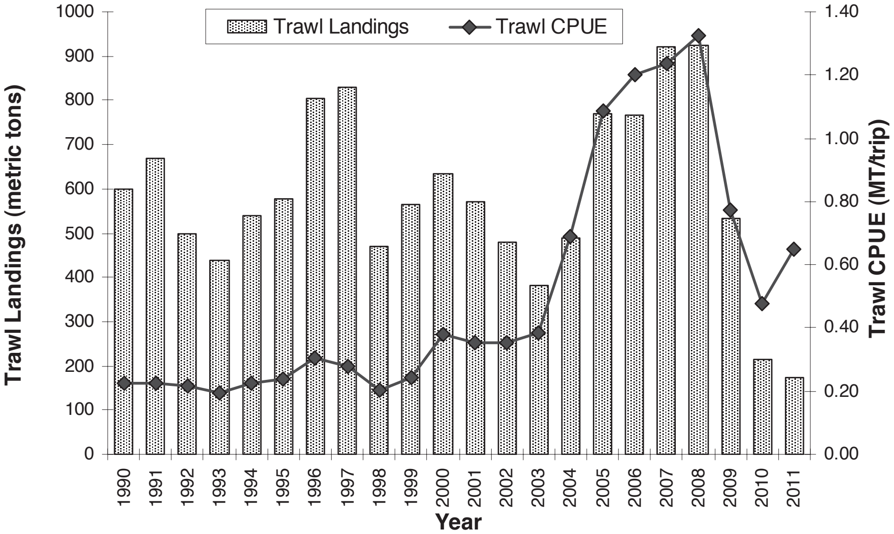

Figure 17. Petrale sole (*Eopsetta jordani*) commercial landings by trawl gear and trawl CPUE, 1990–2011.

species for consumptive use. Because they are caught in deep, offshore waters, the fishery has remained almost entirely commercial.

In 2010 and 2011, significant changes to the fishery occurred due to restricted fishing regulations as a result of stock decline, and landings dropped to the lowest on record since 1931. From 1990–2009, annual landings of petrale sole had an average ex-vessel value of $1.2 million followed by an annual drop in 2010 and 2011 to an ex-vessel value of $557,352 and $534,504, respectively (fig. 16). In 2011, 174 t of petrale sole were landed which is an 18% decrease from 2010 in which 213 t were landed.

Petrale sole is primarily trawl-caught and 98% were taken using trawl gear since 1990. From 1990–2011, a significant shift occurred in the composition of the trawl fleet which affected the catch-per-unit-effort (CPUE). The CPUE, measured by average landings per trip, significantly increased since 2004 (fig. 17) as a result of multiple factors. These factors included: federal government buy back programs reducing the overall fleet size, continued restrictions on the entire groundfish fishery, and higher fuel expenses. The result is a more efficient fleet that has fewer vessels landing the same if not slightly more tonnage than previous years, except for 2010 and 2011 when fishing regulations were severely constrained. Additionally, the implementation of the federal Trawl Individual Quota Program in 2011 will stabilize the catch over the course of the fishing year to further the efficiency of the fleet (see the federal Groundfish Fishery Management Plan for more information).

This fishery is characterized by strong winter and summer seasonality. During winter months, petrale sole aggregate in deep water for spawning and the trawl fleet harvests greater volume with less landings of associated groundfish species (such as chilipepper, *Sebastes goodei*).

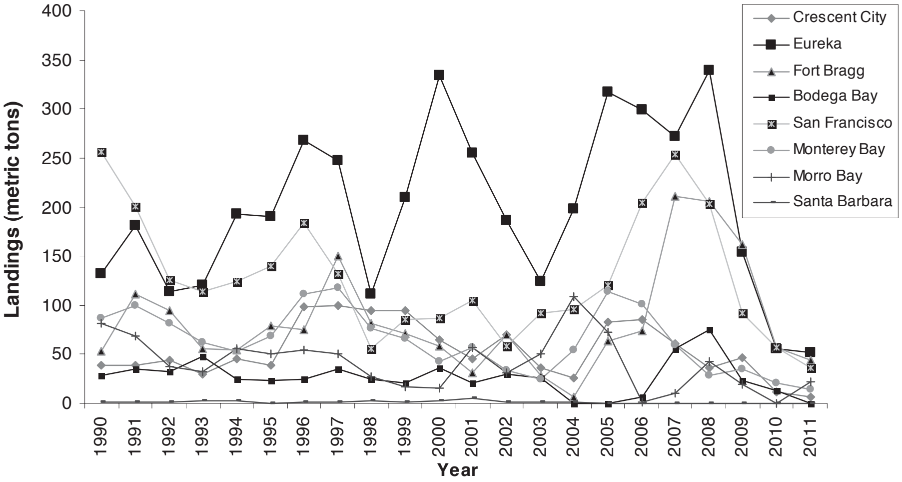

Figure 18. Petrale sole (*Eopsetta jordani*) commercial landings by port complex, all gear types combined, 1990–2011.

Figure 19. Petrale sole (*Eopsetta jordani*) commercial landings, all gear types combined, 1931–2011.

Conversely, during spring and summer petrale sole are found in shallower water—spread out over the continental shelf where they are harvested with a large mixture of various rockfish species. It is commonly caught with sablefish (*Anoplopoma fimbria*), Dover sole (*Microstomus pacificus*), and other flatfishes throughout the year.

During the last decade, the majority of petrale sole were landed in the Eureka port complex, followed by the San Francisco and Fort Bragg port complexes (fig. 18). South of Santa Barbara, petrale sole landings are minimal and do not amount to more than several hundred pounds per year.

Historically, petrale sole landings have been documented in California as far back as the late 1800s, with official documentation beginning in 1916. In early records from 1916–31, petrale sole was recorded as "sole" which was an aggregate category additionally composed of English sole (*Pleuronectes vetulus*), rex sole (*Errex zachirus*), Dover sole (*Microstomus pacificus*) and, to a lesser extent, with rock sole (*Pleuronectes bilineata*), sand sole (*Psettichthys melanostictus*) and other various flatfish species. The average landings of "sole" during this period were 3,629 t per year. It is estimated that petrale sole comprised approximately 20% or 726 t per year of the entire sole landings. Consistent with today's current fishery, trawl gear dominated the entire composition of flatfish landings during this time period and a majority were landed from San Francisco north to the California-Oregon border.

Beginning in 1931, petrale sole was officially recorded under an individual market category so that more accurate accounting of total individual harvest was possible. Despite high landings throughout most of the mid-1900s, which peaked in 1948, since 1980 the fishery landed at or below 907 t per year (fig. 19).

Recreational Fishery. Petrale sole is a very minor component of overall total removals in the recreational fishery. It is not a targeted species, but it is taken while fishing for other species such as rockfishes and other bottomfish. Recreational encounters are limited due to recreational depth restrictions that restrict anglers to 240 feet (40 fms) or less where petrale sole are more common, and its deeper depth distribution. An evaluation of both Marine Recreational Fisheries Statistical Survey (MRFSS) data (1980–89, 1993–97, 1999–2003) and California Recreational Fisheries Survey (CRFS) data (2004–11) suggests that, since 1980, estimated annual recreational landings of petrale sole averaged 2.6 t.

Population Status and Management Considerations. Because of the economic and biological importance of petrale sole, periodic stock assessments are conducted by National Marine Fisheries Service (NMFS) scientists. In 2009, the Pacific Fishery Management Council (Council) adopted a new full stock assessment for one stock along the Pacific west coast of Washington, Oregon, and California. The outcome indicated the stock was at 11.6% of its unfished biomass and officially declared "overfished" (under the NMFS newly revised reference point for flatfish of 12.5% of unfished biomass). The most recent assessment in 2010 included CPUE data from the winter trawl fisheries and accounted for a strong 2007 recruitment; a more optimistic stock status was the result at 18% of the unfished biomass.

Current management of petrale sole is largely driven by the stock status. As a result of the "overfished" status of the 2009 stock assessment, the Council recommended immediate action to decrease the fishing pressure on petrale sole in the 2010 season by limiting access to winter fishing grounds and reducing trip limits. The effect of reducing trip limits led to a 60% decrease in petrale sole landings and a 51% decrease in ex-vessel value from 2009 to 2010, a trend that continued into 2011 (fig. 16). To offset this lost opportunity, the Council also recommended increased trip limits for other healthy, actively managed groundfish species such as sablefish, longspine and shortspine thornyheads (*Sebastolobus altivelis* and *S. alascanus*), slope rockfishes, and Dover sole, in an attempt to balance some of the petrale sole losses. This restriction on petrale sole continued into 2011 based on the outcome of the results of the 2010 stock assessment. The fishery continues to be constrained to allow the stock to fully rebuild, although the 2010 assessment had an improved outlook. An additional benefit to the fishery was the implementation of the NMFS Individual Fishing Quota program which began in early 2011. As anticipated from this program, establishing trawl allocation limits in combination with 100% observer coverage enabled all groundfish trawl-landed species to stay within established catch limits.

All groundfish stocks declared overfished are held to a standard of 10 years to rebuild and require strict management measures in both state and federal waters, including strict annual catch limits. Because petrale sole grow relatively quickly and reach maturity at a young age, the recommended management changes and a more optimistic stock assessment outcome project petrale sole to be fully rebuilt by 2016—well within the 10 year goal.

California Spiny Lobster

A total of 315 t of California spiny lobster (*Panulirus interruptus*) was commercially landed during the 2010–11 season, continuing a trend of 300 t or more in seasonal landing weight begun in the 2000–01 season (fig. 20). While lower than the previous season (341 t), landings were approximately 10 t higher than the lowest catch total of the last 10 seasons (306 t). The 2010–11 ex-vessel value of the lobster fishery was $11.5 million, up from the previous high of $9 million in 2009–10.

The California spiny lobster is the target of both a commercial and recreational fishery during a season extending from the beginning of October to the middle of March. Essential fishery information is collected using fishermen logbooks and dealer landing receipts for the commercial fishery; and spiny lobster report cards, Commercial Passenger Fishing Vessel (CPFV) logbooks, and California Recreational Fisheries Survey (CRFS) data for the recreational fishery. For the commercial fishery (which is trap only) this includes location and date of catch, number of traps pulled, the number of lobster released, and the number, weight, and price paid per pound of lobster kept. For the recreational fishery, the information recorded includes date and location of catch, type of gear (dive or hoop net), and number of lobster retained. The report cards also provide a measurement of fishermen that did not fish for lobster despite purchasing a lobster report card.

Unlike the recreational fishery, which allows anyone with a fishing license and lobster report card to take lobster, the commercial lobster fishery is managed by a restricted access program. The number of commercial lobster permits issued in 1998 was 274. This number has steadily declined and in 2011 there were 197 permits issued. Since 2008, the number of lobster permittees actively fishing has hovered at 150. In 2005, over two-thirds of the commercial lobster permits became transferable. Permit transfers were limited to 10 per season for the first three years, and now there is no restriction on the number of permits that may be transferred. Given the high cost of these permits ($50,000–$100,000) which are sold in private transactions, it's likely that fishermen with newly acquired permits will fish more traps to recoup the cost of the permit. It's not clear if this will adversely affect the lobster population, since the majority of spawning females are undersized and cannot be

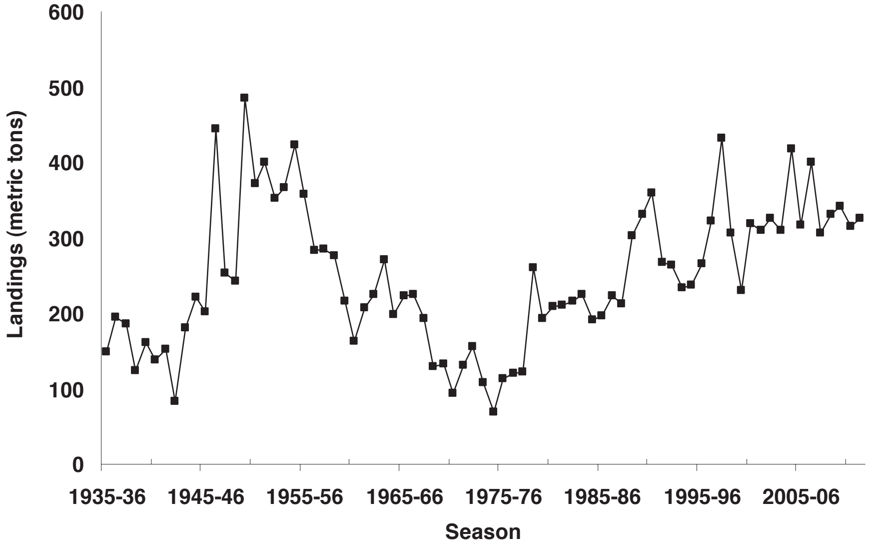

Figure 20. California spiny lobster (*Panulirus interruptus*) commercial landings by season, 1935–36 to 2011–12.

retained. Since 2005, there have been 91 permit transfers, and some of those permits have been transferred more than once.

Currently, there are no limits on the amount of lobster that commercial permittees can land or the number of traps they can use. Traps are generally set along depth contours in the vicinity of kelp beds along the mainland and at all the Channel Islands. Typically, between 100 and 300 traps are set at a time, although operators with larger boats or a crewmember may set more.

Soak times during the 2010–11 season averaged three days, as during 2009–10. The total number of trap pulls in the 2010–11 season is estimated at approximately 973,000 pulls, 120,000 more than in 2009–10, resulting in a catch of approximately 1.95 million lobster, of which 23% were retained. For comparison, in the 2009–10 season, 1.7 million lobster were caught, of which 28% were retained. While more lobster were caught in response to the increased effort in the 2010–11 season, the overwhelming majority of the lobster caught above the 2009–10 seasonal levels were short. Because of this, the number of retained lobster weighed approximately the same as in 2009–10 (315 t).

The median ex-vessel price of lobster for the 2010–11 commercial season was approximately $36.82/kg ($16.70/lb). The ex-vessel price ranged primarily from $35.27/kg ($16.00/lb) to $44.09/kg ($20.00/lb) for the 2010–11 season while the highest price paid in the previous season was $37.48/kg ($17.00/lb). Overall, prices were generally higher in 2010–11 with the ex-vessel value of the lobster fishery estimated at $11.51 million, up from the previous high of $9 million in 2009–10. Landed catch originating around the Point Loma area had the highest ex-vessel value at $2.21 million, representing 19% of the total season value, up from 15% in 2009–10.

Recreational fishermen are allowed to catch lobster by hand when skin diving or scuba diving, or by using baited hoop nets. Up to five hoop nets per person, with a maximum of ten hoop nets per boat, can be used. There is a daily bag and possession limit of seven lobster per fisherman. In both the recreational and commercial fisheries, lobster must have a carapace length of at least 83 mm (3.25 in) to be kept. More lobster are caught with hoop nets than by diving, and since 2005, the more efficient conical-style hoop nets have become progressively more popular than the traditional-style hoop net. During the 2010–11 season, more trips were made with conical-style hoop nets in all counties except San Diego.

Lobster report cards have been used to track recreational catch since the beginning of the 2008–09 season. Required by law to be carried by anyone fishing for lobster, approximately 30,000 cards have been sold each year. Report cards are required to be turned into the Department at the end of the calendar year.

The return rate of lobster report cards fell from 22% of 2008 cards to 11% in 2010, but increased for 2011 to 15%, with report cards still being tallied. For the 2010–11 season, preliminary results indicate that approximately 40% of 18,000 reported fishing trips recorded zero lobster caught (skunked). The number of lobster per trip, including skunked trips, was approximately two, the same catch per unit effort seen each season since the report cards were introduced in the 2008–09 season. Likewise, the total catch reported on each report card returned has remained at nine lobster per card since the 2008–09 season. These numbers estimate the potential extent of the recreational fishing effort. However, there is an additional, unquantified number of lobster taken illegally by poachers. How significant this illegal effort is compared to the reported level of take is unknown.

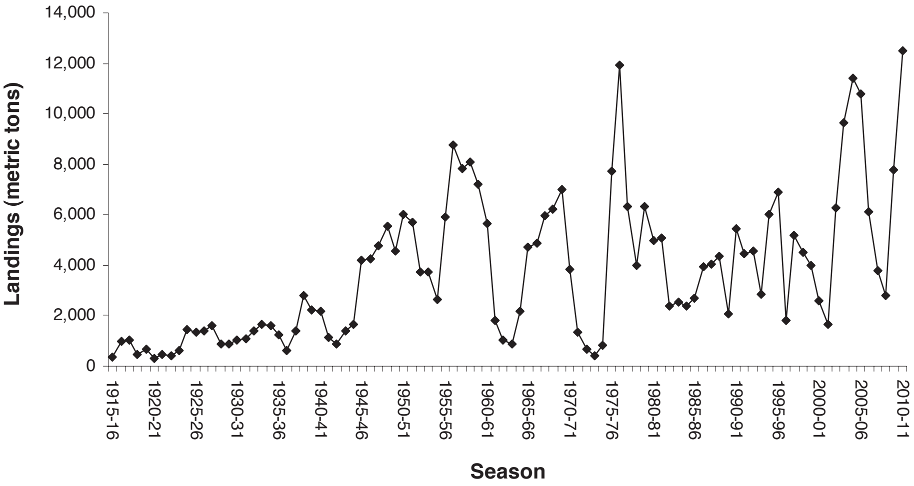

Figure 21. California commercial Dungeness crab (*Metacarcinus magister*) landings, 1915–16 to 2010–11.

Department biologists used the data from the returned recreational report cards to estimate that 25,000 lobster fishermen went fishing in calendar year 2010, and 29,000 went fishing in 2011. An estimated 265,000 lobster were retained in 2010, increasing to 317,000 in 2011. Department creel survey data indicates that a legal-sized (83 mm) lobster weighs on average 0.6 kg (1.3 lbs), allowing a total retained weight of the recreational catch to be estimated. Total retained catch was estimated at 155 t (345,000 lbs) in 2010 and 187 t (413,000 lbs) in 2011, corresponding to 50% and 59% of the commercial catch in 2010 and 2011, respectively. Although these estimates are based on returned report cards, which represent a small fraction of the total number of report cards sold, the size of the recreational fishery is a significant portion of the total lobster harvest in California. The actual percent of the commercial landing represented by the recreational catch is thought to be between 30% and 61%.

Based on results from the Department's lobster stock assessment, which was completed in 2011 and its findings upheld by an independent technical review panel, the current levels of commercial and recreational fishing are considered to be sustainable. The assessment results, which include the size of lobster caught by the combined fisheries, suggest that these fisheries are removing most lobster within a couple of seasons of attaining legal size, and have been doing so for at least a decade and probably longer. One consequence of this is that the spawning stock, upon which the health of the population is dependent, is contained primarily in the sexually mature, sublegal portion of the population. The importance of the relatively few legal-size spawners to the health of the population is currently being explored by the Department. The Department is also interested in determining if the current level of poaching of sublegal lobster is stable. If this level of sublegal poaching is increasing, it could impact the future health of the lobster population.

Dungeness Crab

The fishery for Dungeness crab, *Metacarcinus magister* (formerly *Cancer magister*), spans the west coast of North America from Alaska to Point Conception, California. In California there are two distinct management areas, the northern and central regions, demarcated by the Sonoma/Mendocino county line.

The Dungeness crab fishery has generally been much more productive in the north compared to the central region. However the 2010–11 season was not only a record-breaking season for statewide landings of Dungeness crab, totaling 12,493 t, but landings in the central area totaled 8,666 t and were more than twice the 3,826 t caught in the northern area. Landings in the central management area have not exceeded 3,000 t since the late 1950s and this record season for the area was more than five times the catch of 1,539 t from the previous season. The total landed for the season is over 1.5 times the 10-season moving average of 7,279 t and over 2.5 times the 50-season moving average of 4,671 t (fig. 21).

The average price paid to fishermen was $4.56/kg ($2.07/lb), which was only slightly higher than the 10-season moving average of $4.43/kg ($2.01/lb), but the record landings have resulted in one of the highest total ex-vessel values for the fishery on record, at $56.8 million. Value increased by 66% from the 2009–10 season, which was worth an estimated $34.2 million. Preliminary data from the 2011–12 season continues to show another high year of Dungeness crab landings statewide, 12,133 t (through February 2012), including the central area at 6,178 t. Also, the average price of $6.41/kg ($2.91/lb) paid to fisherman thus far in

2011–12 is almost 1.5 times the price paid the previous season for an ex-vessel value of $75.6 million, surpassing the previous season record. The last decade of Dungeness crab commercial landings has had four of the top five record high seasons of landings (over 9,500 t), contributing to its place as California's second most valuable commercial fishery, behind market squid (*Doryteuthis opalescens*).

The commercial trap fishery is regulated through the state legislature and managed on the basis of size, sex, and seasonal restrictions. Dungeness crab also supports a popular sport fishery that is managed through the Fish and Game Commission primarily by season, size, and bag limit restrictions. Male crabs larger than 159 mm (6.25 in) carapace width (CW) are harvested commercially while up to 10 crabs of either sex and larger than 146 mm (5.75 in) CW can be taken daily by sportfishing, unless taken from a Commercial Passenger Fishing Vessel (CPFV) from Sonoma to Monterey Counties, then the bag limit is reduced to six and the minimum size must be 153 mm (6 in) CW. The sport season begins the first Saturday of November statewide and ends June 30 in the central area and July 30 in the northern area. The commercial season in the central area begins November 15 and ends June 30, while it conditionally begins on December 1 and ends July 15 for the northern area. The timing of the seasons avoids the portion of the lifecycle when most crabs are molting or soft-shelled, and thus vulnerable to predation and handling mortality.

Starting with the 2009–10 season, the California Recreation Fisheries Survey (CRFS) began sampling Dungeness crab sport fishing from shore and private, rental and CPFV vessels. For the 2010–11 recreational season, CRFS estimated that 301,000 Dungeness crabs were caught, or approximately 205 t, based on an estimated weight of 0.68 kg (1.5 lb) per crab. This is less than 2% of the combined recreational and commercial catch for the season.

Mature males annually molt in the summer months and then begin gaining weight in their new shells. The timing of this molt varies, but the December 1 fishery opening along most of the West Coast usually results in adequately filled out crab reaching the popular holiday markets. However, commencing in the 1995–96 season the state legislature authorized an industry-funded preseason crab quality test to ensure crab meat has adequately filled the new hardened shell on the target opening date. The test is conducted in concert with tests in Washington and Oregon. The states then mutually agree, through the Tri-State Crab Committee, on whether to delay the opening of the season in order to let the crabs accumulate more body meat weight. The recent 2011–12 season in the northern management area was the first season to be delayed as late as January 15, the maximum allowed by law. Central California coast crab typically molt earlier than northern crab, and the area is not subject to opening delays by statute. In case of a northern season delay, "fair start" statutes mandate that anyone fishing in the central area must wait 30 days after the delayed northern season opener to fish in those northern waters.

Of the approximately 570 vessels with a 2011 commercial Dungeness Crab Vessel Permit, 435 vessels made at least one landing in the 2010–11 season. About a quarter of these permits are considered "latent," not actively participating in the fishery. Legislation restricted access to commercial Dungeness crab fishing permits beginning in 1995. A limited entry permit system was then enacted by the legislature with the provision that most permits are transferable. However, there is concern among some fishermen that an increase in the use of the latent permits sometime in the future could cause overfishing and worsen the overcrowding on crab fishing grounds.

The Dungeness crab fishery can be characterized as a derby-type fishery where much of the total catch is caught in a relatively short period of time at the beginning of the season. For the 2010–11 season, 86% of the total statewide catch was landed before February, 2.5 months after the season opened in the central management area. There are currently no reliable estimates of effort as there is no limit to the number of traps a vessel may fish or the frequency with which they are fished. According to a 2004 report based on a survey of Dungeness crab vessel permit holders, 171,000 traps were estimated as being fished in California during the 2000–01 season. Concerns over effort, in terms of crab traps deployed in both the central and northern management areas of California, led to multiple unsuccessful legislative attempts by California fishermen to create a trap limit program for their district.

In 2008, Dungeness crab fishermen began working on a cooperative approach to managing their fishery. Their effort resulted in the formation of an advisory group, the Dungeness Crab Task Force (task force) that is facilitated by the Ocean Protection Council under the state's Resources Agency. The task force objective was to make recommendations on management measures such as trap limits, fleet size reduction, and season opening date changes, among others, to the Joint Legislative Committee on Fisheries and Aquaculture and the Department of Fish and Game.

Through the efforts of the task force, new legislation was passed in 2011 that imposes trap limits on Dungeness crab permit holders by the 2013–14 season. Once established, permit holders will be grouped into one of seven tiers, based on their total catch from a prescribed,

TABLE 3
Garibaldi commercial landings and ex-vessel value, 1975–95

Year	Landings (t)	Ex-vessel ($)	Year	Landings (t)	Ex-vessel ($)	Year	Landings (# of fish)	Ex-vessel ($)
1975	0.017	276	1984	0.077	3,398	1993	959	8,157
1976	0.020	0	1985	0.033	1,071	1994	859	8,767
1977	0.000	0	1986	0.071	3,300	1995	99	1,434
1978	0.000	0	1987	0.043	1,988			
1979	0.005	27	1988	0.118	6,864			
1980	0.001	30	1989	0.146	6,797			
1981	0.000	0	1990	0.236	14,144			
1982	0.060	3,714	1991	0.209	13,461			
1983	0.069	4,913	1992	0.018	300			

Data source: CFIS data and compiled landing receipt data for years 1990–95, all gear types combined. Data are not available prior to 1975 and garibaldi (*Hypsypops rubicundus*) landings originating from California ceased in 1996.

consecutive 5-season period. The highest tier is set at a maximum of 500 traps while the lowest tier is set at 175 traps. Permit holders will also be required to purchase a biennial trap permit along with department-issued trap tags for each trap in their tier. If they fail to do so their commercial permit will no longer be valid, potentially removing those "latent" permits from the fishery.

Garibaldi

The garibaldi (*Hypsypops rubicundus*), a member of the damselfish family (Pomacentridae), ranges from Monterey Bay, California to southern Baja California, Mexico. In California, they are rare north of Point Conception, but larvae and juveniles are transported to the north during El Niño events. In the late 1800s, garibaldi was a minor commercial species commonly taken at Santa Catalina Island with set gill nets for Los Angeles fish markets. There has never been any significant sport fishery for garibaldi. In 1995, garibaldi was designated California's state marine fish, and a prohibition on commercial take was implemented on January 1, 1996. Prior to the commercial ban, garibaldi was one of the main targets of the commercial marine aquarium trade.

Adult garibaldi are a brilliant orange color while juveniles are orange with iridescent blue spots. Because of their brilliant colors, both adult and juvenile garibaldi were harvested for the commercial marine aquaria trade, which supplies specimens for live pet, hobby, and display purposes. The take of marine aquaria species occurs statewide primarily in nearshore waters by commercial divers. Methods used to take garibaldi and other finfish for the aquarium trade include traps and hook and line, but primarily consist of dropnets and slurp guns used by divers. Commercial regulations governing the marine aquarium trade were first implemented in 1993, which established a marine aquaria fishing permit and aquaria receivers license, put restrictions on where fish may be taken, and created a list of prohibited species. Before 1993, only a general commercial fishing license was required to land fish destined for the aquarium trade.

According to the California Department of Fish and Game (CDFG) commercial landing receipt data reported by fish businesses, there were little to no landings reported for garibaldi from 1975 to 1981 (table 3). In 1982, 38 landings were made totaling 0.06 t (60.3 kg) and landings increased each year until peaking in 1990 at 0.24 t (236 kg) with 85 reported landings (table 3). The number of reported landings decreased to 10 in 1992 with only 0.02 t (18 kg) landed. The ex-vessel value (not adjusted for inflation) of garibaldi increased from $3,700 in 1982 to a high of $14,100 in 1990, with the price ranging from a high of $71.28/kg ($32.40/lb) in 1983 to a low in 1991 of $16.91/kg ($7.69/lb). The catch during this period mostly originated from the front side of Santa Catalina Island near the Isthmus, and at Palos Verdes and Laguna Beach along the mainland coast (fig. 22a). Before 1993, landing receipts required landings to be reported in pounds; however, most garibaldi (and other organisms in the aquarium trade) were sold by the individual and as a result landing receipts typically only contained estimates for pounds of garibaldi landed. Therefore, while the trends in catch from 1975 to 1992 are likely valid, landings during this period may not reflect true values.

In 1993, a Marine Aquaria Collectors Permit was required for landing species for the aquarium trade and a new landing receipt was created for this fishery requiring landings to be reported as numbers of individuals with price paid per individual. During this first year of new reporting requirements, 20 landings were reported for a total of 959 garibaldi with an average price of $8.50 each and an ex-vessel value of $8,157 (table 3). From 1994 to 1995, landings decreased from 859 to 99 individuals with only 8 and 4 landings reported; however, the price paid per individual increased from $10.20 to $14.50, respectively. After 1992, garibaldi catch shifted from Santa Catalina Island to the front side of San Clemente Island and the Laguna Beach area due to a restriction implemented in 1993 on commercial aquarium trade collecting at Santa Catalina Island (fig. 22b).

During the early 1990s, a commercial aquarium trade

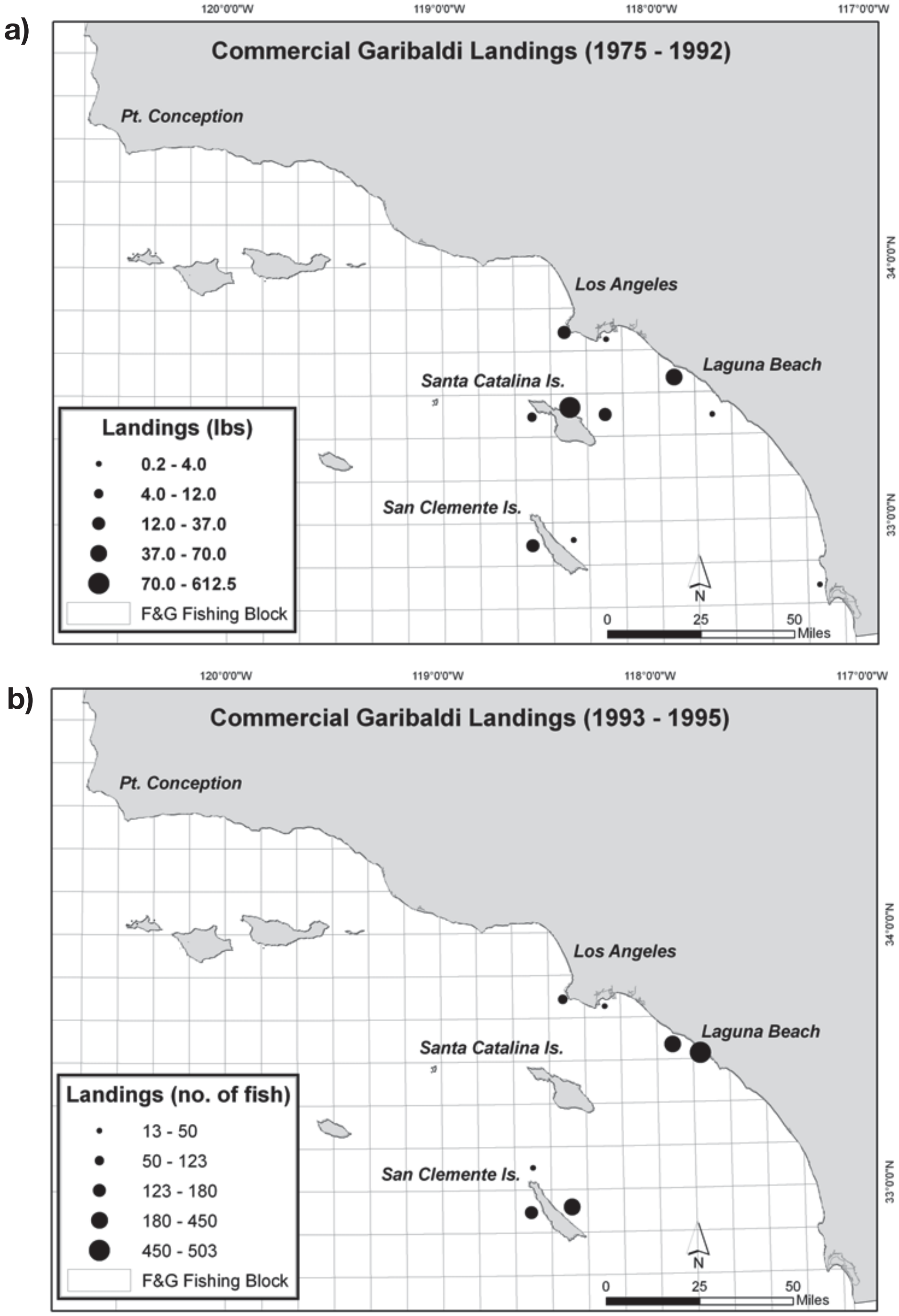

Figure 22. Origin of garibaldi (*Hypsypops rubicundus*) commercial catch: a) pounds landed, and b) numbers of fish landed.

developed for juvenile garibaldi. Although not substantial in terms of weight, because the fish were juveniles, these landings represented a large number of individuals. Because most of this take focused on one area, Santa Catalina Island, there was concern for localized depletion. Likely a result of concerns for garibaldi populations, Assembly Bill 77 (Morrow, 1995) was signed into California State law effective January 1, 1996. This Assembly Bill declared garibaldi the state marine fish and imposed a three year ban on its commercial collection "unless a study, the methodology of which is approved by the Department of Fish and Game, shows a less than significant impact on the population of the resource." Three years later in 1999, the Fish and Game Code was amended to add garibaldi to the list of no-takes species without exceptions. The prohibition on the commercial take of garibaldi continues today and garibaldi are now imported from Mexico where the commercial fishery continues.

Historically, garibaldi was never an important component of the recreational fishery in southern California and no reliable catch data exists. In *How to Fish the Pacific Coast*, published in 1953, the author states that garibaldi are taken in swirling waters along rocky shores but are very difficult to tempt. The author goes on to say, "This fish is of such beauty in the water it should be left there." According to the California Fish and Game Commission (Commission) meeting notes from January 2, 1953, the CDFG presented recommended sportfishing regulation changes that included a recommendation to "prohibit skin diving fishing along the waterfront of Avalon, Santa Catalina Island" as proposed by the Santa Catalina Island Company. This proposed regulatory change was met with opposition because the public wanted to continue to spearfish near Avalon and the main concern was take of garibaldi. So the proposed regulation was modified to a statewide prohibition on the recreational take of garibaldi. At the January 30, 1953 Commission meeting, the "prohibition against the take or possession of garibaldi, by either angling or diving" was adopted. The prohibition on the recreational take of garibaldi is still in place.

White Shark

Globally, white sharks (*Carcharodon carcharias*) are found throughout most seas and oceans with concentrations in temperate coastal waters. The northeastern Pacific (NEP) population ranges from Oregon south to Baja California, Mexico and the Gulf of California, and as far west as the Hawaiian Islands. The white shark has historically interacted with several California commercial fisheries; most often with the set gill net and other entangling net fisheries. An increased appearance of white shark in commercial fisheries coincided with an increase in the popularity of entangling nets after the introduction of monofilament line in the 1970s (fig. 23). The majority of white shark landings were seen in the Southern California Bight (SCB), most often in the set gill net, trammel net, and entangling net fisheries targeting California halibut, Pacific angel shark, and white sea bass (fig. 24).

The SCB constitutes a major portion of the white shark pupping grounds in California, which is probably why a majority of white shark landings in commercial fisheries are of juveniles and young of the year (YOY). A second possible reason for the predominance of this demographic in the catch data is that larger white sharks would be able to break through monofilament nets and hook and line gear without steel leaders. In the 1980s, as seabird and marine mammal mortalities associated with these nearshore fisheries increased and the target species populations declined, regulations were put in place to restrict these fisheries. This indirectly protected white sharks, especially in the vulnerable pupping grounds of the SCB. In 1994, two significant regulations went into effect that supported a rebuilding of the white shark population in California waters. The first was the Marine Resources Protection Act of 1990, which banned entangling nets in state waters (<3 nautical miles of shore and <1 nautical mile of offshore islands). The second was Title 14, CCR, §28.06 and FGC §8599, which prohibits take of white sharks except under Fish and Game permits for scientific or educational purposes. These prohibitions and an overall decrease in the set and drift gill net fisheries resulted in significant declines in white shark landings in commercial fisheries through the 1990s and 2000s. In 2004, white sharks gained federal and international protection in a treaty approved by the United Nations affiliated Convention on International Trade in Endangered Species (CITES). White shark is not a managed species, but it is listed in the Fishery Management Plan (FMP) for West Coast Fisheries for Highly Migratory Species (Appendix E.1.2—Commercial Fisheries—Species-specific Regulations Including Prohibited Species) as a prohibited species in California. This is a reference to Title 14, CCR, §28.06. Internationally, white shark is listed in CITES as an Appendix II species, which restricts trade of a species that may become threatened with extinction to avoid utilization incompatible with their survival.

The increase in commercial white shark landings since 2005 (fig. 23) may appear to be a step backwards from the successes seen in previous years, but over 80% of these landings are for research being conducted on white sharks in California waters. These are primarily tagging studies and short-term captivity of juvenile white sharks by the Monterey Bay Aquarium White Shark Program. Also, this research has increased awareness of this species, and may have resulted in catch being reported that would have previously been discarded at sea. At the same time there was a significant increase in the ex-vessel value of a species that cannot legally be sold, on landings used for both research and non-research purposes. This is possible and legal in accordance with FGC §8599 subdivision (b) which states that commercial fishermen who take white shark incidentally to commercial fishing operations using set gill nets, drift gill nets, or roundhaul nets, if landed alive, may be sold for scientific or live display purposes. This resulted in a small incidental fishery, where live specimens were selling for \$15–\$33/lb (fig. 23). The decline in value after 2009 represents a decrease in the project's dependence on com-

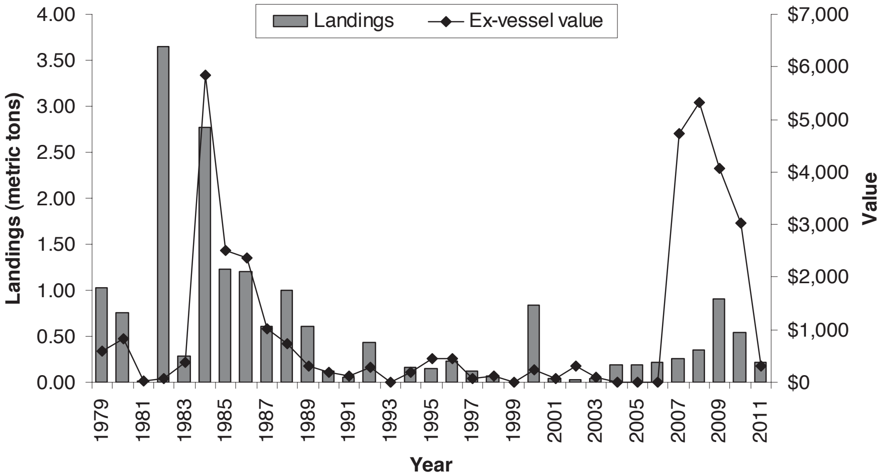

Figure 23. White shark (*Carcharodon carcharias*) commercial landings and value, all gear types, 1979–2008. Data is not available prior to 1979, because previous to 1979 white sharks were not coded separately, but were recorded in a miscellaneous shark category.

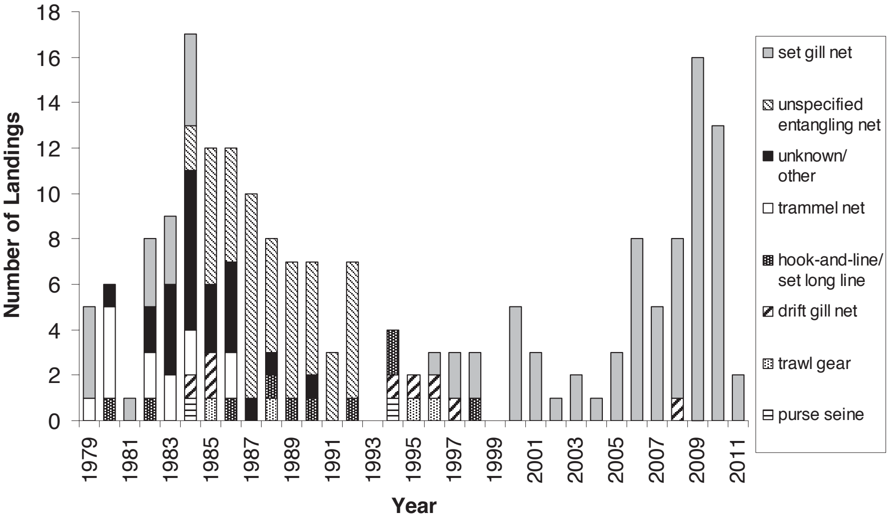

Figure 24. White shark (*Carcharodon carcharias*) commercial landings by gear type, 1979–2008. Data not available prior to 1979.

mercial fishermen as they conducted more of their own trips under a scientific collecting permit.

According to available data from the California Commercial Passenger Fishing Vessels (CPFV) Logbook program and the Marine Recreational Statistical Survey/ California Recreational Fisheries Survey (MRFSS/ CRFS) very few white sharks are caught in recreational fisheries. Since 1980, there have only been seven white shark interactions recorded in CPFV logbook records, and only one record in the RecFIN database (MRFSS and CRFS) since that program's inception in 1980. These records are not a full accounting of recreational activity, but they do show that this species is not commonly in the sport catch.

Adults of this population have been observed aggregating seasonally at two sites along the west coast of North America. One site is a network of hot spots off the coast of central California (CC) west of San Francisco Bay, and the other is off Guadalupe Island, Mexico (GI). Both of these locations support large breeding colonies of northern elephant seals, California sea lions, and other pinniped species, but availability of preferred prey does not account for the density of adult white sharks in the aggregation areas. It is believed the primary reason for these aggregations is mating. No white sharks have been observed mating anywhere in the world, so a lack of direct observation does not invalidate this theory. Several studies using pop-up archival transmitting (PAT) tags and satellite-linked radio transmitting (SLRT) tags to track individual movements and migration patterns have found significant circumstantial and indirect evidence that these two aggregations are where mating occurs for the NEP population. Adult males from both aggregation sites migrate to a Shared Offshore Foraging Area (SOFA) located midway between North America and the Hawaiian Islands. Adult females migrate offshore in a much more diffuse pattern, and are only found passing through the SOFA while males are absent.

Tagging studies also show that white sharks in the NEP exhibit philopatric behaviors and usually return to the same aggregation site where they were tagged. This provides strong evidence that the NEP population is demographically isolated from populations near Australia/New Zealand and western South Africa, even though these populations show little genetic difference. When returning to the adult aggregation sites (CC and GI) males generally arrive over a few weeks from late July through early August, while most females return in October.

There is limited information available on pregnant female and embryonic specimens, but white sharks are believed to reproduce using aplacental viviparity, with the embryos being nourished by oophagy. It has been speculated that females give birth to live litters of 4–14 pups, but this is based on a very limited number of pregnant females that have been caught and examined worldwide. Unlike males that generally migrate directly between their offshore and aggregation sites, pregnant females will migrate to the nearshore waters of the SCB and Baja California, Mexico to give birth before returning to the adult aggregation sites. Appearance of YOY in scientific collections and as incidental catch to the set gill net fishery suggests that parturition occurs May through October, peaking in July with only a minimal amount occurring after August. Young of the year remain in these shallow, warm-water nursery areas for their first summer and fall, feeding on fish and invertebrates. As water temperatures cool in the fall the YOY migrate south to Baja California, Mexico. By the end of their first year YOY will usually weigh approximately 45 kg (100 lbs). As juveniles, the sharks continue to migrate north and south in nearshore waters from the SCB to the Gulf of California, staying in warmer water until they are large enough to exploit colder water areas. Juveniles prey on a variety of fish, invertebrates, and opportunistically scavenge marine mammal carcasses. In their third year, at approximately 2 m (6.6 ft) TL, juveniles begin to venture north of Point Conception. Subadults range widely from Oregon to the Gulf of California. They will begin to visit aggregation sites and make inshore/offshore migrations, but little is known about how they locate these sites, or when and how they switch behavior patterns and begin their migrations. It has been suggested that this may be a time when mixing occurs between the CC and GI populations. As subadults grow in size and skill, they will also start to actively prey on small marine mammals. Only rough estimates can be given for length at which individuals become sexually mature, as a wide range of maturities have been seen amongst sharks of similar size. Given this variance most males become sexually mature at 3.6–4.6 m (11.8–15.1 ft) TL and females at 4.5–5.0 m (14.8–16.4 ft) TL. Females are usually larger than males and have been documented with certainty to grow to a maximum of 6 m (19.7 ft) TL and males to 5.5 m (18 ft) TL. There are records and reports of larger individuals, but a recent examination of these accounts has shown them to be erroneous or unsubstantiated.

White sharks are challenging to study, have a naturally low abundance, and reproduce slowly. As a result, the population is difficult to measure and is vulnerable to incidental fishing pressure, habitat loss, and other negative pressures. A lack of effective means to measure the population may also result in a population decline that is not recognized until after significant decrease has occurred. This makes current and future research on migration patterns, individual identification for population estimates, recruitment and general life history, crucial to our understanding of the species and our ability to protect the population from anthropogenic and environmental impacts.

Algal Blooms

Marine phytoplankton are microscopic, single-celled plants that live in the ocean and can undergo periods of explosive growth due to favorable environmental conditions. These instances are called algal blooms. Phytoplankton are vitally important to the marine ecosystem and play a crucial role in providing food to the base of the food web. Phytoplankton use energy from the sun and carbon dioxide to produce sugar and oxygen through the process of photosynthesis. Toxins produced by algal blooms can be harmful to humans and biological resources; these harmful blooms are commonly referred to as Harmful Algal Blooms (HABs). Potentially harmful phytoplankton species can produce harmful toxins, produce large blooms that can cause depletion of oxygen levels, or some species can produce large oily mats of foam. These harmful algae species are generally present year-round in the water column in very small amounts, but only become a problem for humans and animals when the phytoplankton populations reach particularly high levels. Algal blooms and HABs, commonly referred to as "red tides," are often visible due to pigments produced by the phytoplankton.

Algal blooms can often be visible, but not always. "Red tides" often occur during algal blooms caused by dinoflagellates that produce a reddish pigment called peridinin, which gives the ocean a reddish hue during an algal bloom. *Phaeocystis*, an algae found throughout the world, is typically the algae that causes "green tides."

Water discoloration is not an accurate way to predict if an algae bloom is toxic or dangerous because HABs can occur in clear water, and there are numerous species of phytoplankton that cause visible algal blooms that are non-harmful.

Exactly what causes any individual phytoplankton bloom to become a HAB event or what the exact cause of a particular algal bloom may be is not fully understood. Known factors that influence algal blooms and are used as predictors for HAB events include nutrient levels, bright sunlight, water temperature and salinity, time of year, number of grazers and/or predators, and calm waters with low wind circulation patterns. The nutrient rich and dynamic upwelling zone along the California coast is particularly prone to blooms and HAB events for this very reason.

Not all algal blooms are HAB events, meaning they do not all cause harmful effects. During a phytoplankton bloom, researchers commonly look for the presence of the organisms through cell counts and DNA sampling, presence of a toxin, and harm or impact on the ecosystem, economy and/or human health. The information researchers gather during a bloom helps in identifying whether or not a particular bloom is a HAB event or has the potential of becoming a HAB event.

Also unknown is what causes a species of phytoplankton to release toxins during a HAB event. The Central and Northern California Ocean Observing System (CeNCOOS) reports multiple hypotheses. One hypothesis is that the phytoplankton are acquiring or detoxifying nutrients in the environment. Another hypothesis is the toxins are produced to protect the algae from grazers, such as krill, sardines, and anchovies. A third hypothesis is that the toxin prevents or minimizes the growth of other algae competing for the same resources.

The most common species of HAB-forming phytoplankton species on the California coast include *Akashiwo sanguinea*, *Alexandrium* spp., *Cochlodinium* spp., *Dinophysis* spp., *Lingulodinium polyedrum*, *Phaeocystis* spp., *Prorocentrum* spp., and *Pseudo-nitzschia* spp. The Southern California Coastal Ocean Observing System (SCCOOS) and CeNCOOS Web sites provide information on these species. Additionally, information and tracking of the current status of common HAB-causing phytoplankton species can be found on their Web sites. Researchers from the University of California, California State University, and private research stations submit regularly collected and real time data to the SCCOOS and CeNCOOS data portals allowing for the use and comparison of data collected in the field. The California Department of Public Health (CDPH) regularly tracks information along the California coast on harmful algae that may affect fish and shellfish for human consumption. The CDPH publishes monthly Marine Biotoxin Monitoring Reports which can be found on their Web site. The toxin levels surveyed by the CDPH are obtained from mussel tissue samples.

2011 Significant HAB Event. During 2011, there were multiple algal bloom events on the California coast with one significant HAB event. The HAB event occurred off the Sonoma Coast in August 2011 and continued into September 2011. Coinciding with a large bloom event located nearshore from Bodega Bay north to Anchor Bay and possibly beyond, a large die-off of marine invertebrates occurred. Invertebrate deaths were observed from many taxa including mollusks, echinoderms, and crustaceans. Marine mammals and fish did not appear to be affected by the event. Water samples were collected and it was found that the dominant phytoplankters were dinoflagellates belonging to the *Gonyaulax spinifera* species complex. It is still unclear whether the HAB caused the marine life deaths, but marine scientists are investigating this potential connection. The vector responsible for potentially transferring toxins produced by phytoplankton to the herbivores that died in this event remains unknown. Waterborne toxins including viruses and bacteria may also be involved, but further investigation is needed. Based on the widespread die-off as well as the unknown source and ocean residence time of the toxin responsible, the Fish and Game Commission voted on Sept. 15, 2011 to close the recreational abalone fishery in Sonoma County for the rest of the year. Research into the event is continuing and results will be released to the public as soon as it is available.

Management Considerations. Harmful algal blooms create numerous management considerations for the health and safety of humans and marine animal populations. Federal and state agencies, along with public-private partnerships, are working to establish predictive models for HAB occurrences and improve response time for affected marine resources.

The CDPH places an annual quarantine on sport harvesting of mussels for food from May 1 through October 31. Mussels are most likely to accumulate toxins during this time of year due to increasing phytoplankton populations and potential HAB events. The mussel quarantine provides protection to humans from Domoic Acid (DA) and Paralytic Shellfish Poisoning (PSP). The quarantine can be expanded beyond or prior to the annual time frame and include additional shellfish should monitoring activities indicate unsafe levels of toxins. Public health warnings are issued by local health officers advising people of the quarantine and warn people that clams and scallops may contain toxins as well. During the quarantine, people should remove the viscera from clams and scallops, the siphons from Washington clams, and eat only the remaining white meat.

The CDPH monitors marine toxins in sport and commercial seafood year-round. This monitoring program allows CDPH to follow changes in toxin levels and to alert the public and local health agencies, if necessary. If CDPH finds unsafe toxin levels in seafood, they do not allow the affected species to be commercially harvested or sold; at the same time, they will also issue public warnings for sport harvesters of these species. The annual mussel quarantine does not apply to companies licensed by the state as certified shellfish harvesters. Mussels may be harvested and sold for bait at any time.

Marine mammals and seabirds are also affected by the neurotoxin DA each year in California. DA was first identified by the Marine Mammal Center in Sausalito, CA after a large HAB event in 1998. Marine mammals and birds are affected when they eat prey, like sardines and anchovies, that have been feeding during HAB events. The effect of DA on these animals depends on the amount they eat and the amount of toxin accumulated in the prey. Symptoms include severe cases of seizures and other central nervous system problems, as well as hippocampal degeneration and amnesiac shellfish poisoning. Diagnoses are difficult to establish definitively due to unknown toxicity levels of algal blooms and the unpredictable timing of DA outbreaks. The Marine Mammal Center has been studying the effects of DA on California sea lions, including the effects on memory and learning, to hopefully better understand how DA affects the human population.

In 2007, deaths of southern California sea otters were linked to a new type of HAB. “Superblooms” of cyanobacteria, normally a freshwater species, that produce potent and environmentally persistent biotoxins (microcystins) were linked to the deaths of 21 sea otters. The sea otters were found near the mouths of rivers where freshwater was released to the ocean. Additionally, bioaccumulation of the toxins was found in nearby clams, mussels, and oysters. A recent paper by Miller et al. 2010 suggests that this discovery points to the possibility that humans could be at risk from harvesting shellfish near the freshwater marine interface when high levels of cyanobacteria are present in the freshwater source.

The key to management of HABs is through a statewide and regional HAB monitoring network and forecast system. A February 2009 Working Draft White Paper “Harmful Algal Blooms in the West Coast Region: History, Trends, and Impacts in California, Oregon, and Washington” (Lewitus et al. 2009) strongly recommends the need for a regional network. A regional HAB monitoring network will improve the timeliness of HAB warnings by interstate dissemination of current HAB data, improve the efficiency and decrease the cost of HAB monitoring, improve the development and validation of forecast models, improve the accuracy of data for resource managers, improve public education, and improve the predictive models on factors promoting HABs. A California Current regional network is in the planning stages and will most likely include the efforts of the individual states (California, Oregon, and Washington), as well as monitoring efforts by SCCOOS, CeNCOOS, and the Northwest Association of Networked Ocean Observing Systems (NANOOS).

The greatest strides for creating a HAB monitoring network have been made at the state level. The California Harmful Algal Bloom Monitoring and Alert Program (HABMAP) is an effort initiated by National Oceanographic and Atmospheric Administration (NOAA), California Ocean Science Trust (CA OST), and the Southern California Coastal Water Research Project (SCCWRP) to develop a statewide Harmful Algal Bloom (HAB) alert network system for researchers and end user committees. This network is the culmination of multiple expert level workshops exploring the need for increased HAB monitoring. NOAA awarded $4 million in November 2011 for a five-year project to the SCCOOS and CeNCOOS systems to collaborate on the creation of the HABMAP monitoring network. The network will collect real time data from multiple federal, state, and private research stations. The HABMAP monitoring network and accumulated data will allow for a better understanding of HABs on the California coast. This understanding will ultimately lead to improved management strategies for California's resources. “This new effort will help us address a critical gap in past research, namely understanding the conditions leading to toxic blooms before they become a problem,” said Raphael M. Kudela, professor at the University of California, Santa Cruz and project lead. “We are particularly excited because the project combines expertise from research and state public health managers in California with the developing national observing network established by NOAA.” (NOAA 2011).

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STATE OF THE CALIFORNIA CURRENT 2011–2012: ECOSYSTEMS RESPOND TO LOCAL FORCING AS LA NIÑA WAVERS AND WANES

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ABSTRACT

The state of the California Current System (CCS) since spring 2011 has evolved in response to dissipation of La Niña through spring and summer, resurgence of cooler La Niña conditions in fall and winter, and finally a transition towards ENSO-neutral conditions in spring 2012. The resurgence of La Niña was uneven, however, as indicated by variable responses in broad climate indices such as the Pacific Decadal Oscillation and the multivariate ENSO index, and by latitudinal variability in the timing, strength, and duration of upwelling relative to climatological means. Across the CCS, various measures of ecosystem productivity exhibited a general decline in 2011 relative to 2010, but the magnitude of these declines varied substantially among taxa. Available observations indicate regional variability in climate forcing and ecosystem responses throughout the CCS, continuing a pattern that has emerged with increasing clarity over the past several years. In 2011–12, regional variability was again a consequence of southern regions exhibiting a relatively mild response to climate forcing, in this case tending towards climatological means, while northern regions showed somewhat greater effects of delayed or weaker-than-normal upwelling. In addition to the

effects of local and basin-scale forcing, long-term observations off southern California show declines in dissolved oxygen and increases in nutrient concentrations in waters below the mixed layer, trends that are consistent with recent predictions of how global warming will affect the characteristics of upwelling source waters in the CCS. Such trends must be accounted for more comprehensively in ongoing assessment of the state of the California Current and its responses to environmental forcing. At the time of writing, tropical conditions are ENSO neutral and forecast to transition into El Niño in late 2012. This, combined with unusually high abundances of diverse gelatinous taxa throughout much of the CCS during spring 2012, suggests that the ongoing evolution of the state of the California Current might take a particularly unusual path in the coming year.

INTRODUCTION

This report reviews oceanographic conditions and ecosystem responses in the California Current System (CCS) from spring 2011 through spring 2012 in the context of preceding years' observations. This review is based on observations collected and analyzed by a diverse range of government, academic, and private research programs and submitted in response to an open solicitation for contributions. Following the tradition of previous reports in this series, the purpose of this report on the state of the California Current is to serve as a forum for rapid presentation and preliminary synthesis of environmental and ecosystem observations. Our focus is on reviewing recent observations in the context of historical patterns as a means of identifying changes in the state of the CCS ostensibly related to changing climatic conditions. We emphasize evaluation of augmented or new time series of observations, and where possible, develop insights from spatial patterns described in general terms in the text; supporting maps and other "snapshots" of the CCS, including more detailed information on specific cruises, are available online at observing programs' websites (indicated below). This review focuses on description and preliminary synthesis of available observations. The data sets reviewed herein are the subject of ongoing research to understand links between climate and ecosystem processes, work that is well beyond the scope of the present paper. Sparse information on methods related to data collection and analysis is included in footnotes; for many programs, more detailed descriptions of methods are available in previous State of the California Current reports or online.

The report is organized as follows. First, as in previous reports, we review recent historical conditions and describe variability and trends in indices of large-scale climate modes (e.g., the Pacific Decadal Oscillation), followed by a description of recent, basin-scale information from the tropical and northern Pacific Ocean. This review provides a broad temporal and spatial context for observations that focus more specifically on patterns and structure in physical forcing and responses at scales that span the entire CCS. Second, we summarize the state of the CCS in terms of available hydrographic and plankton data collected during repeated ship-based surveys that occupy designated stations at more or less regular intervals throughout the year (fig. 1). Third, building from our synthesis of the state of the ecosystem "base" of the CCS, we review data on abundance or productivity of several taxa at higher trophic levels based on observations from directed surveys or place-based study sites (fig. 2). Such taxa can respond to climate variability and change on multiple time scales, ranging from days to decades (Melin et al. 2010; Sydeman et al. 2012), and as such, may be useful as integrative indicators of ecosystem state. Finally, in the Discussion, we synthesize observations throughout the CCS to assess how the state of the CCS has evolved through the past year, and provide a look towards the future.

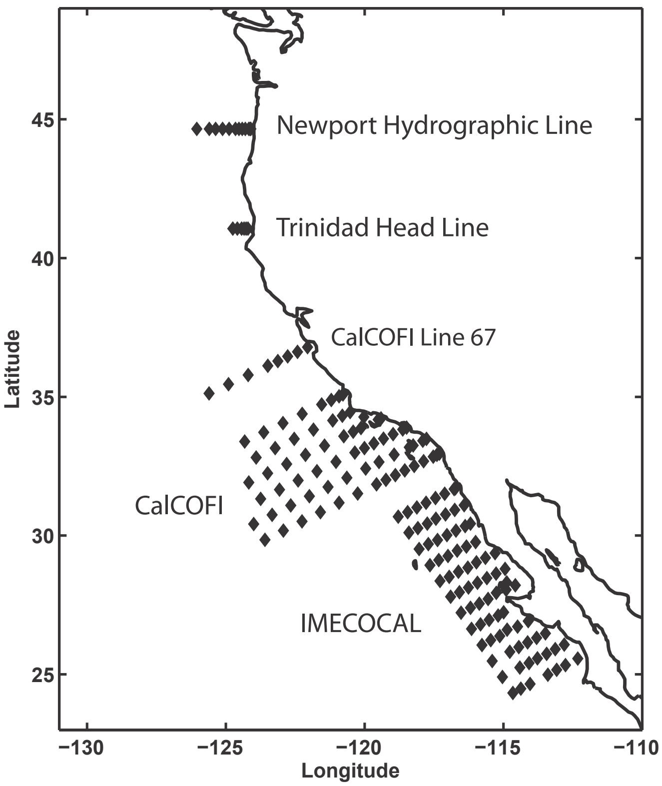

Figure 1. Station maps for surveys that are conducted multiple times per year during different seasons to provide year-round observations in the California Current System. The CalCOFI survey (including CalCOFI Line 67) are occupied quarterly; the spring CalCOFI survey grid extends just north of San Francisco. The IMECOCAL survey is conducted quarterly or semiannually. The Newport Hydrographic Line is occupied biweekly. The Trinidad Head Line is occupied at biweekly to monthly intervals.

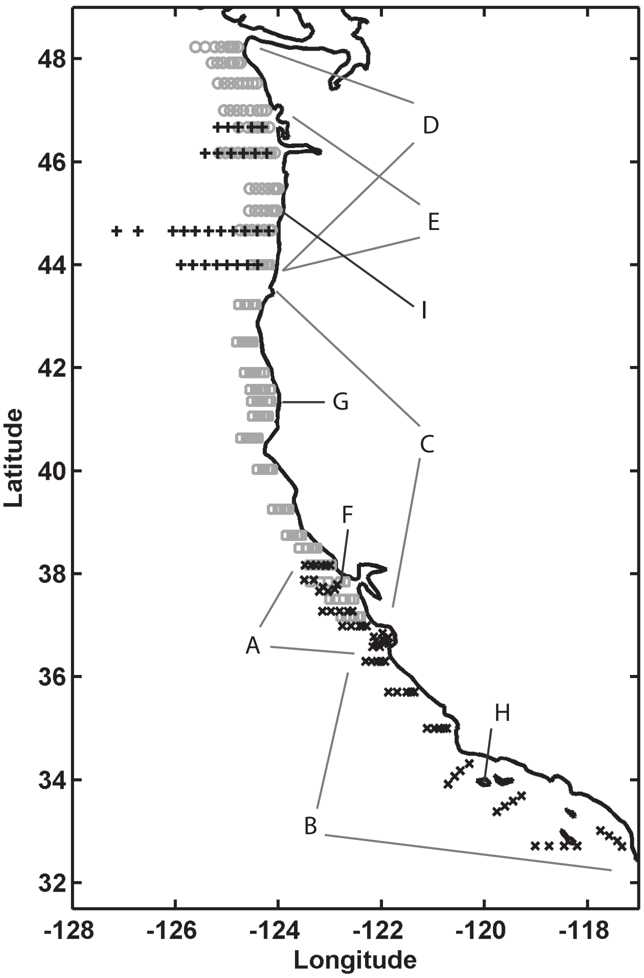

Figure 2. Location of annual or seasonal surveys, including locations of studies on higher trophic levels, from which data are included in this report. Different symbols are used to help differentiate the extent of overlapping surveys. A. SWFSC FED midwater trawl survey core region (May–June) B. SWFSC FED midwater trawl survey south region (May–June). C. SWFSC FED salmon survey (June and September) (grey squares). D. NWFSC salmon survey (May, June, and September). E. NWFSC pelagic rope trawl survey (May through September). F. Southeast Farallon Island. G. Castle Rock. H. San Miguel Island. I. Yaquina Head Outstanding Natural Area. The spatial extent of California Current Ecosystem surveys is partly indicated by data shown in Figure 22, but also extends northwards through much of the CCS.

RECENT EVOLUTION OF THE STATE OF THE CALIFORNIA CURRENT

A shift to cool conditions following the 1997–98 El Niño (Bograd et al. 2000; Peterson and Schwing 2003; Chavez et al. 2003, 2011) drove ecosystem responses consistent with those expected for such a transition, e.g., increased phytoplankton and zooplankton production, as well as occasional shifts in zooplankton community structure (Brinton and Townsend 2003; Lavaniegos and Ohman 2007). Two events impinged on the CCS in 2002–03: an intrusion of subarctic waters (the signature of which was detectable in parts of the CCS into 2007) and a mild tropical El Niño (Venrick et al. 2003). Strong ecosystem responses to the intrusion of anomalously cool, fresh, and nutrient-rich waters (e.g., enhanced productivity) were observed only in the northern CCS (e.g., off Oregon); it is thought that the effects of El Niño were likely to have countered any similar responses off southern California and Baja California (Venrick et al. 2003; Wheeler et al. 2003; Bograd and Lynn 2003; Goericke et al. 2004). Since 2004, regional variability has dominated over coherent CCS-wide patterns (Goericke et al. 2005, 2007; Peterson et al. 2006; McClatchie et al. 2008, 2009; Bjorkstedt et al. 2010, 2011). The late onset of upwelling in 2005 and 2006 led to delayed spin-up of productivity in coastal waters, with strongly negative consequences for higher trophic levels in the northern CCS (Brodeur et al. 2006; Peterson et al. 2006; Sydeman et al. 2006; Lindley et al. 2009; Takahashi et al. 2012). Cool conditions associated with La Niña prevailed from mid-2007 through 2008 into early 2009, but regional variability was again dominant: increases in productivity in the central and northern CCS were not matched by similar responses off southern California and Baja California despite evidence of hydrographic effects of La Niña (McClatchie et al. 2008, 2009). The general pattern of substantial contrasts between the northern and southern regions of the CCS persisted into the short-lived, relatively weak El Niño event in late 2009 through early 2010, during which southern California returned to near climatological mean values and did not indicate any subsequent response to El Niño, while the northern CCS warmed substantially following the decline of La Niña and was strongly affected by intense downwelling during winter 2009–10 (Bjorkstedt et al. 2010). Moreover, as the El Niño diminished rapidly in early 2010, upwelling off central and southern California resumed unusually early and strongly for a spring following an El Niño, but recovery from El Niño in early 2010 appears to have been less robust in the northern CCS (Bjorkstedt et al. 2010). This regional variability persisted into fall 2010 and through the 2010–11 winter as upwelling continued at climatological mean intensity in the south, while shutting down in the north, giving way to a mix of downwelling associated with winter storms and extended periods of quiescent conditions that persisted well into spring 2011 (Bjorkstedt et al. 2011). Ecosystem responses tracked these patterns, with relatively robust productivity in the south and evidence for relatively poor productivity in the north similar to that observed in the lead up to the 2009–10 El Niño (Bjorkstedt et al. 2011).

NORTH PACFIC CLIMATE INDICES

In contrast to the consistently warm conditions that dominated the CCS prior to the strong 1997–98 El Niño, the Pacific Decadal Oscillation (PDO) (Mantua

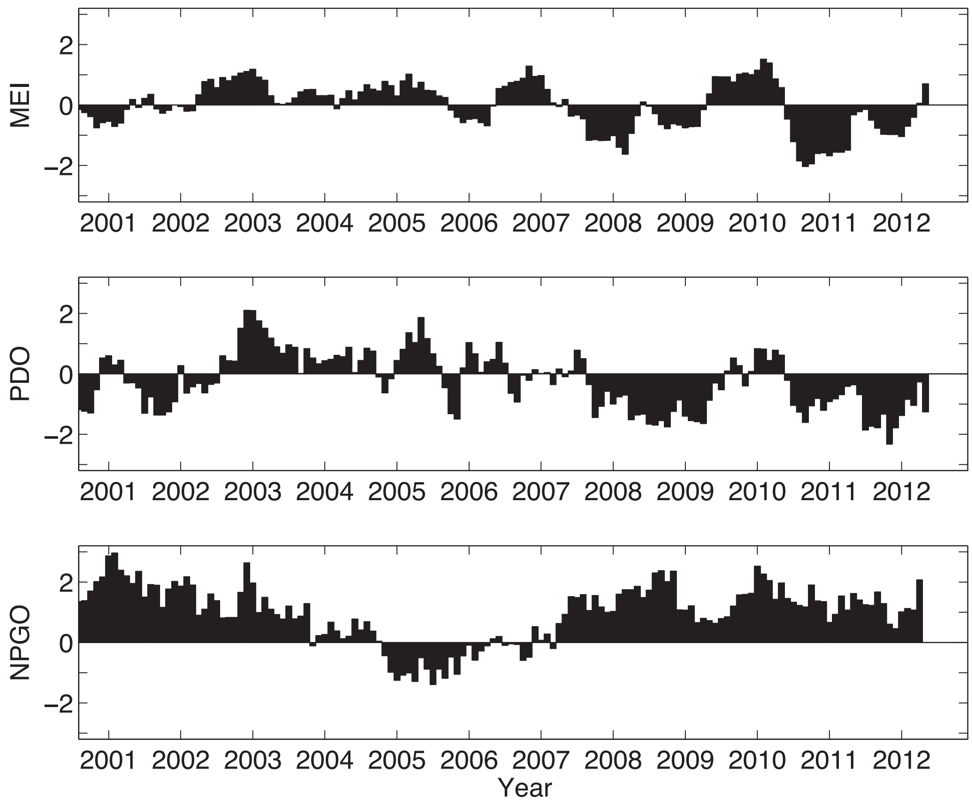

Figure 3. Recent time series of monthly mean values for three ocean climate indices especially relevant to the California Current: the multivariate ENSO index (MEI; top panel; data retrieved from http://www.esrl.noaa.gov/psd/people/klaus.wolter/MEI/table.html), the Pacific Decadal Oscillation (PDO; middle panel; data retrieved from http://jisao.washington.edu/pdo/PDO.latest), and the North Pacific Gyre Oscillation (NPGO; bottom panel; data retrieved from http://www.o3d.org/npgo/data/NPGO.txt) for January 1984-May 2012).

et al. 1997) index suggests that the North Pacific has since been in a generally cooler state (fig. 3a). However, the PDO has been for the past decade fluctuating at intervals of approximately two to four years between cool states marked by negative values of the PDO index and associated negative anomalies in sea surface temperature throughout the CCS (e.g., 1998–2001, 2008–09) and warmer states of positive PDO and positive SST anomalies (e.g., 2003–06) (fig. 3a, and see below). This pattern appears to be continuing through the past year: following the strong La Niña conditions that developed in summer 2010, the PDO briefly reverted towards neutral values in spring 2011 before again shifting to strongly negative values, including some of the most negative (cool) values observed in the past decade (e.g., –2.33 in November 2011; fig. 3a). Over the past several years, since at least 2008, variability in PDO has exhibited a high degree of coherence with the Multivariate El Niño Southern Oscillation Index (MEI) (Wolter and Timlin 1998) (figs. 3a,b). The MEI shifted dramatically from El Niño to La Niña conditions in early 2010 and remained in a strongly La Niña state until increasing rapidly towards neutral values into early 2011. In contrast to the PDO, the MEI did not indicate a return to stronger La Niña conditions in summer 2011 and has instead remained between a moderate La Niña and neutral (fig. 3b). Moderate to weak La Niña conditions had prevailed in the tropical Pacific since July 2010, but the negative SST anomalies steadily weakened in the first half of 2012. ENSO-neutral conditions were present by April 2012, with the Niño 3 index turning slightly positive. The persistence of such variability means that the question of whether a sustained decadal "regime" has been established in the CCS remains open and subject to some debate. The North Pacific Gyre Oscillation (NPGO) (Di Lorenzo et al. 2008), which is a measure of the strength of gyral circulation in the North Pacific, has also covaried with MEI and PDO, but has been predominantly positive since the late 1990s, indicating anomalously strong equatorward flow in the CCS (fig. 3c). Negative NPGO during 2005 and 2006 corresponds to the period of unusually low productivity observed through much of the CCS. The NPGO index was variable but generally remained positive through 2011 and into 2012, reflecting the persistence of stronger-than-normal gyral circulation in the North Pacific (fig. 3c).

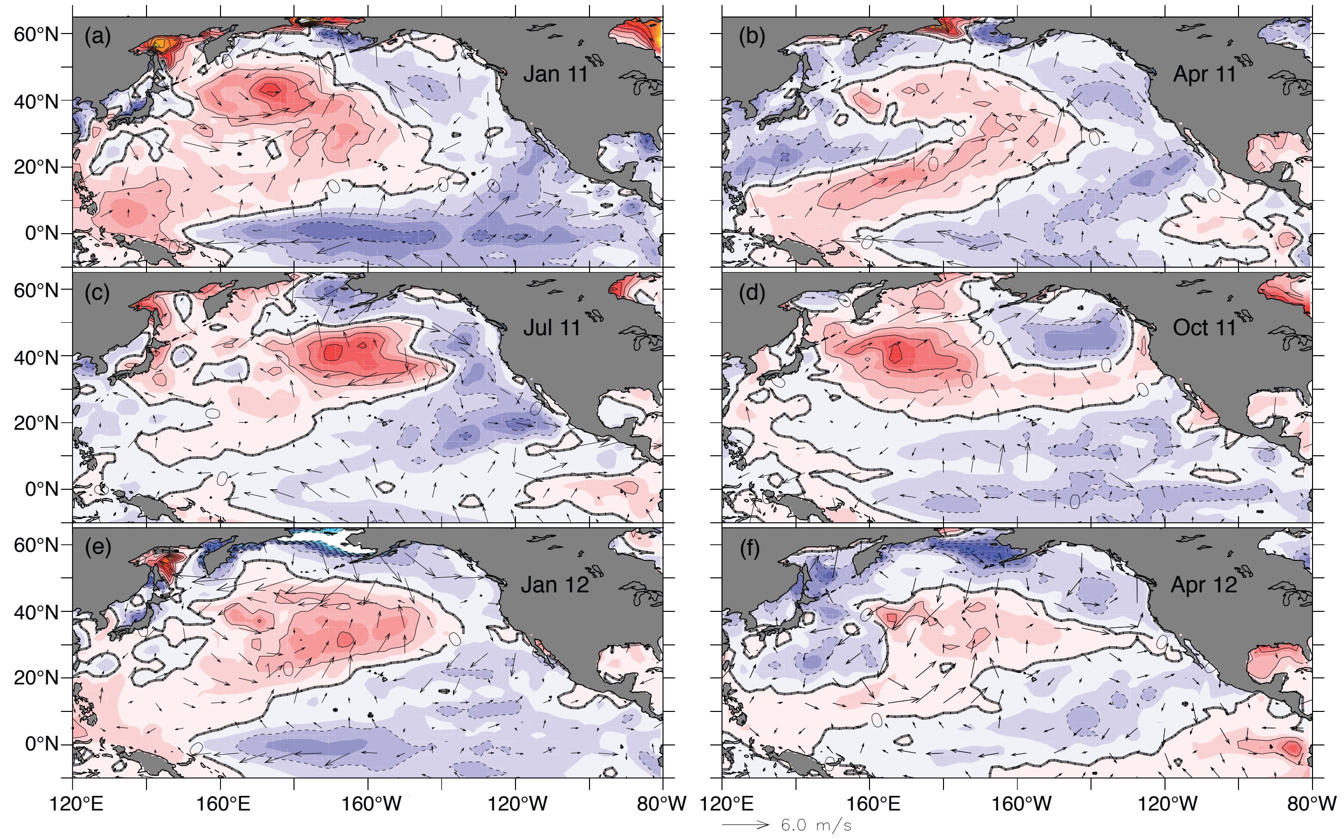

Figure 4. Anomalies of surface wind velocity and sea surface temperature (SST) in the north Pacific Ocean, for (a) Jan 2011, (b) April 2011, (c) July 2011, (d) October 2011, (e) Jan 2012, and (f) April 2012. Arrows denote magnitude and direction of wind anomaly (scale arrow at bottom of figure). Contours denote SST anomaly. Shading interval is 0.5°C and contour interval is 1.0°C. Negative (cool) SST anomalies are shaded blue; positive (warm) SST anomalies are shaded red. Wind climatology period is 1968–96. SST climatology period is 1950–79. Monthly data obtained from the NOAA-CIRES Climate Diagnostics Center.

NORTH PACIFIC CLIMATE PATTERNS[1]

Figure 4 illustrates the spatial evolution of climate patterns and wind forcing over the North Pacific related to trends in the basin-scale indices reviewed above. SSTs along the North American coast were close to normal in winter 2011 (fig. 4a) but transitioned through spring (fig. 4b) and summer (fig. 4c) 2011 to cooler conditions (SST anomalies of –0.5° to –1.0°C) coupled with warmer-than-normal SST (>+1.0°C) in the western and central North Pacific, a pattern that has persisted in recent years. Strong anticyclonic wind anomalies dominated the Northeast Pacific through summer 2011, resulting in cool SST anomalies throughout the Gulf of Alaska and California Current (fig. 4c). A brief period of warm SST anomalies in the eastern North Pacific in September–October 2011 (fig. 4d) transitioned back to cool SST anomalies in early winter 2011–12, driven by anticyclonic wind anomalies (fig. 4e). This pattern weakened going into spring 2012 with warm SST anomalies emerging in the eastern equatorial Pacific (fig. 4f).

Upwelling in the California Current

The onset of upwelling in spring 2011 was relatively early and strong from Baja through central California (fig. 5). In contrast, the date of the "spring transition" off Oregon was very close to the long-term mean (mid-April) following anomalously strong and late downwelling associated with spring storms in the northern part of the CCS. Upwelling was more or less normal across much of the CCS through spring and early summer 2011 (but was anomalously strong off Baja California). Stronger than normal upwelling developed across much of the CCS during midsummer 2011, reflecting persistently strong anticyclonic wind anomalies over the North Pacific (figs. 4b,c, 5). Upwelling strength declined significantly across the CCS in September, leading to an unusually early termination of the upwelling season off Oregon (the 2011 upwelling season off Oregon was among the shortest observed: only 153 days relative to a mean of 179 days) (fig. 5). Despite this decline, continued upwelling events (see review of buoy observations below) contribute to anomalously strong net upwelling (weak net downwelling) through much of the California Current south of 40°N into autumn 2011. A period of

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[1] Further details on month-to-month and interannual global ocean climate variability can be found at CPC's "Monthly Ocean Briefing" archive (http://www.cpc.ncep.noaa.gov/products/GODAS).

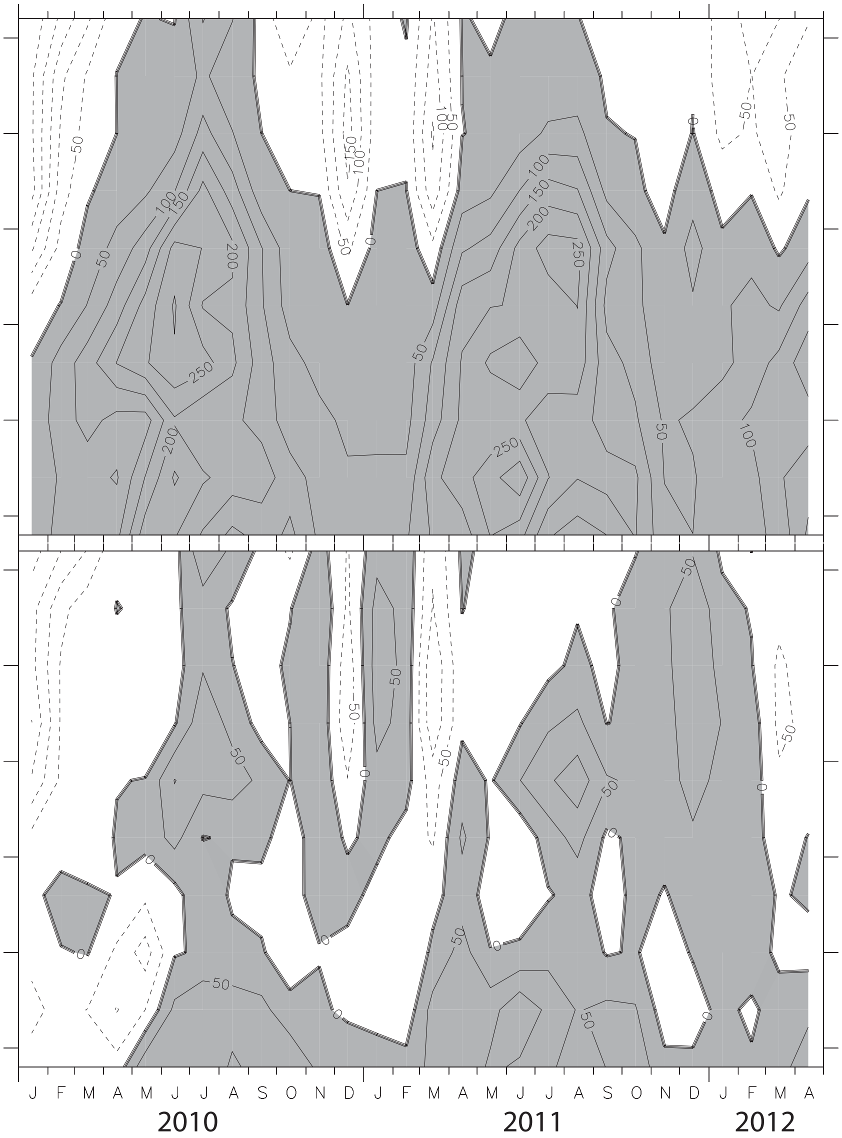

Figure 5. Monthly upwelling index (top) and upwelling index anomaly (bottom) for January 2010–April 2012. Shaded areas denote positive (upwelling-favorable) values in upper panel, and positive anomalies (generally greater than normal upwelling) in lower panel. Anomalies are relative to 1948–67 monthly means. Units are in m^3 s^{-1} per 100 km of coastline.

unusually strong upwelling occurred throughout much of the CCS (up to nearly 45˚N) in winter 2012, but this was followed by a return to weaker-than-normal upwelling, including predominantly southerly winds and downwelling well into spring 2012.

Trends in cumulative upwelling[2] (measured from November 1 to better capture ecologically important winter dynamics, c.f. Logerwell et al. 2003; Schroeder et al. 2009; Black et al. 2010, 2011) illustrate the potential contribution of upwelling-driven enrichment to ecosystem pre-conditioning in late fall and late winter along much of the coast (i.e., between 36˚N and 48˚N), as well as the consequences of subsequent periods of sustained downwelling that push 2011–12 trajectories towards those observed during the preceding year (fig. 6). The effects of downwelling in late spring are weaker in the south, where cumulative upwelling remains comparable to (33˚N) or high relative to preceding years (36˚N).

Observations at coastal NDBC buoys reflect these large-scale patterns in the form of highly coherent time series of surface wind and SST observations but also reveal strong variability at "event" scales of a few days to weeks in both alongshore surface winds and SST (fig. 7). As in 2010, 2011 was marked by numerous upwelling-relaxation events during the spring and summer and

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[2] Cumulative upwelling was calculated from the 6-hourly Bakun Index obtained from the NOAA Fisheries Environmental Research Division obtained through http://www.pfeg.noaa.gov/products/PFEL/modeled/indices/PFELindices.html.

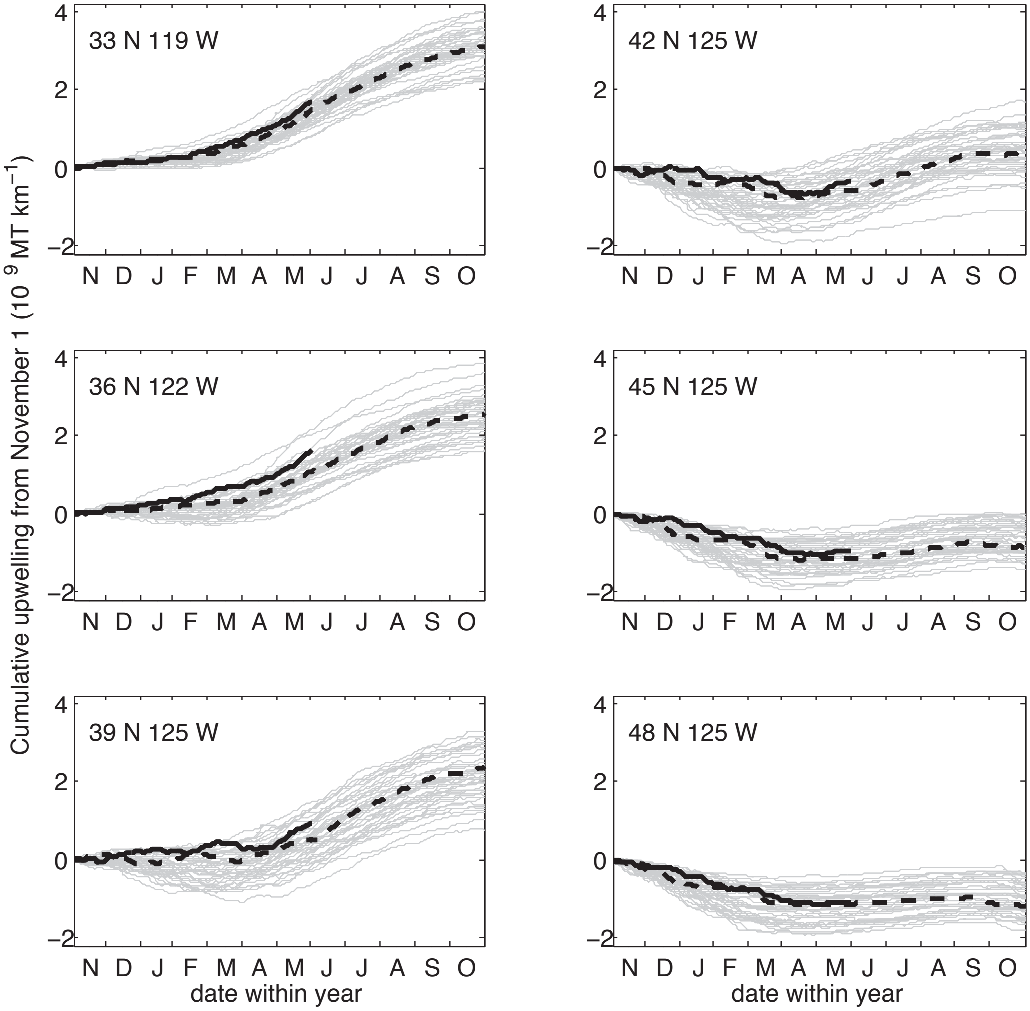

Figure 6. Cumulative upwelling from November 1 (of previous year) calculated from the Bakun Index at indicated locations along the West Coast of North America for 1967–2010 (grey lines), 2011 (dashed line), and 2012 (solid line). Calculation of cumulative upwelling from November captures important variability during the winter “pre-conditioning” period (cf. Schroeder et al. 2009; Black et al. 2010).

strong upwelling-downwelling transitions throughout the fall and winter, with much of this variability observed in the northern CCS (fig. 7). The persistence of strong variability in event-scale forcing, as has been apparent since 2007, may be linked to high intraseasonal (30–60 day) variability in the tropics associated with the Madden-Julian Oscillation[3] (Zhang 2005).

Cooler SSTs persisted through much of summer and autumn 2011, except for the warming event in October, reflecting the cumulative effect of numerous strong coastwide upwelling events (figs. 4d, 7). Persistent, anomalously strong upwelling (weak downwelling) affected much of the CCS during early 2012, resulting in strong negative SST anomalies. SSTs throughout much of the CCS shifted towards climatological values in April 2012.

HF Radar Surface Current Observations[4]

Seasonal mean surface currents observed with HF radar reveal a characteristic pattern of southerly currents in spring developing into marked offshore flow in summer with a general weakening in the fall and a tendency for weak northward flow in winter. In spring 2011 (March–May), offshore jets are evident south of several major headlands, including Cape Mendocino, Point Arena, and Cape Blanco (fig. 8). Offshore flow, although weaker than in the north, is also seen at Point

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[3] http://www.cpc.noaa.gov/products/precip/CWlink/MJO/mjo.shtml

[4] High Frequency (HF) Radar currents presented herein are calculated hourly at 6-km resolution using optimal interpolation (Kim et. al. 2008; Terrill et. al. 2006) and further averaged to 20-km resolution prior to display. Real-time displays of HF-Radar surface currents can be viewed at the regional association websites: http://www.sccoos.org/data/hfrnet/ and http://www.cencoos.org/sections/conditions/Google_currents/. HF radar observations are supported by NOAA’s Integrated Ocean Observing Systems (IOOS) and participating universities (listed at http://cordc.ucsd.edu/projects/mapping/) and make use of a network of radars initially constructed with support from the state of California and the NSF.

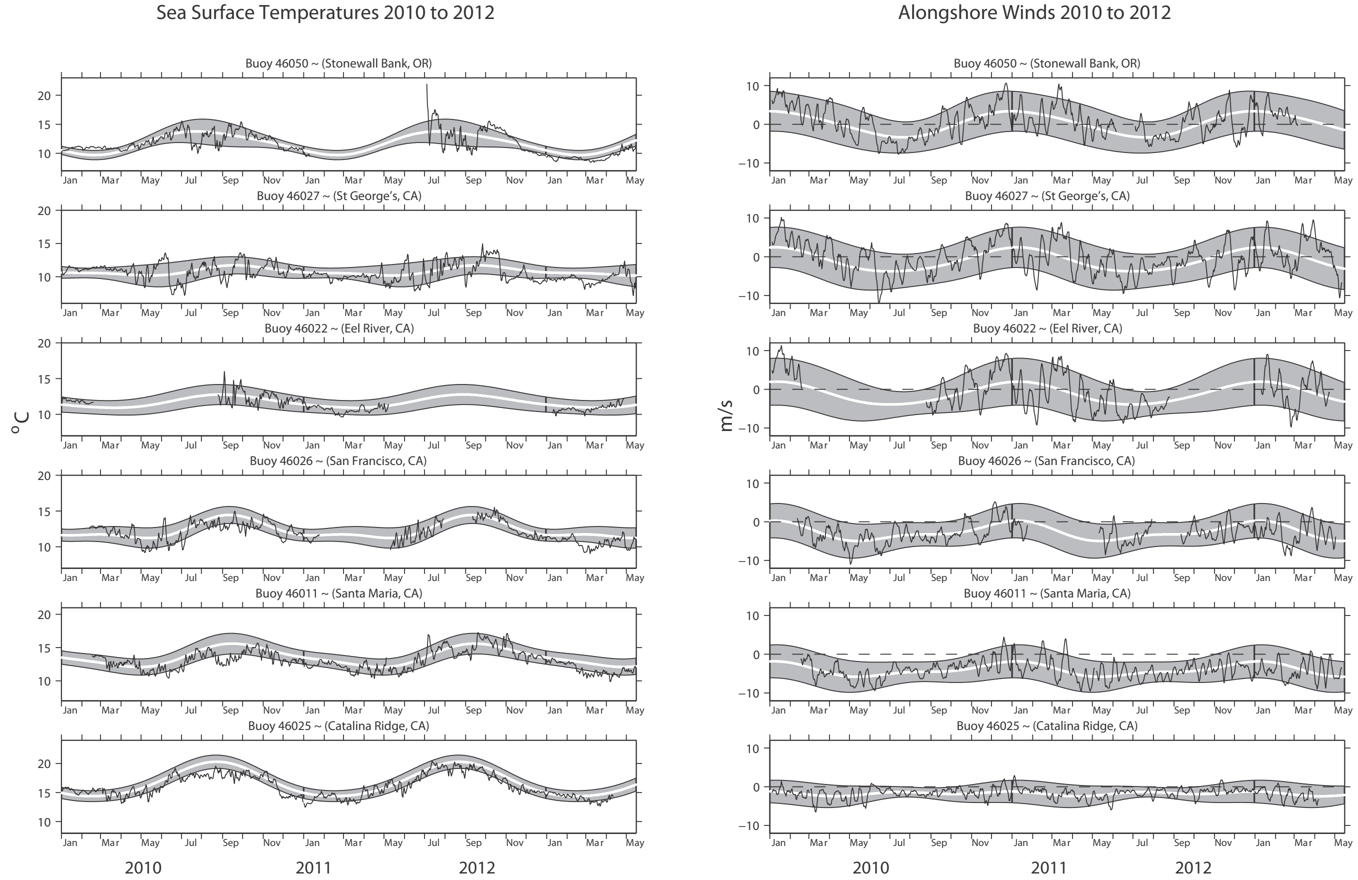

Figure 7. Time series of daily-averaged SST (left) and alongshore winds (right) for January 2010–April 2012 at selected NOAA National Data Buoy Center (NDBC) coastal buoys. Bold white lines are the biharmonic annual climatological cycle at each buoy. Shaded areas are the standard errors for each Julian day. Series have been smoothed with a 7-day running mean. Data provided by NOAA NDBC. Coordinates for buoy locations are at http://www.ndbc.noaa.gov/to_station.shtml.

Conception, and mean flows were predominantly southward throughout the Southern California Bight. Mean surface currents are generally stronger during summer 2011 than in spring, with a general offshore flow marked by broad maxima south of Cape Blanco, Cape Mendocino and Point Sur (fig. 8). In contrast, offshore flows are not enhanced and remain relatively weak over the shelf and slope in the greater Gulf of Farallones (36°–38°N) and in the Southern California Bight (32°–34°N) during summer 2011. In fall, weak poleward flow develops and dominates in the Southern California Bight and offshore flow weakens between Cape Blanco and Point Conception (34°–43°N). In contrast to previous years, mean northward flow during winter (December 2011 to February 2012) is evident only north of Cape Blanco, particularly in the vicinity of the Columbia River plume, while broad offshore flows persist off Cape Blanco, Point Arena, and Point Conception (fig. 8). This contrasts with winter 2009–10 when an average northward flow was observed throughout the CCS during the weak El Niño (Bjorkstedt et al. 2010) and with winter 2010–11 when northward flow dominated north of Cape Mendocino (Bjorkstedt et al. 2011). More strikingly, in neither 2009–10 nor 2010–11 did offshore flow features persist through winter, yet the signature of such features is apparent during winter 2011–12.

A time series of surface flow past Point Reyes illustrates variability in the timing, strength, and duration of southward flows over the past 11 years (fig. 9). The Point Arena coastal jet seen in Figure 8 shows up here as strong southward flow past Point Reyes in April–June but quickly diminishes to negligible net alongshore flow nearshore and weakens at offshore locations through the summer. This pattern is consistent with previous years, but the net flow is generally weaker than in previous years, such that flows in summer 2011 are comparable with those observed in 2006. Weak flows occur in spite of a marked seasonal peak in upwelling index in summer. However, alongshore currents continue to covary strongly with monthly water level at Point Reyes. Alongshore flow is more coherent across the shelf in winter 2011–12 and includes strong southward flows in early 2012 that are captured in the broader pattern of southward and offshore flow during winter 2011–12

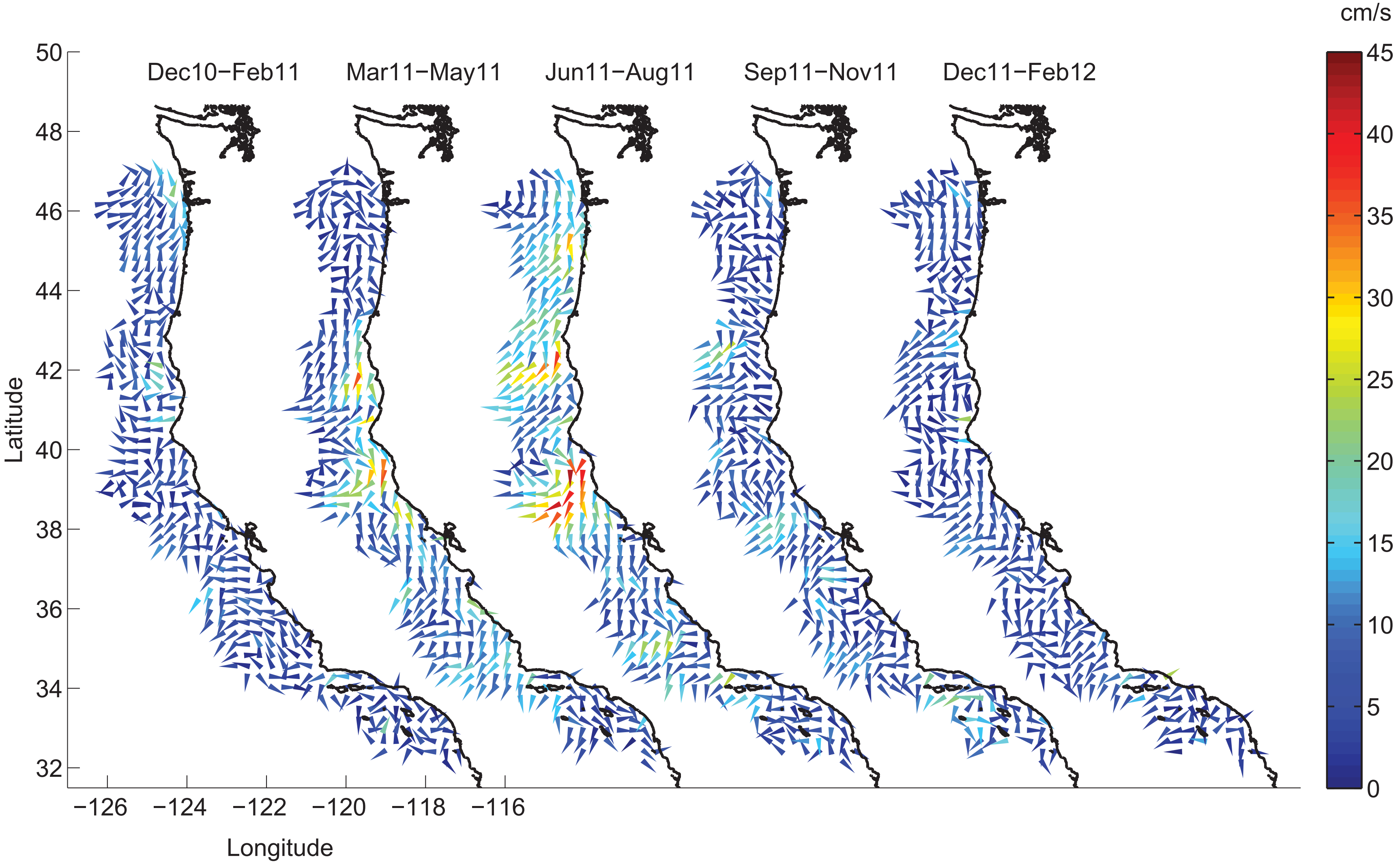

Figure 8. Maps of seasonal mean surface current in the CCS measured with HF radar for December 2010 through February 2012. From left to right, the seasons are winter (December–February 2011), spring (March–May), summer (June–August), fall (September–November), and winter (December–February). Mean surface currents are calculated at 20-km resolution from hourly HF-radar observations. Current speed is indicated by color and current direction is indicated by orientation of arrowheads. The base of the arrow is at the observation location. For clarity, currents are displayed for every fifth grid cell in both north-south and east-west directions.

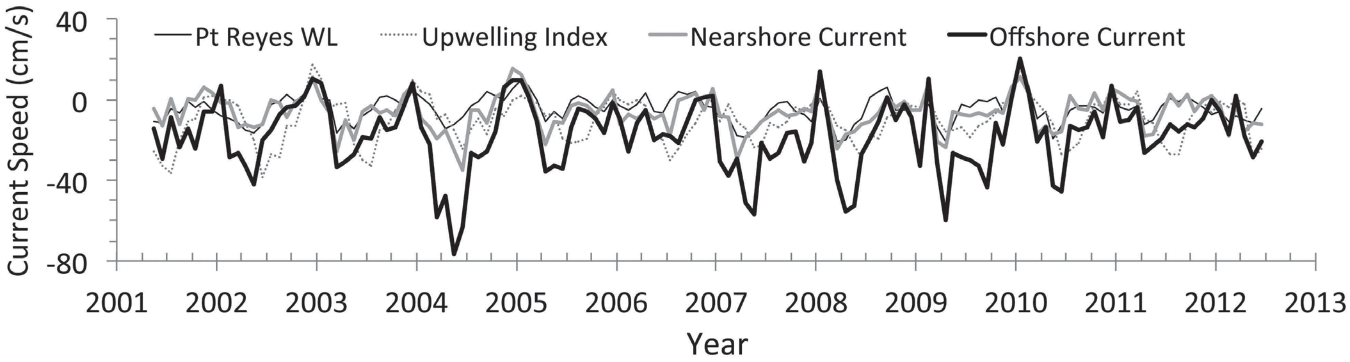

Figure 9. Monthly averages of spatially averaged surface flow past Point Reyes, California between 30 km and 60 km offshore (38°00' to 38°10'N and 123°20' to 123°40'W; thick black line) and between 0 and 15 km offshore (38°00' to 38°10'N and 123°00' to 123°10'W; thick grey line). Positive values indicate poleward flow. Also shown are monthly mean cross-shelf Ekman transport indexed by the negative Upwelling Index at 39°N (fine, grey dashed line; plotted as onshore Ekman transport, in units of 10 m^3/s per 100 m of coastline) and monthly mean sea level measured at at Point Reyes NOAA tide gauge (fine black line; plotted as sea level relative to 1m above MLLW, in units of cm).

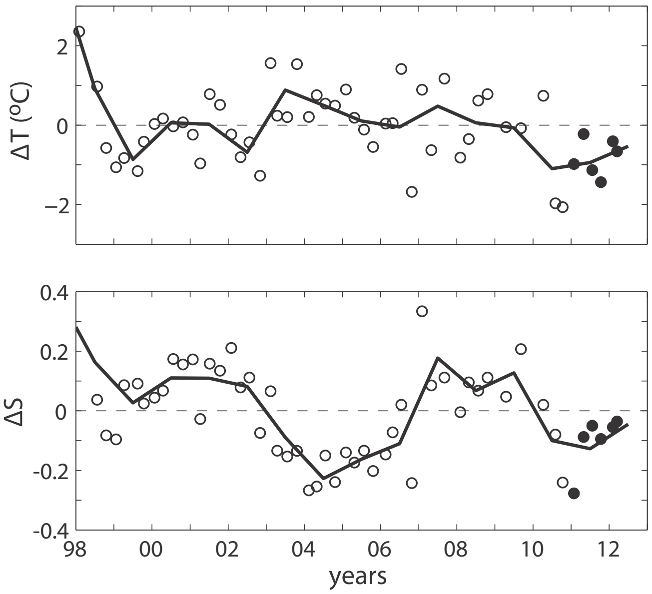

Figure 10. Mixed layer temperature anomaly (°C) and mixed layer salinity anomaly off the Baja California Peninsula (IMECOCAL grid). Each symbol represents the average anomaly for each cruise conducted. Data from the 2011 and 2012 surveys are plotted as solid symbols. The thick solid line indicates annual average.

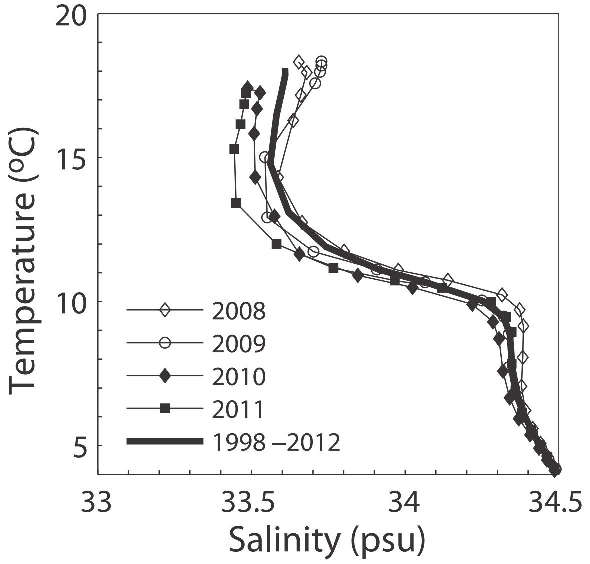

Figure 11. Annual mean T-S curves for 2008–2011 across the IMECOCAL region. The long-term mean (January 1998–March 2012) is indicated by the thick line. Each data point indicates one standard depth, from surface to 1000 m.

(figs. 8, 9). Southward flow again develops in spring 2012 and can be expected to weaken through the summer, as has been observed in previous years.

REGIONAL SUMMARIES OF HYDROGRAPHIC AND PLANKTON DATA

Several ongoing surveys provide year-round hydrographic and plankton observations across the CCS but vary substantially in terms of spatial extent and temporal resolution (fig. 1). In the following section we review recent observations from these surveys from south to north.

Baja California (IMECOCAL[5])

Following the trend described in last year's report, mixed layer temperatures off Baja California remained cooler than the long-term average during 2011 and into 2012, with some evidence from recent surveys for a weak trend towards the climatological mean (fig. 10). This modest warming was especially apparent in the region north of Punta Eugenia (ca 28°N) that is more strongly affected by northern waters (data not shown),

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[5] IMECOCAL cruise schedules, data collection protocols, analysis methods, and additional substantiating data are described in detail at http://imecocal.cicese.mx.

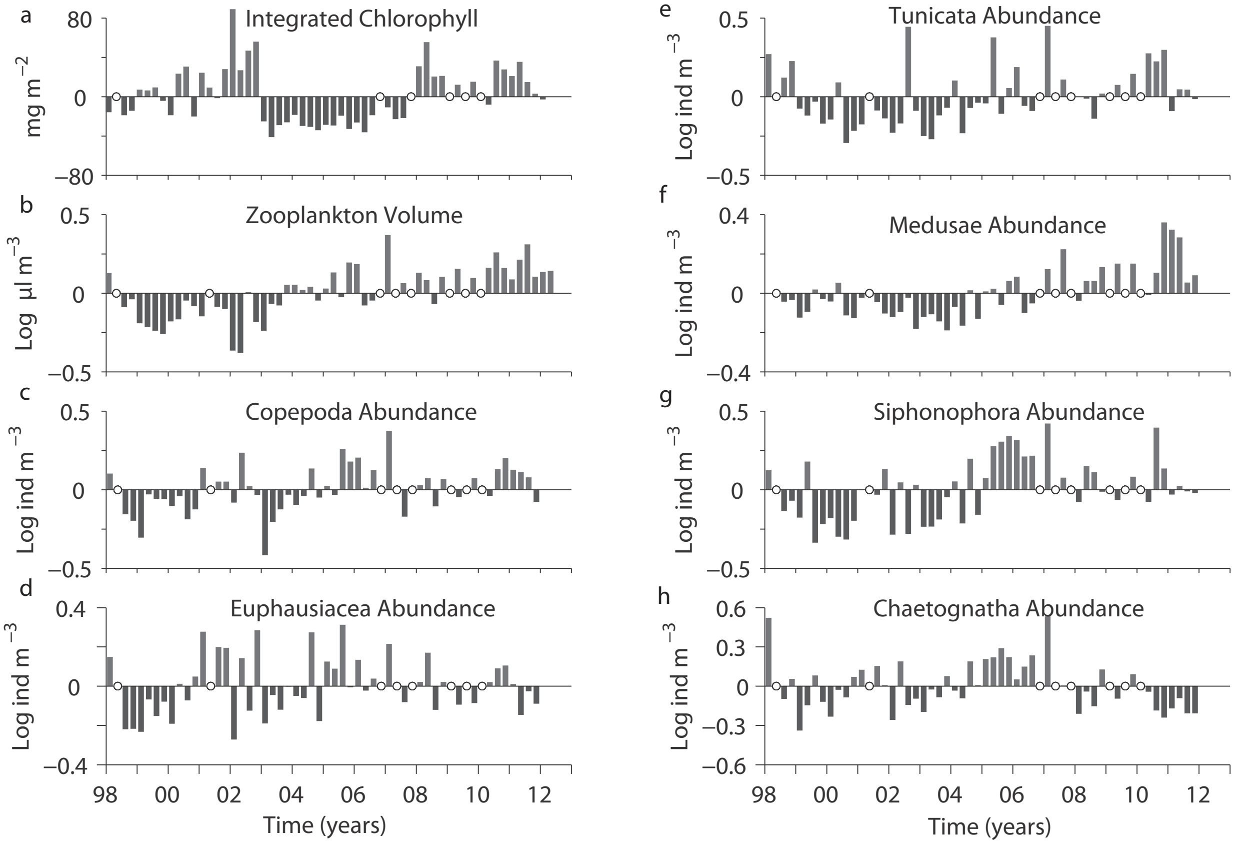

Figure 12. Time series of anomalies in 0–100 m integrated chlorophyll *a*, zooplankton volume and group abundance anomalies for the IMECOCAL region. Each bar represents the anomaly for a single cruise from the long-term mean. Open circles indicate cruises that were not conducted or were omitted due to limited sampling.

while mixed layer temperatures south of Punta Eugenia remained consistently cooler than mean conditions during 2011–12. Salinities within the mixed layer also continued to be below (fresher than) the climatological mean (largest anomalies in December 2010 and January 2011), after the effects of an intrusion of subtropical waters towards the coast starting in 2008–09 dissipated with the transition to La Niña conditions following the weak 2010 El Niño. By 2012, mixed layer salinities returned to climatological means north of Punta Eugenia, even as relatively fresh conditions persisted over the region to the south. Dissipation of positive salinity anomalies in the upper water column and freshening of the upper water column that began during 2010 continued into 2011 as depicted by the annual TS averages (fig. 11). Consistent with the trends in mixed layer properties, TS mixing curves for two cruises in early 2012 (January and March, not shown) also indicate a return to climatological conditions in the upper 200 m.

Relatively high concentrations of chl *a* in the upper water column (0–100 m) persisted into 2011 but declined in late 2011 through early 2012 (fig. 12a). Bulk zooplankton (measured as displacement volume) continued to be well above the mean for the observational record, a pattern that reflects the ongoing dominance of gelatinous groups that have a large influence on volume biomass measured (figs. 12b–h). During 2010, tunicates were numerically dominant, with a large increase in hydromedusae by fall 2010 that persisted through 2011 (figs. 12e,f). The apparent resurgence of crustacean zooplankton reported last year (Bjorkstedt et al. 2011) appears to have reversed, with both copepod and euphausiid densities declining through 2011 and into early 2012 (figs. 12c,d). The decline in (numerical) density appears to have been rather general across zooplankton taxa, although the shift to greater dominance by hydromedusae appears to have prevented a parallel decline in displacement volume (figs. 12b–f).

Southern California (CalCOFI[6])

Mixed layer temperatures were below long-term, seasonally adjusted averages during the last year (fig. 13a), consistent with the basin-wide trends (figs. 4, 7). Con-

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[6] Results are presented here as cruise averages over all 66 stations in the standard CalCOFI grid or as anomalies with respect to the 1984–2008 time series to augment ongoing time series of observations. Detailed descriptions of the cruises and methods used to collect data and analyze samples are given in previous reports and are available at http://www.calcofi.org.

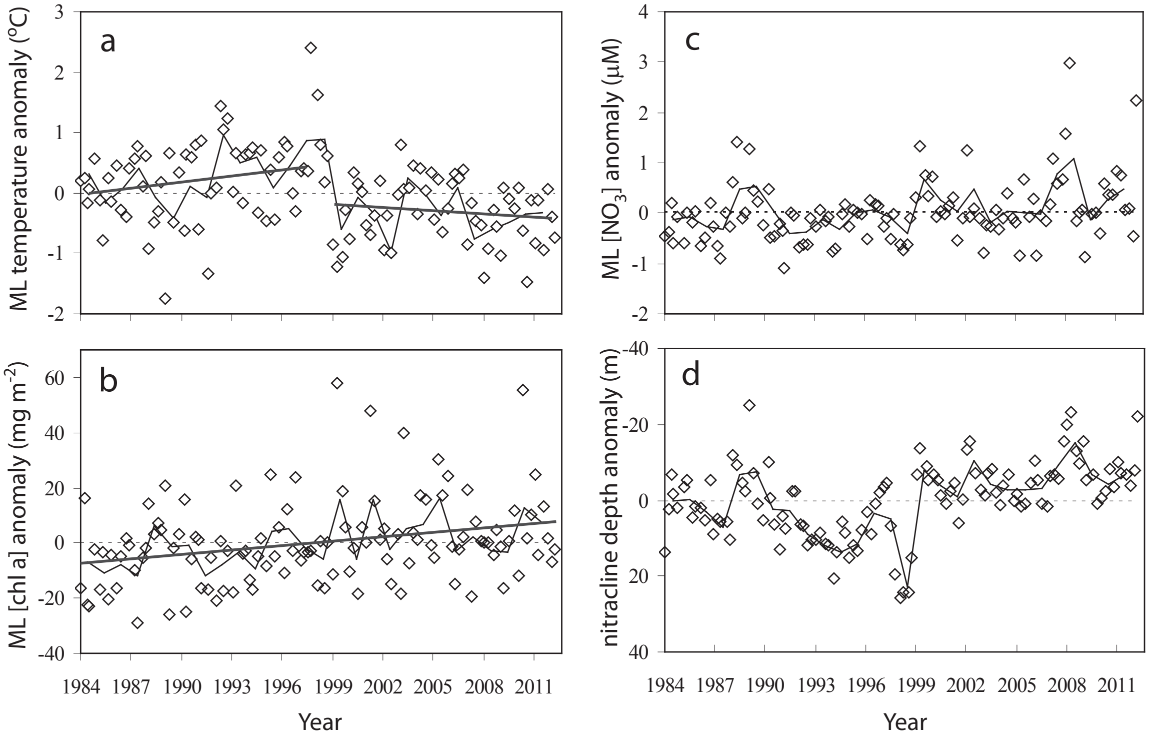

Figure 13. Property anomalies from long-term, seasonally-adjusted means for the mixed layer of the CalCOFI standard grid: (a) temperature, (b) chl *a* concentration, (c) nitrate concentration, and (d) nitracline depth. Data from individual CalCOFI cruise data are plotted as open diamonds. The thin solid lines represent the annual averages. Dotted lines represent zero anomaly for reference. Straight solid lines, when present, indicate long-term linear trends. The discontinuous trend in temperature is based on separate fits to anomaly data for the periods prior to and after, but not including, the 1998–99 ENSO event.

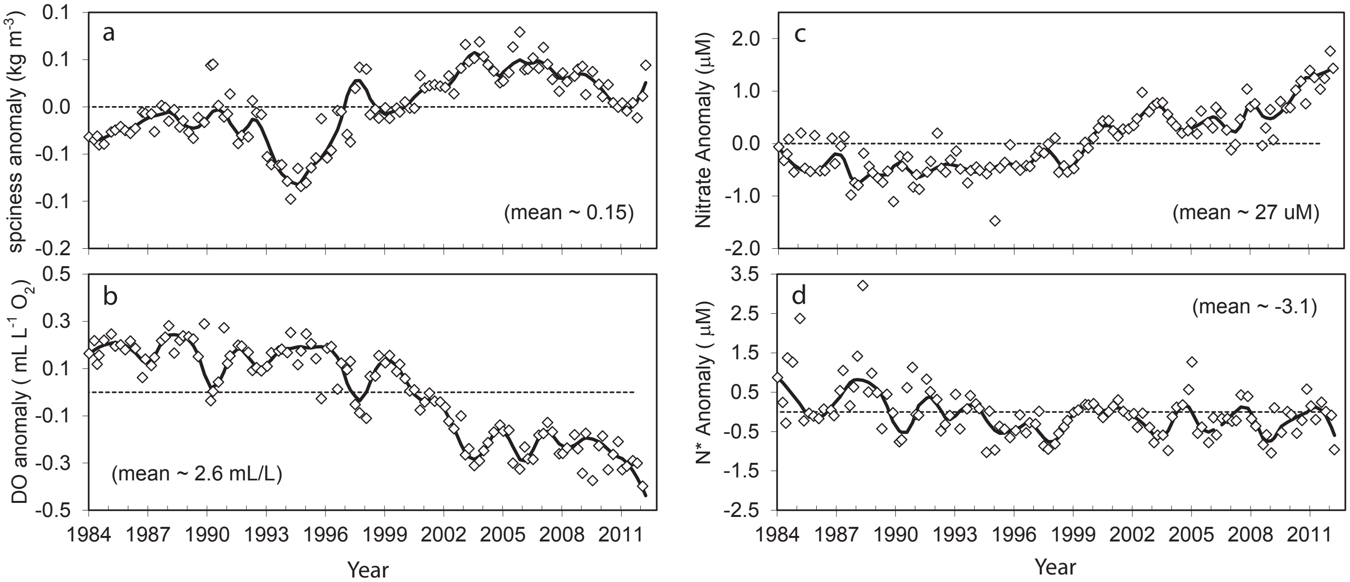

Figure 14. Anomalies of hydrographic properties at the σ_t 26.4 isopycnal (open diamonds) averaged over the standard CalCOFI stations: (a) spiciness, (b) dissolved oxygen, (c) nitrate concentration, and (d) N*, a biogeochemical indicator which reflects the deficit of nitrate in a system relative to concentrations of phosphate (Gruber and Sarmiento 1997). The solid line represents a loess fit to the data; average values for the properties are given as well.

centrations of chl *a* were close to long-term seasonally adjusted averages (fig. 13b), as were concentrations of nitrate, except for the spring 2012 values, which were extremely high (fig. 13c). The apparent discrepancy between spring 2012 nitrate and chl *a* can be explained by the relatively early initiation of upwelling in the spring of 2012 (fig. 5) and the early date of the cruise. Mixed layer temperatures observed off Point Conception during the February 2012 CalCOFI cruise were about 13°C. By March 2012 temperatures in that area

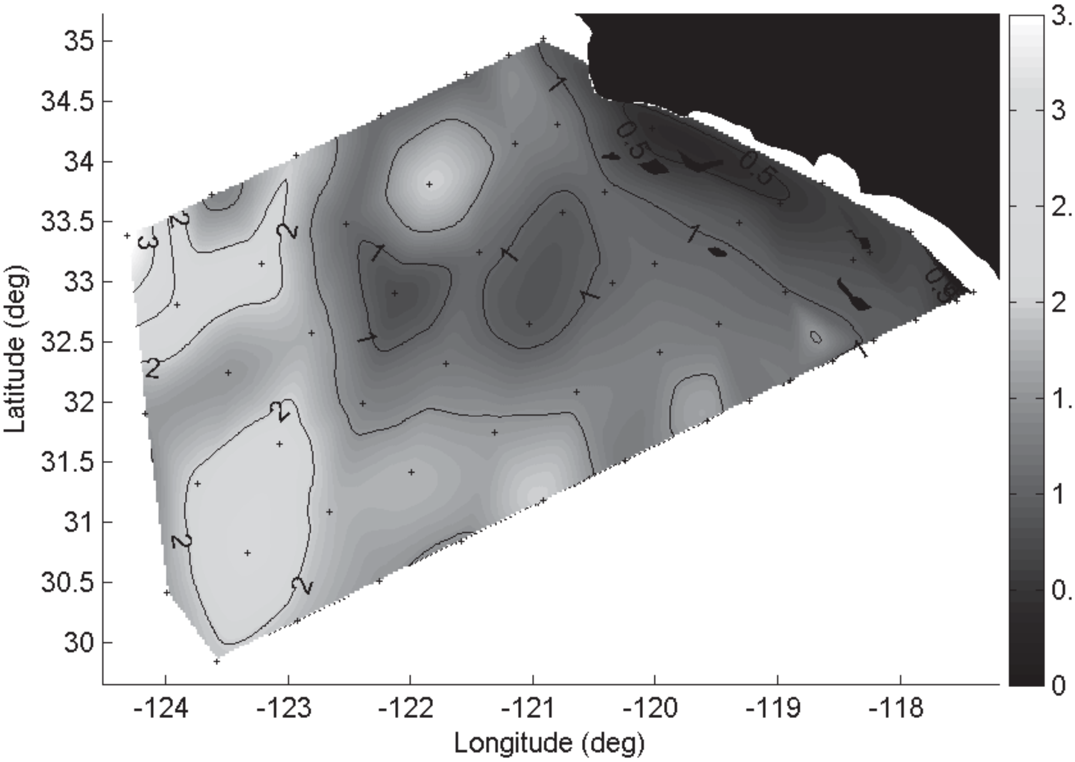

Figure 15. The spatial distribution of nitrate concentration anomalies (µM) at the 26.4 isopycnal for the time period summer 2011 to spring of 2012 relative to the 1984 to 2008 time period. Note that nitrate concentrations are consistently higher than in the early period (i.e., all anomalies are positive), but that anomalies are smaller near the coast and large anomalies are observed only in the western portion of the sampled region.

ranged from 11°C to 12.5°C, a sign of strong upwelling[7]. Concentrations of chl *a* concentrations at that time were still low, likely because the spring bloom had not yet occurred. The very shallow depth of the nitracline (fig. 13d) during the spring of 2012 is due to the strong upwelling, i.e., lifting of isopycnals, and may also reflect basin-wide changes (see below).

Conditions at the σ_t 26.4 isopycnal[8] (fig. 14) continued to change (cf. Bjorkstedt et al. 2011). Spiciness at the isopycnal has been fairly constant over the last decade (fig. 14a), suggesting that no dramatic changes in water masses have occurred. However, concentrations of oxygen continued to decrease (fig. 14b) and those of nitrate to increase (fig. 14c), reaching values that have not been observed since these measurements began in 1984. The relatively constant values of N* (fig. 14d), at least over the last decade, are consistent with the hypothesis that the balance of remineralization and denitrification in the tropical North Pacific has not changed significantly[9]. The spatial expression of the nitrate increase shows the strongest signal in the offshore areas and relatively weak signals along the coast (fig. 15), consistent with a basin-wide mechanism forcing the observed changes rather than the effects of local processes changing properties of the California Undercurrent. The mechanisms driving observed trends in nitrate and DO concentrations are a focus of active ongoing research, but we note that the trends in nitrate concentration are consistent with the process described in a modeling study by Rykaczewski and Dunne 2010, i.e., that concentrations of nitrate will increase in the CCS as a consequence of global warming due "to enrichment of deep source waters entering the CCE[cosystem] resulting from decreased ventilation of the North Pacific." An alternative explanation for such increases is increased remineralization of organic matter at the depths where the nitrate increases are observed; however, this mechanism requires increased rates of production or increased rates of export production, rate changes that have so far not been observed.

Zooplankton displacement volume (ZDV), a proxy for zooplankton biomass, was near the long-term mean

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[7] Cruise-by-cruise spatial plots of hydrographic and associated data are available at http://data.calcofi.org/bottle-data/cruise-hydrographic-data/hydrographic-figures.html; preliminary data for 2012 cruises are available at http://www.calcofi.org/component/content/article/50-datareports/468-soc-maps.html.

[8] The σ_t 26.4 isopycnal is located within the pycnocline and is typically found at a depth of about 200 m off S. California. It provides a useful reference layer because it is insensitive to local forcing affecting the surface mixed layer. Changes in water properties at this isopycnal therefore indicate evidence of changes in regional water masses, and changes in the depth of this isopycnal indicate the effects of circulation patterns (e.g., eddies) or large scale waves (e.g., Rossby waves).

[9] N* is a biogeochemical indicator which reflects the deficit of nitrate in a system relative to concentrations of phosphate (Gruber and Sarmiento 1997).

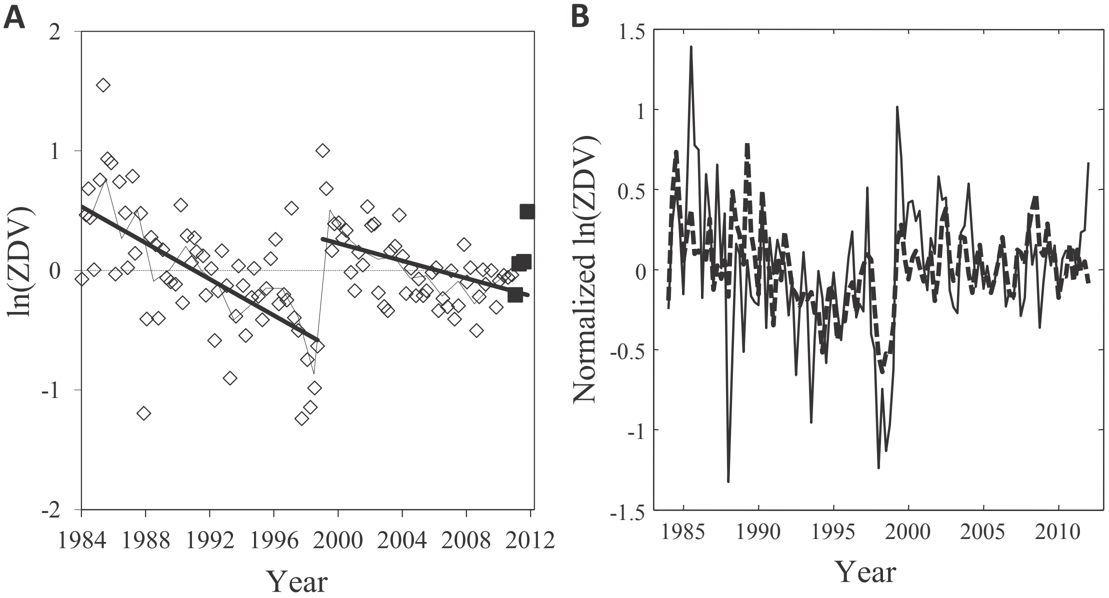

Figure 16. (a) Average anomalies of log-transformed zooplankton displacement volumes (ZDV) for each cruise plotted against time. Solid lines indicate trends based on linear fits to data prior to and after the 1998–99 ENSO event. (b) Detrended ZDV anomalies (solid lines) and predicted values based on an autoregressive model with external inputs (ARX [4, 2, 0]), cf. Box and Jenkins 1970 fitted to ZDV and nitracline depth (dashed lines). Note that zooplankton data are only available up to the fall of 2011.

during 2011 (fig. 16a). The spring 2012 cruise was especially remarkable for the abundance of gelatinous zooplankton captured (see Gelatinous Zooplankton, below). A visual comparison of ZDV anomalies and nitracline depth (fig. 13d) suggests that these two variables continue to covary through 2011 (ZDV data for early 2012 are not yet available). An autoregressive model[10] fit to the data (fig. 16b) identified a significant negative relationship between ZDV and nitracline depth at zero lag (regression coefficient –0.028 ± 0.009 [95% c.i.]) and a significant positive relationship at a lag of one season (approximately 3 months; 0.014 ± 0.011) (fig. 16b). The negative relationship between ZDV and nitracline depth at zero lag is easily understood: decreases in nitracline depth will support increases in phytoplankton biomass likely to be dominated by larger phytoplankters (Goericke 2011) and thereby support zooplankton production. However, the delayed positive relationship between ZDV and nitracline depth is more difficult to understand.

Central California

Observations in Monterey Bay[11] show that surface waters remained cooler and fresher than mean conditions through spring 2011 and into early summer 2011 consistent with runoff from heavy late-season rains, after which cooler temperatures continued but salinity increased to exceed climatological mean (fig. 17). Concentrations of chl *a* throughout the upper water column remained lower than climatological means well into summer 2011, but unusually high concentrations had developed by fall (fig. 17). Cooler, saltier water and greater chl *a* concentrations are apparent in early 2012. Deeper waters were consistently cooler and saltier than long-term mean conditions (fig. 17). Primary productivity and concentrations of chl *a* continued to remain relatively high since 1997–98 (Chavez et al. 2011).

Northern California Current: Northern California (Trinidad Head Line[12])

Hydrographic observations along the Trinidad Head Line during 2011 and early 2012 reflected the broad basin-scale patterns: generally weak upwelling in 2011 throughout the northern CCS with an early cessation of upwelling in fall 2011, evidence for upwelling events during winter 2012, and subsequent effects of downwelling events in early 2012 (fig. 18). Concentrations of chl *a* were relatively high over the shelf in spring and summer 2011 but, in contrast to observations off central California, transitioned rapidly to low concentrations following the cessation of sustained upwelling in September 2011, and remained low into early 2012, presumably as a consequence of limited upwelling-driven enrichment during periods with sufficient light for phytoplankton blooms to develop.

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[10] An autoregressive model was fit to accommodate significant autocorrelation in ZDV at lags of 1 and 3 seasons. The analysis presented here is based on fitting an autoregressive model with external inputs (ARX [4, 2, 0]), cf. Box and Jenkins, 1970 using the Statistics and System Identification toolboxes of Matlab (Version 7.12, The MathWorks Inc., Natick, MA, 2012).

[11] Data on temperature and salinity at the surface and 100 m for Monterey Bay are based on MBARI monthly cruises and mooring data.

[12] See http://swfsc.noaa.gov/HSU-CFORT/ for a description of methods. Surveys are carried out on Humboldt State University's R/V *Coral Sea*.

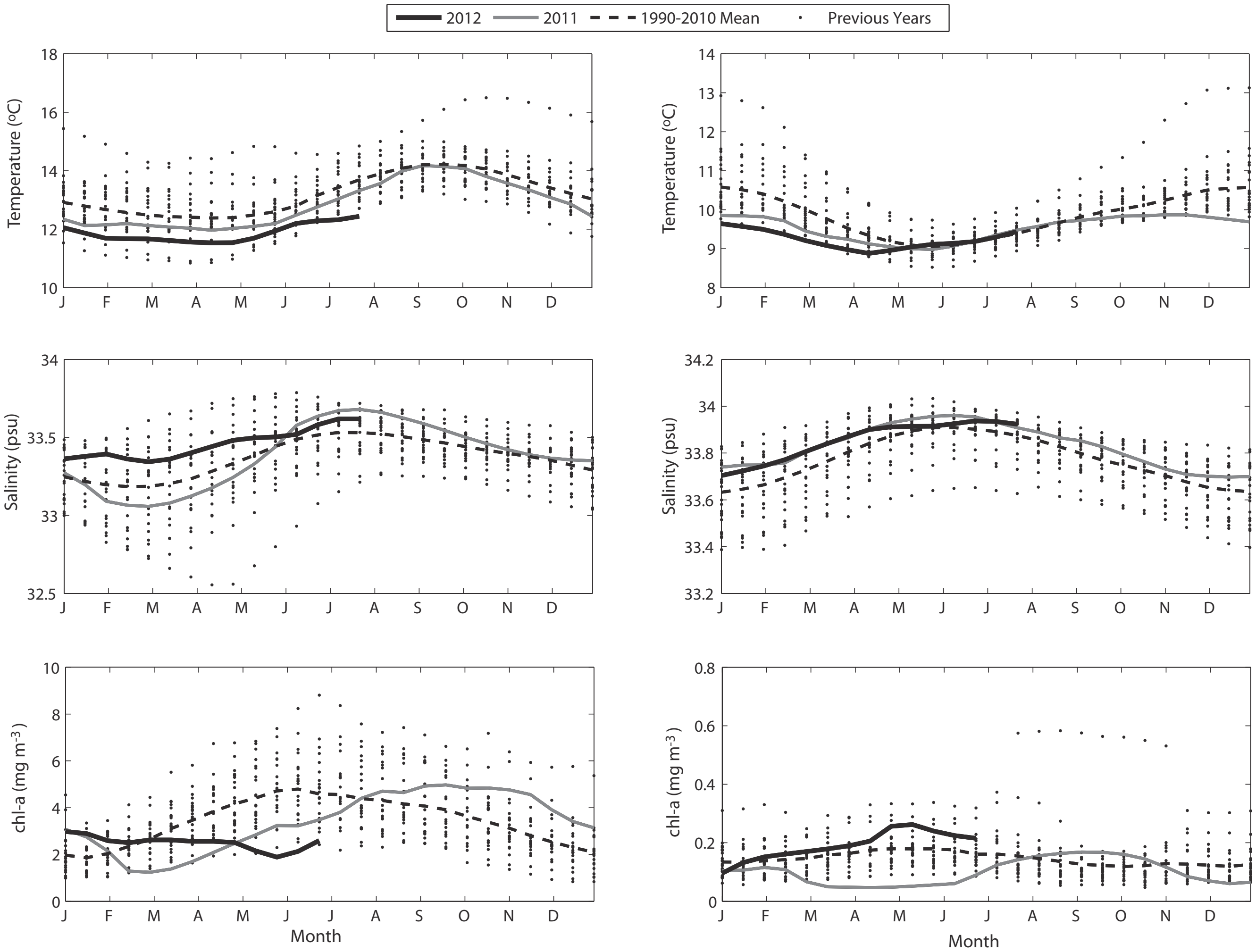

Figure 17. Temperature (top panels), salinity (middle panels) and chl *a* concentration (bottom panels) at the surface (left hand column) and at 100 m (right hand column) observed at the M1 mooring. Note changes in y-axis scale between surface and 100 m plots for each variable.

The copepod assemblage[13] observed at a mid-shelf station (TH02: 41.06°N, 124.27°W, 77 m water depth) reflects variability in hydrographic conditions. The productive period coincident with the 2011 upwelling season was marked by a substantial presence of northern neritic species in the copepod assemblage (fig. 18). Northern neritic species, which had been exhibited greater variability and in 2010, declined rapidly in abundance and frequency of occurrence following the cessation of upwelling in fall 2011. The assemblage has since been dominated by species with more southern or oceanic affinities (fig. 18). Interestingly, the observed pattern in copepod assemblage structure in 2011–12 resembles that observed during the weak El Niño of 2009–10. Preliminary examination of surface currents derived from HF radar in this region (fig. 8) suggests that unusual circulation patterns in the lee of the Cape Blanco upwelling jet may have favored retention of southern and oceanic taxa near the coast, disrupted connections between coastal waters off northern California and sources of boreal taxa to the north (see below), or caused conditions unfavorable to northern neritic species to persist into spring 2012 off northern California.

Northern California Current: Oregon (Newport Hydrographic Line[14])

Despite strongly negative PDO and very cold SST anomalies at NOAA Buoy 46050 (approximately 32 km off Newport, OR) related to recent La Niña conditions,

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[13] Copepod data are based on samples collected from near the sea floor (or a maximum depth of 100 m) to the surface with vertical tows of a 0.5 m ring net fitted with 202 µm mesh and a TSK flowmeter, following a protocol identical to that implemented on the Newport Hydrographic Line.

[14] Regular sampling of the Newport Hydrographic Line continued on a biweekly basis along the inner portions of the line (out to 25 nautical miles from shore). Details on sampling protocols are available in previous reports and at http://www.nwfsc.noaa.gov/research/divisions/fed/oeip/ka-hydrography-zoo-ichthyoplankton.cfm. Temperature anomalies along the Newport line are based on the Smith et al. 2001 climatology. Copepod data are based on samples collected with a 0.5 m diameter ring net of 202 µm mesh, hauled from near the bottom to the sea surface. A TSK flowmeter was used to estimate distance towed.

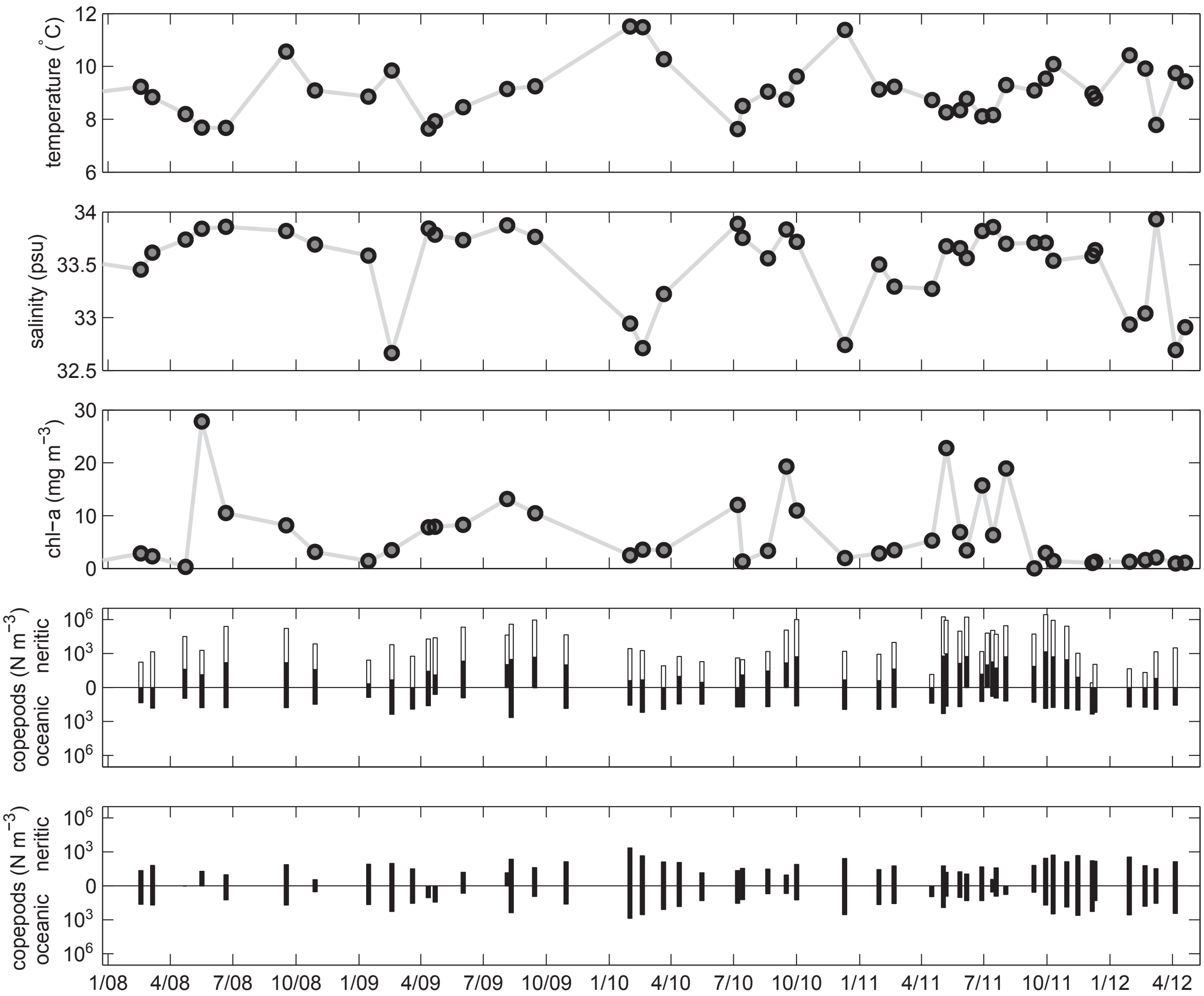

Figure 18. Top three panels: Near-bottom temperature, near-bottom salinity, and mean water-column chlorophyll *a* concentration, respectively, at station TH02 along the Trinidad Head Line. Bottom two panels: numerical density of northern and southern copepods, respectively, with ascending bars indicating neritic species and descending bars, oceanic species. Species assignments are based on Hooff and Peterson 2006. In the plot of northern neritic species, total density is indicated by the open bars and the solid bars represent species other than the dominant *Pseudocalanus* to highlight the loss of northern neritic species in 2012. Note that abundance scales are logarithmic.

shelf waters off central Oregon have not been unusually cold. Deep water at a mid-shelf station (NH-5: 44.65°N, 124.18°W, 60 m water depth) has been neither very cold nor salty during spring 2011 or spring 2012 (fig. 19, left panel), which is a consequence of the absence of strong upwelling in the northern CCS (figs. 5, 6). The effects of weak upwelling persisted through the summer, with summer 2011 near-bottom temperatures being among the warmest observed in the past 15 summers (fig. 19, right panel). Deep water temperatures during the autumn 2011 and winter 2012 were slightly below normal. Across all seasons, averaged temperature and salinity were near median values.

In mild contrast to patterns in local forcing (i.e., weak upwelling), the copepod community on the Oregon shelf (indexed by observations at station NH05) continued to reflect cool conditions, consistent with broader indices (e.g., PDO and offshore SST anomalies) and the presence of persistent, equatorward flow throughout the spring and summer (fig. 9). Species richness remained relatively low throughout 2011, an indicator of a "boreal copepod community" and greater-than-average transport of subarctic water into the northern California Current (fig. 20) (cf. Kiester et al. 2010). This pattern is corroborated by the "northern copepod biomass anomaly" time series[15], which has been strongly positive since spring 2010 (fig. 20). The biomass of northern copepod spe-

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[15] This index captures the relative changes in the biomass of three lipid-rich boreal neritic copepod species: *Pseudocalanus mimus*, *Calanus marshallae* and *Acartia longiremis*.

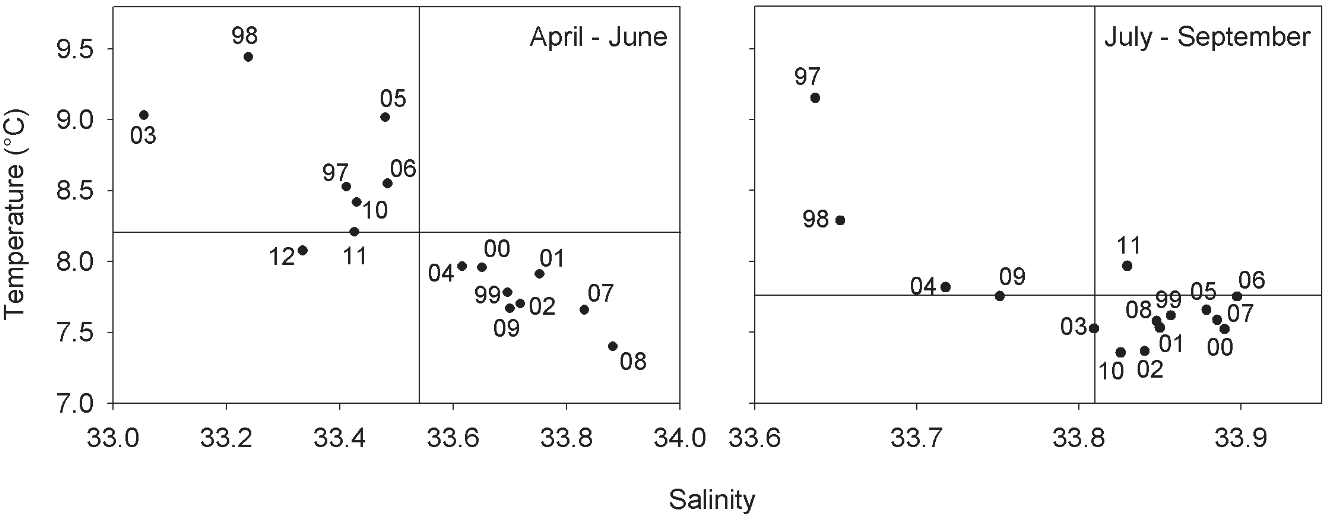

Figure 19. Seasonal mean temperature and salinity at 50 m depth at NH-5 along the Newport Hydrographic Line for spring (top panel) and summer (bottom panel). Note changes in scale on both temperature and salinity axes. Numbers next to points indicate year of observations.

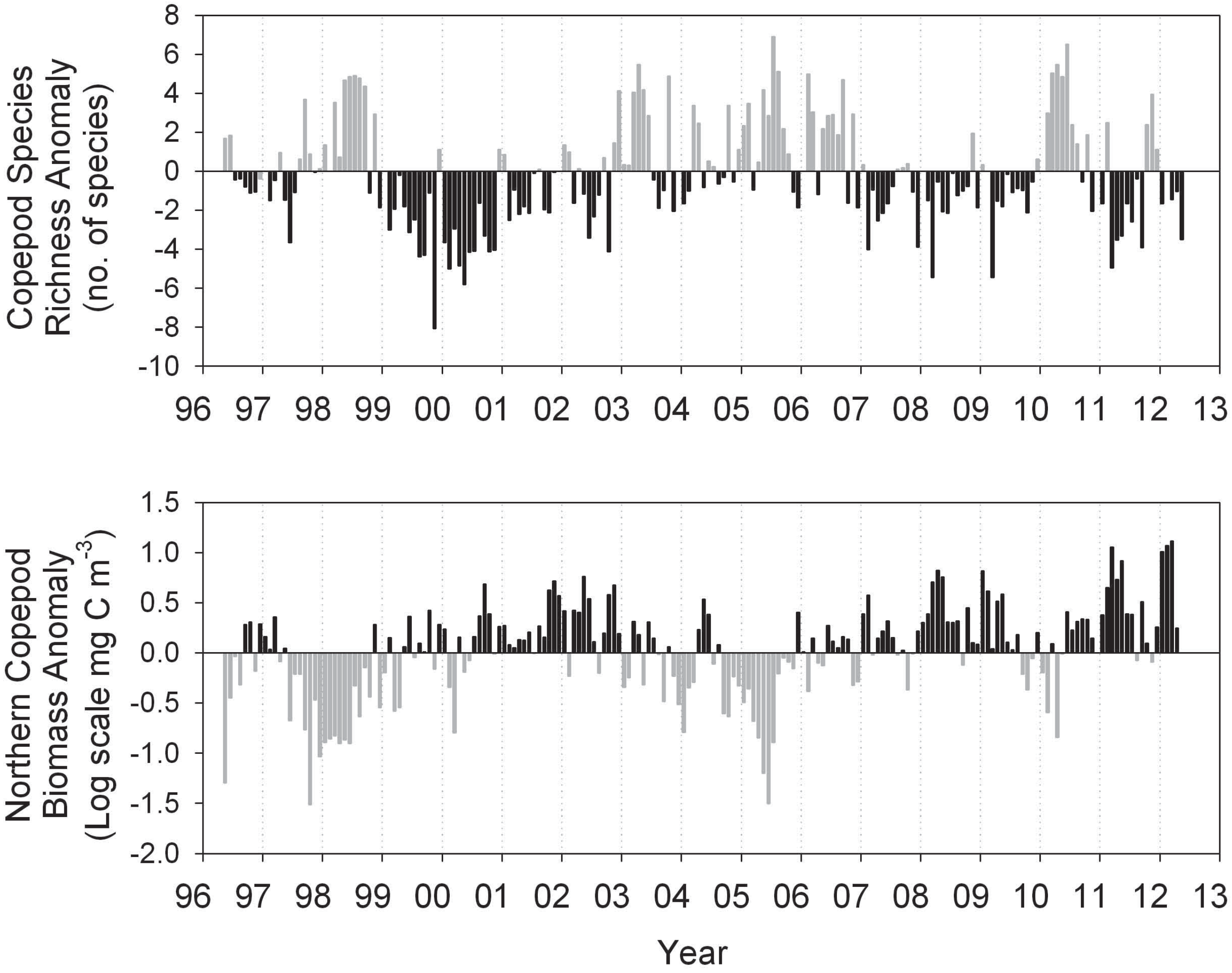

Figure 20. Monthly averaged anomalies in copepod species richness (upper panel) and biomass of three dominant 'northern' copepod species (*Pseudocalanus mimus*, *Calanus marshallae* and *Acartia longiremis* copepods (lower panel) based on biweekly sampling at station NH-5 off Newport, Oregon.

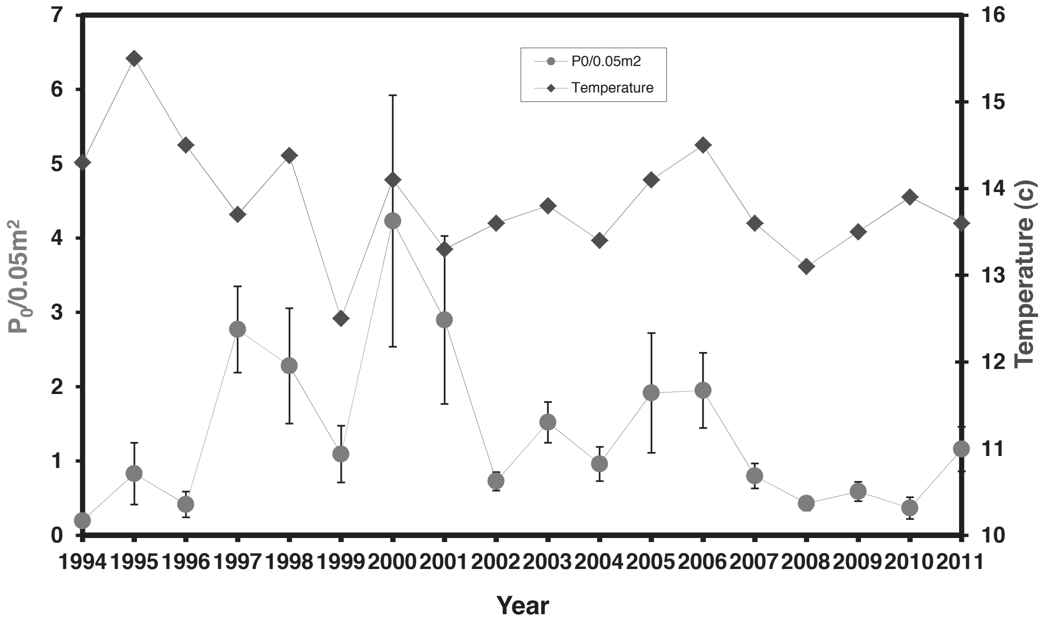

Figure 21. Time series of daily egg production (P_0/0.05 m^2) of Pacific sardine (circles; ±1 standard error) and average sea surface temperature (°C) (diamonds; ±1 standard error) during pelagic egg surveys conducted during March–April of each year.

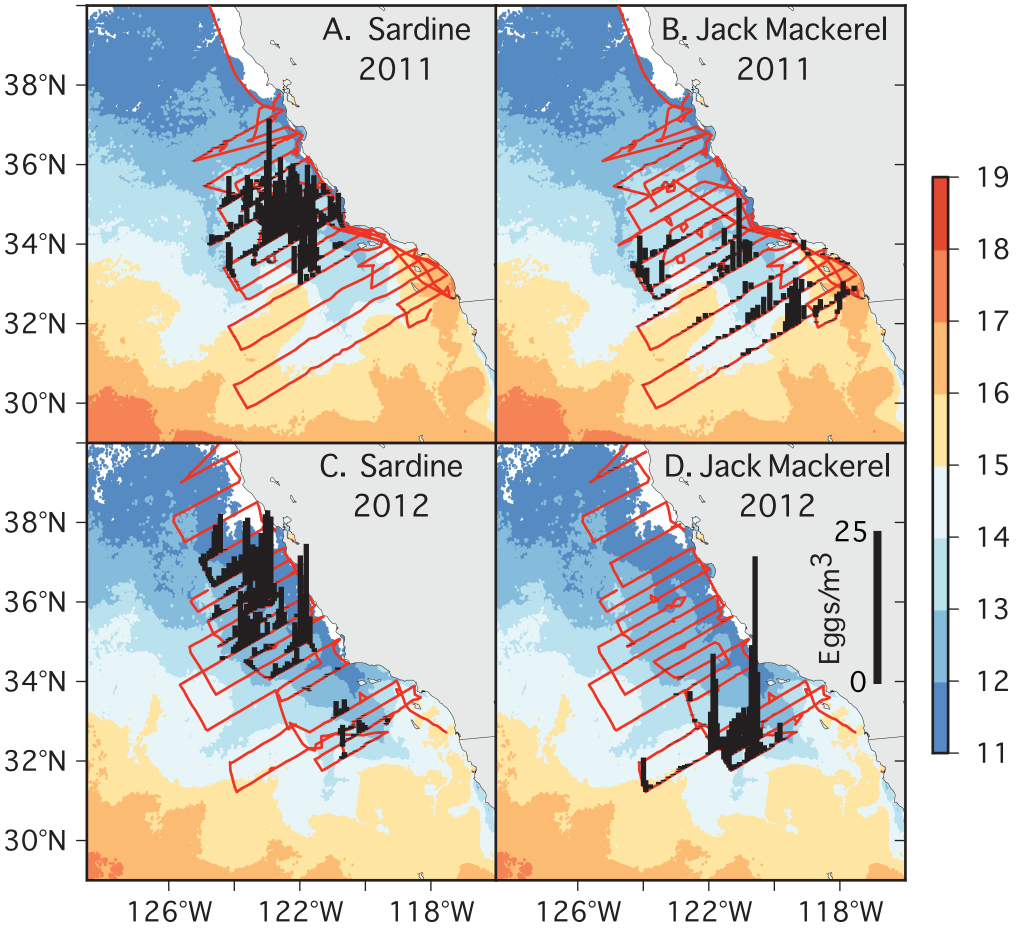

Figure 22. Densities of eggs (black bars) of Pacific sardines (right-hand panels) and jack mackerel (left-hand panels) collected with the Continuous Underway Fish Egg Sampler (CUFES) along the ship tracks (red lines) during NOAA coast-wide cruises conducted in spring 2011 (upper panels) and spring 2012 (lower panels). The underlying color image shows a monthly composite of satellite AVHRR 1.4 km resolution sea surface temperature (°C) coincident with the survey period in each year.

cies in winter 2012 (January–March) was the highest recorded in the 17–year time series, as was total copepod biomass, which was more than double the normal winter-time average.

SYNTHESIS OF OBSERVATIONS ON HIGHER TROPHIC LEVELS

Pelagic Fishes Off Southern California[16]

In spring 2011, Pacific sardine (*Sardinops sagax*) egg densities were higher than in previous years but not as high as had been observed in 2005 and 2006. As in 2010, daily egg production in 2011 again departed from an apparent historical pattern of increased daily egg production coinciding with increased mean sea surface temperature (fig. 21), indicating that the fluctuation of sardine egg densities is likely due to not only temperature but other factors, such as spawning biomass (Jacobson and MacCall 1995; McClatchie et al. 2010).

In 2011, sardine eggs were distributed over a wider area to the south than what had been observed in 2010 (fig. 22). No sardine eggs were observed north of CalCOFI line 68 or south of CalCOFI line 90. Preliminary data suggest that the spatial distribution of sardine eggs in the spring of 2012 was even broader than in 2011, ranging from San Francisco to offshore from the Southern California Bight, with the greatest concentrations observed between San Francisco and Point Conception (fig. 22). Coupled with the expanded distribution, however, egg densities appeared to be lower than in 2011 by perhaps a factor of two, although no quantitative comparison has been made yet. Northern anchovy (*Engraulis modax*) eggs were rarely encountered (data not shown), but this is not surprising because they spawn primarily earlier in the year. Jack mackerel (*Trachurus symmetricus*) eggs showed an interesting separation from sardine eggs: the jack mackerel were common in the Southern California Bight (SCB), while the sardine eggs were found mostly off central California (fig. 22). It is more common to find jack mackerel eggs further offshore than sardine eggs, but this is not always the case, as shown by the north-south separation observed in 2012.

Central and Northern California Pelagic Ecosystems

Analysis of catch composition and abundance of key taxa from annual mid-water trawl surveys[17] off central California indicated relatively high productivity in 2011 and 2012 for the species and assemblages that tend to do better with cool, high transport conditions, including juvenile rockfish (*Sebastes* spp.), market squid (*Dorytehuthis opalescens*) and euphausiids (primarily *Euphausia pacificus*, *Thysanoessa spinifera*, and *Nematoscelis difficilis*) (fig. 23). In 2011, juvenile rockfish were more abundant then they had been since the early 2000s, and although abundance of juvenile rockfish was lower in 2012, it remained relatively high (fig. 23). Market squid and euphausiids were at above-average levels in 2011 and very high levels in 2012, with the relative abundance of market squid in particular estimated to be at its highest level in the time series (fig. 23). Other coastal pelagic species (adult northern anchovy and Pacific sardine) continued to be encountered at low levels, although this is likely a greater reflection of their local availability and ocean conditions rather than their coastwide or regional abundance.

The six indicators shown in Figure 23 continue to represent trends across a broader suite of taxa within this region[18] (fig. 24). As in 2010 and 2011, observations in 2012 continued to indicate a pelagic micronekton community structure similar to that seen in the early 1990s and early 2000s (fig. 25). These trends reflect (1) persistent, strong, positive covariance among young-of-the-year groundfish (e.g., rockfishes, sanddabs [*Citharichthys* spp.] and Pacific hake [*Merluccius productus*]), cephalopods and euphausiids, (2) positive covariance among coastal pelagic and mesopelagic species, and (3) negative correlation over time between the respective "groundfish" and "pelagic" assemblages.

The 2012 survey was unusual in that the abundance of several types of gelatinous zooplankton (reviewed below) was extraordinarily high, resulting in damaged sampling gear and some offshore trawl stations being abandoned for the first time in the 30-year history of this survey. Moreover, there is some evidence that distributions of several taxa in 2012 differed from patterns typical of previous cool, productive periods, in that during 2012,

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[16] Spring California Current Ecosystem (CCE) surveys are executed from late March through April. In spring 2011, the survey was conducted aboard the NOAA ship *Bell M. Shimada* and the F/V *Frosti*, during which time the *Bell M. Shimada* also supported sampling for spring CalCOFI cruise. During such surveys, CalVET tows, bongo tows, and surface trawls are conducted aboard both vessels, and samples are collected using the Continuous Underway Fish Egg Sampler (CUFES). In spring 2012, the survey was conducted aboard the NOAA ship *Bell M. Shimada* and the FSV *Ocean Starr*. Data from both CCE and spring CalCOFI cruises in 2011 were included in the estimation of spawning biomass of Pacific sardines. Data from all spring cruises were used to examine the spatial distributions of Pacific sardine, northern anchovy, and jack mackerel.

[17] Observations reported here are based on midwater trawl surveys that target small (1–20 cm) pelagic fishes and invertebrates conducted off central California (a region running from just south of Monterey Bay to just north of Point Reyes, CA, and from near the coast to about 60 km offshore) since 1983 (see Sakuma et al. 2006 for methods and details on spatial extent of survey). Cruises have been conducted on the NOAA ship *David Starr Jordan* (1983–2008), the NOAA ship *Miller Freeman* (2009), the F/V *Frosti* (2010), the F/V *Excalibur* (2011), and the NOAA ship *Bell M. Shimada* (2012). Certain taxa were not consistently enumerated prior to 1990 (e.g., krill and market squid). Data for the 2012 survey presented here are preliminary, and data collected since 2009 do not account for potential vessel-related differences in catchability. Most taxa reported are considered to be well sampled, but the survey was not specifically designed to accurately sample krill.

[18] Principal Components Analysis (PCA) was applied to the covariance among fifteen of the most frequently encountered species and species groups. The first and second principal components explain 36% and 16% of the variance in the data respectively.

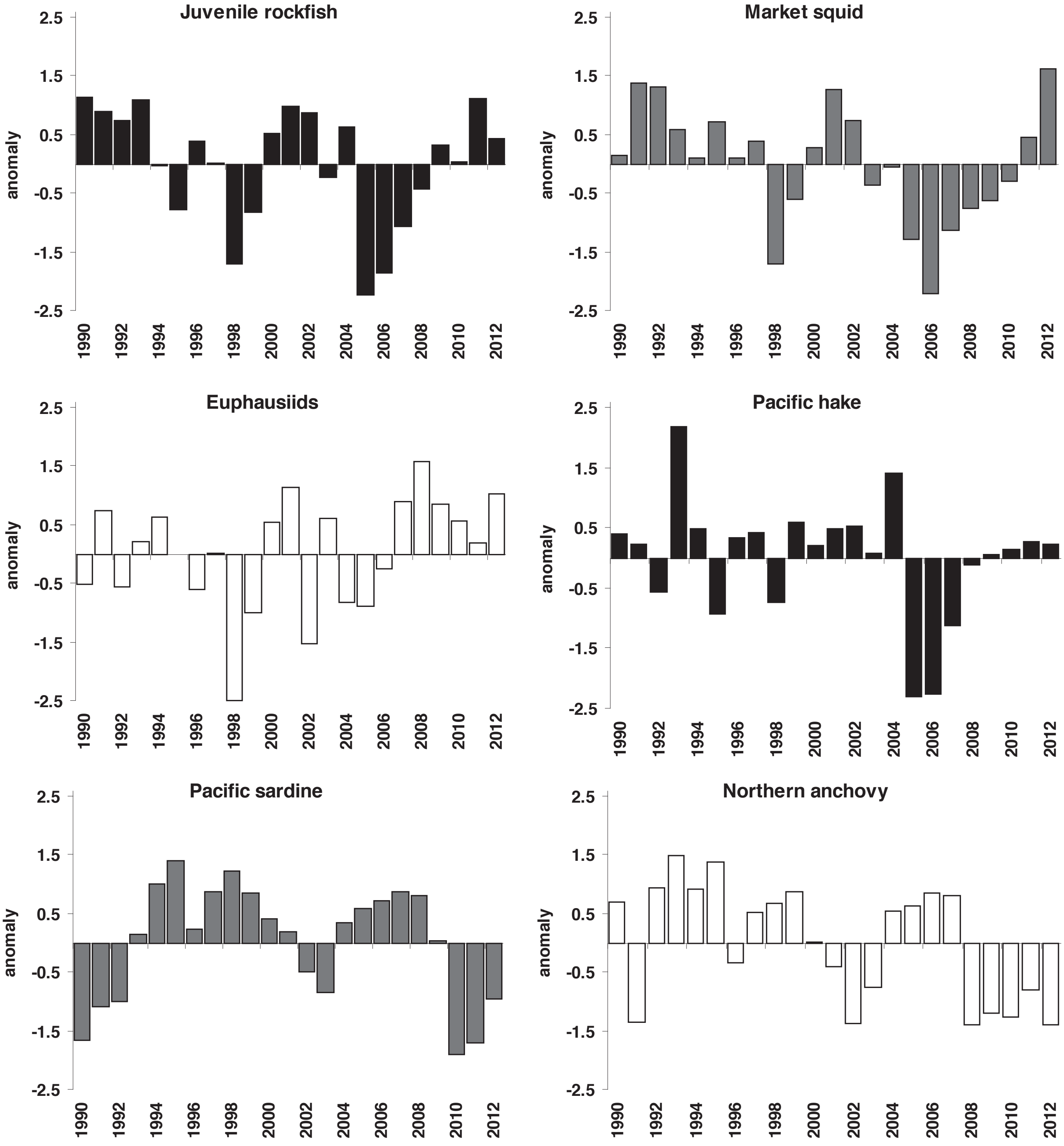

Figure 23. Long-term standardized anomalies of several of the most frequently encountered pelagic forage species from the SWFSC FED midwater trawl survey in the core region off central California from 1990 to 2012.

small gelatinous zooplankton more abundant in offshore waters, while krill, squid, and juvenile groundfish were more concentrated in coastal waters rather than more broadly distributed across and off the shelf. Future analysis will examine the patterns and causes of this spatial variability in abundance.

Several of the trends reported during the mid-water trawl survey were also apparent in surveys that target juvenile salmon off central and northern California (reported below) and that often directly followed the mid-water trawl survey. Several clupeids (northern anchovy, Pacific sardine, and Pacific herring [*Clupea pal-*

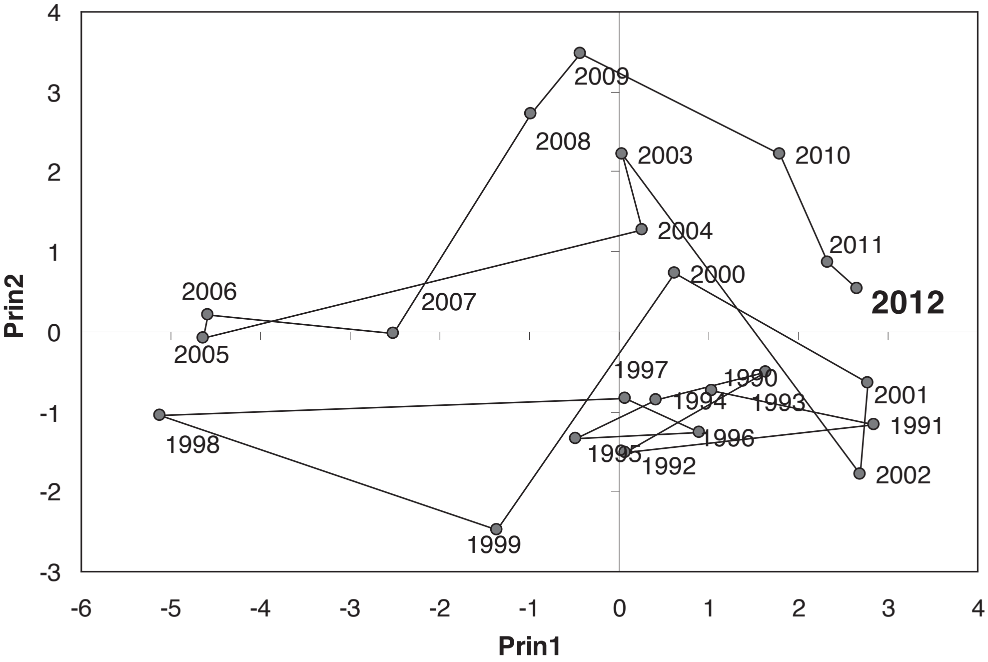

Figure 24. Principal component scores plotted in a phase graph for the fifteen most frequently encountered species groups sampled in the SWFSC FED midwater trawl survey in the core region off central California from 1990–2012.

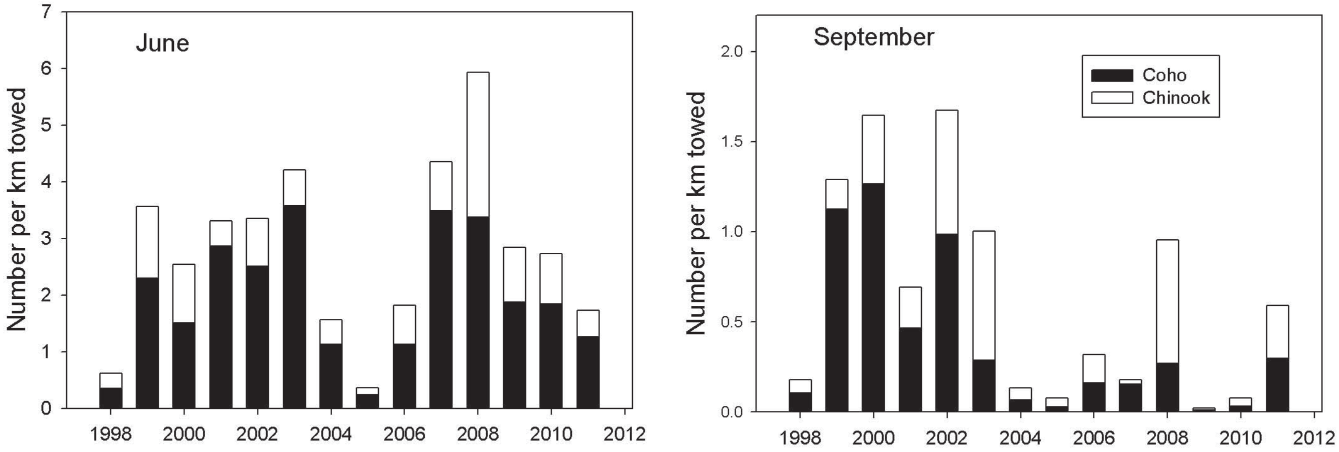

Figure 25. Catches of juvenile coho (black bars) and Chinook (white bars) salmon off the coast of Oregon and Washington in June and September, from 1998-2011.

lasii]) which had been abundant in 2007 were absent or rare in 2010 and 2011, but market squid had become unusually abundant. In contrast, juvenile rockfish, which were abundant in the rope-trawl catches during summer 2010, were observed at much lower densities in summer 2011. Causes for this discrepancy are being investigated, but may relate to latitudinal or seasonal differences in the surveys, to variability in the species each survey encounters, or to variability in the birthdate distributions of surviving juveniles from year to year.

Juvenile Pacific Salmon

Catches of juvenile coho salmon (*Oncorhynchus kisutch*) in pelagic rope trawl surveys off Oregon and Washington[19] were about average in June 2011 yet were relatively high in September 2011 (i.e., after the juveniles' first summer at sea), ranking 5th most out of 14 years of sampling (fig. 25). In contrast, catches of juvenile (primarily sub-yearling) Chinook salmon (*O. tshawytscha*) in June 2011 were relatively low (10th most out of 14 years of sampling), but catches of older juveniles (including yearling migrants) was greater in September 2011 than in previous years (fig. 25). Data from surveys in June 2012 are not yet verified, but preliminary indications are that catches were higher than in 2011.

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[19] Survey protocols are available at http://www.nwfsc.noaa.gov/research/divisions/fed/oeip/kb-juvenile-salmon-sampling.cfm.

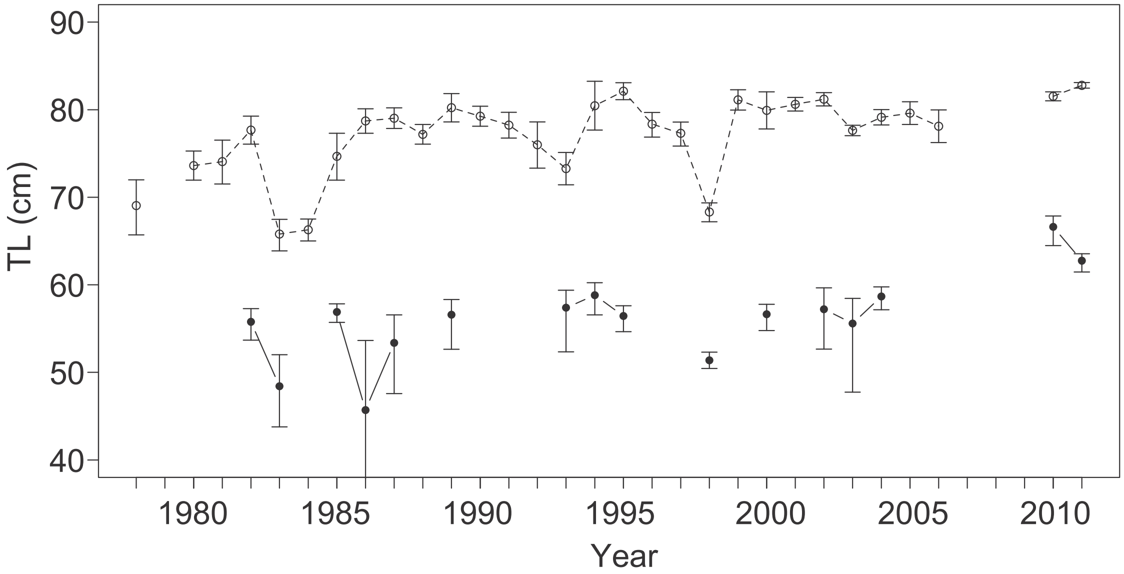

Figure 26. Mean total length (cm) of age-2 (filled circles, solid lines) and age-3 (open circles, dotted lines) Sacramento River fall-run Chinook recovered in recreational ocean fisheries in July of each year, 1978–2011. Error bars are 95% confidence intervals on maximum likelihood estimates. Convergent estimates could not be obtained for some years due to fishery closures, small sample sizes, or if fish were small relative to the legal size limit for retention (often 50 cm, sometimes 55–60 cm), which causes problems for the truncated likelihood methods used to fit these data (Satterthwaite et al. 2012).

Rope trawl surveys for juvenile salmon have recently been re-implemented in the coastal waters off central and northern California[20]. In contrast to low abundances (mean catch rate of 0.2 fish per 10^6 m^3 in 2007) associated with the collapse of the Central Valley Fall-Run Chinook salmon fishery (Lindley et al. 2009), recent midsummer surveys encountered high densities of juvenile Chinook salmon in both 2010 and 2011 (6.9 and 9.0 fish per 10^6 m^3, respectively). Although no quantitative comparisons have yet been made, preliminary data from the 2012 survey suggest that densities one-third to one-half those observed in 2010 and 2011. The 2010 cohort of juvenile Chinook salmon was still present in high numbers as subadult fish in July 2011, indicating relatively low mortality during the first year. Densities of juvenile Chinook salmon remained high into fall 2011, suggesting low over-summer mortality and good recruitment. The number of subadult fish was again high in the 2012 survey, despite evidence of higher over-winter mortality than in the previous year.

In July 2010, densities of juvenile coho salmon (fish that entered the ocean in spring 2010) off central and northern California were low relative to catch rates for juvenile Chinook salmon (0.3 versus 6.9 fish per 10^6 m^3, respectively), which is likely due, in part, to large differences in hatchery production of the two species in California. Subsequent catches of this cohort as subadults in 2011 suggest high survival during the first year at sea, similar to observations of Chinook salmon. Abundance of juvenile coho salmon appeared to be higher in July 2011 than in July 2010 (0.9 versus 0.3 fish per 10^6 m^3, respectively), but very few juvenile coho were captured during the fall survey in 2011. It is unclear whether this decline is due to poor over-summer survival, to movement to depths below the reach of the surface trawl, or to dispersal outside the survey area. Early results from the 2012 survey indicate that overwinter survival for this cohort may have been much lower than for the winter of 2010–11. Preliminary data from the 2012 survey indicate that juvenile coho salmon were caught in densities similar to those observed in 2011.

In addition to evidence that abundance remained high throughout 2011, growth conditions[21] for Sacramento River fall-run Chinook salmon appear to have been favorable in spring 2011 (although not as favorable as in spring 2010). Age-2 fish recovered in July of 2011 (which entered the ocean in spring of 2010) were among the largest on record, exceeded only by age-2 fish in 2010 (fig. 26). The unusually large size of age-3 fish in 2011 provides additional evidence that conditions in 2010 were favorable for salmon growth. Record numbers of age-2 fall-run Chinook returned to the Sacramento and Klamath Rivers in 2011 (PFMC 2012), suggesting high survival through 2010 and 2011, or unusually high rates of early maturation.

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[20] These surveys are closely coordinated with the surveys off Oregon and Washington, and implement similar protocols.

[21] See Satterthwaite, et al. 2012 for further description of the data and modeling approach. The results presented here are based on independent maximum likelihood estimates for each year.

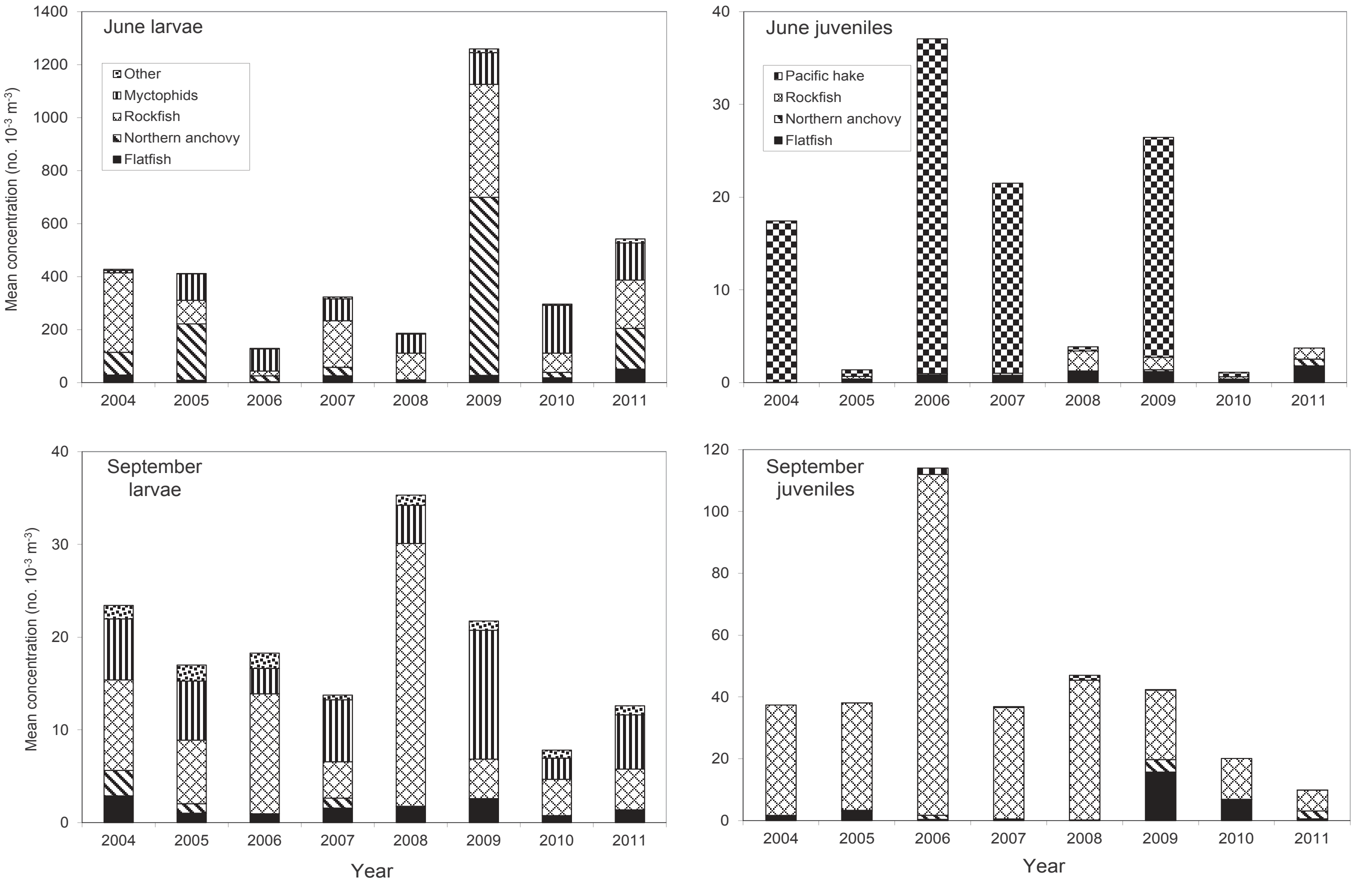

Figure 27. Mean concentrations of dominant taxa for fish larvae (left) and juveniles (right) collected in June (upper) and September (lower) off the coasts of Oregon and Washington in 2004–11. Note that y-axes scales from June to September are reduced ~35-fold for larvae and are increased ~3-fold for juveniles.

Early Life History Stages of Fishes in the Northern CCS

Ichthyoplankton assemblages[22] off the coasts of Oregon and Washington in June and September 2011 exhibited mean concentrations and relative abundance of the dominant taxa that corresponded closely to the average community structure found in the same area and months during the previous seven years (fig. 27). However, the juvenile fish community[23] exhibited low concentrations in June 2011 relative to similar seasons in previous years, while the September 2011 concentrations were the lowest recorded in the eight-year time series (fig. 27). Within this overall pattern, however, the abundance of juvenile rockfishes in June showed recent changes similar to that observed off central California, but September catches continued to decline; further analysis is needed to evaluate these patterns with respect to individual species. Myctophids (combined juveniles and adults) comprise the majority (~55%) of the pelagic midwater trawl catches of fish in this region and occurred at concentrations near seasonal means observed over the previous seven years in both June and September 2011.

The nearshore (9–46 km from shore) ichthyoplankton community along the Newport Hydrographic (NH) line (44.65°N) during winter (January–March) 2012 exhibited relatively high biomasses of Pacific sand lance (*Ammodytes hexapterus*) and low biomasses of rockfish (*Sebastes* spp.), which is consistent with cooler oceanic conditions in the northern California Current (Brodeur et al. 2008; Auth et al. 2011). These patterns may reflect the influence of cross-shelf transport during upwelling in winter 2012, i.e., offshore dispersal of larvae from beach-spawning sand lance and transport of rockfish larvae from adult populations on the shelf and upper slope to waters beyond the range of the survey.

Pink Shrimp

Catch rates of pink shrimp (*Pandalus jordani*) were unusually high in 2011, and have been so since 2009, with

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[22] See Auth 2011 and Phillips et al. 2009 for details on sampling methods for larval and juvenile fishes. Briefly, samples were collected primarily at night using oblique tows of a 60 cm bongo net (335 µm mesh) from 100 m (or within 5 m of the sea floor). Samples were preserved in 95% ethanol, which was replaced after ca. 72 hours. All larval fish in each sample were removed, counted, and identified to the lowest taxonomic level possible.

[23] Data on juvenile fishes presented here have been corrected to resolve a database error, and supercede those presented in Bjorkstedt et al. 2011.

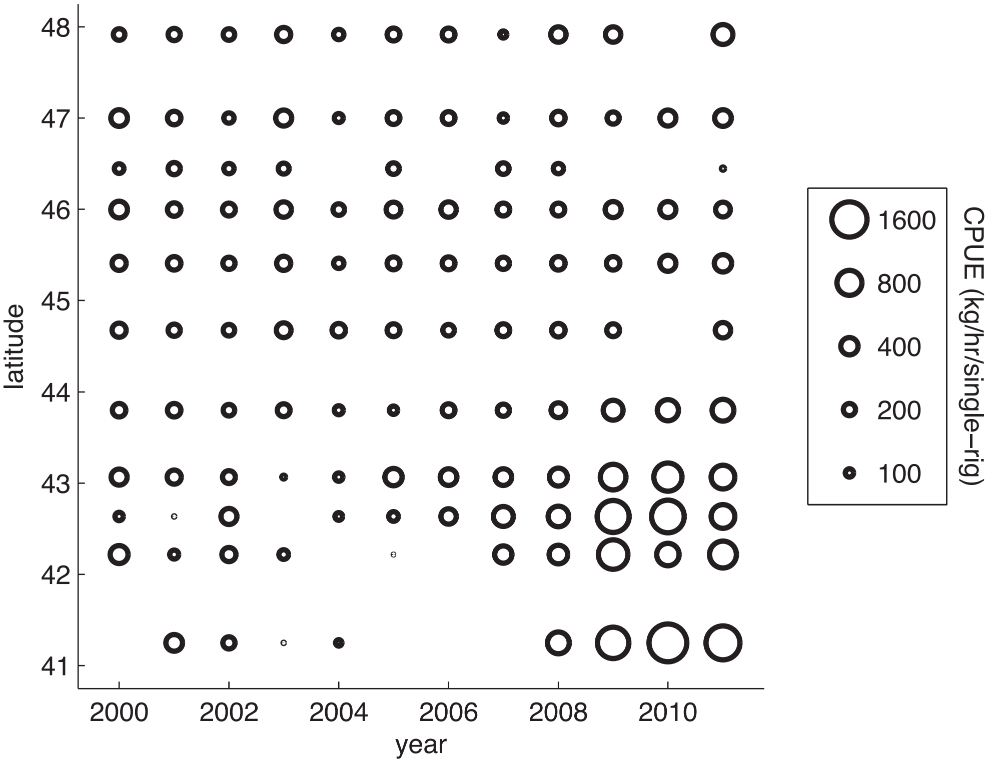

Figure 28. Catch-per-unit-effort (CPUE) in the pink shrimp (*Pandalus jordani*) fishery off Washington, Oregon and northern California. Missing symbols indicate insufficient data to calculate a robust estimate of CPUE as a consequence of low effort.

the greatest catch rates occurring south of Cape Blanco and into northern California (fig. 28). Catches in both 2010 and 2011 have been dominated by shrimp from the 2009 year class (i.e., shrimp hatched in spring 2009), particularly south of Cape Blanco. More recent recruitments are difficult to evaluate quantitatively due to fishers avoiding areas with smaller shrimp; however, fishers' observations appear to corroborate forecasts of average recruitment of shrimp hatched in spring 2011, based on environment-recruitment relationships (Hannah 2011).

Gelatinous Zooplankton

Oregon/Washington. Large gelatinous zooplankton taxa have been quantified in large pelagic surface trawls off Oregon and Washington since June 1999[24]. The dominant species, *Chrysaora fuscescens*, was not very abundant in June the first two years of sampling, but since that time has become the majority of the jellyfish catch (fig. 29), consistently occurring in high abundance in the years following 2001. The smaller hydromedusa, *Aequorea* spp., was found in most years but was numerically dominant only in 1999 and 2000. The next most abundant species, *Aurelia labiata*, occurred in relatively low abundances in this region. By September, *C. fuscescens* dominates the catches in all years except 2010, reaching maximum biomass in 2007. Abundances of these large medusae overall were the lowest for both monthly periods during the El Niño of 2010, and have only rebounded slightly in 2011 (fig. 29). However, surveys on the shelf in both these years witnessed particularly high densities of salps of offshore origin, especially in the fall of 2010 and spring of 2011.

Central/Northern California. In contrast to the trends observed off Oregon and Washington, the abundance of *C. fuscescens* captured during late-spring midwater trawl surveys between Point Reyes and Monterey Bay appears to have increased by at least a rough factor of two to five from the mid-2000s to 2010–11 (fig. 30). The largest catches of *C. fuscescens* consistently occur within the Gulf of the Farallones. It is likely that the increase in density of *C. fuscescens* in this region is substantially larger, as it is exceedingly difficult to quantify the abundance of *C. fuscescens* at high densities with the current sampling protocols. In contrast, catches of *Aurelia* spp. are more variable, and total abundance of *Aurelia* spp. rarely exceeds that of *C. fuscescens.* The largest catches of *Aurelia* spp. typically occur inside Monterey Bay, predominantly in the "upwelling shadow" (Graham and Largier 1997) in the northern part of the bay.

Trends in the abundance of *C. fuscescens* encountered

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[24]See Suchman et al. 2012 for collection methods.

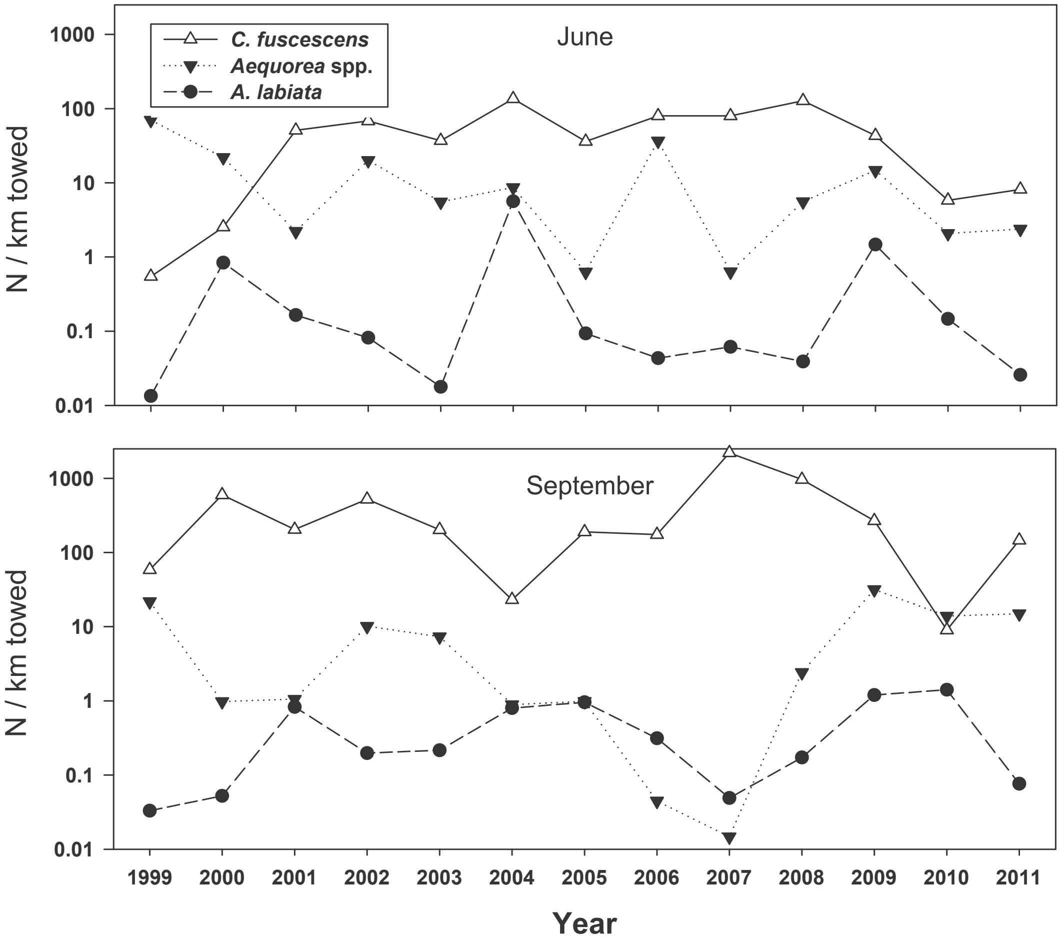

Figure 29. Catches of the three dominant species of jellyfish in pelagic surveys off the coast of Oregon and Washington in June and September, from 1999 to 2011.

during the midwater trawl survey are consistent with changes in abundance observed during the SWFSC salmon surveys conducted in early summer, in which the *C. fuscescens* were two to five times more abundant (at least) in 2010–11 (mean catches of 116–255 individuals per 10^6 m^3) than in 2007 (57 individuals per 10^6 m^3). In contrast, *Aurelia* spp. declined from rather high abundance in 2007 (426 individuals per 10^6 m^3) to very low abundances in 2010–11 (0.5 to 4.9 individuals per 10^6 m^3).

Quantitative counts of other gelatinous taxa during the midwater trawl survey had been discontinued after 2001 but were resumed in 2012 upon recognizing the unusual abundance of gelatinous taxa during the 2012 midwater trawl survey. The abundance of *Thetys vagina* in the historical "core region" of the survey (roughly Point Reyes to Point Pinos) remained well within the range of previously observed "outbursts" (fig. 30). In contrast, the numerical abundance (and by a greater margin, the volume) of other salps and pyrosomes far exceeded previously recorded values (fig. 30). Catches of salps and pyrosomes were even higher in southern parts of the survey (fig. 30).

Southern California. The spring 2012 CalCOFI cruise also encountered unusual numbers and volumes of diverse gelatinous taxa—a pattern noted as exceedingly unusual by NOAA staff who have participated in CalCOFI surveys for over 25 years. Gelatinous zooplankton were most abundant north of Point Conception and in offshore waters, coincident with the region where high concentrations of sardine eggs were observed (fig. 22).

Seabirds and Marine Mammals

At-sea density of seabirds off southern California[25]. Based on analysis of data on seabird abundance at sea, seabirds in the CalCOFI region have declined (Hyrenbach and Veit 2003) and their distribution has shifted

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[25] Surveys of marine birds have been conducted in conjunction with seasonal CalCOFI/CCE-LTER cruises since May 1987. Observations are collected by experienced observers, who identify and count seabirds within a 300 m wide strip transect while the ship is underway at speeds >5 k (see Yen et al. 2006 for details). Relative abundance is expressed as density of birds at sea (birds km^{-2}).

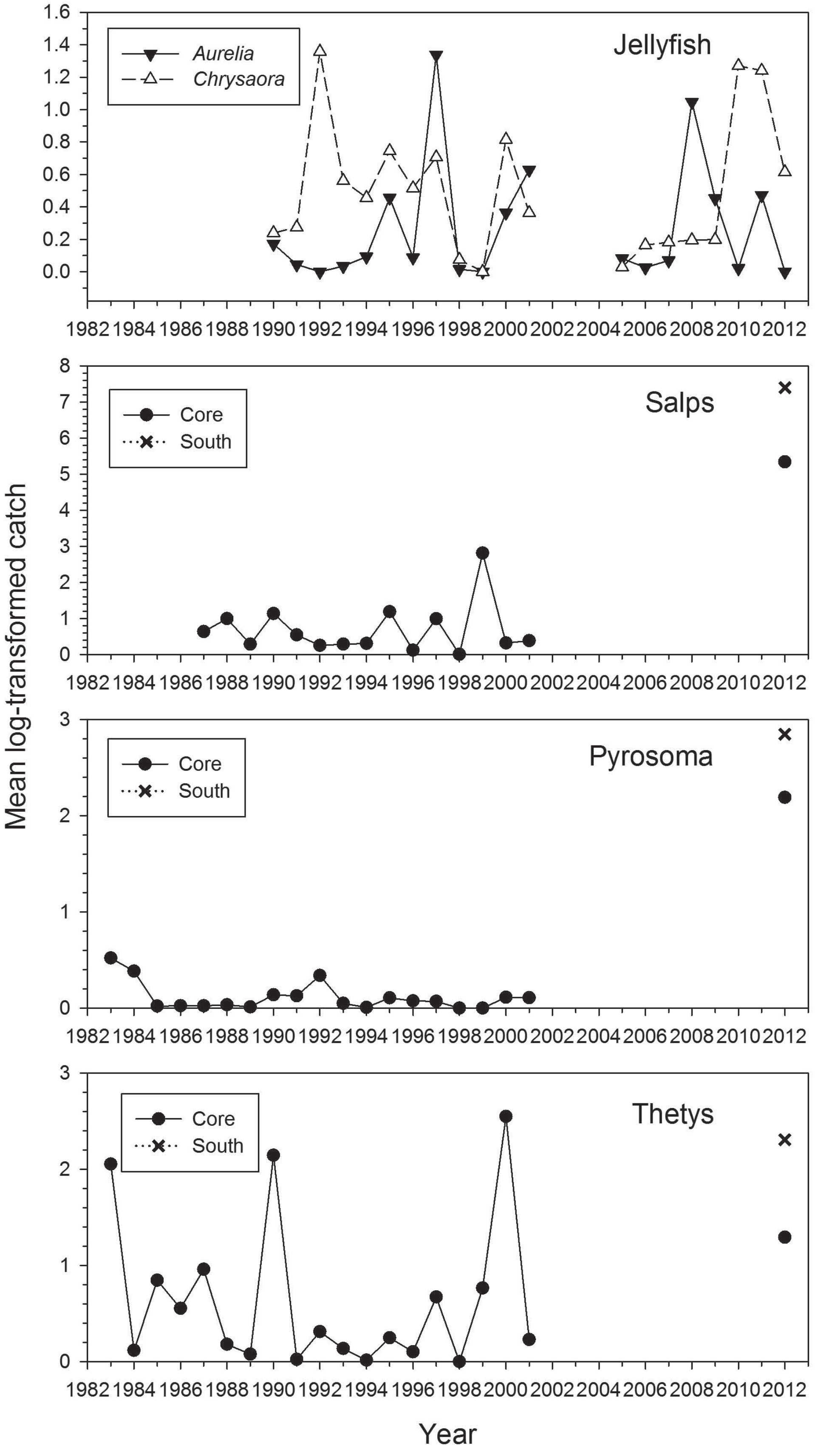

Figure 30. Catches of gelatinous plankton from the core and southern regions of the SWFSC/FED midwater trawl survey.

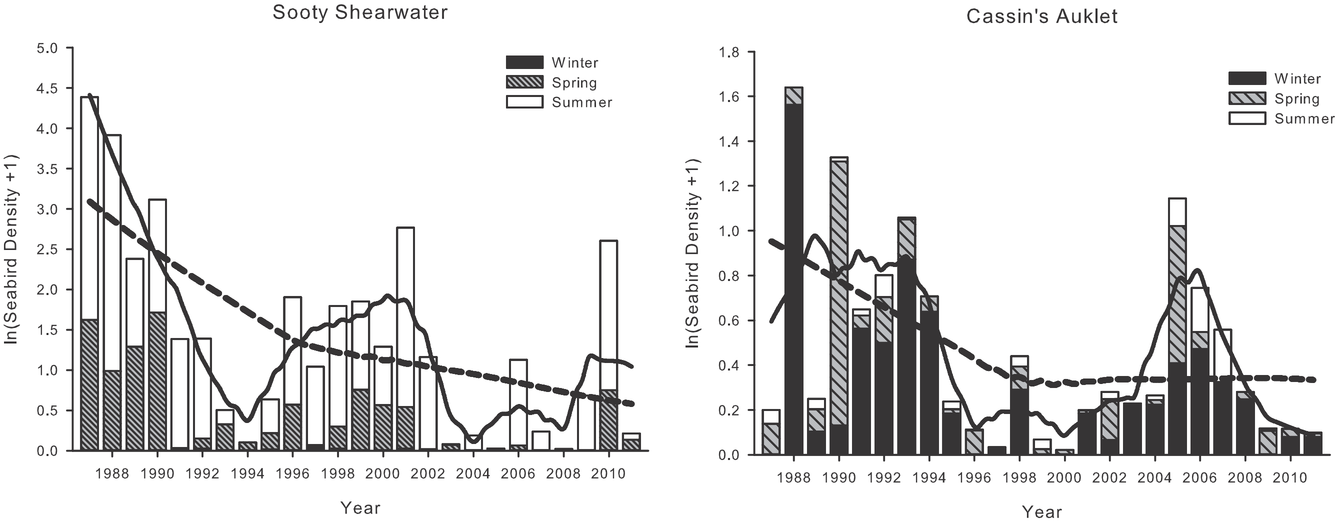

Figure 31. Patterns of change in the abundance (expressed as at-sea density) of sooty shearwaters (*Puffinus griesus*; upper panel) and Cassin's auklets (*Ptychoramphus aleuticus*; lower panel) over three seasons: winter, spring, and summer. Lines indicate LOESS fits with sampling proportions of 0.8 (dashed line) or 0.2 (solid lines).

towards the coast over the past 25 years, and these trends in abundance and distribution have persisted through summer 2011. Two species provide representative examples of these patterns: (a) sooty shearwaters (*Puffinus griesus*), which are migrants from the southern hemisphere and are most abundant in the California Current during the spring and summer (i.e., during the austral winter), and (b) Cassin's auklets (*Ptychoramphus aleuticus*), which are resident in the California Current year-round, but are most abundant in the CalCOFI region in winter.

Shearwater density has declined in a log-linear fashion since surveys began in the late 1980s, with each successive peak in abundance (i.e., 1990, 2001, 2010) lower than the preceding one (fig. 31a). Trends (declines) in abundance were similar in both spring and summer. Shearwater density in 2011 was greatly reduced from the preceding year and is comparable to levels observed during previous troughs in at-sea densities, suggesting that foraging conditions were not as favorable as last year for these migrants (fig. 31a).

Following an apparent decline from high densities of auklets observed in the late 1980s, the abundance of auklets observed off southern California appears to be relatively stable or perhaps declining slowly, based on slight declines in peak densities observed during winter in the 1990s and 2000s (fig. 31b). Recent unusual increases in density in spring 2005 and summer 2005–07 are likely to reflect large-scale colony abandonment from the Farallon Islands, and/or non-breeding by auklets in those years (Sydeman et al. 2006). The density of auklets was little different in 2011 from 2010, and densities of auklets off southern California during Spring 2011 were very low (fig. 31b).

Breeding success of seabirds at Southeast Farallon Island. Breeding success of seabirds during the 2011 breeding season at Southeast Farallon Island (SEFI) was average for most species (fig. 32) (Warzybok et al. 2011). Among the piscivorus seabirds, productivity of common murres (*Uria aalge*), rhinoceros auklets (*Cerorhinca monocerata*), pelagic cormorants (*Phalacrocorax pelagicus*), and pigeon guillemots (*Cepphus columba*) declined from high values observed in 2010 to values very near the long-term means observed for each species (fig. 32). Less favorable ocean conditions and a decline in abundance of forage fishes, particularly juvenile rockfish, from the previous year likely contributed to the lower productivity for these seabirds when compared to the previous year. Cassin's auklets (*Ptychoramphus aleuticus*), which feed primarily on euphausiids, exhibited exceptionally high productivity (fig. 32). The average number of chicks fledged per breeding pair was the second highest on record, and reflected a high rate of successful double brooding. Brandt's cormorants (*Phalacrocorax penicillatus*) experienced near complete breeding failure in 2011, marking the fourth consecutive year of very low reproductive success, and western gulls (*Larus occidentalis*) had their poorest year on record, surpassing the record low productivity observed during 2010 (fig. 32).

Breeding success and diets of seabirds at Castle Rock. Common murres nesting at Castle Rock National Wildlife Refuge[26] show a somewhat different pattern of reproductive success over the past several years than has been observed at SEFI (fig. 33, upper panel). Breeding success in 2011 was the second highest observed in this

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[26] The proportion of nests that successfully fledged young is based on a subset of approximately 75 nests that were monitored every other day. Diet observations occurred for an average of 80 hours each year while common murre chicks were present.

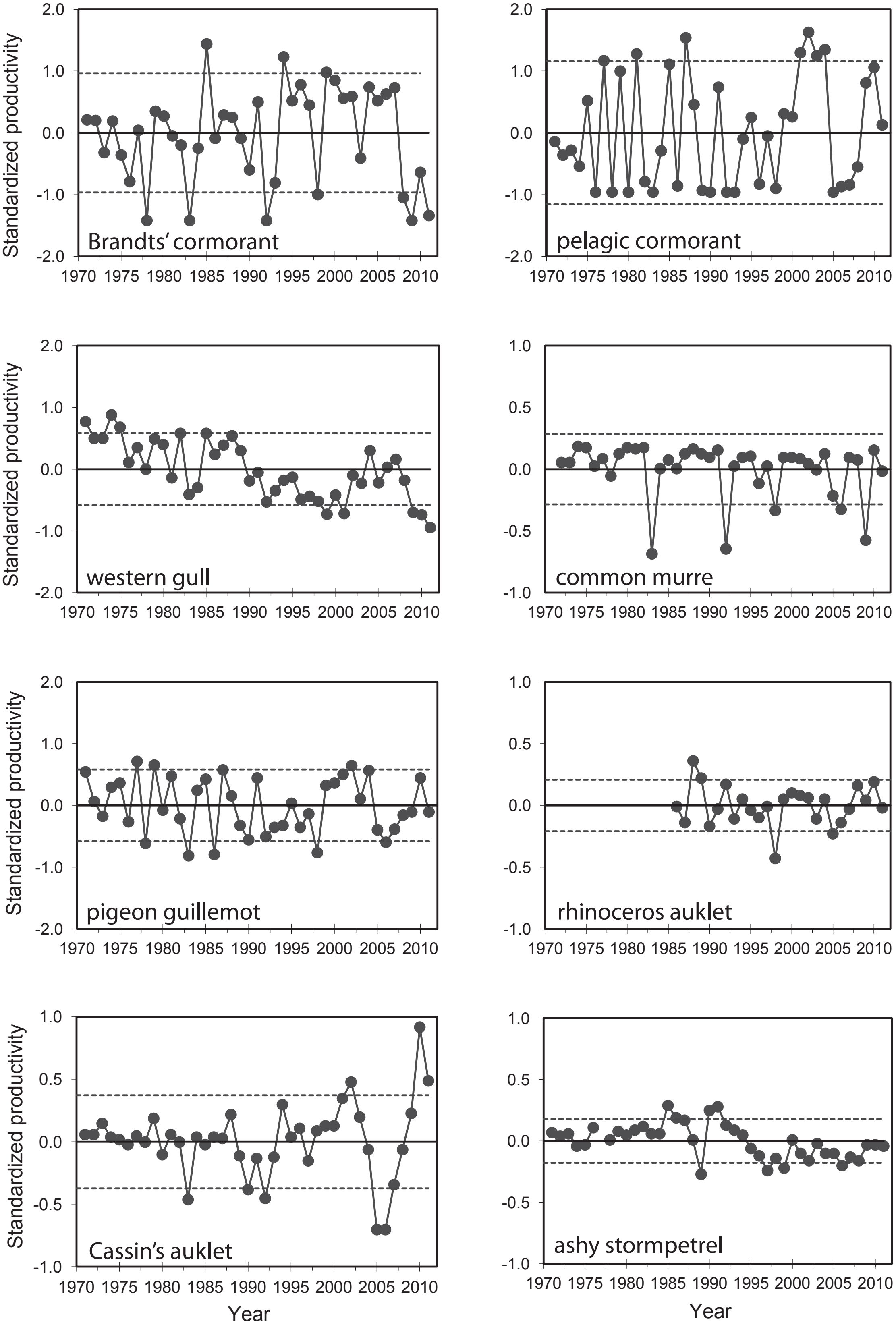

Figure 32. Productivity anomalies of productivity (annual productivity – long term mean) for 8 species of seabirds breeding on SE Farallon Island, 1971–2011. Dashed lines represent 80% confidence intervals for the long term means. Species are Brandts' cormorant (*Phalacrocorax penicillatus*), western gull (*Larus occidentalis*), pigeon guillemot (*Cepphus columba*), Cassin's auklet (*Ptychoramphus aleuticus*), pelagic cormorant (*Phalacrocorax pelagicus*), common murre (*Uria aalge*), rhinocerous auklet (*Cerorhinca monocerata*), and ashy storm petrel (*Oceanodroma homochroa*).

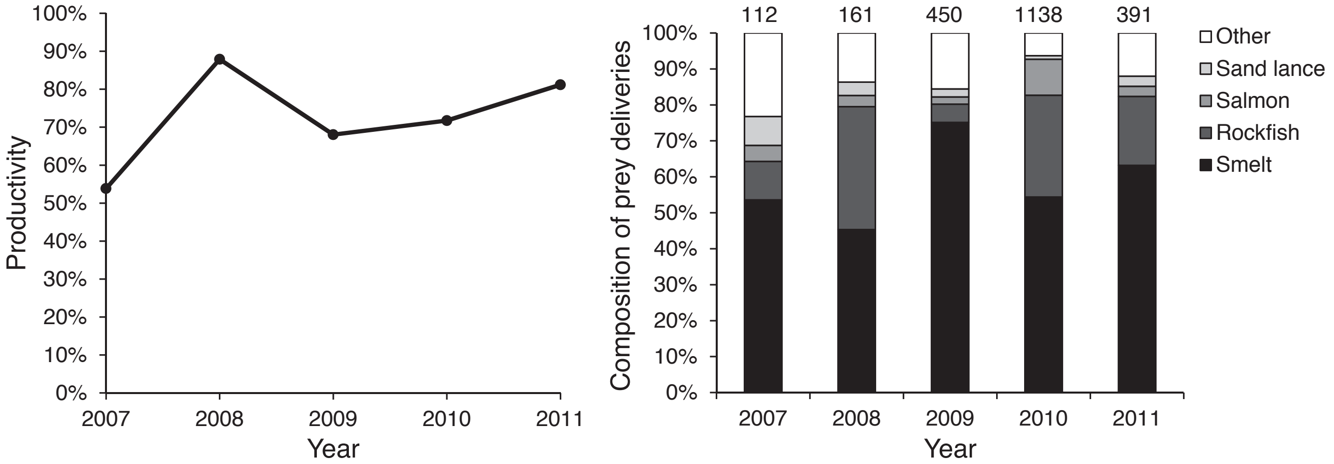

Figure 33. Upper panel: Percentage of common murre (*Uria aalge*) nests that successfully fledged young (upper panel) between 2007 and 2011 at Castle Rock National Wildlife Refuge, Del Norte County, California. These data do not include the success of second clutches which are rare. Lower panel: composition of prey delivered to common murre chicks and between 2007 and 2011 at Castle Rock National Wildlife Refuge, Del Norte County, California. Numbers above each bar indicate the total number of identified prey deliveries for each year.

short time series and continues a trend towards increasing productivity since 2009. Replacement clutches are rarely observed in this colony: in 2010, 4 of 7 replacement clutches successfully fledged, but no replacement clutches were observed in 2011.

In 2011, a total of 16 prey types were delivered to murre chicks, and prey composition was generally similar to other years, with smelt (Osmeridae) being the predominant prey fed to chicks (fig. 33, lower panel). Unlike other years, however, 2011 was the first year that shrimp[27] were seen (2% of prey deliveries). The proportion of rockfish in deliveries declined from 2010 into 2011.

Breeding success and diets of seabirds at Yaquina Head, Oregon. Reproductive success of common murres at Yaquina Head Outstanding Natural Area (YHONA)[28] was very low in 2011 (0.22 chicks fledged pair^{-1}), which was less than half that observed over the previous 4 years of the time series (mean 0.69 ± 0.05 [SE] chicks fledged pair^{-1}). While much of this decline can be attributed to greatly increased predation rates on eggs and chicks (3 to 10 times higher than in 2007–10), prey deliveries to chicks indicate that foraging conditions for murres also appeared to be suboptimal (fig. 34). In particular, flatfishes (Bothidae or Pleuronectidae), which are suboptimal prey, were unusually common among deliveries to chicks during 2011, in contrast to the dominance of smelt (Osmeridae) and Pacific sand lance (*Ammodytes hexapterus*) in previous years. Pacific sand lance (*Ammodytes hexapterus*), which are usually associated with cool, productive conditions, increased in murres' diets in 2011, but remained quite low relative to productive years like 2008. The proportion of juvenile rockfishes in prey deliveries also declined from 2010 to 2011. The dramatic increase in predator disturbance in 2011 observed at YHONA was further corroborated by reports of predators (e.g., bald eagles) causing extensive reproductive loss at other seabird colonies on the northern Oregon coast, and may reflect regional-scale factors affecting predators' distribution or their prey resources.

Productivity of California sea lions at San Miguel Island[29]. California sea lions (*Zalophus californianus*) are permanent residents of the CCS—they breed in the California Channel Islands and forage throughout the CCS in coastal and offshore habitats—and have been shown to respond to changes in the CCS on different temporal and spatial scales (Melin et al. 2010). Two indices provide measures of foraging conditions for California sea lions at different times of the year: pup production (an indicator of prey available to pregnant females from October to the following June) and pup weight at four months of age (an indicator of prey available to lactating females from June to October). Pup production reflects conditions encountered in the females range in coastal

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[27] It is impossible to identify shrimp unambiguously to low taxonomic level using current methods for observing prey deliveries. Shrimp prey were identified as being from the broad taxonomic group Caridea, which includes pandalid shrimps such as the pink shrimp (*Pandalus jordani*).

[28] The proportion of breeding pairs that successfully fledged young was calculated as a mean among 10 to 12 plots each containing 7 to 25 breeding pairs that were monitored every 1 to 3 days. Murre chicks that remained on the colony ≥ 15 days were considered successfully reared to fledging age. Diet data were collected on 2 to 5 days per week during the chick-rearing period. Single prey items carried in the bill of adult murres were digitally photographed for identification. Each year, diet samples from 36 to 585 (median = 146) adult murres were identified.

[29] San Miguel Island, California (34.03°N, 120.4°W) is one of the largest colonies of California sea lions, representing about 45% of the U. S. breeding population. The number of pups born is estimated from the total number of dead (cumulative) and live pups (survivors) counted by the end of July in each year. Mean weight of pups at 4 months of age is based on data collected for 200 to 500 pups adjusted to a standard 1 October weighing date. This research was conducted under NMFS Permit 16087 issued to the National Marine Mammal Laboratory.

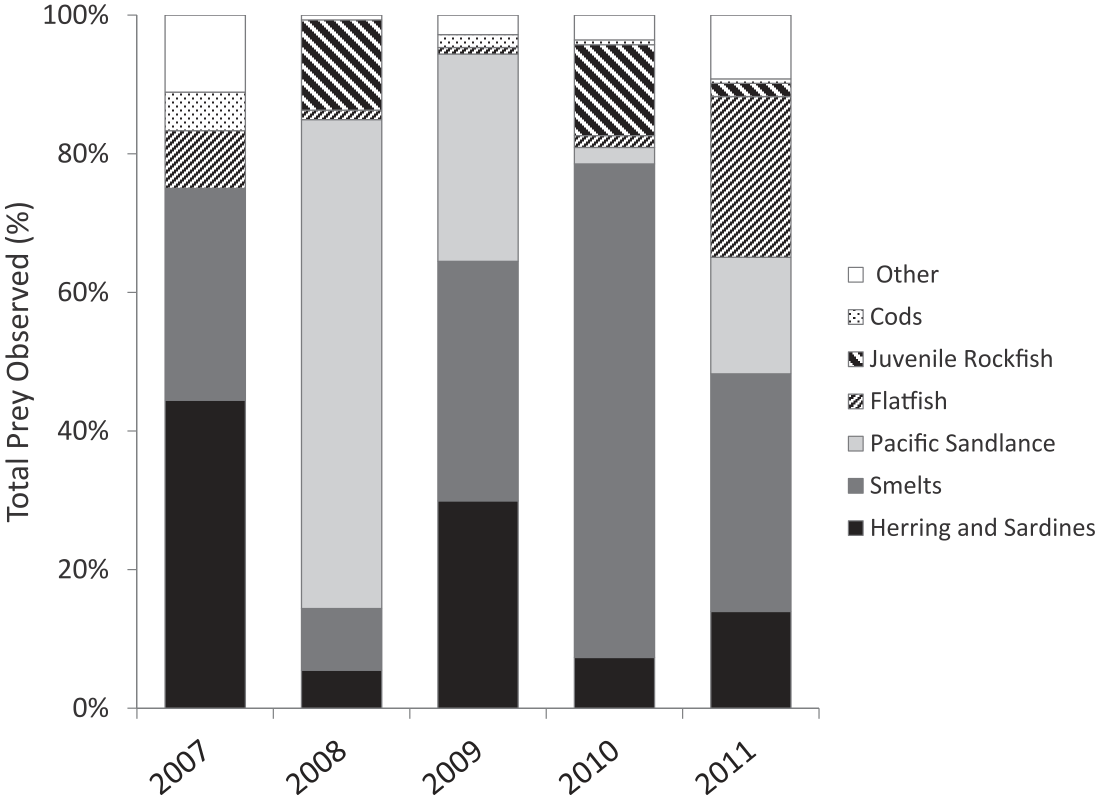

Figure 34. Composition of prey delivered to common murre (*Uria aalge*) chicks between 2007 and 2011 at Yaquina Head Outstanding Natural Area, Oregon.

waters throughout the southern part of the CCS (south of Monterey Bay), while pup weight is an indicator of conditions females encounter during 2 to 5 day foraging trips away from their pup (Melin et al. 2010).

In 2011, the estimated pup production by California sea lions at San Miguel Island (SMI) was the highest ever recorded and was 28% higher than mean production (fig. 35, upper panel). After the substantial decline in production in 2010 associated with the 2009–10 El Niño, the increase in 2011 suggests that pregnant females experienced particularly good foraging conditions from fall 2011 through early summer 2011.

In contrast to pup production, mean weights of 4-month-old pups on SMI were significantly lower in 2011 compared to the long-term mean (fig. 35, lower panel), suggesting that adult female sea lions encountered poor foraging conditions during summer 2011. Mean pup weights in 2011 were similar to mean weights in 2009, when a collapse in the seasonal upwelling patterns off the central California coast caused unusually high pup mortality and dramatically reduced the condition of 4-month-old pups (Melin et al. 2010).

DISCUSSION

During 2011 and early 2012, the evolution of the state of the California Current reflected mixed, and sometimes seemingly contradictory, basin-scale and local forcing. Although La Niña conditions persisted across the California Current System (CCS) during much of 2011 and into 2012, the strength of cool anomalies and associated conditions was variable over time and space. Climate conditions, as represented by the MEI and PDO, displayed a modest relaxation towards neutral conditions in early-to-mid 2011. However, whereas the MEI suggests that subsequent recovery towards La Niña conditions was less robust than that observed in early 2010 following the 2009–10 El Niño (Bjorkstedt et al. 2011), the PDO indicated a strong return to La Niña, reaching some of the strongest negative (cool) anomalies in the recent record. The NPGO remained consistently but moderately positive, while exhibiting substantial variability and possibly a mild decline in strength throughout 2011 and into early 2012. The persistence of cool, but more moderate, conditions indicated by basin-wide indices was corroborated through field observations at several moorings and from several ongoing hydrographic surveys. In 2010, several of these surveys had encountered the coldest average conditions in the observational record (Bjorkstedt et al. 2011); 2011 observations were much closer to long-term mean conditions and in some cases, tended to the warm side in coastal regions of the northern CCS.

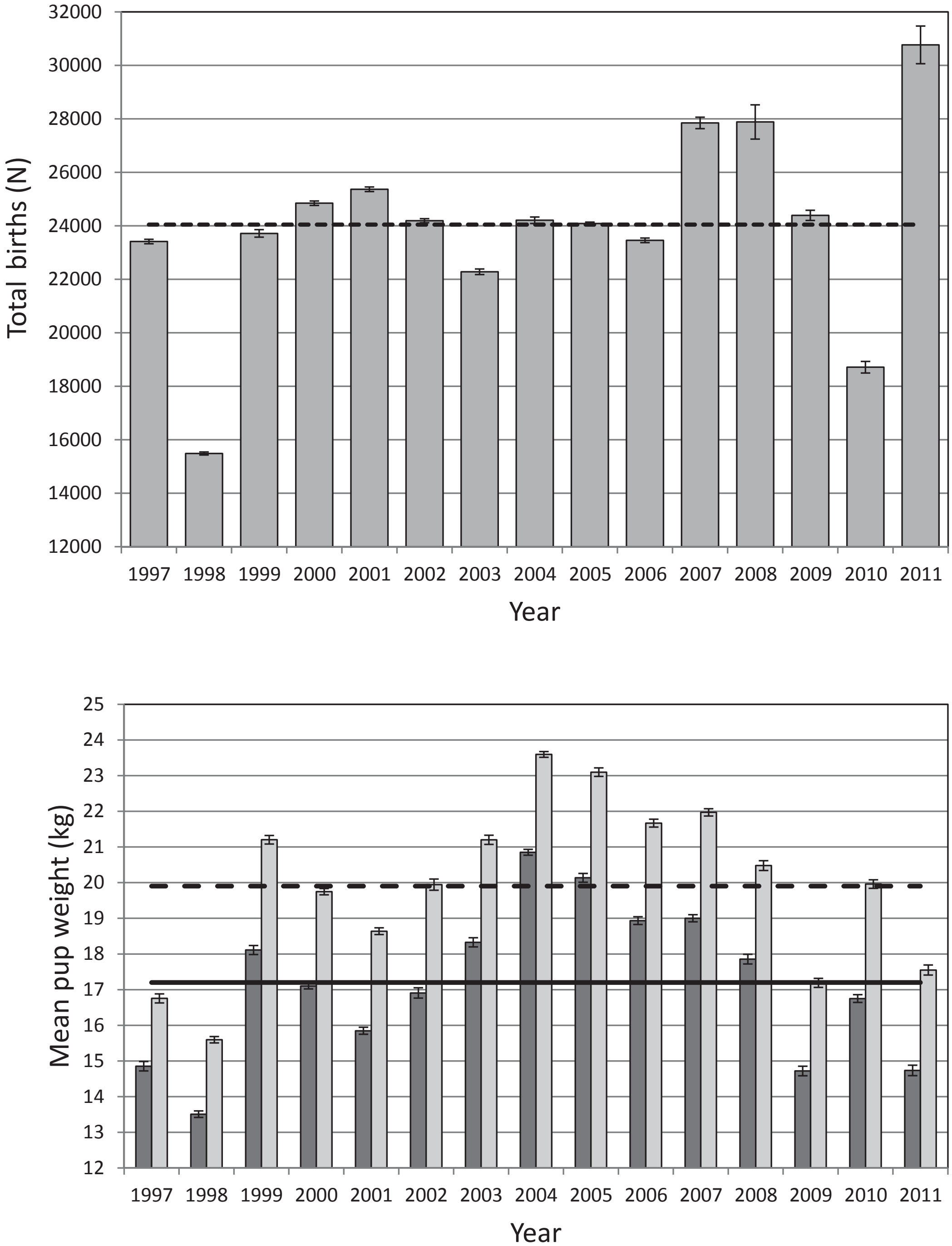

Figure 35. Upper panel: Estimated number of California sea lion pup births (± 1 standard deviation) at San Miguel Island, California. Dashed line indicates mean over time series. Lower panel: Mean weights (±1 standard deviation) of 4 month old female (dark grey) and male (light grey) California sea lion pups at San Miguel Island, California. Lines indicate means for females (solid line) and males (dashed line) over the time series.

Within the broader climate context, available information indicates latitudinal variability in the timing and strength of local forcing, particularly with respect to the evolution of upwelling intensity along the coast. Ecosystem responses at lower trophic levels reflect these dynamics in both time and space. For example, in 2011, upwelling strengthened in the southern part of the CCS relatively early but was generally near the climatological mean, except in the very southern part of the CCS. Correspondingly, concentrations of chl *a* and mesozooplankton (e.g., copepods) were elevated off Baja California for much of 2011, while biological metrics (e.g., chl *a* concentrations and zooplankton displacement volume) off southern California were close to long-term means, despite the generally cool conditions.

In contrast, upwelling was relatively weak throughout early 2011 from central California north, only picking up strength in June and July before dropping off rapidly in late summer through early fall. Ecosystem consequences of this pattern are most apparent at the base of the food chain. For example, concentrations of chl *a* in Monterey Bay remained low through the spring and summer while upwelling was weak. High concentrations of chl *a* concentrations (i.e., concentrations typically observed in spring and early summer) were achieved only in late summer, following the onset of sustained upwelling. A similar pattern appears to have played out off northern California, with weak upwelling leading to lower than normal chl *a* concentrations in spring and summer 2011, and a rapid decline in chl *a* concentrations following the early cessation of sustained upwelling. Further north, off Oregon, weak upwelling had a physical signature (i.e., moderate temperatures of deep waters on the shelf despite cool SSTs at coastal buoys and the PDO) and apparent ecological consequences, e.g., a substantial decline in abundance of juvenile fishes despite evidence of consistent larval production and copepod indices less strongly indicative of the prevailing cool conditions than might otherwise be expected based on the PDO.

Several higher level ecosystem indicators suggest that the effects of persistent cool, productive La Niña conditions propagated through the ecosystem across southern and central CCS during 2011 but also indicate that productivity in general was weaker than in the previous year and that not all levels of the coastal ecosystem benefitted equally. Reproductive success of seabird populations on Southeast Farallon Island declined across the board from 2010, yet most species either fared quite well (Cassin's auklets, which feed on krill) or maintained productivity at or above long-term mean levels (several piscivorous taxa). The performance of auklets was corroborated by their low at-sea densities in the CalCOFI region—a further indication that euphausiid stocks were sufficiently productive for auklets to remain near their breeding sites (cf. Sydeman et al. 2006). Growth rates of Chinook salmon off California during the early part of the year declined modestly from 2010 to 2011, although they remained greater than had been observed in previous years. Indices of reproductive success in California sea lions capture signals of year-to-year changes in ocean productivity: pup production increased from 2010 to 2011, presumably reflecting better foraging conditions for female sea lions from fall 2010 through spring 2011 than during the 2009–10 El Niño, yet pup growth declined from 2010 to 2011 as the strong La Niña conditions that developed in summer 2010 were not repeated in 2011. The decline in at-sea densities of shearwaters off southern California suggests that foraging conditions in spring and summer 2011 were not as favorable as in the previous year. Increased predation was the proximate driver of low productivity of common murres on Yaquina Head, but the inclusion of suboptimal prey in murres' diets corroborates other evidence of declines in ecosystem productivity, particularly of juvenile fishes, off Oregon.

In contrast to these general trends, common murres in northern California (Castle Rock) appeared to exhibit a modest increase in productivity, raising the question of which spatial or temporal differences in ecosystem structure or forage base might underlie latitudinal variability in reproductive success of seabirds. In this case, reproductive success of murres remained high despite a decline in juvenile rockfish abundance (a common indicator of seabird productivity off California, e.g., Wells et al. 2008), which suggests that murres may be taking advantage of alternate prey, such as unusually abundant shrimp, to maintain reproductive success. While it is not clear whether alternate prey can offset declines in availability of juvenile rockfish or other prey, this example illustrates how data on diet and insights from fisheries-dependent data can inform our view of the California Current.

We note that while the general responses of higher trophic levels are consistent with observed forcing dynamics, the preliminary evaluations presented in this report do not necessarily account well for several possible ecological mechanisms for the observed changes. For example, several of the metrics discussed in the preceding paragraph may include unquantified contributions of density-dependence on reproductive performance or mortality due to predation or other factors. Other time series (e.g., at-sea densities of sooty shearwater) may include the effects of latitudinal shifts (e.g., Sydeman et al. 2009) as well as population processes happening outside the CCS. Finally, in contrast to measures of per capita reproductive success for long-lived organisms, changes in short-lived species such as market squid may be indicators of changes in abundance over time and thus integrate population growth over multiyear trends rather than yielding independent estimates of annual recruitment success.

As has been the case in several recent reports from this series (Goericke et al. 2005, 2007; Peterson et al. 2006; McClatchie et al. 2008, 2009; Bjorkstedt et al. 2010, 2011), available data lead to a conclusion that regional structure is a consistent characteristic of the CCS (e.g., Thomas and Brickley 2006; Thomas et al. 2009; Bograd et al. 2009). Resolving the structure with respect to regions' spatial extent, the scale of transition zones between regions, and the underlying mechanisms remains difficult due to differences in the temporal, spatial, and taxonomic scales at which data are collected throughout the CCS.

Several aspects of the observations presented above argue strongly for the importance of maintaining and modestly expanding the resolution and extent of observations throughout the CCS and for promoting greater integration of available data into this (and other) summary reports. Reasons for doing so are several. Perhaps foremost, the California Current is likely to show particular sensitivity to the effects of climate change (Checkley and Barth 2009) and ocean acidification (Gruber et al. 2012). The time series of CalCOFI data continues to show trends in dissolved oxygen (cf. Bograd et al. 2008, and this report) and nutrient concentrations (this report) that lend empirical support to model-based predictions of changes in upwelling source water characteristics associated with climate change (Rykaczewski and Dunne 2010). Continued development of capacity for assessment of such changes and their consequences elsewhere along the coast should be a priority.

A second reason is to enhance our ability to provide rapid assessment of spatial variability in ecosystem state. Broadly distributed, comparable observations are essential for assessing such variability, and they also provide insight into the applicability and reliability of ecosystem indicators based on historical time series of spatially limited observations. Variability in reproductive success of common murres from Oregon to central California provide one example where expanding the scope of observations leads to a broader perspective, even as it raises further questions about the underlying mechanisms. In another example, the dynamics of copepod community structure off Oregon and northern California have been generally coherent over much of the time series available for comparison (Bjorkstedt et al. 2011), yet this pattern appears to have been disrupted in early 2012, possibly as a consequence of unusual circulation patterns. Such events, if undetected, compromise the potential for ecosystem indicators based on local observations, even those as successful as the copepod-based indices derived from the Newport Hydrographic line, to apply broadly along the coast. Likewise, survey designs that do not fully encompass at-sea distributions of seabirds and pelagic fishes hinder our ability to evaluate whether apparent trends in abundance are real or are due to changes in distribution. For some taxa, such as seabirds, synthesis of observations CCS with data from elsewhere in the Northeast Pacific has been informative (e.g., Sydeman et al. 2009). For others, such as pelagic fishes, coast-wide surveys have had some success and are expected to make increasing contributions to future syntheses. Smaller-scale, high-frequency survey programs have emerged as a successful strategy for assessing the dynamics of the California Current in regions and seasons where weather can severely constrain the effectiveness of large-scale surveys, and are particularly useful in resolving year-round dynamics (Bjorkstedt et al. 2010, 2011). Efforts to enhance and improve the resolution of more traditional oceanographic data streams should be complemented by expanding the spatial range of data on higher trophic levels (e.g., seabirds); as demonstrated in this report, such data have substantial potential to yield greater insight to regional structure.

Looking forward, the resurgence of La Niña conditions in late 2011 appears to have supported relatively high productivity going into early 2012. Throughout much of the CCS, upwelling in late fall 2011 and early winter 2012 appears to have had particularly strong effects in the central part of the CCS, with increased enrichment going into early 2012 compared to that going into early 2011. The scope and direction of ecosystem responses to forcing during winter 2011–12 is as yet unclear, particularly in the northern CCS, but preliminary evidence suggests that early 2012 has been relatively productive.

However, these same observations suggest that 2012 may prove to be a particularly unusual year. Upwelling during winter 2011–12 would be expected to set the stage for high productivity throughout much of the CCS (Logerwell et al. 2003; Schroeder et al. 2009; Black et al. 2010, 2011), yet ecosystem surveys in spring and summer 2012 have encountered unusually high concentrations and volumes of gelatinous zooplankton throughout much of the CCS, so the ultimate consequences of early enrichment are difficult to forecast. Preliminary observations also suggest that the cross-shelf distribution of several taxa may be different in 2012 from those in previous years marked by cool, productive conditions. These observations, coupled with the emergence of ENSO-neutral conditions going into summer 2012 and the forecast development of El Niño in late 2012, suggest that the ongoing evolution of the state of the California Current will be very interesting indeed.

ACKNOWLEDGMENTS

We thank three anonymous reviewers for their comments that improved this manuscript and provide guidance for continued development of reports in this series. Xuemei Qiu and Reiko Michisaki assisted with several of the plots included in this paper. Financial and collaborative support for the science reported here comes from diverse agencies and government entities, including NOAA's National Marine Fisheries Service (NMFS) and its Stock Assessment Improvement Plan (SAIP) and Fisheries and the Environment (FATE) programs, Mexico's Consejo Nacional de Ciencia y Tecnología (CONACyT), the U.S. National Science Foundation (NSF), Bonneville Power Administration (BPA), the United States Fish and Wildlife Service (USFWS), NOAA's Integrated Ocean Observing Systems (IOOS) program and university partners through the Coastal Observing Research and Development Center, California's Ocean Protection Council, and Redwood National and State Parks. The David and Lucile Packard Foundation supported central California mooring observations. The Baker Trust, the Marisla Foundation, the Campini Foundation, the Kimball Foundation, and the Mead Foundation supported seabird work on Southeast Farallon Island. We also thank the captains and crew of the vessels that supported this work, including R/V *Coral Sea*, R/V *Francisco de Ulloa*, *Elahka*, FS/V *Ocean Starr*, R/V *New Horizon*, FS/V *Bell M. Shimada*, F/V *Frosti*, F/V *Miss Sue*, F/V *Piky*, and F/V *Excalibur*. We also sincerely thank the many dedicated individuals who have participated in, advised, collaborated in, or otherwise contributed to the collection, management, and analysis of these data both in recent years and in the past.

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Part II

SYMPOSIUM OF
THE CALCOFI CONFERENCE
2011

MAKING ECOSYSTEM-BASED MANAGEMENT A REALITY: THE PACIFIC FISHERY MANAGEMENT COUNCIL AND THE CALIFORNIA CURRENT INTEGRATED ECOSYSTEM ASSESSMENT

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ABSTRACT

Implementing ecosystem-based management requires both scientific assessments of ecosystem interactions and policy analysis of the interactions between the laws that manage the ecosystem and its resources. The California Current Integrated Ecosystem Assessment (IEA) process brings together scientists from a host of disciplines to assess the interactions and status of the California Current Ecosystem. However, the generation of scientific information does not automatically lead to management action. U.S. fisheries law facilitates and allows ecosystem-based management but does not require it, a situation that can either encourage creativity or stifle action. The Pacific Fishery Management Council (Pacific Council) is engaged in an ecosystem-based fishery management process to better understand the California Current Ecosystem and how ocean resource management processes and priorities interact to affect the ecosystem. For the California Current IEA to support movement toward ecosystem-based management, it must better account for how our laws affect natural resources and drive management processes.

INTRODUCTION

"Implementation of the IEA process for the California Current is now underway. Potentially, it represents a major advance toward regional ecosystem-based management. To many, the reality, as opposed to the promise, of ecosystem-based management is far from clear. Integration of environmental considerations into the management of living marine resources has proven remarkably difficult, which leads us to examine how it can be best achieved in the California Current." J. A. Koslow, September 2011, instructions to speakers for the 2011 CalCOFI meeting.

The conundrum Koslow poses is familiar to scientists in many disciplines. If there is strong scientific opinion in support of a course of action, why is there not political movement toward taking that action? Answers to that question vary with the abilities of scientists to communicate their findings with policymakers and the general public, and with the laws and political frameworks that affect the desired legal or regulatory change. While ecosystem-based management certainly requires the support of a vast array of scientific efforts, it also fundamentally requires new ways of thinking about public policy and management processes. Scientists have developed models to help us think about the functions of ecosystems as a whole (e.g. Polovina 1984; Jorgensen 1986; Christensen and Pauly 1992; Walters et al. 1997; Aydin et al 2002; Christensen and Walters 2004; Fulton et al. 2004; Kishi et al. 2007). In doing so, they bring together data and ideas from diverse disciplines—biology, oceanography, chemistry, and physics, but often miss the essential human dimensions of ecosystem-based management (Fulton et al. 2011). For ecosystem-based management to become a reality, managers must see not just the applications of those models to the ecosystems and people they govern, but must also think about how to bring together the political minds, networks, and incentives that affect those ecosystems.

In recent decades, scientific literature has explored the general concept of ecosystem-based management (Slocombe 1993; Grumbine 1994; Kaufmann et al. 1994; Christensen et al. 1996) as well as the more specific application of ecosystem-based management to the marine environment (Larkin 1996; Botsford et al. 1997; Link et al. 2002; Pikitch et al. 2004; Arkema et al 2006; Crowder and Norse 2008; Levin and Lubchenco 2008). Link 2002 framed the question for living marine resources, suggesting that we are not actually attempting ecosystem management, but rather attempting fisheries management in an ecosystem context. This question of defining ecosystem-based management has captured the interest of ocean and fisheries scientists, as they have fleshed out definitions (Brodziak and Link 2002; Slocombe 1998), and made suggestions on how to do it (Leslie and McLeod 2007; Marasco et al. 2007), and provided analyses of the California Current Ecosystem (MacCall 1986; McGowan et al. 1998; Goericke et al. 2004; Field and Francis 2005; Goericke et al. 2005; Peterson et al. 2006; Goericke et al. 2007; DiLorenzo et al. 2008; McClatchie et al. 2008 McClatchie et al. 2009; Bjorkstedt et al. 2010). Scientists have been making suggestions on governance (Crowder et al. 2006; Ruckelshaus et al. 2008) and "commanding" other scientists on how to conduct ecosystem science (Francis et al.

2007). In the U.S., Congress ultimately paid attention to all of this literature and requested a summary of the state of science to support an ecosystem approach to fishery management (NMFS 2009). Given these and many other scientific efforts, what would move ecosystem-based fisheries management in the California Current and elsewhere beyond discussions within scientific publications and closer to a reality in practice? Our laws, policies, and economies are manifestations of how human societies and minds interact. If ecosystem-based management is to move toward reality, it must include examinations of human institutions and ideas about governance, cultural goals, and economic priorities.

THE MAGNUSON-STEVENS ACT, ECOSYSTEM-BASED MANAGEMENT, AND THE PACIFIC FISHERY MANAGEMENT COUNCIL

While U.S. laws initially come from the minds and will of Congress, they must be approved by the president, and then interpreted and implemented by one or more of the many agencies within the executive branch [U.S. Const. art. I–III]. Dissatisfied members of the public may then have the opportunity to request, through one or more lawsuits, that the judicial branch provide a new or differently nuanced interpretation of the law. A significant result of this process is that the meaning of a law, or the methods for interpreting that law, can change over time. In other words, a law cannot be understood by simply reading the text of the legislation itself; its meaning must be assessed within the frame of congressional will, executive implementation, and judicial interpretation.

One of the most influential federal laws shaping U.S. living marine resource management is the Magnuson-Stevens Fishery Conservation and Management Act (Magnuson-Stevens Act). The Magnuson-Stevens Act governs fish and fisheries within the U.S. Exclusive Economic Zone, those marine waters within 3–200 nm offshore of the U.S. coast. While the act allows "integrating ecosystem considerations into fisheries management" [16 U.S.C. §1801(a)(11)], it does not explicitly require ecosystem-based management (MacPherson 2001; Parenteau et al. 2008; Salcido 2010). The act has no definition for the terms "ecosystem-based management," "ecosystem approaches to management," or even "ecosystem" [16 U.S.C. §1802], although the conservation and management requirements of the act comport with many of the principles of ecosystem-based management. Three major Magnuson-Stevens Act conservation objectives have spurred scientific efforts to expand our understanding of relationships between different species and between those species and their habitats: rebuild overfished stocks and end overfishing [16 U.S.C. §1853(a)(10)], monitor and minimize bycatch [16 U.S.C. §1853(a)(11)], and identify and protect essential fish habitat [16 U.S.C. §1855(b)]. Taken together, actions to meet those goals bring us closer to the principles that Grumbine 1994 ascribed to ecosystem management, particularly, "maintain viable populations of all native species in situ" and "represent, within protected areas, all native ecosystem types across their natural range of variation." However, MacPherson's (2001) explanation of ecosystem-based management within a Magnuson-Stevens Act context still applies today: the principles and policies of the act provide opportunities for implementation, but do not mandate the use of an ecosystem-based approach in fisheries management.

The Magnuson-Stevens Act retains many of the original principles from its first iteration in 1976, but it has also been significantly revised by each of the three branches of government, through congressional reauthorizations, through the executive branch implementing the law in highly varied U.S. marine ecosystems, and through judicial interpretation of the requirements of the law in different courts nationwide. The original language of the law also set up, and still maintains, a dynamic relationship between the science and management processes, requiring that fishery "conservation and management measures shall be based on the best scientific information available" [16 U.S.C. §1851(a)(2)]. This seemingly simple and common-sense requirement has supported decades of rigorous scientific inquiry. That dynamic relationship manifests as a large-scale conversation about how and what new scientific information can help us to better understand the fish stocks and habitat we manage. If the best available fisheries science can provide managers with science tools that supplement and complement such essential management tools as stock assessments, then those tools will influence how resource managers and policy-makers at every level of government think about marine ecosystems and the law. In other words, new scientific information can influence how the law is implemented, when and if that information is deemed "best available."

The Magnuson-Stevens Act authorizes eight regional fishery management councils to guide federal fisheries management in the United States, advising the National Oceanic and Atmospheric Administration (NOAA) in its implementation of the act. Jurisdictions of the eight regional councils roughly coincide with large marine ecosystems (Sherman 1991), possibly indicating some insight on the part of Congress into the notion of ecosystem-based fisheries management, or at least the concept that fisheries management should be spatially driven to avoid myriad potential jurisdictional conflicts. Fish and fisheries within the U.S. portion of the California Current Ecosystem are managed with the advice of the Pacific Council. Fishery management councils are quasi-governmental bodies consisting of members of the public, representatives from U.S. states and tribes, and representatives from federal agencies [16 U.S.C. §1852]. Government and public interests are further represented on council advisory bodies with varying responsibilities: reviewing the strength of scientific information developed to serve the council process; representing the interests of particular fishing, environmental, or community groups; developing federal, and sometimes state and tribal, regulatory measures to implement the advice of the councils. Each council's Scientific and Statistical Committee is the arbiter of whether scientific information is appropriate for use in council management decisions [16 U.S.C. §1852]. The primary functions of the councils are to prepare, review, and amend fishery management plans for fisheries under their geographic areas of authority, working within venues that are both open to the public and in locations appropriate to the geographic areas managed [16 U.S.C. §1852]. Fishery management plans are required to meet ten national standards[16 U.S.C. §1851(a)], and to include a host of provisions ranging from describing and identifying essential fish habitat to describing the vessels and gear used, and revenues from, each fishery managed under the plan [16 U.S.C. §1853].

Fishery management councils are taking a range of creative approaches to implementing ecosystem-based management. Some councils have already developed fishery ecosystem planning documents (NPFMC 2007, SAFMC 2009, WPFMC 2009). Other councils without formal ecosystem plans are still using new scientific information and Magnuson-Stevens Act authority to implement ecosystem-based management measures through programs that—for example—better monitor and estimate fisheries' bycatch (Jannot et al. 2011), engage in a strategic planning process for fisheries' futures (MAFMC 2012), and establish overfished species rebuilding plans with multi-sector restrictions to account for directed and incidental catch (GMFMC 2011). The concept of the fishery ecosystem plan as a strategic fishery management planning document evolved from a 1998 report from the U.S. Ecosystem Principles Advisory Panel (EPAP 1998), a panel mandated and funded by the Magnuson-Stevens Act [16 U.S.C. §1882]. Although the act itself does not require fishery ecosystem plans, the panel's work inspired fishery management councils to explore ecosystem-based fishery management planning.

The Pacific Council's fishery management programs include an array of ecosystem-based fishery management measures (PFMC 2011a, PFMC 2012), and it is in the process of developing a fishery ecosystem plan. In part, the Pacific Council intends its fishery ecosystem plan to "enhance the Council's species-specific management programs with more ecosystem science, broader ecosystem considerations and management policies that coordinate Council management across its Fishery Management Plans and the California Current Ecosystem" (PFMC 2011b). The Pacific Council also intends its fishery ecosystem plan to "provide a framework for considering policy choices and trade-offs" as they affect managed species and the California Current Ecosystem, recognizing a need for improved understanding of how the ecosystem affects California Current Ecosystem fish and fisheries, and vice versa (PFMC 2011b). The fishery ecosystem plan is ultimately intended to complement, rather than supplement, the conservation and management measures the Pacific Council has already developed to improve the long-term sustainability of fisheries through protections to the stocks themselves and to habitat (PFMC 2012; Seagraves and Collins 2012).

THE CALIFORNIA CURRENT IEA IN THE POLICY PROCESS

In the U.S., NOAA has been developing its framework for Integrated Ecosystem Assessments (IEAs) to provide a scientific basis for ocean ecosystem-based management (Levin et al. 2008, 2009). IEAs are intended to provide a means of summarizing ecosystem status, screening and prioritizing potential risks, and evaluating alternative management strategies against a backdrop of environmental variability (Levin et al. 2008). Ocean ecosystem modelers have commented that large-scale ecosystem models, like those used within IEAs, can provide natural resource managers with strategic (long-term), rather than tactical (short-term), advice for management decisions (Fulton 2010; Link 2010; Kaplan et al. 2012). Most decisions made within the fishery management council process, however, are tactical and require fairly specific scientific advice. Table 1 details the Pacific Council's Scientific and Statistical Committee reviews conducted and reported on in 2011, illustrating that most scientific analyses reviewed for their utility in decision-making deal with tactical management decisions, often addressing near-term allowable harvest levels. Large-scale recent strategic decisions in the Pacific Council process have been related to the development of the fishery ecosystem plan, and to Magnuson-Stevens Act requirements to develop new processes for setting annual catch limits for all species [16 U.S.C. §1852] and to review requirements for essential fish habitat designations for its managed species [50 C.F.R. §600.815].

NOAA's California Current IEA program, described in more detail elsewhere in this report, is beginning to provide technical reports on the status of the California Current Ecosystem and on the interactions within the ecosystem between the physical environment, human activities, and ocean life (Horne et al. 2010; Ainsworth et al. 2011; Levin and Schwing 2011). California Cur-

TABLE 1
Scientific Analyses Reviewed by the Pacific Council's Scientific and Statistical Committee (SSC) in 2011

2011 Pacific Council Meetings	SSC reviews in 2011, based on SSC reports to the Pacific Council (available online: http://www.pcouncil.org/council-operations/council-meetings/past-meetings/)	Tactical (T)/ Strategic (S)
March	• 2011 experimental fishing permit for an aerial sardine survey	T
	• Review of 2010 West Coast salmon fisheries and summary of 2011 stock abundance forecasts	T
	• Identification of salmon stocks not meeting annual conservation objectives	T
	• Sacramento Fall Chinook overfishing assessment	T & S
	• 2011 Pacific whiting assessment and harvest specifications	T
	• Ecosystem-based management planning report	S
April	• 2011 experimental fishing permit for an aerial sardine survey	T
	• Acoustic–trawl survey methodology for coastal pelagic species abundance	T
	• 2011 salmon abundance estimation methodology review	T
	• 5-year review of salmon essential fish habitat designations	T & S
	• Harvest specifications and stock assessment considerations for 2013–2014 groundfish fisheries	T
	• 5-year review of groundfish essential fish habitat designations	T & S
June	• Classifying salmon harvest reference points and needed analysis in support of those classifications	S
	• Economic analysis of the North Pacific albacore fisheries	T
	• Groundfish stock assessments for 2013–2014 fisheries	T
	• Socioeconomic analyses needed for 2013–2014 groundfish harvest specifications and management measures	T
	• Socioeconomic analyses needed for trailing actions under trawl rationalization	T
	• Pacific mackerel management for 2011–2012	T
	• Ecosystem-based management planning report	S
September	• Albacore tuna stock assessment	T
	• Groundfish stock assessments for 2013–2014 fisheries	T
	• Biennial management process for and models used in development of 2013–2014 groundfish fisheries	T
	• Needed science improvements for the next groundfish management biennium	T & S
	• Columbia River tule and Sacramento River winter Chinook management	T & S
	• 2011 salmon abundance estimation methodology review	T
	• Estimating Pacific halibut bycatch in groundfish fisheries	T
November	• 2011 salmon abundance estimation methodology review	T
	• Groundfish stock assessments for 2013–2014 fisheries	T
	• Groundfish management specifications for 2013–2014 fisheries	T
	• Pacific sardine assessment and coastal pelagic species management measures for 2012	T
	• Integrated Ecosystem Assessment report	S
	• Fishery Ecosystem Plan—DRAFT	S

rent IEA scientists and the Pacific Council and its advisory bodies have been discussing where and how best to bring IEA products and reports into the Pacific Council process (Levin and Wells 2011; PFMC 2011c). Initially, IEA-generated information will likely enter the Pacific Council process through an annual report on the state of the California Current Ecosystem, much like the state of the California Current paper produced for CalCOFI Reports, but tailored to focus on those biophysical trends known to affect shifts in abundance of managed species (PFMC 2012).

NOAA's foundational description of the IEA process necessarily focused on the scientific processes needed to implement an IEA (Levin et al. 2008). Nonetheless, that process is intended to provide analysis of ecological interactions relative to "specified management goals" (Levin et al. 2008). Who then is to specify those management goals, and how? NOAA's vision for the IEA process proposes beginning with a scoping process that would be independent from any legal context, yet also a primary source for determining "specified management goals" (Levin et al. 2008, 2009; deReynier et al. 2010). For managers, however, scoping on policy issues occurs within frameworks created by the laws that authorize and guide policy discussions. Scoping on U.S. natural resource management issues commonly occurs as part of a process to review a potential management action using the National Environmental Policy Act (NEPA) review process. Under implementing regulations for NEPA, scoping is a process "for determining the scope of issues to be addressed and for identifying the significant issues related to a proposed action" [40 C.F.R. 1501.7]. NEPA scoping does not occur independently from policy initiatives; NEPA provides the framework for analysis of potential actions authorized by other federal laws or programs. If IEA products are to be useful to a management process, they must consider policy questions (or specified management goals) that our laws require us to ask. For example, an IEA examination of the potential trophic effects of regularly harvesting managed species' populations at twice their optimum yield levels might be interesting, but managers are prohibited by law from setting such harvest levels and thus might not find such an examination useful.

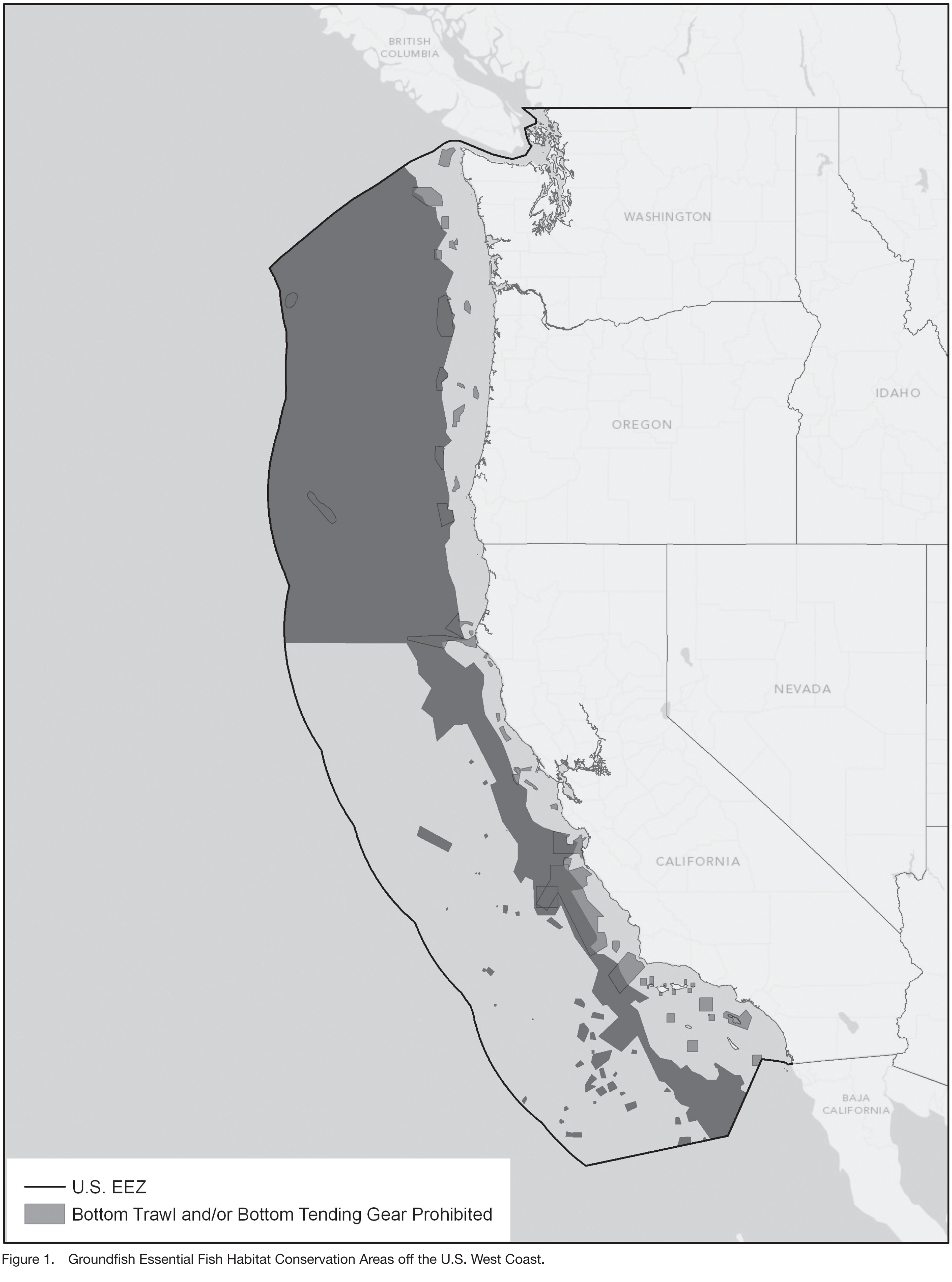

Figure 1. Groundfish Essential Fish Habitat Conservation Areas off the U.S. West Coast.

IEA scientists will need to better engage with managers if IEA products are to be useful to management decisions. And, managers will need to begin ecosystem-based assessments of how the laws and policies they implement affect regional ocean resource management priorities. Those policy assessments could well be just as complex and lengthy as the scientific assessments provided for IEAs. In 2004, the U.S. Commission on Ocean Policy's final report discussed how a range of U.S. laws affect ocean ecosystem management, and provided Appendix D, which briefly summarized federal ocean and coastal-related commissions, committees, councils, laws, and programs (USCOP 2004). According to that appendix, there are 45 major laws with varying degrees of specificity and influence that affect the use and management of ocean and coastal ecosystems and resources. The implementation of any law that addresses where and how humans interact with the natural environment will vary from region to region to accommodate the unique qualities of the managed resources and the human cultures and economies that interact with those resources. For IEAs to become essential management tools, there must be parallel policy assessment processes to determine the ecosystem-based management questions derived from current laws and relevant to management concerns within a given ecosystem. Some examples of how a policy analyst might ask cross-jurisdictional questions based on the federal laws and policies that affect California Current Ecosystem resources include:

- Under the Magnuson-Stevens Act, the Pacific Council is in the midst of the required 5-year reviews of the essential fish habitat components of its four fishery management plans [50 C.F.R. §600.815], and will face the same review requirements another 5 years hence. In preparation for that next round of review, could the California Current IEA assess the effects of fishing gear on essential fish habitat under a variety of fishing effort scenarios derived from the effort shifts that may result from the Pacific Council's trawl rationalization program?
- Under the Department of the Interior, Environment, and Related Agencies Appropriations Act, 2010, federal agencies have been required to draft a National Fish, Wildlife and Plants Climate Adaptation Strategy. Could the California Current IEA assess the potential effects of short-term climate shift and long-term climate change on the ability of marine mammal populations to achieve their optimum population levels under the Marine Mammal Protection Act? How might fisheries harvest levels authorized by the Magnuson-Stevens Act interact with climate change to affect marine mammal populations protected by the Marine Mammal Protection Act?
- The five National Marine Sanctuaries off the U.S. West Coast have adopted a joint Ocean Acidification Action Plan (Lott et al. 2011) that, among other things, calls for the selection of indicator species for the different sanctuary habitats in the five sanctuaries that would be appropriate for monitoring the environmental effects of ocean acidification, in keeping with the research requirements of the Federal Ocean Acidification Research and Monitoring Act of 2009 and the National Marine Sanctuaries Act. Could the California Current IEA help to identify appropriate indicator species for each of the sanctuaries and assess the trophic effects of changes in population levels of those species?

To actually be used in management decisions, results from any of these analyses would need to undergo more rigorous peer review processes than those provided through journal publication processes. The Magnuson-Stevens Act requires that science in support of fishery management council decisions be reviewed through council Scientific and Statistical Committees [16 U.S.C. §1852(g)]. As regional IEAs becomes more mature, the quality of their science products should be tested through a process similar to the Center for Independent Experts (CIE) process used so successfully for fish stock and mammal abundance assessments (Brown et al. 2006). For IEA products intended to support fishery management councils, advance CIE-type review would help already overburdened Scientific and Statistical Committees to focus the scopes of their own reviews of IEA products. For IEA products intended to support non-fisheries decisions, a CIE-type review would be essential to address managers' concerns about how much weight decision-making or long-term planning should give to a new science process and its products.

CONCLUSION

For management processes to embrace ecosystem-based management, they require not just scientific information about the state of an ecosystem and its component parts, but also analyses of how the laws and policies that affect the ecosystem interact with each other and steer the management of the ecosystem. The Pacific Council is using its fishery ecosystem plan development process to gain a better understanding of the California Current Ecosystem, and to more clearly assess how its management programs interact with each other across its fishery management plans. The work of developing the fishery ecosystem plan will ensure that the dialogue concerning the best available science for use in fisheries management includes increasing attention to ecosystem science. While the Pacific Council's efforts necessarily focus on fisheries, not the full range of human activities within the ecosystem, its work can serve as a solid base for more broad-scale efforts to make ecosystem-based management a reality within the California Current Ecosystem. As the stewards of living marine resources, the Pacific Council can set the tone for a deeper regional understanding of the linked fortunes of sustainable human activity within the marine environment and the sustained long-term status of the marine ecosystem. For the Pacific Council and other policy-making bodies to make more full use of information derived from the California Current IEA requires policy analysts and legal scholars to join the IEA discussion and to assess how the laws they implement apply specifically within the California Current Ecosystem, and within an intellectual environment of new and changing scientific information.

ACKNOWLEDGEMENTS

I am grateful to David Fluharty, Isaac Kaplan, Frank Lockhart, and the members of the Pacific Fishery Management Council's Ecosystem Plan Development Team for many useful conversations on issues discussed within this paper. I am also grateful to the four anonymous reviewers for their insightful comments on the manuscript.

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ECOSYSTEM MODELING FOR THE CALIFORNIA CURRENT INTEGRATED ECOSYSTEM ASSESSMENT

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EXTENDED ABSTRACT

Marine ecosystem assessment is an ambitious goal that requires tools to synthesize a broad range of information related to ecological, fishery, and economic factors. Contributors to the California Current Integrated Ecosystem Assessment (Levin et al. 2009; Levin and Schwing 2011) have applied a range of statistical and simulation approaches, including qualitative modeling, time series analysis, food web models, and end-to-end ecosystem models. End-to-end ecosystem models are one type of tool that allows strategic planning, evaluation of management actions, and risk assessment (Plagányi 2007; Rose et al. 2010; Fulton et al. 2011).

At the CalCOFI conference I discussed the role of a spatially explicit Atlantis end-to-end simulation model. A brief overview of the Atlantis code base is available at http://atlantis.cmar.csiro.au/ and in Fulton et al. 2011; and an overview of the California Current application is available at http://www.nwfsc.noaa.gov/publications/documents/atlantis_ecosystem_model.pdf as well as in recent publications (Horne et al. 2010; Kaplan et al. 2011). I then presented two case studies, and a recent report made to the Pacific Fishery Management Council that included results from Atlantis and other Integrated Ecosystem Assessment tools.

The first case study (published as Kaplan et al. 2012) quantified the effects on ecosystem health that can be attributed to individual fishing fleets and gears, and their interactions. In the context of ecosystem-based fisheries management, the goal was to consider the indirect and cumulative effects of fishing, in addition to estimating direct fishing mortality. Simulations testing the effects of single fleets suggested that three groundfish gears primarily had direct impacts on harvested species, while effects from the pelagic purse seine fleet extended through predator-prey links to other parts of the food web. Our simulations identified six fleets that caused the bulk of negative impacts on a set of ecosystem health metrics. Specific fleets impacted different aspects of ecosystem health, but most effects were simply additive—the combined effect of two fleets was simply the sum of the individual fleets' effects. The analyses offer one way to sharpen the focus of ecosystem-based fisheries management in the California Current, emphasizing impacts and interactions of particular stressors.

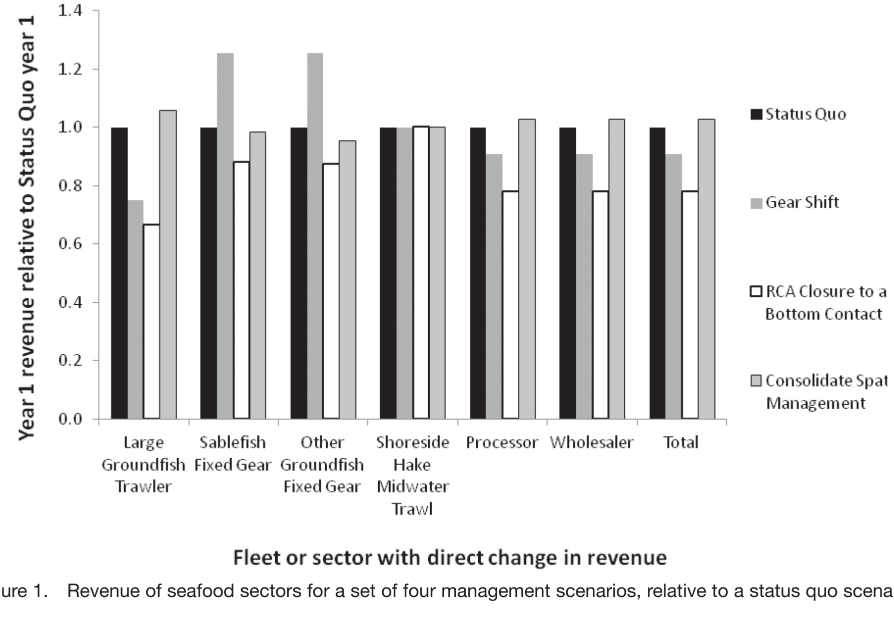

Figure 1. Revenue of seafood sectors for a set of four management scenarios, relative to a status quo scenario.

The second case study (published as Kaplan and Leonard 2012) combined the Atlantis ecosystem model with an economic model (IO-PAC) (Leonard and Watson 2011) to trace how changes in fishery management and seafood landings impact the broader economy. The potential effects of broad fisheries management options were explored, including status quo management, switching effort from trawl to other gears, and spatial management scenarios. Relative to the status quo, the other scenarios here involved short-term ex-vessel revenue losses, primarily to the bottom trawl fleet (fig. 1). Other fleets, particularly the fixed gear fleet that uses pots and demersal longlines, gained revenue in some scenarios. Income impacts on the broader economy mirrored the revenue trends. The long-term forecast (15 years) from the Atlantis ecosystem model predicted substantial stock rebuilding, increases in fleet catch, and roughly a 25% increase in income and jobs that derive directly and indirectly from fisheries. Linking the ecological and economic models allowed evaluation of fishery management policies using multiple criteria, and comparison of potential economic and conservation trade-offs that stem from management actions.

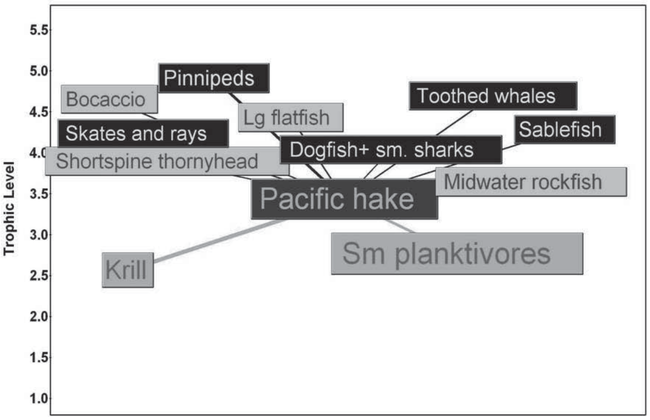

Figure 2. Primary food web of adult Pacific hake, *Merluccius productus*. Taken from http://www.pcouncil.org/wp-content/uploads/H1b_ATT1_DD_CA_ECO_NOV2011BB.pdf. Major prey items of Pacific hake are krill and small planktivores, and other light-colored boxes are both prey and predators of hake. Dark-colored boxes are major predators of hake. Position in the y-direction is approximately related to trophic level. Size of the box is related to biomass of the group. Links between boxes represent links in the food web; most diet information depicted here involves adult predators. The diagrams exclude minor prey items and predators that inflict small proportions of predation mortality on the focal group. Food web visualization software (Ecoviz 2.3.6) was provided by Dr. Kerim Aydin, NOAA AFSC.

Finally, at the CalCOFI conference I discussed ongoing ecosystem modeling efforts and needs within the Integrated Ecosystem Assessment. These efforts include improved modeling of fleet dynamics for the groundfish fleets, simulating climate change and ocean acidification, and the desire to extend the geography of the Atlantis model south of Point Conception. I also discussed one recent presentation of ecosystem information to the Pacific Fishery Management Council, using Atlantis and other tools to highlight climate and trophic effects on harvested species (fig. 2). Such efforts are a key part of the Integrated Ecosystem Assessment, and seek to distill results from several tools into forms relevant to decisions for managed species.

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OVERVIEW OF ECOSYSTEM-BASED MANAGEMENT AND INTEGRATED ECOSYSTEM ASSESSMENTS

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EXTENDED ABSTRACT

The rationale, justification, and simple definition of ecosystem-based management (EBM) are noted. This EBM policy and technical background forms the context for a definition, delineation, and evaluation of Integrated Ecosystem Assessments (IEAs). The challenges associated with IEAs, particularly regarding their multiple roles or overlap with other efforts, are duly noted. In lieu of specific technical details and examples for each element of an IEA, a conceptual treatment of each facet of the six step IEA process is provided. A schema is highlighted to denote the important principles of applying IEAs. The contribution of scientific endeavors (modeling, indicators, thresholds, assessment, risk analyses, and management simulation evaluations), stakeholder outreach, and monitoring are mapped to the IEA process, identifying key roles each can play in the success of an IEA. Important lessons learned and affirmation from international arenas adopting this approach, as well as identification of important steps remaining delineate what is still a nascent, but certainly a maturing development of IEAs.

EXTENDED INFORMATION

There are a plethora of policy documents now espousing ecosystem-based management (EBM) as a preferred way to manage the natural resources found in the oceans. The national ocean policy of 2010 states that EBM is the guiding principle for ocean resource management in the United States. One of the key ways to implement EBM is to execute Integrated Ecosystem Assessments (IEAs). We note that IEAs are a tool and process to accomplish EBM. Adapting the Levin et al. diagram (fig. 1), we note the adaptive nature of IEAs when implemented, and also the importance of involving—often and early—a wide range of stakeholders in the process.

From the scoping and involvement with stakeholders, key storylines can be developed. Those can then be populated with important indicators to track. Once those indicators are initially established, a suite of analytical approaches (modeling, indicators, thresholds, assessment, risk analyses, and management simulation evaluations [MSE]) can be employed in an IEA process to assess ecosystem status relative to the stated EBM goals.

Multiple facets of outreach are required in all areas of the IEA process. Adopting webpages, regular reports, short "glossies," and a suite of meetings are all necessary to usefully conduct interaction among all interested parties. This facet of IEAs should not be underestimated in terms of time or value to the process.

Some of the key lessons learned in the nascent development of IEAs thus far include:

- Multidisciplinary expertise essential
    - Jacks of all trades helpful (i.e., jargon-swapping capabilities)
- Communicate
    - Internally, externally, frequently
- Set target timelines and goals
    - Keep up the full court press

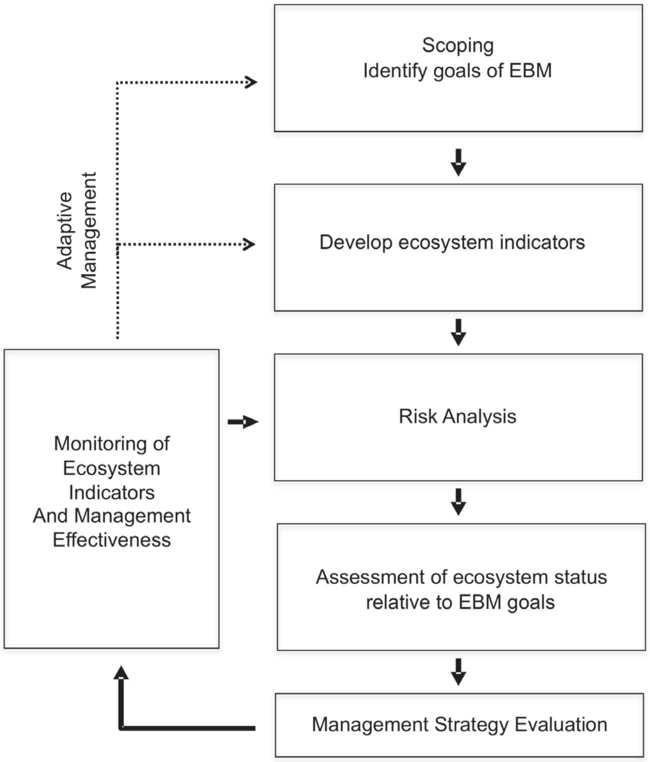

Figure 1. A modified Levin diagram of the IEA process.

- Ensure elements of an IEA have champions
  - Give ownership
- Not every bit of science or research, although inherently may be of interest, is germane for IEAs
  - Needs to map onto IEA process (i.e., the Levin diagram; fig. 1)
- International vetting and best practices testing is ongoing and useful
  - EBM is now being implemented…all around the world
- There is a strong need to cull from among myriads of indicators

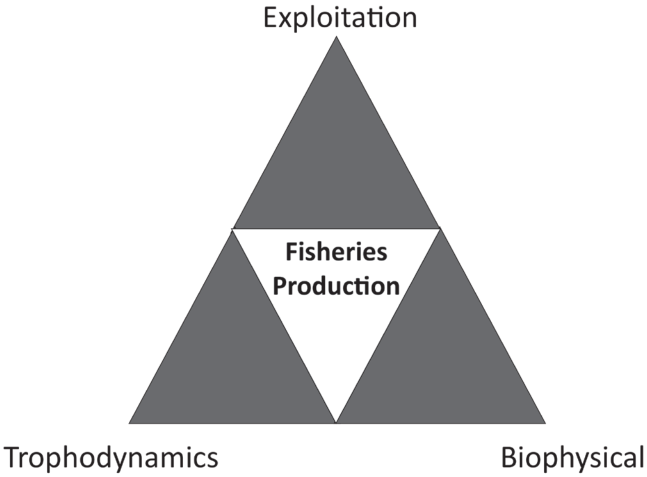

Figure 2. The triad of drivers, indicating the overlap of processes and the need for adequate and pertinent indicators.

- For indicators to be useful they need to be:
  - Integrative
  - Aggregative
  - Relevant
  - Multidisciplinary
  - Representative
  - Based on well-established data series
  - Defensible, as likely to be used in further research and management thresholds
  - All denoting the need to map back to a storyline (fig. 2)
- For modeling and analytical efforts
  - Multi-model inference preferred
  - MSE and testing required
  - Match model type with appropriate model use
  - Rigor up front helps confidence in outputs

To conclude, some of the key lessons learned from the beginnings of implementing IEAs highlight the need for continued and ongoing scoping sessions. Some of the key analytical needs remaining are establishing pressure-response thresholds used for decision criteria among indicators, as well as multivariate integration. Operating models to match ocean and human aspects of ecosystems and management simulations (MSE) need continued development. Risk assessment methods and applications, even qualitative approaches, will continue to emerge in the implementation of IEAs.

As EBM is implemented in ocean use management, IEAs will be an important tool and process to do so.

Part III

SCIENTIFIC CONTRIBUTIONS

THE ICHTHYOPLANKTON OF KING HARBOR, REDONDO BEACH, CALIFORNIA 1974–2009

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ABSTRACT

We report on twelve larval fish taxa, plankton volume, and total larvae caught in monthly ichthyoplankton tows in King Harbor, Redondo Beach from 1974–2009. Plankton volume, total larvae, and all but three taxa significantly declined throughout this study. Larval declines were primarily correlated with plankton volume and negatively correlated with a rise in sea surface temperature (SST). Taxa that did not decline were gobies and *Hypsypops rubicundus*. Localized processes, red tides, and other episodic events appeared to be associated with annual failures in larval production. With the exception of negative correlations with SST, oceanographic metrics (MEI, PDO, NPGO, NPI, and CUI) were not correlated with larval catch for individual taxa. Instead, SST, CUI, and MEI may be explanatory for the decline in plankton volume. Plankton volume was a potential major driver in the overall decline in ichthyoplankton observed during this study.

INTRODUCTION

While decades of research exist on the ichthyoplankton of the California Current and associated processes, by comparison, studies of the nearshore ichthyoplankton of the Southern California Bight are limited spatially, temporally, and taxonomically (Moser and Watson 2006) with some notable exceptions (Lavenberg et al. 1986; Moser and Watson 1990; McGowen 1993). Studies of the nearshore ichthyoplankton assemblages of the Southern California Bight have primarily focused on the effects of once-through-cooling associated with coastal generating stations and typically have been conducted over relatively short temporal scales and limited taxonomic categories (Schlotterbeck and Connally 1982; Barnett et al. 1984; Jahn and Lavenberg 1986; Walker et al. 1987; Watson 1992). These coastal generating station-funded surveys highlighted the importance of how this assemblage has changed since the 1970s.

The period between the initial studies in the 1970s and early 1980s and more recent times (2000s) has been punctuated by profound oceanographic variability (Bograd and Lynn 2003). Perturbations in the Southern California Bight oceanography include at least one large oceanographic regime shift ca. 1976–77 (Miller et al. 1994), a globally significant El Niño ca. 1982–83 (Alheit and Bakun 2010), a dramatic fluctuation in the ENSO cycle 1997–99 (Schwing et al. 2000), delayed upwelling and anomalously warm waters without an El Niño signature in 2005 (Pierce et al. 2006; Schwing et al. 2006), and a recent period of remarkably cool waters in the Southern California Bight (Bjorkstedt et al. 2010). Many of these patterns were decoupled from the Pacific Decadal Oscillation (PDO). Di Lorenzo et al. (2008) found the PDO correlated only with sea surface temperature south of 38°N, while the North Pacific Gyre Oscillation (NPGO) significantly related to most productivity measures (e.g., nutrients, chlorophyll *a*) south of 38°N. While these oceanic climate indices are generally applicable to the California Current, most of the United States portion of the Southern California Bight inshore of the Channel Islands is largely dominated by the California Countercurrent (Hickey 1992; Hickey 1993; Bograd and Lynn 2003; Di Lorenzo 2003). The interannual variability in the strength of the California Countercurrent has been previously linked to recruitment strength in the area (Selkoe et al. 2006; Selkoe et al. 2007). Undoubtedly fish recruitment is linked to the larval pool.

The PDO, NPGO, and coastal indices (Di Lorenzo et al. 2008; Parnell et al. 2010) recorded a substantial shift in oceanographic conditions circa the mid-1970s that resulted in a transition to a predominantly warmer, nutrient-deficient regime in the SCB. Since this transition, the coastal fauna has witnessed substantial changes in abundance and composition that transcends taxonomic groups (Roemmich and McGowan 1995; Sydeman et al. 2001; McGowan et al. 2003; Sydeman et al. 2009; Parnell et al. 2010; Miller et al. 2011). Corresponding changes in the nearshore ichthyoplankton have yet to be described, although they are expected given the consistency across taxonomic groups in the juvenile and adult stages. Such analyses, however, are hampered by the triennial sampling frequency used by the California Cooperative Oceanic Fisheries Investigation during the 1970s, which limited its resolution to detect the mid-1970s shift in ichthyoplankton. Therefore, the novelty of the King Harbor series (Stephens et al. 1994) becomes magnified as it stands as the only long-term record available to document a shift in the ichthyoplankton associated with the previously discussed regime shift. Considering this research, we hypothesize that there has been a long-term decline in nearshore ichthyoplankton productivity over the last four decades.

Santa Monica Bay is the most northern semi-enclosed bay in the Southern California Bight, featuring a complex physical oceanography. The major currents affecting the bay are the northwestern flow of the California Current from the Santa Barbara Channel and the Southern California Countercurrent from the southeast (Nezlin et al. 2004). Both of these currents are seasonal and influence the bay through complex cyclonic eddies as they move offshore past the Malibu and Palos Verdes headlands (DiGiacomo and Holt 2001). It features three submarine canyons that intersect a relatively long shelf, the most dramatic of which is the Redondo Submarine Canyon terminating in Redondo Beach proximate to King Harbor (Hickey 1993), the location of the Redondo Beach Generating Station which withdraws and discharges water near the mouth of the harbor with another independent intake located deeper within the harbor (Stephens et al. 1994) (fig. 1). As a result of the proximity of the canyon head to the shore, both King Harbor and the Redondo Pier have experienced devastating storm destruction from wave action since their construction. The heavy winter storms of 1983 and 1988 were the most recent examples of these episodic events. Following the 1988 storm events, the breakwaters were rebuilt and strengthened in 1989, after which the marina was dredged. King Harbor has been the location of red tides that occur in Santa Monica Bay (Somner and Clark 1946), which were absent from the early 1970s until 1995 (Gregorio and Pieper 2000). In the enclosed embayment, the red tides can cause anoxia and associated fish and benthic organism kills as were observed in 2005, when a red tide persisted along the southern California coastline for most of the summer and fall (Shipe et al. 2008).

The ichthyofauna of King Harbor, Redondo Beach has been studied intensively and continually since 1974 (Terry and Stephens 1976; Ellison et al. 1979; Stephens et al. 1994; Pondella et al. 2002). This study has been used to document regime shifts (Stephens et al. 1994; Holbrook et al. 1997), long-term trends in ecological and fishery species (Pondella et al. 2002), El Niño Southern Oscillation effects (Stephens et al. 1994) and has been cited as a time series indicating the effects of climate change (Hughes 2000). While global climate change is a specter that lurks over our nearshore environment, the timely nature of such nearshore ichthyofauna studies are critical for the understanding of the newly implemented marine protected areas in the region as larval connectivity was a key component in the reserve network design and essential for its long-term success (Watson et al. 2010). It is within this context, monthly ichthyoplankton tows were conducted continually from 1974–2009 (Stephens et al. 1994; Stephens and Pondella 2002). We used this unique time series to examine how the nearshore larval fish assemblage has evolved over time, how these changes relate to oceanographic indices, and whether or not it is returning to its pre-1976–77 regime shift assemblage.

MATERIAL AND METHODS

From January 1974 through July 2009, monthly surface ichthyoplankton samples were conducted at two stations (1 and D) along and immediately proximate to the mouth of King Harbor, Redondo Beach (fig. 1) (Stephens et al. 1986; Stephens et al. 1994). From 1974 through 1977 only Station D was sampled. Station 1 was sampled from 1978–2009, while Station D was not sampled from 1978–80, but was sampled from 1981–2009.

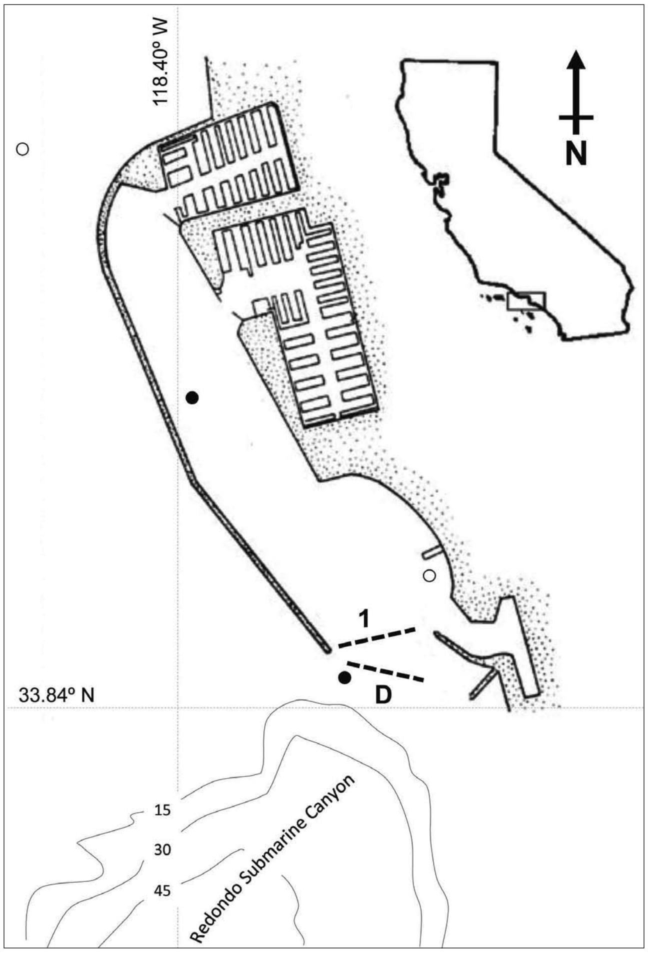

Figure 1. King Harbor, Redondo Beach, California. Location of stations 1 and D (hatched lines) where monthly nocturnal surface plankton tows were conducted from 1974–2009. Intake structures for the generating station are the solid circles, outfall structures are the open circles. Bathymetric contour intervals are shown in meters.

TABLE 1

Pearson's *r* correlation coefficients (with corresponding p-values; significant values are in bold text) for relationships between larval density, total plankton volume or specific larval taxon and various oceanographic indices including: Pacific Decadal Oscillation (PDO), multivariate ENSO index (MEI), North Pacific Gyre Oscillation (NPGO), North Pacific Index (NPI), Cumulative Upwelling Index at 33°N (CUI), and the sea surface temperature recorded at the Scripps Institution of Oceanography Pier in La Jolla, California (SST). Additionally, type of data transformation are provided for each variable.

	Catch Rank	MEI (p-value)	PDO (p-value)	NPGO (p-value)	NPI (p-value)	CUI (p-value)	SST (p-value)	Plankton Volume (p-value)	Transformation
Larvae density		–0.11	–0.10	0.09	0.19	**0.35**	**–0.45**	**0.70**	none
		(0.53)	(0.58)	(0.61)	(0.27)	**(0.04)**	**(0.01)**	**(<0.01)**	
Total plankton volume		**–0.40**	–0.18	0.20	0.22	**0.46**	**–0.65**		none
		(0.02)	(0.29)	(0.25)	(0.19)	**(0.01)**	**(<0.01)**		
Hypsoblennius sp.	1	–0.13	0.02	0.02	0.04	0.33	**–0.42**	**0.60**	sqrt
		(0.44)	(0.93)	(0.92)	(0.83)	(0.05)	**(0.01)**	**(<0.01)**	
Paralichthys/Xystreurys sp.	2	0.13	0.22	–0.18	0.00	0.07	–0.24	**0.46**	Log (x+1)
		(0.44)	(0.20)	(0.28)	(1.00)	(0.68)	(0.15)	**(0.01)**	
Hypsypops rubicundus	3	0.18	0.00	0.02	0.06	0.09	0.26	–0.28	square root
		(0.29)	(0.99)	(0.92)	(0.72)	(0.59)	(0.13)	(0.09)	
Genyonemus lineatus	4	–0.08	0.05	–0.10	0.06	0.26	**–0.60**	**0.62**	third root
		(0.66)	(0.79)	(0.58)	(0.74)	(0.13)	**(<0.01)**	**(<0.01)**	
Gobiidae A/C complex	5	0.26	0.25	–0.19	–0.09	0.15	–0.23	**0.37**	square root
		(0.12)	(0.14)	(0.28)	(0.59)	(0.38)	(0.18)	**(0.03)**	
Engraulis mordax	6	0.05	0.08	–0.04	–0.01	0.13	**–0.44**	**0.61**	Log (x+1)
		(0.76)	(0.64)	(0.80)	(0.97)	(0.44)	**(0.01)**	**(<0.01)**	
Lythrypnus sp.	7	0.27	0.32	–0.27	–0.02	0.28	–0.01	0.09	Log (x+1)
		(0.11)	(0.06)	(0.11)	(0.92)	(0.10)	(0.95)	(0.61)	
Seriphus politus	8	–0.07	0.08	0.07	0.02	0.30	**–0.57**	**0.74**	fourth root
		(0.68)	(0.63)	(0.70)	(0.92)	(0.08)	**<0.01**	**(<0.01)**	
Paraclinus integripinnis	9	0.19	0.24	–0.24	0.05	0.08	–0.03	**0.38**	Log (x+1)
		(0.28)	(0.16)	(0.17)	(0.76)	(0.64)	(0.89)	**(0.02)**	
Rhinogobiops nicholsii	10	–0.02	–0.08	0.18	0.04	**0.33**	–0.26	**0.46**	Log (x+1)
		(0.90)	(0.66)	(0.29)	(0.82)	**(0.05)**	(0.13)	**(0.01)**	

Considering the proximity of these stations and incomplete sampling over the entire time series, the surface night samples at Station 1 and Station D were combined to generate the 1974–2009 time series data set. Two minute plankton tows were conducted with a 333-µm mesh standard conical meter net. Samples were immediately preserved in a 5% formaldehyde-borate solution. The displacement volume of plankton was determined in the lab. All fish larvae were sorted, counted, and identified to the lowest possible taxon (Moser 1996) and recorded by larval stage (e.g., yolk sac, preflexion, flexion, postflexion). To reduce the influence of the larval production of the harbor and associated localized processes, yolk sac and preflexion larvae were not used in these analyses; all other larval stages were combined. Larval catch (# of individuals) and plankton volume (ml) was standardized to filtered water volume (1000 m^3) using a TSK flowmeter from January 1974–July 2008 and a General Oceanics Mechanical flowmeter (Model 2030R), thereafter. We also examined the following environmental conditions relevant to the study area, each represented by various indices including: Pacific Decadal Oscillation (PDO) (Mantua et al. 1997), multivariate ENSO index (MEI) (Parnell et al. 2010), North Pacific Gyre Oscillation (NPGO) (Di Lorenzo et al. 2008), North Pacific Index (NPI) (Trenberth and Hurrell 1994), Cumulative Upwelling Index at 33°N (CUI) (Schwing et al. 1996), and the sea surface temperature recorded at the Scripps Institution of Oceanography Pier in La Jolla, California (SST) (Shore_Station_Program 2011).

For statistical analyses, we calculated annual mean densities and standard errors of late-stage larvae (#/1000 m^3) and plankton volume (ml/1000 m^3) by averaging across processed tows for each calendar year. In order to assess the relationship of the larval community among years, analyses were conducted in PRIMER (PRIMER-E_ Ltd. 2007) using the following routine. The annual mean density of larval taxa which comprised the top 99% of the overall cumulative catch were log (x+1) transformed and a Bray-Curtis similarity index was calculated. We ran a hierarchical cluster analysis with a SIMPROF test using 1000 permutations for the dendrogram to indicate significant group structure at a 0.05 significance level. We then used two-dimensional, non-metric multidimensional scaling (nMDS) to further examine segregation among years.

To describe the stationarity of the major component's annual means over time (years) within this data set we used the multiple regression package in STATISTICA (StatSoft 2007) on the top 10 larval taxa caught in the time series, the plankton volume, and total larval density. Prior to regression analyses data were tested for normal-

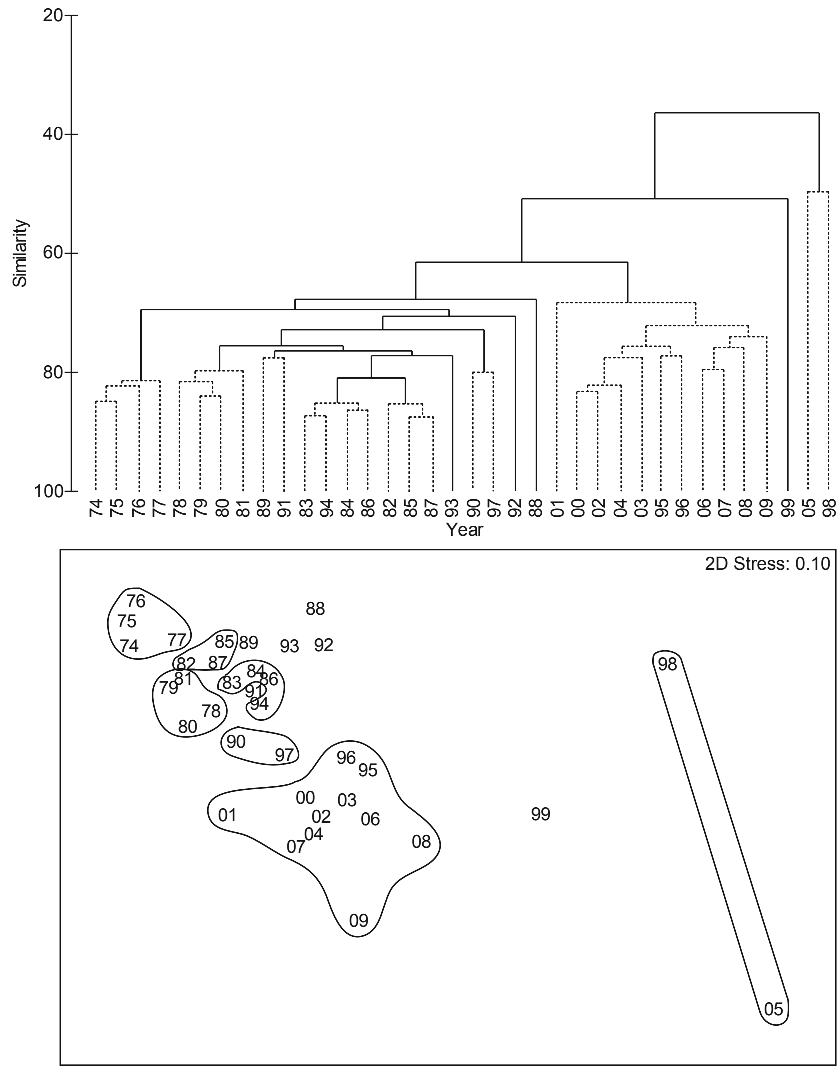

Figure 2. Bray-Curtis similarity matrix dendrogram of the annual larval community (above), dashed lines indicate groups of samples not separated (at significance level 0.05) by SIMPROF. nMDS two-dimensional ordination of the similarity matrix (below), significant clusters (as indicated by SIMPROF) are encircled with black lines. Years 89 and 91 together also form another significant cluster that was not encircled.

ity and autocorrelation. Departures from normality were tested using the Shapiro and Wilk *W* statistic in STATISTICA (StatSoft 2007), and data that were not normally distributed were transformed based upon their distribution (Legendre and Legendre 1998) (table 1). First order serial correlation was tested with the Durbin-Watson d statistic ($d_u \geq 1.52$) (Studenmund 2001) using residual analysis in R (R Development Core Team 2011). Where autocorrelation was detected, data were averaged over two-year periods, which successfully removed the serial correlation (Studenmund 2001). The normalized data were then tested for correlations with mean annual oceanic indices (MEI, PDO, NPGO, NPI, CUI and SST) and plankton volume using Pearson's *r* correlation coefficient in R (R Development Core Team 2011). Data that could not be transformed to a normal distribution were not further analyzed. To illustrate temporal (annual) patterns, untransformed data are presented with trend lines fitted to them. Two important harvested taxa (*Paralabrax clathratus* and *Sardinops sagax*) were also included, however they were not treated in the correlation analyses due to model assumption violations.

RESULTS

From 1974–2009, 640 (annual mean = 17.77, median = 18) ichthyoplankton tows at Stations 1 and D (fig. 1) were completely processed and included in these analyses. Larvae (N = 88,208) comprised 99 taxa of which 31 represented 99% of the standardized catch. The larval community changed appreciably over the study period from the 1974–77 assemblages to the current condition. The cluster analysis with SIMPROF test identified 12 significant clusters of years (fig. 2). Clusters tended to form chronologically, demonstrating a general trend of larval

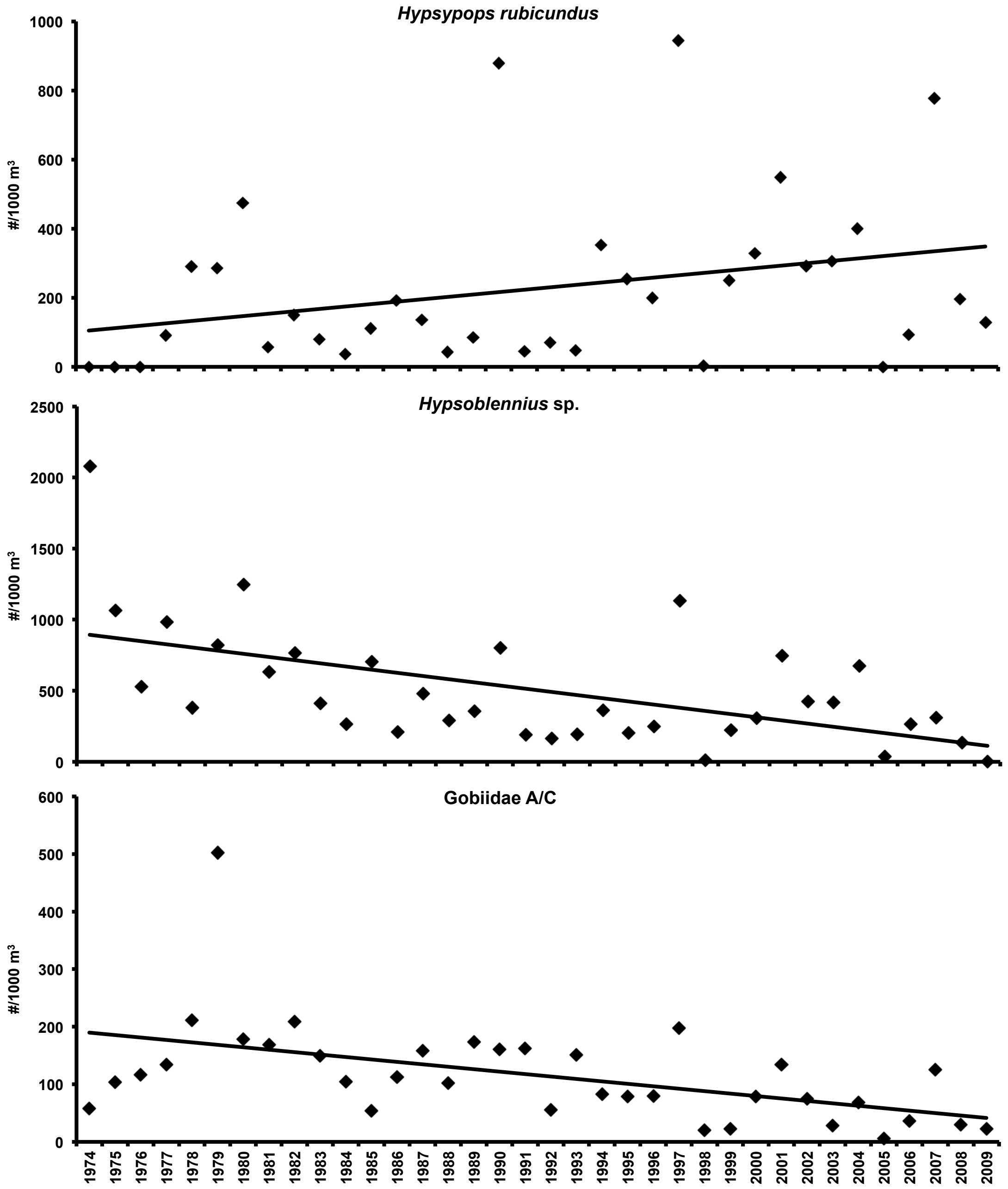

Figure 3. Larval density (# / 1000 m^3) of *Hypsypops rubicundus*, *Hypsoblennius* sp. and Gobiidae A/C complex from 1974–2009.

community change from the 1974–77 cluster to the cluster containing the most recent years. Three years (1998, 1999, and 2005) lay outside this trend, being only approximately 50% or less similar to the rest of the time series.

Most taxonomic groups demonstrated a significant decline in abundance over the study and/or became virtually absent from the larval assemblage by the mid-1990s. The most abundant larval taxon, *Hypsoblennius* sp., started the time series at slightly above 2000 larvae / 1000 m^3 in 1974 and had a long-term continual significant decline (R = 0.560, $F_{1,34}$ = 15.5, $p < 0.001$), becoming rare (3.7 larvae per 1000 m^3) by 2009. Low *Hypsoblennius* catches were also observed in 1998 and 2005 (fig. 3; 12.2 and 38.3 larvae / 1000 m^3). A significant decline was also observed in *Paraclinus integripinnis* (fig. 4, R = 0.428, $F_{1,34}$ = 7.64, p = 0.009) and in the Gobiidae A/C complex (*Clevelandia ios*, *Ilypnus gilberti* and *Quietula y-cauda*; fig. 3, R = 0.576, $F_{1,34}$ = 16.9, $p < 0.001$). The *Paralichthys/Xystreurys* species complex also declined significantly (R = 0.484, $F_{1,34}$ = 10.4, p = 0.003) with very few larvae captured from 1995–2009 (fig. 5). This second pattern was also observed in both sciaenid species, which declined precipitously (*Genyonemus lineatus*: R = 0.869, $F_{1,34}$ =

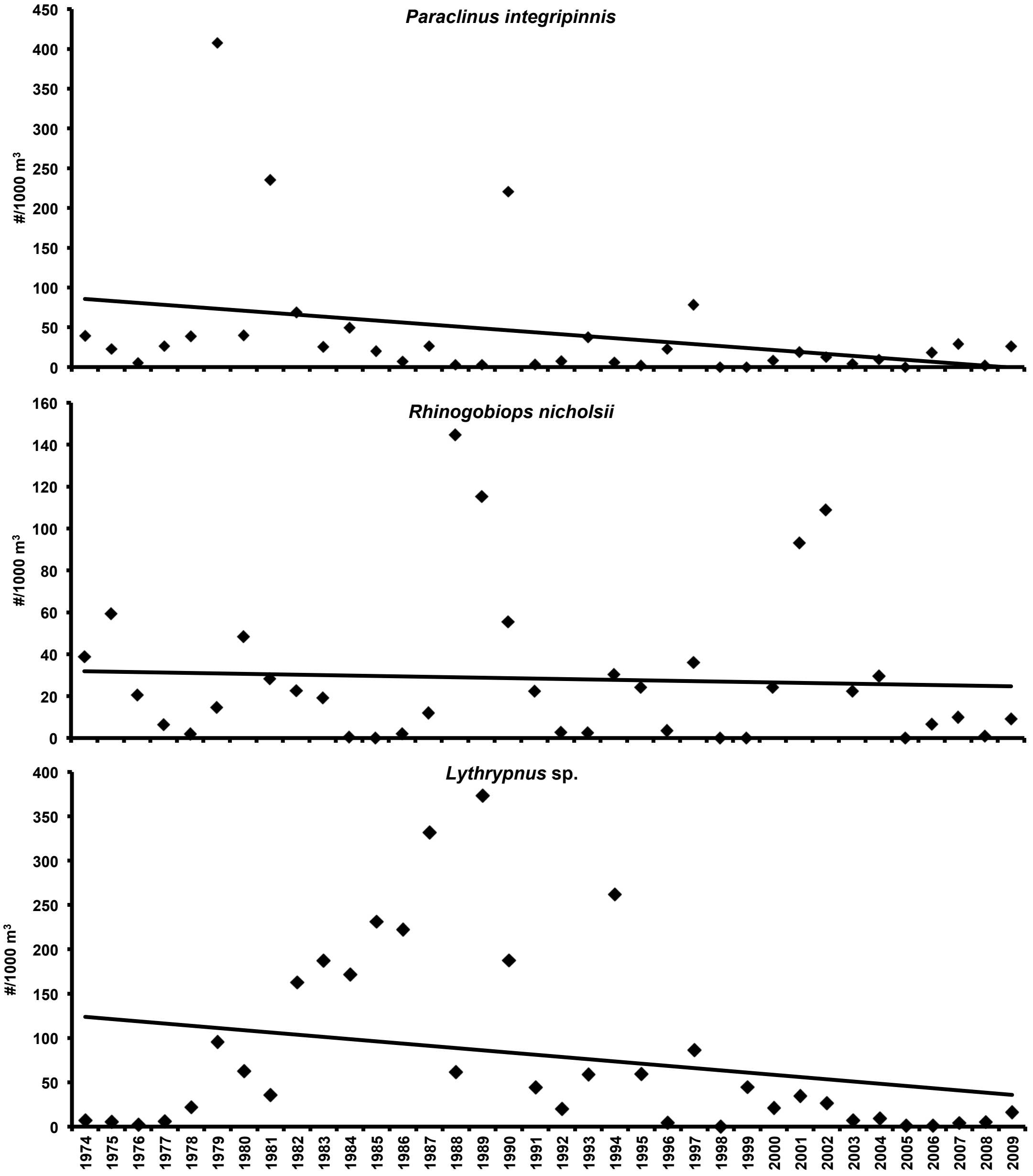

Figure 4. Larval density (# / 1000 m³) of *Paraclinus integripinnis*, *Rhinogobiops nicholsii* and *Lythrypnus* sp. from 1974–2009.

104.8, $p << 0.001$; *Seriphus politus*: 0.868, $F_{1,34} = 103.5$, $p << 0.001$). By 1995, *G. lineatus* were virtually absent from the larval assemblage and *S. politus* larvae all but disappeared in 1993 (fig. 5). This pattern of a significant decline and then near-absence by the mid-1990s was also observed in *Engraulis mordax* (fig. 6; $R = 0.867$, $F_{1,34} = 102.7$, $p << 0.001$), *Sardinops sagax* and *Paralabrax clathratus* (fig. 6).

A few taxa deviated from this general pattern of decline. The catch of *Hypsypops rubicundus* larvae was variable, did not exhibit first-order serial correlation ($d_u = 2.00$, $p = 0.904$), yet significantly increased (fig. 3; $R = 0.353$, $F_{1,34} = 4.8$, $p = 0.035$). No larvae were caught from 1974–76 or in 2005, and only 2.8 larvae / 1000 m³ were caught in 1998. *Lythrypnus* sp. larvae also were absent in the early 1970s, but built to a peak in 1989 (373 larvae / 1000 m³) and then crashed by 2005 (fig. 4). A stationary, yet fluctuating time series was observed for *Rhinogobiops nicholsii* (fig. 4; $R = 0.101$, $F_{1,16} = 0.16$, $p = 0.691$). In fact, the annual catches of *R. nicholsii* exhibited first-order serial correlation ($d_u = 1.21$, $p = 0.002$).

Overall larval density (fig. 7; $R = 0.637$, $F_{1,34} = 23.3$, $p < 0.001$) and plankton volume (fig. 7; $R = 0.731$, $F_{1,16} = 23.3$, $p < 0.001$) significantly declined throughout the study period. Total larval density was correlated

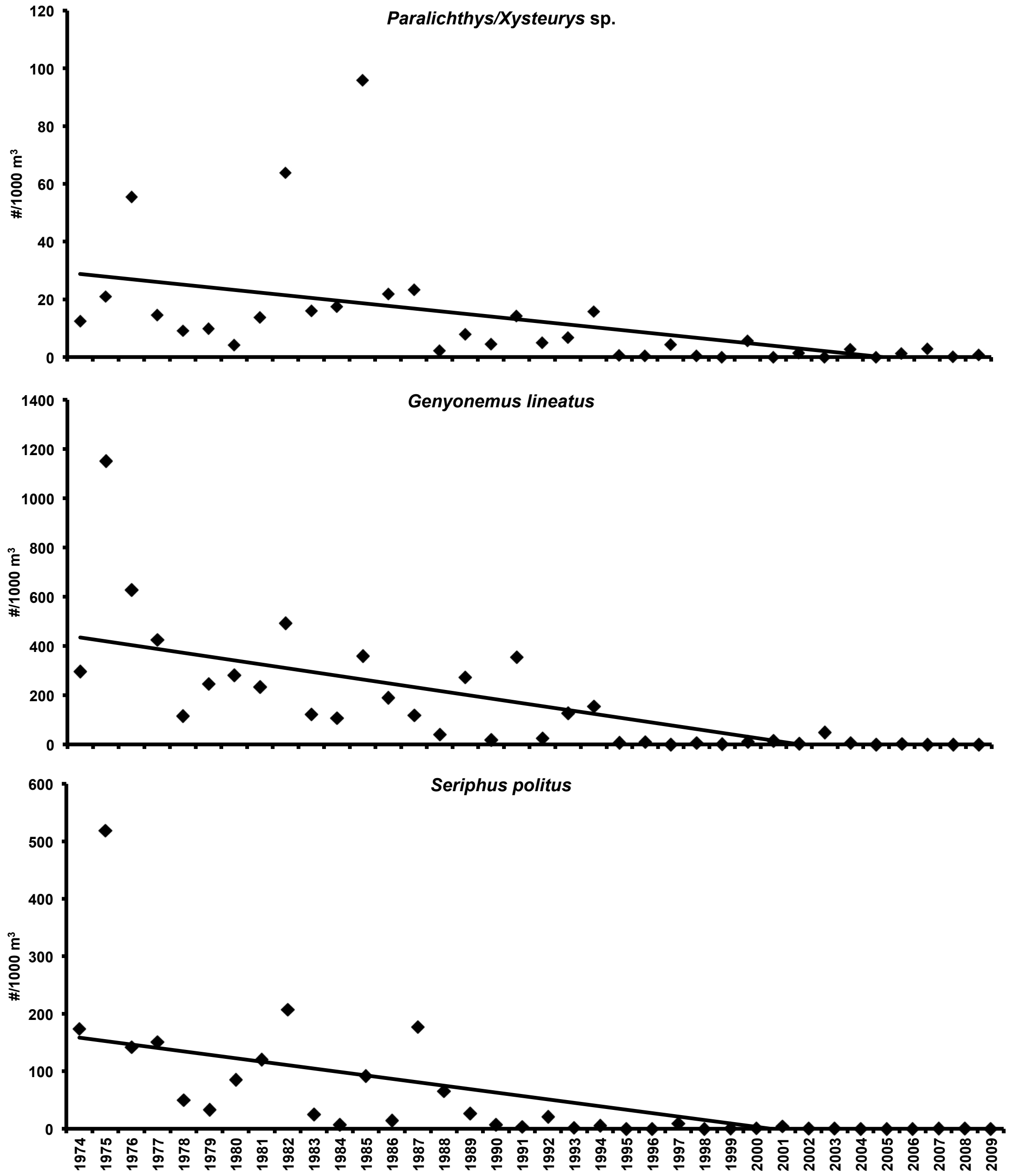

Figure 5. Larval density (# / 1000 m^3) of *Paralichthys/Xystreurys* sp., *Genyonemus lineatus* and *Seriphus politus* from 1974–2009.

with the plankton volume ($R = 0.695, p < 0.001$). Larval catch peaked in 1975 (3579 larvae / 1000 m^3) with a nadir in 2005 (84 larvae / 1000 m^3). After the 1970s, the highest larval catch was in 1997 (2538 larvae / 1000 m^3) followed by the second lowest catch in 1998 (59 larvae / 1000 m^3). While the decline in plankton volume followed a cyclical pattern resulting in first-order serial correlation ($d_u = 1.23, p = 0.014$), the overall pattern may also be described by an inflection during the early 1990s. The lowest plankton volume reported was in 1993 (52 ml / 1000 m^3) down from a high in 1975 (407 ml / 1000 m^3). From 1991 through 2009, the time series has some variation but is essentially stationary, remaining at approximately 25% of what was observed in 1974 (359 ml / 1000 m^3) and 1975 (407 ml / 1000 m^3) and approximately 50% of the plankton volume from 1976–90 (mean = 208 ml / 1000 m^3). By 2009, we captured 15% (194 larvae / 1000 m^3) of the larvae compared to the peak in 1975; similarly, there was a 70% decline in plankton volume between these years (407 ml / 1000 m^3 and 122 ml / 1000 m^3, respectively). Overall larval catch and plankton volume were positively correlated with the CUI (larvae: $r = 0.348, p = 0.037$; volume: $r = 0.460, p = 0.005$) and negatively correlated with SST

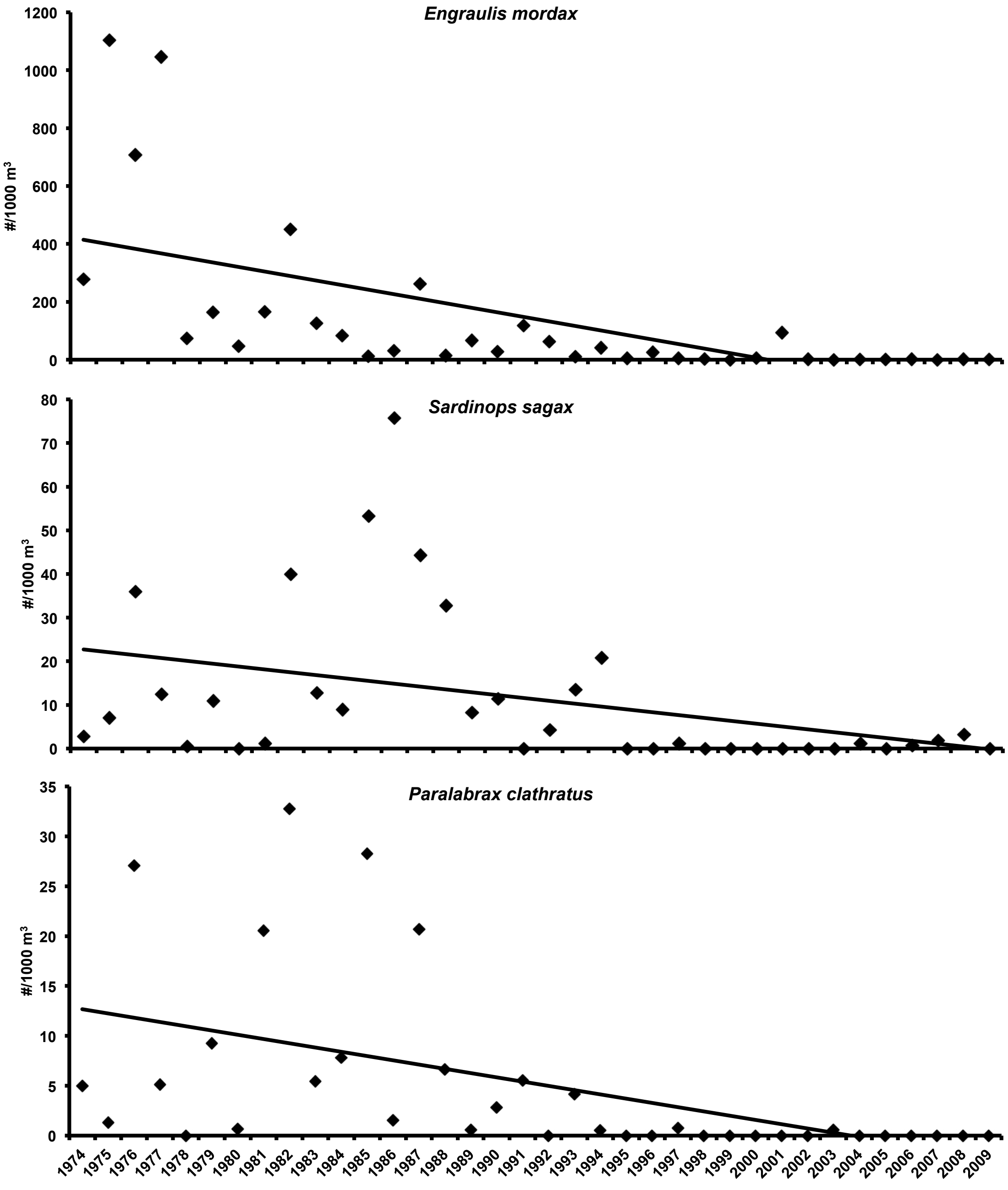

Figure 6. Larval density (# / 1000 m^3) of *Engraulis mordax*, *Sardinops sagax* and *Paralabrax clathratus* from 1974–2009.

(larvae: $r = -0.453$, $p = 0.005$; volume: $r = -0.645$, $p < 0.001$). Plankton volume was also negatively correlated with the MEI ($r = -0.399$, $p = 0.016$), the only correlation with a climate index detected.

The response of various taxonomic groups to the oceanographic metrics varied appreciably, although with the exception of correlations with SST and CUI, oceanographic metrics (MEI, PDO, NPGO, and NPI) were not correlated with larval catch for individual taxa (table 1). *Hypsoblennius* catches were negatively correlated with SST (table 1; $r = -0.420$, $p = 0.011$). Sea surface temperature was also negatively correlated with the annual larval density of the two sciaenids, *Genyonemus lineatus* ($r = -0.602$, $p < 0.001$) and *Seriphus politus* ($r = -0.569$, $p < 0.001$). *Paralichthys/Xystreurys*, *Hypsypops rubicundus*, Gobiidae A/C, *Lythrypnus* sp., and *Paraclinus integripinnis* larval catches did not correlate with the oceanographic metrics (table 1). Only *Rhinogobiops nicholsii* was correlated with the CUI ($r = 0.329$, $p = 0.050$). All taxonomic categories were correlated with plankton volume except for *Hypsypops rubicundus* and *Lythrypnus* sp.

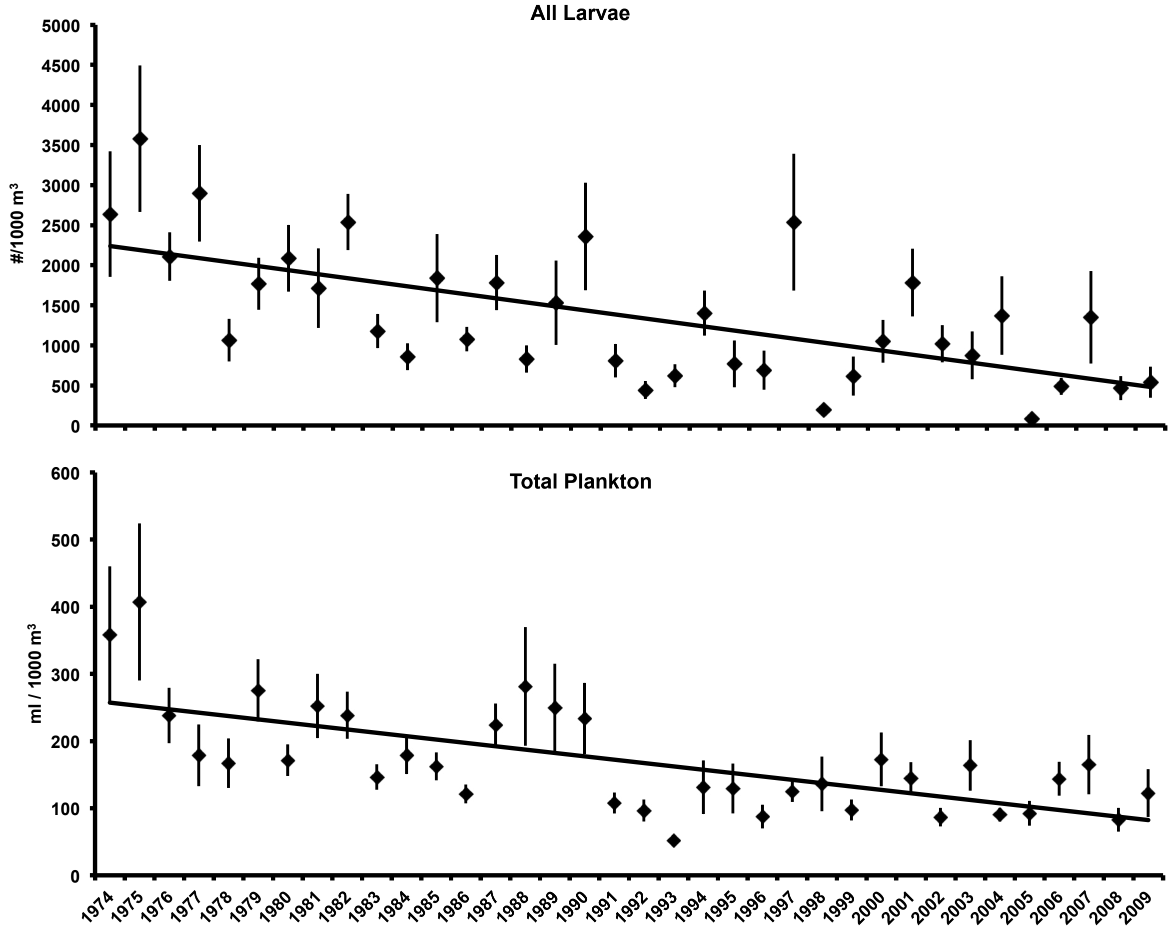

Figure 7. Total larval density (# / 1000 m³) and plankton volume (ml / 1000 m³) from 1974–2009. Error bars represent standard error.

DISCUSSION

The long-term trajectory of the ichthyoplankton assemblage of King Harbor is one of declining abundance with some aberrant annual assemblages (1998, 1999 and 2005), but no tendency toward returning to its pre-1976–77 condition (fig. 2). The 1998 and 1999 assemblages appeared to have been affected by the strength of 1997–99 ENSO, while previous ENSO effects were muted. The most unusual year was 2005, which was characterized by low larval densities and plankton volumes. We do not measure the volume of phytoplankton but, while not directly tested, we hypothesize that the unusually strong red tide that year (Shipe et al. 2008) resulted in low larval success. This poor larval year class may have been a result of larval mortality and/or reduced spawning success. One hint of the latter is the poor performance by nesting species (*Hypsypops rubicundus* and *Hypsoblennius* sp., fig. 3), whose larval catch was likely linked to nesting success.

Larval catch from these reef-nesting species (Clarke 1970; Stephens et al. 1970) was nearly synchronous after *Hypsypops rubicundus* became established on the reef in 1977. For instance, both species had peaks in catch in 1980, 1990, and 1997; minor peaks in 1994, 2001, and 2004; and poor catches in 1984, 1988, 1991–93, 1998 and 2005. While yolk-sac and preflexion larvae were excluded from the analyses, reducing the influence of localized nests, these taxa still dominated the assemblage. Thus, these patterns were indicative of regional processes and/or they exhibited larval retention. *Hypsypops rubicundus* was the only taxon that catch increased over the study period. This was due to the rarity of adults and associated larval production on the reef from 1974–76 (Stephens et al. 1986). Excluding these years, the time series was stationary from 1977–2009 ($R = 0.158$, $F_{1,31} = 0.8$, $p = 0.381$). The appearance of *H. rubicundus* after 1976 clearly supports the hypothesis of a regime shift and the northern range shift of this subtropical species (Stephens et al. 1994). However, since our data set contains only three years in the cool phase prior to the regime shift, metrics such as the PDO or NPGO do not correlate with this change, as *H. rubicundus* was still established and nesting in the harbor at the terminus of this study. In fact, *H. rubicundus* and *Lythrypnus* sp. are the only taxa we report on whose abundances are not correlated with one of the studied metrics (table 1). *Hypsoblennius* sp. declined significantly, and while this was negatively correlated with SST and positively correlated with plankton volume (table 1), we note that the harbor has not been dredged since 1989 and the inner reefs have been silting in, reducing blenny habitat (Pondella personal observation). Nonetheless, *Hypsoblennius* was declining prior to 1989. Thus, multiple factors affect the success of nesting species in King Harbor.

The reef gobies, *Lythrypnus* sp. and *Rhinogobiops nicholsii*, did not have a significant change over time, but followed very different trajectories. *Rhinogobiops nicholsii* catch correlated with upwelling and plankton volume, which were also correlated with each other (table 1). *Lythrypnus* sp. started the time series like *Hypsypops rubicundus*, another indication of a regime shift with the infusion of this southern group. The cause of its decline after the peak in 1989 seems more mysterious, but is likely rooted in a series of poor year classes of a relatively short-lived species. We also observed a decline in *Paraclinus integripinnis*, another small, cryptic reef species (fig. 4). With the exception of *R. nicholsii*, all the small reef associated fishes (*Hypsoblennius* sp., *Lythrypnus* sp., and *P. integripinnis*) declined.

All other taxa either significantly declined or became absent during this study. All of the commercial and recreational species (figs. 5 and 6) followed a similar pattern of variable but declining larval catches through the 1990s, with little or no catch through the remainder of the time series. All of these declines were correlated with plankton volume, with *Seriphus politus*, *Genyonemus lineatus*, *Engraulis mordax* and the *Paralichthys/Xystreurys* group also negatively correlated with SST (table 1). In the laboratory, both *G. lineatus* and *Paralichthys californicus* eggs exhibited poor hatching success at water temperatures > 20°C, so perhaps the increasing SST contributed to these declines (Gadomski and Caddell 1996). Recent reports for *S. politus*, *G. lineatus*, *Paralabrax clathratus*, and *P. nebulifer* have demonstrated a similar decline in the adult populations of these fishes (Erisman et al. 2011; Miller et al. 2011) suggesting that poor larval production was a factor in these declines. This pattern also appears be occurring with one of the two primarily pelagic species in our study, *Engraulis mordax*. Commercial landings have declined since 2001 (CDFG 2011) along with rather steady declines in larval catches in the core CalCOFI region since 1987, with the exception of a large single year increase in 2005 (Fissel et al. 2011). For the other pelagic species, *Sardinops sagax*, commercial landings have remained steady near their allowable harvest levels (CDFG 2011), while annual larval densities from CalCOFI sampling appear to be increasing or stable since the early 1980s (Moser et al. 2001; Moser et al. 2002). This pattern is in contradiction to the decline in larval densities we observed, however, *S. sagax* spawning has been largely occurring north of Point Conception and/or well offshore of southern California during this time period, potentially making larvae less available in our sampling area (NOAA Fisheries Resources Division: http://swfsc.noaa.gov/textblock.aspx?Division=FRD&id=16135). Overall commercial or recreational species fared far worse than non-fished species during this study with larval catches going to zero by the mid-1990s.

The Redondo Beach Generating Station withdraws and discharges cooling water at multiple locations in and around the King Harbor (Stephens et al. 1994) (fig. 1), potentially concerntrating or dispersing larvae at the sampling area. However, a previous study provided no indication that annual larval densities are influenced by annual variation in cooling water flow (Miller et al. 2009). While a significant positive correlation between annual flow rates and annual *S. politus* larval densities was observed over the entire period both data sets were available (1979–2006), this was a spurious statistical artifact of including all data (years) in the analysis. While cooling water volumes have tended to decline since their peak in 1980, with the lowest flow levels occurring after 2003 (see Miller et al. 2009; fig. 8a), if the years after *S. politus* densities declined to 0 (i.e., after 1994; fig. 5) are excluded from the correlation analysis, no relationship is observed with cooling water flow ($r = 0.028$, $p = 0.90$).

The most ubiquitous indicator for decline in the various larval taxa was the significant decline in plankton volume. It is curious that, while a significant decline in plankton volume can be described by a linear model, after its nadir in 1993, volumes remained stable, but this was concomitant with the disappearance of multiple larval taxa from our catches. Plankton volume was negatively correlated with an increase in SST over this time period, a finding consistent with the hypothesis that the warming waters of the Southern California Bight is associated with a reduced nutrient nearshore environment (Parnell et al. 2010). Macroscale oceanographic indices CUI and MEI also appear to be factors associated with plankton production (Stephens et al. 1994). Plankton volume and its correlates (SST and CUI) appeared to be informative in describing the significant decline in overall larval density from 1974–2009. While we did not explicitly test this hypothesis, it seems reasonable to assert that reduced plankton volume was a significant factor in the decline of late stage larvae in this nearshore environment due to reduced foraging opportunities.

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DESCRIPTIVE TRENDS IN SOUTHERN CALIFORNIA BIGHT DEMERSAL FISH ASSEMBLAGES SINCE 1994

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ABSTRACT

Despite intense localized monitoring, few regional assessments of demersal fish assemblages are conducted in the Southern California Bight (SCB). The goal of this study was to describe temporal changes in regional-scale SCB demersal fish assemblages (density, biomass, size class) in relation to regional environmental changes (temperature and related climate indices). Nearly 600 small otter trawls were conducted by collaborating agencies between 3 and 200 m depth during the summers of 1994, 1998, 2003, and 2008 under a standardized sampling plan. Summer water temperature at depth between 1950 and 2008 has remained relatively stable although temperatures in 1998 and 2008 were above the long-term mean while the 1994 and 2003 temperatures were at or below the mean. Mean demersal fish density increased each survey between 1994 and 2003 before declining in 2008, while mean biomass increased each survey since 1994 reaching its maximum in 2008. Based on community similarity analyses, the 1998 survey was appreciably different than the other three surveys, with 2003 and 2008 being the most similar. This could be the result of anomalously warm-water conditions recorded during the 1997–98 El Niño and the resultant temporary poleward expansion of numerous species. Although the sample size was limited to four regional surveys, the best predictors of mean demersal fish density and biomass were the Northern Pacific Gyre Oscillation and the Multivariate El Niño-Southern Oscillation Index. Increasing temperature, or similar patterns in environmental indices, resulted in reduced density and biomass. Furthermore, habitat valuation revealed a trend of increasing value with depth and latitude with the southern inner shelf areas scoring the lowest habitat value. With the addition of more data, regional surveys such as these surveys provide a good foundation on which to analyze changes in demersal fish assemblages.

INTRODUCTION

Southern California Bight (SCB) shelf demersal fish assemblages are commonly monitored by dischargers in compliance with state and federal regulatory requirements (Mearns 1979; Love et al. 1986; Stull and Tang 1996). Nearly 12,000 samples are collected annually along this 300 km coastline to assess the health of demersal fish assemblages in response to discharges (Schiff et al. 2002). Despite this level of effort, few studies have documented trends in these assemblages beyond site-specific programs. For instance, Stull and Tang (1996) identified changes in demersal fish assemblages near one outfall in Los Angeles linked to improving wastewater effluent quality and natural environmental variability.

The challenge of interpreting trends in local-scale data is that regional influences can have an enormous effect on local results. Regional scale information provides the context for local trends, helping discern true differences from background stimuli. Such spatially robust studies potentially reveal significant information including wholesale population declines (Holbrook et al. 1997), generalized overfishing impacts (Myers and Worm 2003), site-specific anthropogenic discharge impacts (or lack of impacts, Conversi and McGowan 1994), influence of hypoxic conditions (Bograd et al. 2008; McClatchie et al. 2010), and/or climatic forcing (Perry et al. 2005; Genner et al. 2010). Disentangling interactions of regional scale natural influences from local anthropogenic stressors often requires the use of spatiotemporally extensive, fisheries-independent data (Hsieh et al. 2008; Hsieh et al. 2009; Genner et al. 2010).

In the SCB, there are two monitoring programs that can be used to evaluate regional trends over the last fifteen years. The first is the SCB Regional Marine Monitoring (Bight), completed regional surveys in 1994, 1998, 2003, and 2008 (Allen et al. 2007; Miller and Schiff 2011). The second is the California Cooperative Oceanic Fisheries Investigation (CalCOFI). CalCOFI measures the hydrography of the SCB water column (Bograd and Lynn 2003) and provides environmental data from a spatial scale relevant to the Bight program, thereby filling data gaps for measurements not collected during the Bight surveys. Together, the CalCOFI hydrographic series and the Bight Program provide data sets with sufficient spatial similarity to warrant a review of the relationship between the demersal fish assemblages of the SCB shelf and physical environmental changes.

This study aims to describe and quantify temporal changes in SCB demersal fish assemblages in relation to regional environmental variability. Such an endeavor has not been attempted in southern California since Mearns (1974) evaluated fish community responses to seasonal dissolved oxygen patterns. The temporal changes in SCB demersal fish assemblages will be assessed by spatial dimensions of known importance including depth and latitude. Fish community characteristics include species distributions, abundance, biomass, fish length, and habitat value. Environmental changes include temperature and various climate indices including the Northern Pacific Gyre Oscillation (NPGO) (Di Lorenzo et al. 2008), the Pacific Decadal Oscillation (PDO) (Mantua et al. 1997), and the Multivariate El Niño-Southern Oscillation Index (MEI) (Wolter and Timlin 2012).

MATERIALS AND METHODS

Bight Sampling for Demersal Fish

The Bight Program uses a stratified probabilistic survey design (Stevens 1997). Three strata were sampled in each survey: 5–30 m = inner shelf (IS); 31–120 m = middle shelf (MS); and 121–200 m = outer shelf (OS). In addition, three latitudinal strata were sampled in each survey: 33.6°–34.2°N = Northern SCB; 33.3°–33.6°N = Central SCB; and 32.3°–33.3°N = Southern SCB. Each station was sampled once per survey by a consortium of participating agencies (publicly owned treatment works, academics, and consultants) during the summer (July–September) with a standardized 7.6 m head-rope semiballoon otter trawl net with a 1.25 cm cod-end mesh. Trawls were towed parallel to the target isobaths at each station for ≈ 10 min at 0.8–1.0 m/sec. The difference between the start and stop fishing GPS coordinates recorded on the deck of the towing vessel was used to calculate the distance trawled. Two assumptions were used: 1) the net retained contact with the bottom during the entire designated fishing period, and 2) the GPS coordinates acted as a proxy for the net's relative position. Upon retrieval, trawl catches were sorted, identified to species and measured to nearest cm (standard length [SL], total length [TL] or disc width [DW], where appropriate). All recorded lengths were rounded up to the next size class (e.g., a 6.1 cm fish = 7 cm size class).

CalCOFI Sampling for Hydrography

CalCOFI conducts quarterly hydrographic surveys of the California Current hydrography. Methods used by CalCOFI are summarized in Bograd and Lynn (2003). CalCOFI uses a fixed grid sampling design, of which data from four transects from San Diego to Point Conception (lines 83–93) from stations numbering less than 50 on each line corresponding to approximately the same sampling frame as the Bight Program were used.

Data Analysis

Abundance and biomass data were standardized to the area swept. Underwater measurements by EQA-MBC (1975) determined the 7.6 m otter trawl net spread 4.9 m on average while under tow and fishing. Thus, the area swept in this analysis represents the distance trawled (m) × 4.9 m. The Shannon-Wiener Diversity Index was calculated for each depth strata by year using the derived densities. A raw density-weighted mean latitude and depth of each survey year's catch was calculated using the coordinates (depth) where fishing started. No density or biomass transformations were made prior to weighting. Environmental indices reviewed in the analysis include mean summer temperature (°C), PDO, NPGO, and the MEI. Mean extended summer (June–September) values for each index encompass the survey year and the preceding four years. Water temperature at 70 m recorded by CalCOFI (2011) for the survey year and the preceding four years was used. Temperatures were compared against the mean latitude, depth, and overall catch for all fishes, after removing the two most common species (no *Citharichthys*), and each of the two most common species individually. Climate indices were only compared against density and biomass independent of latitude or depth of capture. Low statistical power ($\beta < 0.80$) resulting from our small sample size ($n = 4$ surveys) precluded advanced, significance-testing regression modeling. Therefore, conclusions were restricted to comparing coefficients of determination (R^2) rather significance at $\alpha = 0.05$ level. The sensitivity of these results to fluctuations in the dominant species were evaluated by excluding the abundant species and examining them individually as well as examining the entire catch as a whole.

Based on the probabilistic design of the Bight Program, density by stratum was area-weighted using the ratio estimator approach following Thompson (1992):

$$m = \frac{\sum_{i=1}^{n} (p_i * w_i)}{\sum_{i=1}^{n} w_i},$$

where:

m = Area-weighted mean density for stratum j.
p_i = Parameter value (e.g., density) at station i.
w_i = Area weight for station i.
n = Number of stations in population j.

The standard error of the mean was calculated using the following equation.

$$\text{Standard error (SE)} = \sqrt{\frac{\sum_{i=1}^{n} ((p_i - m) * w_i)^2}{\left(\sum_{i=1}^{n} w_i\right)^2}},$$

where:

m = Area-weighted mean concentration for population j.
p_i = Parameter value (e.g., density) at station i.
w_i = Area weight for station i.
n = Number of stations in population j.

Similarities in overall community composition, as indicated by the species abundance distribution, were examined using percent similarity index (PSI, Whittaker 1952) using the equation:

$$PSI = 100 - 0.5 * \Sigma | A_i - B_i |$$

where:

A_i and B_i are the percentages of species i in samples A and B, respectively.

Fish length frequency distributions and mean lengths for each survey year were examined for shifts in the overall size structure of the whole catch and each of the four most commonly measured species. Abundance-weighted mean lengths were calculated for each comparison (i.e., year, latitude, depth). Annual mean lengths across all stations were compared using a Friedman Rank Sum Test. Furthermore, the annual total mean lengths were compared against the overall mean across all four Bight surveys to place each annual value into a long-term context. The mean length by 0.2°N latitude and 20 m depth bins were also analyzed for all species combined, and the most common species separately, to identify possible spatial variability in the catch.

Habitat values were calculated for each stratum in each year based on fish guilds described in Bond et al. (1999) and further supplemented by Pondella (2009) using a modification of the Bond et al. (1999) equation:

$$HV = \Sigma_{24}^{1} (mean\ length * F * D)^{0.5}$$

where:

F = proportional frequency of occurrence on a scale of 0–1 and
D = density (count/hectare).

The habitat valuation analysis focused on the demersal assemblages. Therefore, pelagic and midwater fishes (e.g., northern anchovy *Engraulis mordax*) were excluded as their catches likely represent sampling during midwater deployment or retrieval (Biagi et al. 2002). A listing of the 74 species used in the habitat valuation analysis (Appendix A). Habitat value differences by year, strata, and latitudinal region were compared separately using a Kruskall-Wallis (KW) analysis of variance with a Bonferroni multiple comparison test (Sokal and Rohlf 1995).

RESULTS

A total of 597 tows completed during the four Bight surveys (table 1) caught 131,961 fish weighing a total of 3541 kg and representing 160 demersal species (Appendix B). Sampling effort was greatest in 1998 and least in 2008. Distribution of sampling sites among the three shelf strata was the most equitable in 2008 when 29 (±3, standard error) stations were sampled in each shelf stratum. The sampling distribution in 1998 was the most variable with 81 (±25) stations sampled in each zone. Sampling was consistently most intense along the middle shelf followed by the inner shelf and the outer shelf, in descending order.

The 15 most common species averaged 79% of the total abundance and 77% of the total biomass across the four surveys (tables 2, 3). These patterns were most heavily influenced by the density and biomass of Pacific sanddab (*Citharichthys sordidus*), which ranked first in abundance and biomass overall. Pacific sanddab, longspine combfish (*Zaniolepis latipinnis*), and English sole (*Parophrys vetulus*) were the only species taken in all years and depth zones among the 15 most common species. Of the species ranking second through fifth in density, only halfbanded rockfish (*Sebastes semicinctus*) and stripetail rockfish (*S. saxicola*) ranked among the top ten in biomass at fifth and ninth, respectively. English sole and California halibut (*Paralichthys californicus*) ranked second and third in biomass, respectively, but English sole was only the 14th most common fish taken while California halibut was not among the 15 most commonly caught species. Not unexpectedly, highly abundant species tended to be smaller fishes as compared to those species with high biomass.

Observed differences in species abundance distributions may reflect changes in the local physiochemical structure of the waters overlying the SCB shelf. Mean annual summer seawater temperatures recorded at 50 m, 100 m, and 200 m were significantly corre-

TABLE 1
Number of successful trawl events by shelf stratum in each of the four Bight monitoring surveys (1994, 1998, 2003, and 2008).

Shelf Strata	1994	1998	2003	2008	Total
Inner (5–30 m)	32	77	43	32	184
Middle (31–120 m)	58	126	86	33	303
Outer (121–200 m)	20	40	27	23	110
Survey total	110	243	156	88	597

TABLE 2

Mean area-weighted and unadjusted (raw) density (count/1000 m^2) by year and depth zone for the 15 most common species taken during the Bight program demersal surveys (1994, 1998, 2003, and 2008).

Area-Weighted Density	1994				1998				2003				2008			
Species	IS	MS	OS	Tot.	IS	MS	OS	Tot.	IS	MS	OS	Tot.	IS	MS	OS	Tot.
Citharichthys sordidus	0.2	16.8	6.7	11.2	0.4	13.1	26.6	12.9	1.3	55.6	33.4	39.4	2.5	22.9	31.3	18.2
Citharichthys stigmaeus	6.9	1.7	—	2.7	3.3	4.1	—	3.3	31.5	8.6	0.0	12.8	24.2	3.0	—	8.8
Icelinus quadriseriatus	0.3	4.1	0.0	2.5	0.0	4.7	0.0	3.1	1.7	9.6	—	6.3	1.9	17.7	—	10.1
Sebastes semicinctus	—	0.8	0.2	0.5	—	0.6	0.5	0.4	0.0	16.1	3.2	10.4	—	9.7	2.2	5.6
Sebastes saxicola	0.0	1.6	4.7	1.7	—	0.7	2.1	0.8	0.0	10.0	17.9	8.8	—	2.5	10.4	3.0
Zaniolepis latipinnis	0.2	2.6	0.0	1.6	0.0	2.1	0.4	1.4	0.8	11.1	0.3	7.0	0.0	5.4	0.6	3.0
Lyopsetta exilis	—	0.3	15.1	2.4	—	0.2	14.8	2.5	—	0.2	20.8	3.2	—	0.2	26.5	4.4
Porichthys notatus	0.0	4.3	14.8	4.8	—	2.2	2.4	1.8	0.4	2.0	1.8	1.6	0.1	2.3	2.2	1.6
Citharichthys xanthostigma	0.7	3.3	—	2.2	0.5	5.7	0.0	3.8	0.5	3.0	0.0	1.9	0.2	3.0	0.1	1.7
Microstomus pacificus	—	2.1	6.5	2.2	—	1.7	6.7	2.2	0.0	4.9	5.4	3.8	—	1.2	3.7	1.3
Zalembius rosaceus	0.8	2.1	0.1	1.5	0.0	1.1	0.4	0.8	3.8	1.9	0.4	2.1	1.3	6.1	1.5	4.0
Genyonemus lineatus	2.3	—	—	0.6	25.1	1.6	—	5.7	2.2	0.0	—	0.5	0.2	0.0	—	0.1
Zaniolepis frenata	—	0.4	2.4	0.6	—	0.6	10.3	2.0	—	1.5	10.1	2.4	—	1.0	8.1	1.8
Parophrys vetulus	0.5	0.5	0.2	0.5	0.4	0.4	1.3	0.6	1.8	1.3	1.4	1.4	1.7	5.9	2.8	4.2
Synodus lucioceps	0.6	0.5	0.1	0.5	5.2	5.6	0.0	4.7	0.8	0.2	—	0.3	1.1	0.5	—	0.6
All species combined	17.0	50.0	71.0	45.0	47.0	54.0	76.0	56.0	53.0	140.0	115.0	115.0	40.0	93.0	102.0	79.0
Number of Species	38	65	39	86	54	90	59	129	55	83	56	109	50	56	44	93
Species Diversity	2.3	2.5	2.4	2.9	1.8	2.8	2.2	3.0	1.9	2.33	2.34	2.6	1.8	2.5	2.17	2.8
Raw Density																
Citharichthys sordidus	0.1	2.5	0.8	3.3	0.1	0.9	1.5	2.5	0.3	3.7	1.7	5.7	0.4	2.2	2.1	4.7
Icelinus quadriseriatus	0.1	1.7	0.0	1.9	0.0	1.6	0.0	1.6	0.6	4.6	—	5.2	0.5	5.4	—	5.9
Citharichthys stigmaeus	1.1	0.3	—	1.4	0.4	0.3	—	0.7	4.5	0.9	0.0	5.5	3.6	0.7	—	4.4
Genyonemus lineatus	0.4	—	—	0.4	10.5	0.2	—	10.7	0.2	0.0	—	0.2	0.1	0.0	—	0.1
Sebastes saxicola	0.0	0.4	1.0	1.4	—	0.3	0.8	1.1	0.0	2.0	2.9	5.0	—	0.6	2.2	2.7
Lyopsetta exilis	—	0.2	1.6	1.8	—	0.1	2.0	2.1	—	0.0	2.9	2.9	—	0.1	2.7	2.8
Sebastes semicinctus	—	0.2	0.1	0.2	—	0.1	0.2	0.3	0.0	3.3	0.3	3.5	—	1.1	0.5	1.6
Porichthys notatus	0.0	0.8	1.4	2.2	—	0.5	0.5	1.0	0.1	0.4	0.2	0.7	0.1	0.5	0.4	0.9
Microstomus pacificus	—	0.4	0.7	1.1	—	0.3	0.9	1.2	0.0	0.7	0.7	1.5	—	0.3	0.6	0.9
Zaniolepis latipinnis	0.1	0.6	0.0	0.7	0.0	0.4	0.2	0.6	0.2	1.6	0.1	2.0	0.0	0.9	0.2	1.2
Zalembius rosaceus	0.1	0.5	0.0	0.6	0.0	0.4	0.2	0.6	0.5	0.6	0.1	1.2	0.4	1.2	0.4	2.0
Zaniolepis frenata	—	0.1	0.5	0.6	—	0.1	0.9	1.0	—	0.2	1.1	1.3	—	0.2	1.1	1.4
Synodus lucioceps	0.3	0.2	0.0	0.5	0.8	1.7	0.0	2.5	0.2	0.1	—	0.3	0.2	0.2	—	0.4
Citharichthys xanthostigma	0.3	0.6	—	0.8	0.1	1.2	0.0	1.3	0.2	0.6	0.0	0.8	0.1	0.5	0.0	0.7
Parophrys vetulus	0.1	0.2	0.1	0.4	0.1	0.2	0.3	0.5	0.4	0.3	0.3	1.0	0.4	0.7	0.4	1.5
All species combined	4.3	11.9	10.6	26.7	16.3	11.5	10.5	38.4	9.9	24.1	15.1	49.1	8.3	18.5	14.3	41.2

Note: "—" = none taken; 0.0 = < 0.05.

lated ($p < 0.05$), with correlation coefficients (r) ranging between 0.29 (50 m vs. 200 m) and 0.71 (50 m and 100 m) (figs. 1b,c,d). Summer seawater temperatures at 50 m since 1949 averaged 11.3°C while temperatures in survey years (1994, 1998, 2003, and 2008) were both above and below the mean with 11.2°C, 13.2°C, 10.7°C, and 12.3°C, respectively. A similar pattern was observed at 100 m, albeit with less variation and mean summer temperatures of 9.4°C, 10.4°C, 9.1°C, and 10.6°C, respectively. Lastly, at 200 m, temperatures were least variable over time and each survey year was near the long-term average (8.4°C) except 2008 when the temperature was 1.0°C warmer at 9.4°C. The seawater temperature during the survey year, however, often misrepresented conditions that dominated the intervening years. For example, 2008 temperatures were above average while temperatures since the 2003 survey were predominantly below average. Therefore, temperature analyses focused on the mean across the years since the previous survey to better account for intervening conditions. This same principle was applied to the climate indices NPGO, PDO, and MEI.

Comparisons of the species abundance distributions via the PSI indicated a high degree of similarity (≈ 80%) between the 2003 and 2008 catches (fig. 2). Less similarity was observed between the 2003 and 2008 surveys and the 1994 and 1998 surveys (fig. 2). The 1998 survey results were the most unique at <55% similarity to any of the other three surveys. Comparisons among the relative density of the 15 most common species helps explain the similarities and differences among Bight surveys (fig. 2). For example, Pacific sanddab accounted for ≈ 23% of total catch in all but the 2003 survey when it accounted for >30% of the catch. The most distinct difference between earlier and later surveys pertains to plainfin midshipman (*Porichthys notatus*), which was commonly taken in 1994 but not in 2003 or 2008. Catches of species ranked 6–14 were markedly higher in 1998

TABLE 3
Mean area-weighted and unadjusted (raw) biomass (kg/1000 m^2) by year and depth zone for the 15 most common species taken during the Bight program demersal surveys (1994, 1998, 2003, and 2008).

Area-Weighted Biomass	1994				1998				2003				2008			
Species	IS	MS	OS	Tot.	IS	MS	OS	Tot.	IS	MS	OS	Tot.	IS	MS	OS	Tot.
Citharichthys sordidus	0.01	0.23	0.29	0.18	0.01	0.41	1.01	0.43	0.04	0.93	1.22	0.76	0.04	0.44	2.45	0.65
Parophrys vetulus	0.07	0.07	0.03	0.06	0.03	0.05	0.12	0.05	0.08	0.14	0.09	0.12	0.06	0.30	0.22	0.22
Paralichthys californicus	0.56	0.04	—	0.16	0.29	0.04	—	0.08	0.20	0.03	—	0.07	0.14	—	—	0.04
Citharichthys xanthostigma	0.05	0.11	—	0.08	0.02	0.14	0.00	0.09	0.03	0.14	0.00	0.10	0.01	0.11	0.00	0.06
Sebastes semicinctus	—	0.02	0.00	0.01	—	0.00	0.01	0.00	0.00	0.09	0.10	0.07	—	0.37	0.07	0.21
Pleuronichthys verticalis	0.12	0.06	—	0.06	0.10	0.05	0.00	0.05	0.07	0.09	0.02	0.08	0.12	0.13	0.03	0.11
Lyopsetta exilis	—	0.00	0.29	0.04	—	0.01	0.24	0.04	—	0.00	0.42	0.06	—	0.00	0.51	0.09
Genyonemus lineatus	0.19	—	—	0.05	0.44	0.11	—	0.15	0.12	0.00	—	0.03	0.01	0.00	—	0.01
Sebastes saxicola	—	0.02	0.16	0.03	—	0.02	0.07	0.02	0.00	0.08	0.43	0.11	—	0.04	0.27	0.06
Citharichthys stigmaeus	0.05	0.01	—	0.02	0.04	0.04	—	0.03	0.21	0.07	0.00	0.09	0.23	0.02	—	0.08
Microstomus pacificus	—	0.06	0.21	0.07	—	0.03	0.16	0.05	0.00	0.08	0.13	0.07	—	0.03	0.17	0.04
Porichthys notatus	—	0.09	0.31	0.10	—	0.05	0.07	0.04	0.02	0.05	0.10	0.05	—	0.03	0.09	0.03
Zaniolepis latipinnis	0.01	0.06	—	0.04	—	0.05	0.01	0.03	0.03	0.15	0.01	0.10	0.00	0.09	0.02	0.05
Scorpaena guttata	0.04	0.11	—	0.08	0.01	0.04	0.00	0.03	0.04	0.08	0.02	0.06	0.02	0.05	0.01	0.03
Synodus lucioceps	0.05	0.15	0.02	0.11	0.07	0.07	0.00	0.06	0.02	0.01	—	0.01	0.03	0.02	—	0.02
All species combined	1.43	1.31	1.73	1.40	1.47	1.52	2.27	1.63	1.19	2.56	3.49	2.37	0.83	2.00	4.42	2.05
Raw Biomass																
Citharichthys sordidus	0.01	0.29	0.28	0.58	0.00	0.24	0.87	1.11	0.06	0.90	1.05	2.01	0.04	0.44	2.45	2.93
Lyopsetta exilis	—	0.00	0.29	0.29	—	0.01	0.29	0.30	—	0.01	0.56	0.56	—	0.00	0.51	0.51
Genyonemus lineatus	0.33	—	—	0.33	1.09	0.11	—	1.20	0.07	0.00	—	0.08	0.03	0.00	—	0.04
Paralichthys californicus	0.57	0.09	—	0.66	0.28	0.15	—	0.43	0.26	0.06	—	0.31	0.14	—	—	0.14
Parophrys vetulus	0.07	0.08	0.03	0.17	0.01	0.06	0.12	0.20	0.07	0.16	0.14	0.36	0.06	0.30	0.22	0.57
Sebastes saxicola	—	0.02	0.17	0.19	—	0.03	0.09	0.11	0.00	0.07	0.42	0.49	—	0.04	0.27	0.31
Microstomus pacificus	—	0.06	0.24	0.30	—	0.03	0.15	0.18	0.00	0.08	0.13	0.21	—	0.03	0.17	0.20
Porichthys notatus	—	0.12	0.30	0.42	—	0.06	0.07	0.13	0.01	0.05	0.08	0.15	—	0.03	0.09	0.12
Citharichthys xanthostigma	0.05	0.14	—	0.19	0.01	0.23	0.01	0.26	0.07	0.17	0.00	0.24	0.01	0.11	0.00	0.12
Pleuronichthys verticalis	0.12	0.07	—	0.19	0.05	0.07	0.00	0.13	0.09	0.11	0.02	0.22	0.12	0.13	0.03	0.27
Citharichthys stigmaeus	0.05	0.01	—	0.07	0.02	0.02	—	0.04	0.24	0.05	0.00	0.28	0.23	0.02	—	0.26
Zaniolepis frenata	—	0.01	0.06	0.07	—	0.01	0.11	0.12	—	0.04	0.18	0.22	—	0.01	0.18	0.19
Sebastes semicinctus	—	0.02	0.00	0.03	—	0.00	0.02	0.02	0.00	0.07	0.05	0.12	—	0.37	0.07	0.44
Scorpaena guttata	0.05	0.09	—	0.14	0.00	0.06	0.00	0.07	0.04	0.15	0.01	0.20	0.02	0.05	0.01	0.08
Synodus lucioceps	0.05	0.12	0.03	0.20	0.05	0.14	0.00	0.19	0.01	0.02	—	0.03	0.03	0.02	—	0.04
All species combined	1.58	1.47	1.80	4.84	2.58	1.73	2.13	6.44	1.28	2.62	3.30	7.20	0.91	2.00	4.42	7.33

than the remaining years, thus resulting in the greater PSI differences.

Mean demersal fish density along the continental shelf increased slightly through 2003 before declining again in 2008, although 2008 remained above the mean density recorded in 1994 and 1998 (fig. 1a; tables 2, 3). Similarly, mean biomass increased in 2003 and 2008 from 1998. Comparisons between fish density and biomass against the average temperature at 70 m for the intervening years resulted in a pattern of decreasing density and biomass with increasing temperature (fig. 3). For all species combined, the R^2 was 0.70 for density and 0.85 for biomass. To determine the effect of the highly abundant species on this relationship, data were reanalyzed after filtering out both Pacific sanddab and speckled sanddab (*Citharichthys stigmaeus*), and then for each of these dominant species individually to examine their impact on the relationship. There was an effect of these dominant species on the overall relationship as the R^2 for both density and biomass increased with their exclusion. Speckled sanddab density and biomass exhibited a relationship with temperature similar to that described for all species. Pacific sanddab density and biomass, however, exhibited a substantially reduced relationship with temperature. Given its consistent first ranking in density across all surveys, this likely accounted for the improved relationship observed between density or biomass with temperature after removing Pacific sanddab.

The three climate indices also had relationships to regional fish density or biomass (table 4). The direction of each relationship was consistent with the general productivity characterizations of each climate index. For example, negative NPGO or positive PDO equated to low productivity periods and resulted in lower demersal fish density and biomass. Of the three climate indices, the MEI and the NPGO were the most correlated with patterns in fish community metrics; mean R^2 were 0.81 and 0.80, respectively. The PDO was the least descriptive climate index with the lowest mean $R^2 = 0.70$, but also the second highest standard error consistent with the wide variation among analysis-specific values. The NPGO was the most explanatory index for density with

TABLE 4

Coefficient of determination (R^2) of the trendline describing the relationship between each environmental index and each abundance index. Density refers to the area-weighted mean count/1000 m^2 and biomass represents the area-weighted mean kg/1000 m^2. No *Citharichthys* data set represents the data for each abundance metric after removing *C. sordidus* and *C. stigmaeus*. NPGO = North Pacific Gyre Oscillation, PDO = Pacific Decadal Oscillation, MEI = Multivariate ENSO Index, and temp = mean water temperature at 70 m. See Material and Methods for description of the mean calculation for each environmental index.

	Index			
Metric	NPGO	PDO	MEI	Temp
Density				
All species	0.99	0.92	0.85	0.70
No Citharichthys	0.98	0.79	0.94	0.83
C. sordidus	0.90	0.73	0.66	0.48
C. stigmaeus	0.99	0.92	0.93	0.82
Biomass				
All species	0.47	0.39	0.74	0.85
No Citharichthys	0.92	0.86	1.00	0.96
C. sordidus	0.17	0.12	0.41	0.56
C. stigmaeus	0.96	0.85	0.98	0.91
Mean	0.80	0.70	0.81	0.76
SE	0.11	0.10	0.07	0.06

a $R^2 > 0.90$ for all four community metrics. Temperature was the least explanatory with a $R^2 \leq 0.83$ for all four fish community metrics. Patterns in biomass, however, were best described by temperature and the MEI, including a nearly straight-line relationship between the MEI and the no *Citharichthys* group of demersal fishes. In all cases, no clear relationship between Pacific sanddab and environmental indices were observed and these comparisons consistently yielded the lowest coefficient of determination in each analysis.

Demersal fish community density and biomass generally shifted southward with increasing water temperature (fig 4). In 1994 and 1998, the relatively warmer periods, density and biomass were centered between 33.5° and 33.6°N latitude. In 2003 and 2008, the relatively cooler periods, density and biomass were centered between 33.6° and 33.7°N latitude. These latitudinal relationships using all species ($R^2 = 0.92$ for density and 0.81 for biomass) were largely driven by movement in Pacific sanddab ($R^2 = 0.83$) populations. Depth patterns in demersal fish density and biomass were variable and exhibited fewer relationships with latitude than observed for temperature. For example, a modest ($R^2 = 0.50$) rela-

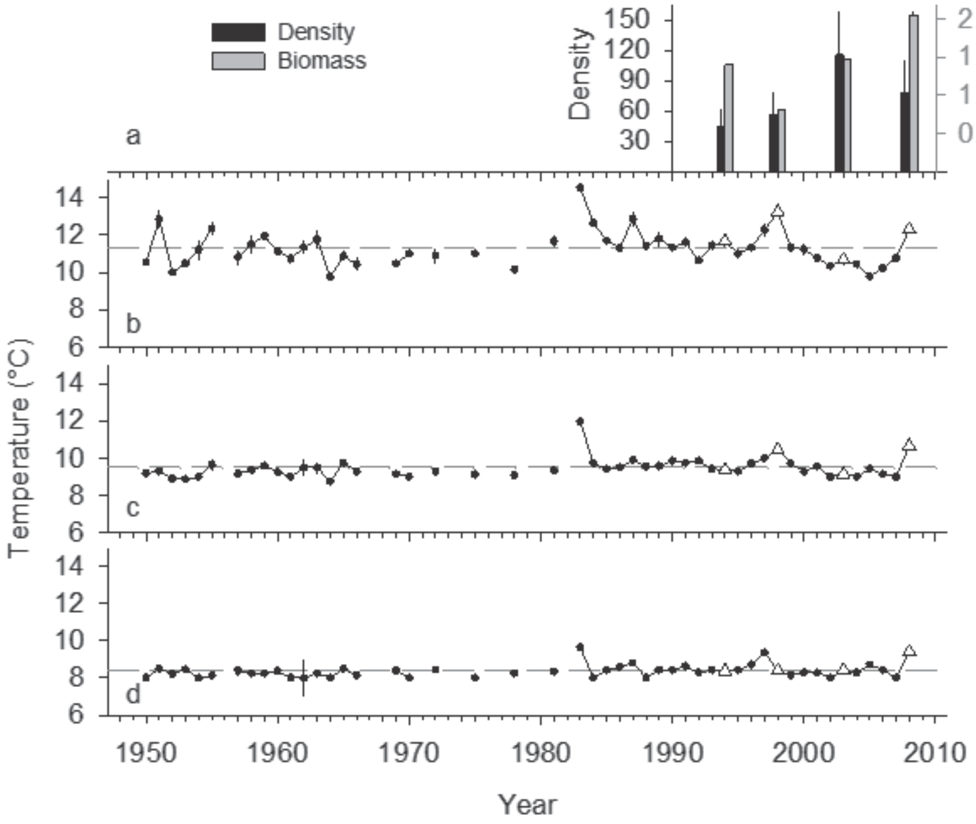

Figure 1. a) Mean annual demersal fish density (count/100 m^2 ± s.e.) and biomass (kg/100 m^2 ± s.e.) recorded during the 1994, 1998, 2003, and 2008 surveys at stations on the inner shelf, middle shelf, and outer shelf. Mean summer water temperature recorded during the CalCOFI hydrographic surveys at stations located inshore of Station 50 along survey lines 83.3, 86.7, 90.0, and 93.3 at the b) 50-, c) 100-, and d) 200-m depth strata. The four Bight Regional Monitoring survey years are denoted by the open triangles in each plot. Dashed line in each plot represents the long-term (1949–2008) mean temperature at each depth.

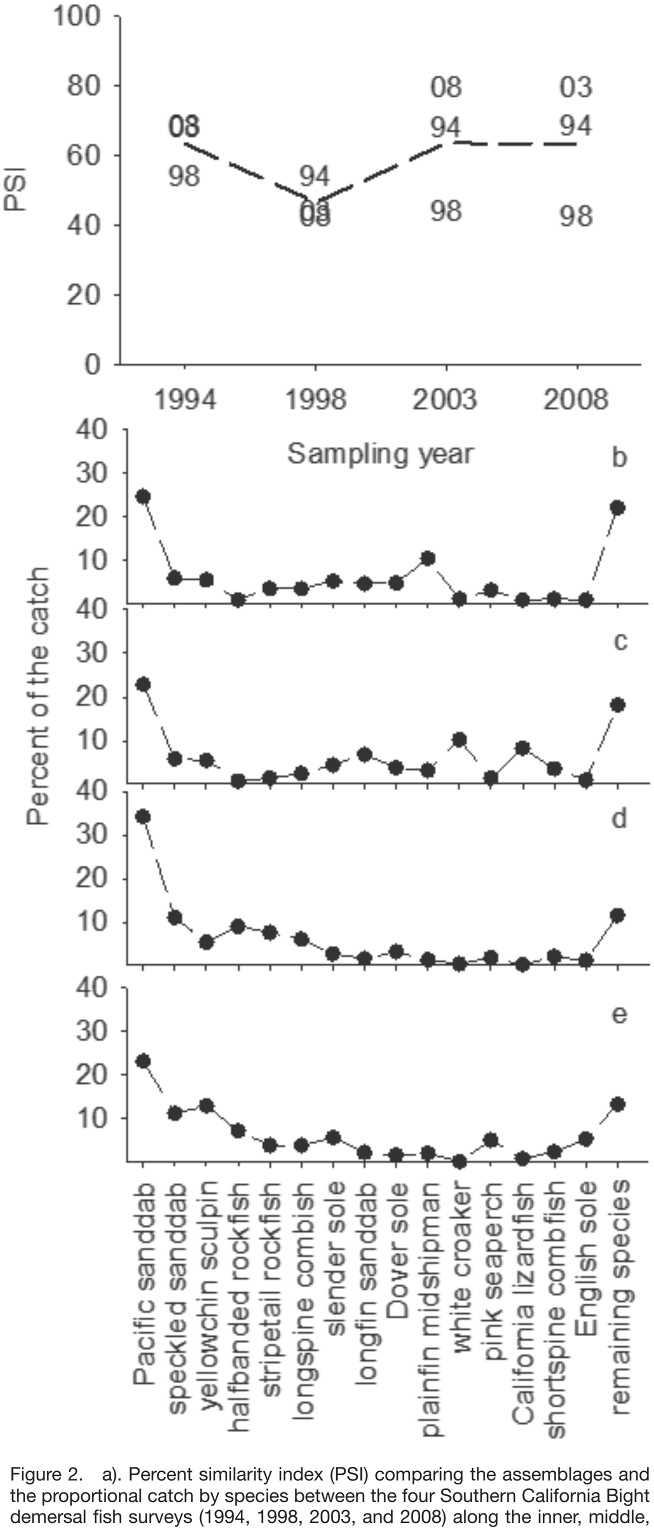

Figure 2. a). Percent similarity index (PSI) comparing the assemblages and the proportional catch by species between the four Southern California Bight demersal fish surveys (1994, 1998, 2003, and 2008) along the inner, middle, and outer shelves. Numbers represent the years compared against the base year listed on the x-axis. 2003 and 2008 overlap for the comparisons with 1994 and 1998. Species distribution of the 15 most common species, listed in order of decreasing abundance, across all four surveys, combined, plotted by survey: b) 1994, c) 1998, d) 2003, and e) 2008.

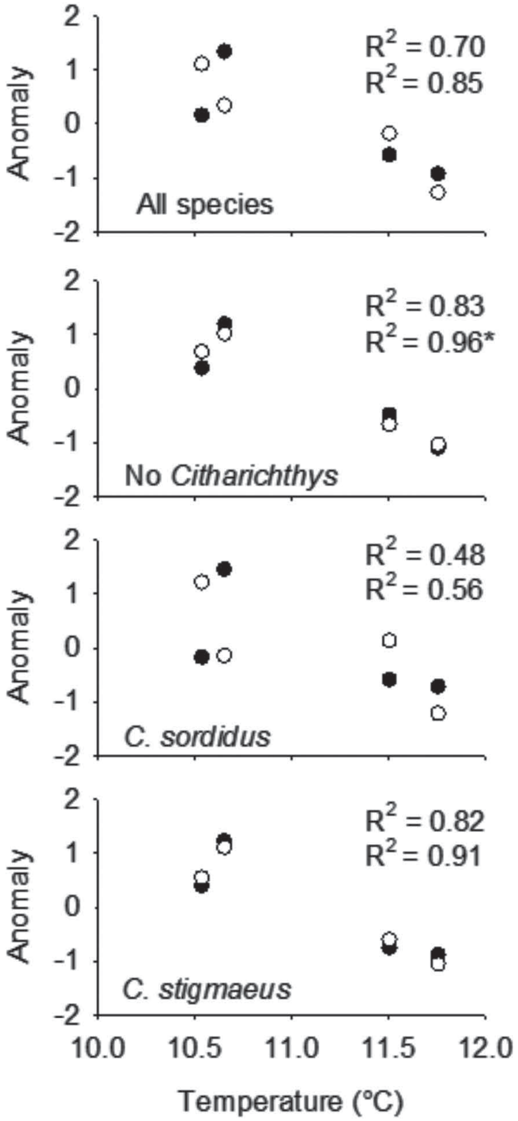

Figure 3. Standardized anomalies of annual mean density (count/100 m²; black circles – ●) and biomass (kg/100 m²; white circles – ○) versus the ~5-year running mean temperature at 70 m for all species combined, all species after excluding *Citharichthys sordidus* and *C. stigmaeus*, *C. sordidus*, and *C. stigmaeus*. Coefficient of determination (R²) for the linear regression through each set is presented. Top R² reflects density and bottom R² reflects biomass.

tionship was observed between speckled sanddab biomass depth and latitude.

The OS demersal fish community consistently had more fish per unit area (density and biomass) than either the IS or the MS (tables 2, 3). Diversity and species richness, however, was typically greatest along the MS compared to the IS or OS. In nearly every survey, the IS recorded the lowest density, biomass, diversity, and species richness.

The seven most abundant species taken from all four surveys combined accounted for ≥69% of the total catch regardless of depth stratum (fig. 5). Eleven species-stratum combinations had increasing trends while 10

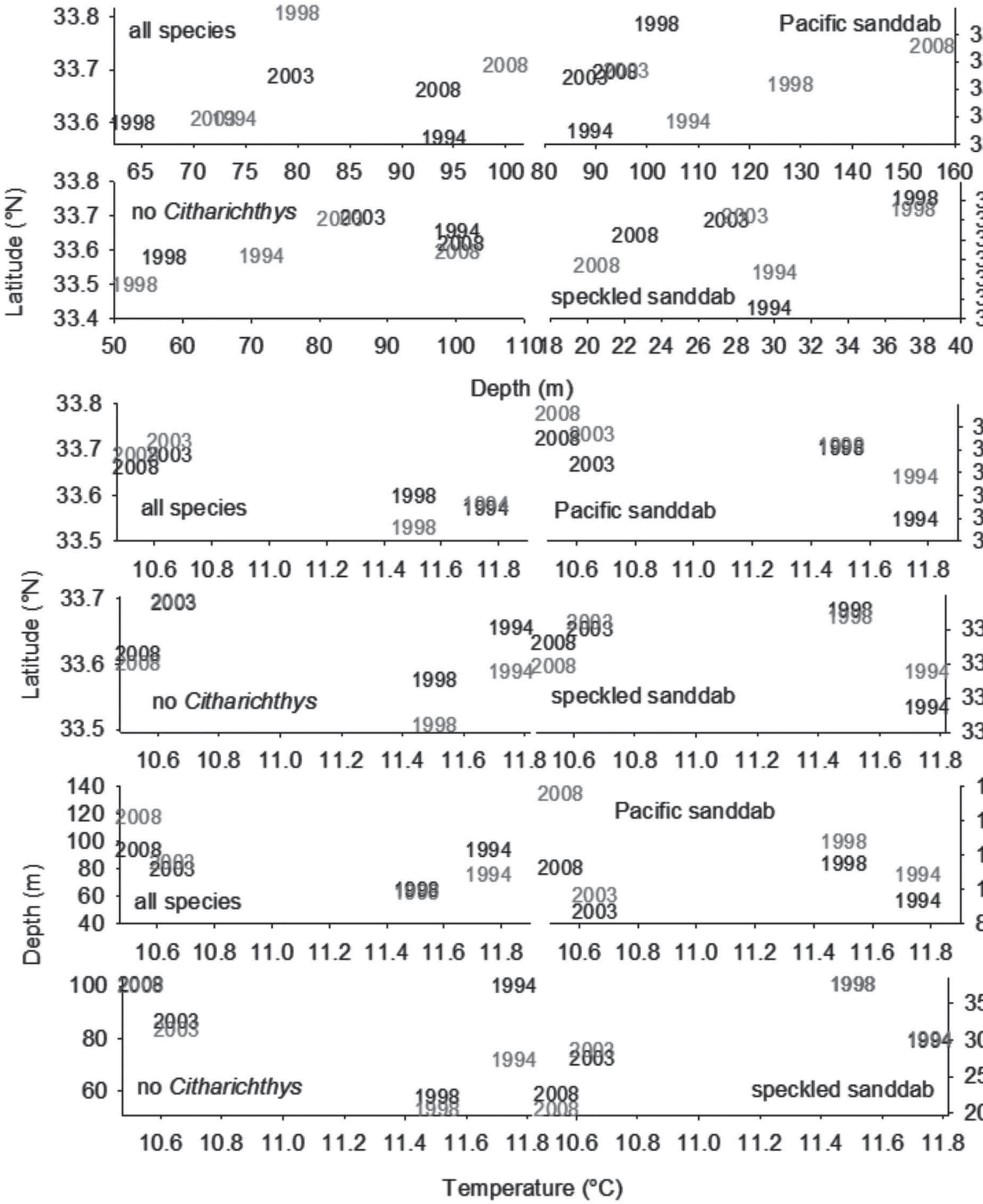

Figure 4. Area-weighted mean density (count/100 m²) and biomass (kg/100 m²) centers of distribution by latitude, depth, and latitude per temperature at 70 m. Grey = biomass and black = density. The survey year is overlaid on the data point in each figure.

species-stratum combinations declined over time. Species with substantially increasing densities during the four surveys included Pacific sanddab and speckled sanddab along the IS; yellowchin sculpin and halfbanded rockfish along the MS; and Pacific sanddab, slender sole (*Lyopsetta exilis*), and stripetail rockfish along the OS. Decreasing densities were most noticeable in many species along the IS, California lizardfish (*Synodus lucioceps*) along the MS, and plainfin midshipman and Dover sole (*Microstomus pacificus*) along the OS.

In total, all four surveys were dominated by demersal fishes in the 6 to 14 cm size classes (fig. 6). Average demersal fish lengths in 1994 and 1998 did not change much (10.5 cm and 10.7 cm, respectively). Demersal fish length frequencies were generally consistent between 1994 and 1998, with a subtle size-class mode shift from 6 and 7 cm size classes in 1994 to 7 to 10 cm size classes in 1998. In 2003, however, the mean fish length declined over 1 cm (9.5 cm) due to the influence of fishes ≤7 cm. This pattern reversed in 2008 as the catch increased in size to an average of 11.0 cm with few individuals in smaller size classes, particularly those ≤6 cm. These dif-

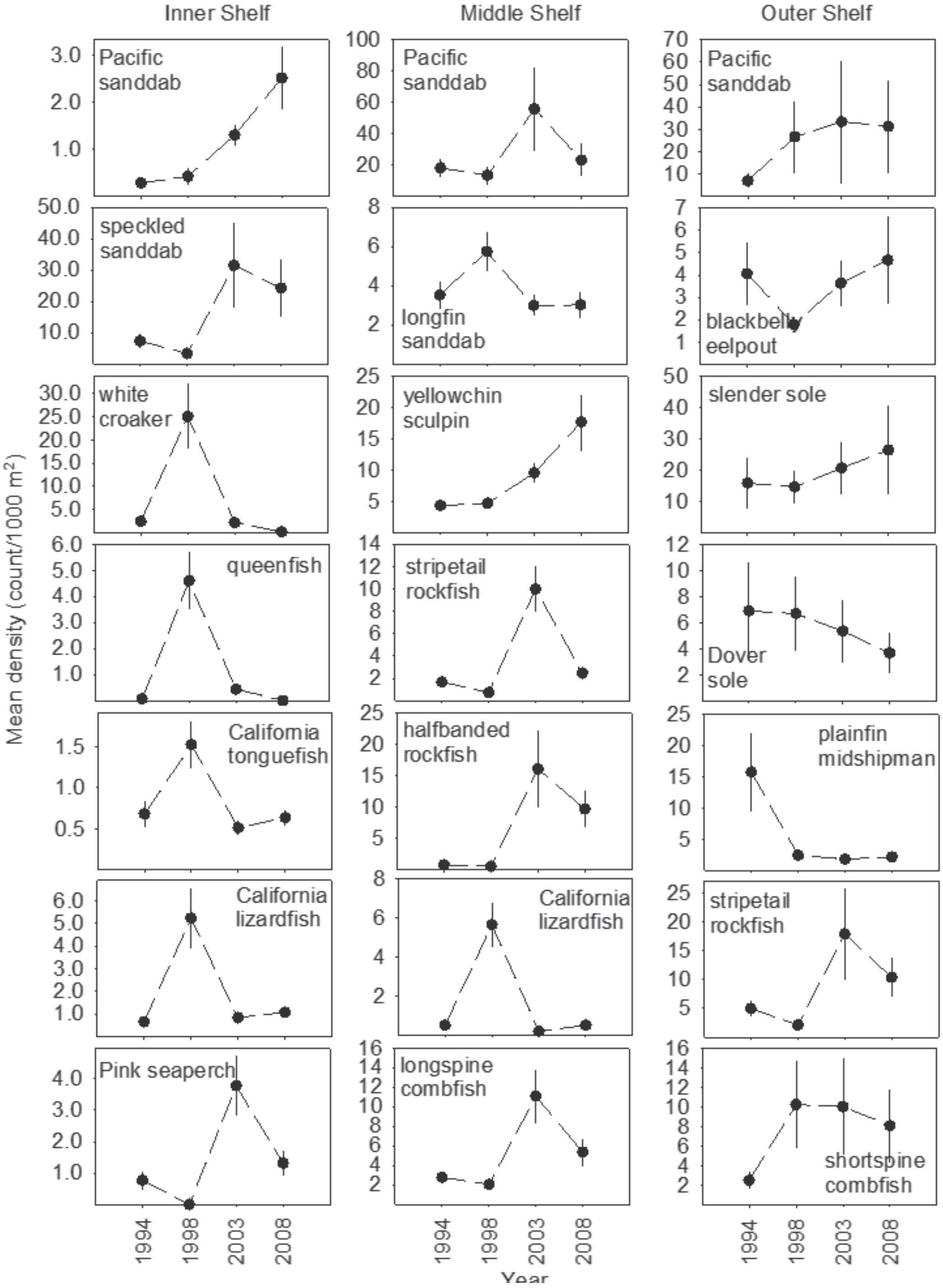

Figure 5. Mean annual density (count/1000 m²) ± standard error for the seven species most commonly taken during otter trawls in each shelf strata during the four Bight monitoring surveys (1994, 1998, 2003, and 2008).

ferences were statistically significant (Friedman Rank Sum, $\chi^2 = 27.45$, df = 3, $p < 0.001$). Differences in fish length between survey years were reflected in size class distributions for the most common species (fig. 7). In Pacific sanddab for instance, between 3% and 8% of the population was ≤4 cm size class in each of the three earliest surveys, but comprised only 2% in the 2008 survey. In contrast, 13% of the Pacific sanddab population was ≥20 cm size class in 2008, while only 6% to 10% of the population was ≥20 cm size class in each of the three earliest surveys. Similarly, length-frequency distributions in each of the four common demersal fish species exhibited smaller size classes in 2008 than was taken in 2003. Even extending to the 12 most common spe-

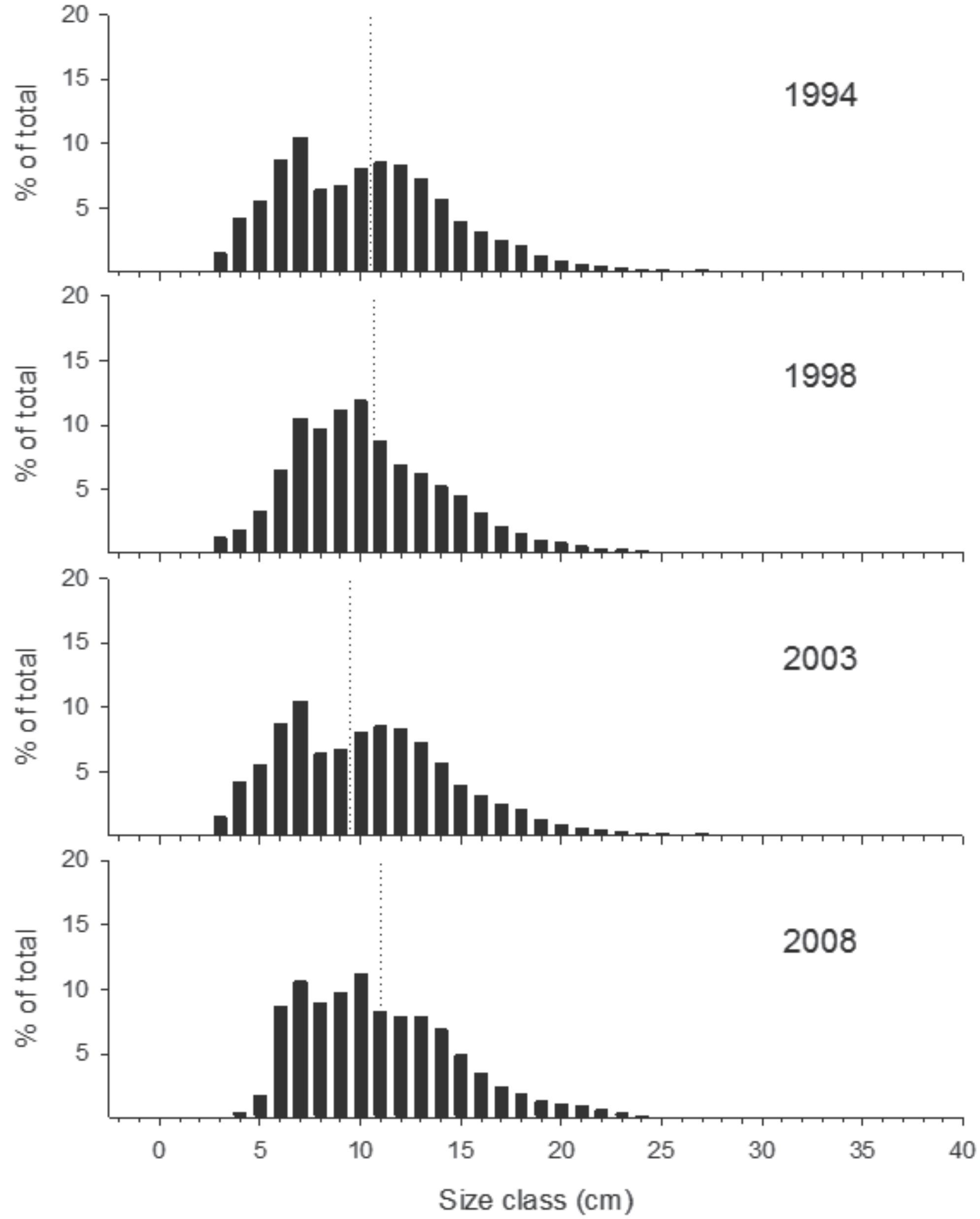

Figure 6. Length frequency distribution of all fishes (up to the 40 cm size class) taken by survey year with the mean length indicated by the vertical dashed line.

cies, mean length in 2008 was greater than, or equal to, the grand mean length observed across all four survey years (Appendix C).

Mean fish length varied with latitude and depth across surveys (fig. 8). During most survey years, the minimum mean length was taken at the southern latitudes (≤33.0°N) and then increased with increasing latitude. For example, Pacific sanddab lengths were generally >10 cm north of 33.6°N while the opposite was observed south of 33.6°N. Unlike length:latitude comparisons, the distribution of lengths by depth differed between all species combined and the dominant demersal fish species, Pacific sanddab. The maximum mean fish length occurred at the shallowest and deepest depths for all species combined consistently across surveys, with the mid-depth sampling recording the lowest mean fish length. In contrast, maximum average Pacific sanddab lengths typically increased with increasing depth consistently across surveys.

The habitat value analysis revealed differences among most years (KW, H = 67.28, df = 3, $p < 0.01$) (fig. 9). Mean habitat values derived for 1998 and 2008 were different from all other years, while those for 1994 and 2003 were different only from 1998 and 2008 but not each other. Examination by depth found the IS habitat value was significantly lower than the remaining two

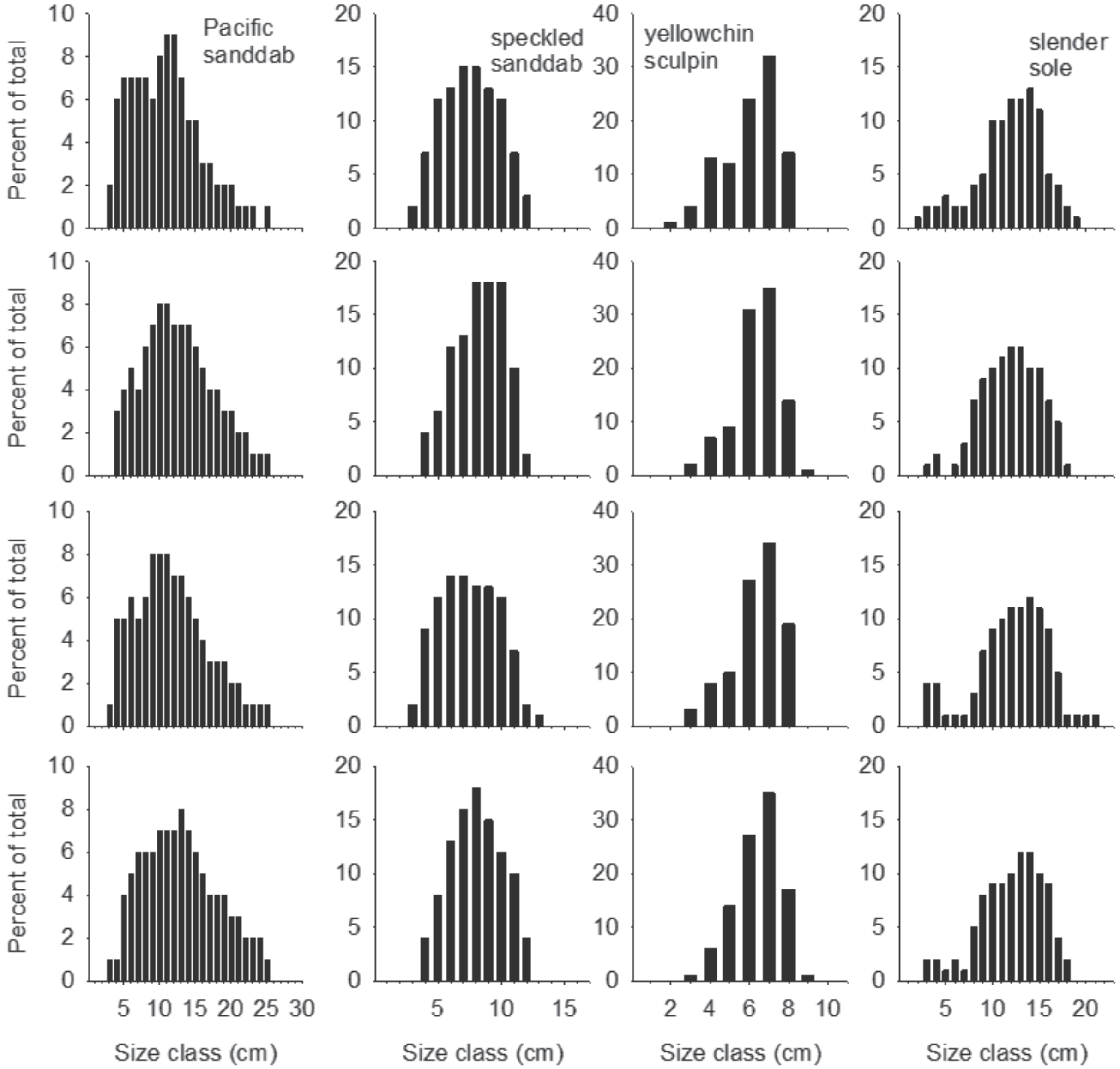

Figure 7. Length frequency histograms for the four most common species taken across all four surveys. Top row = 1994 survey; second row = 1998 survey, third row = 2003 survey, last row = 2008 survey.

areas, with no significant difference between the MS and OS (KW, H = 79.07, df = 2, $p < 0.01$). Finally, the southern area exhibited a significantly lower habitat value than either the central or northern areas (KW, H = 12.37, df = 2, $p < 0.01$).

DISCUSSION

In the SCB regional surveys between 1994 and 2008, 160 species were identified including several new to the area (Allen and Groce 2001; Groce et al. 2001; Lea et al. 2009). Comparing the regional surveys clearly indicated that these demersal fish assemblages are dynamic, changing in species composition, abundance, and biomass over time. The significance of these periodic, regionalized surveys cannot be underestimated. Localized trawl monitoring programs typically find far fewer species (Stull and Tang 1996). The regional surveys not only revealed bightwide variability in abundance of selected species, but that population movements either in latitude or depth are common, both of which could result in mistaken assumptions about species shifts at local-scale impact-based monitoring programs.

Large-scale temporal changes in the demersal fish community were evident during the SCB regional surveys. The 1998 survey was appreciably different from the other three surveys, with 2003 and 2008 being the most similar. Anomalous oceanographic conditions existed in 1998 as a result of the 1997–98 El Niño and the resultant temporary poleward expansion of numerous species (Lea and Rosenblatt 2000). In addition, many of the species

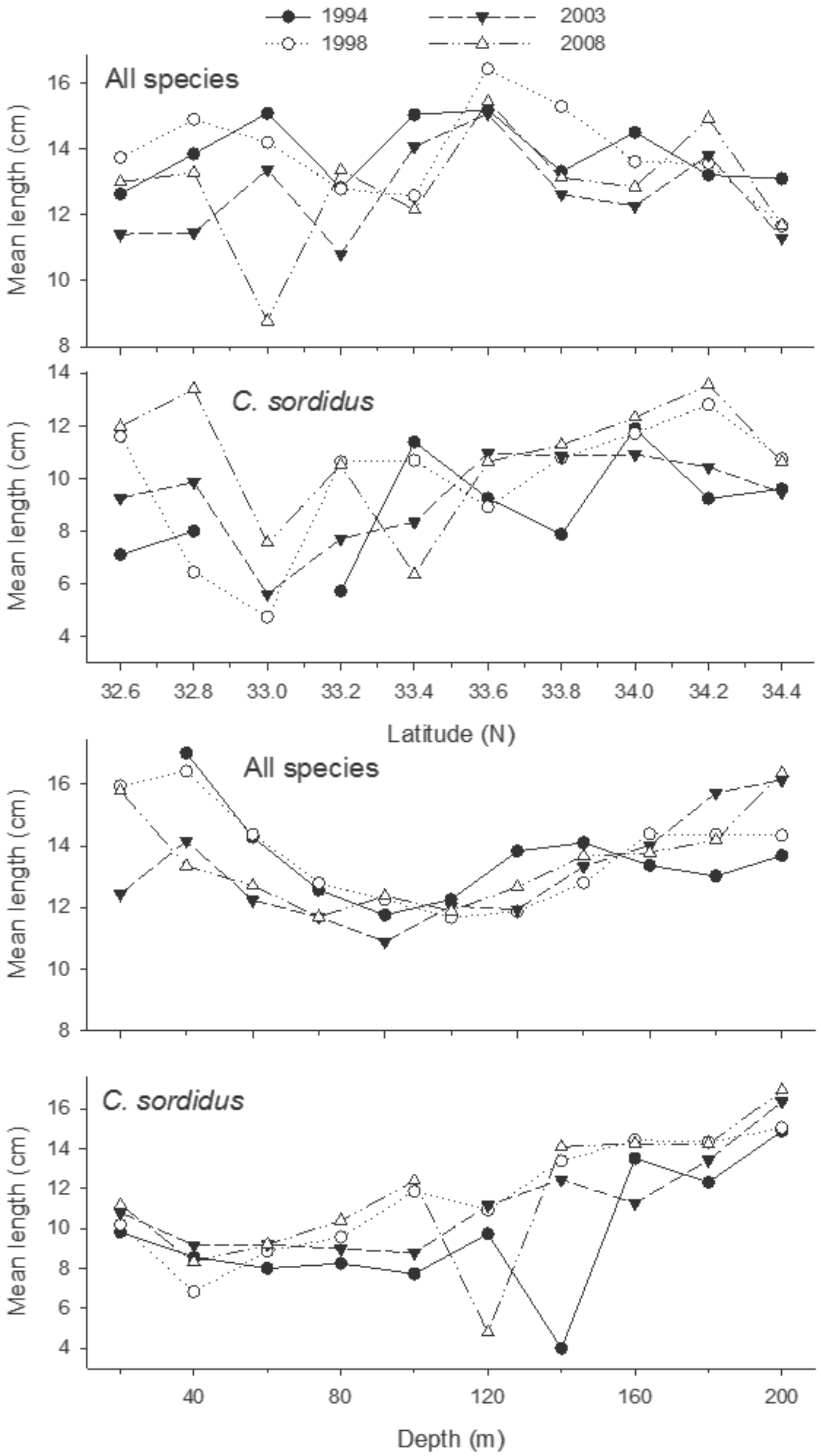

Figure 8. Abundance-weighted mean lengths by latitude and depth for all species combined and *Citharichthys sordidus* by survey year: 1994, 1998, 2003, and 2008.

that were comparatively common in 1998 were often minimally represented in the remaining surveys. Moreover, numerically dominant species during 1994, 2003, and 2008 such as Pacific and speckled sanddabs, had reduced abundance in 1998. Arguably, the fish assemblage sampled during the 1998 survey was reflective, at least partially, of the El Niño conditions.

Density, biomass, and mean fish length also indicated differences between regional surveys. The 2008 survey had the second greatest bightwide density and the single

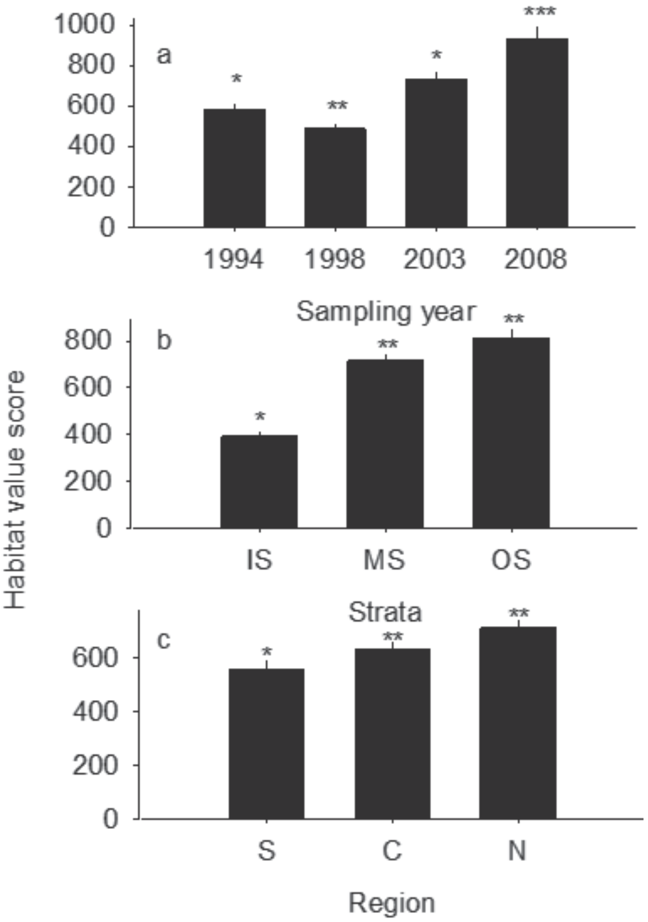

Figure 9. Mean (+ standard error) habitat value by a) survey year (all regions and shelf strata combined), b) by strata (all regions and years combined), and c) by region (all years and shelf strata combined). Asterisks denote significant differences.

greatest biomass for any of the four surveys. What precipitated this pattern is perhaps the most pressing question resulting from this analysis. Did the assemblage change resulting in this shift? The PSI indicates no appreciable change in the assemblage's species composition, with the exception of the influx of tourist species in 1998. Therefore, the increased biomass with reduced density is not likely caused by a change in the species structure, e.g., phenotypically larger fishes have not replaced smaller fishes. If the same species are there, just fewer individuals weighing more, did the average fish size change? Species-specific length analyses were consistent with a generalized increase in size across the assemblage as the 2008 mean length was larger than the preceding surveys. More importantly, reduced abundances in the smallest size classes suggest poor larval settlement (ecological recruitment) occurred between 2003 and 2008. No change in sampling protocols has occurred and the aforementioned consistency in species assemblage across surveys reinforce that these measures were not artifacts of sampling or species replacements. The SCB demersal fish assemblage information collected during the Bight surveys indicates a shift to bigger, likely older, individuals of the same suite of species that was present in 2003, and likely before, due to depressed larval settlement.

Region-wide changes in demersal fish density and biomass were correlated with environmental conditions. The NPGO and MEI were the most predictive environmental indices and the PDO was the least predictive of the demersal fish assemblage metrics. The PDO is derived from sea surface temperature (SST) anomalies (Mantua et al. 1997), and therefore correlates with only SST in the SCB with little or no relationship to other oceanographic variables in the area (Di Lorenzo et al. 2008). In response, Di Lorenzo et al. (2008) developed the NPGO from sea surface height data and found it correlated with several oceanographic variables in the SCB. The MEI represents a compilation of several disparate oceanographic metrics, including sea level pressure, SST, surface air temperature, etc. (Wolter and Timlin 2012). The inclusion of measures beyond temperature in the calculation of NPGO and MEI may be responsible for the improved correlations in our analyses of a mixed stock (species and age-structure) fish community. Each species likely responds best to a unique set of environmental conditions that is encapsulated by metrics beyond SST.

One limitation of our study is the small sample size of only four regional surveys. This limits our statistical power to detect trends. Not to disregard the overall importance of these findings, caution should be used in their interpretation. While high R^2 values were detected, this could be a function of simply lining up four dots. These results, especially for those relationships resulting in a $R^2 > 0.95$, warrant some consideration and future investigation. More emphatic conclusions can be made regarding those analyses that indicated a poor relationship, $R^2 < 0.70$. Again, more data is needed, but at this point the PDO appears to have minimal, if any, bearing on demersal fish assemblages. Moreover, the climate observations in demersal fish assemblages of the SCB is similar to reports both from within the SCB and elsewhere by others examining both extensive temporal (Holbrook et al. 1997; Perry et al. 2005) and spatial scales (Mearns 1974; Juan-Jorda et al. 2009). Clearly, more regional surveys of the SCB will be needed to support a more extensive and statistically powerful analysis of trends, including non-climate forced changes, but preliminary evaluations of these suggest a climate link with most species except Pacific sanddab.

While several unique patterns were identified with the SCB regional demersal fish surveys, at least two well-known patterns were reaffirmed. The first was depth-related spatial patterns. Depth is a well-established principal factor segregating the SCB demersal fish community (Mearns 1979; Young et al. 1980; Juan-Jorda et al. 2009; Toole et al. 2011) and the analysis of SCB regional surveys reflects this spatial pattern (Allen and Pondella 2006; Miller and Schiff 2011). The second reaffirmation was the general lack of demersal fish community impacts due to offshore discharges of treated wastewater, particularly in the MS region. Neither abundance nor biomass appeared to be degraded in the MS region. Receiving the majority of wastewater discharge, impacts from these discharges would be expected to be most clearly manifested along the MS, but no such evidence was detected. This is consistent with local trend data near the discharge outfalls that have indicated fish community recovery after increased wastewater treatment (Stull and Tang 1996) and the lack of tumors, lesions, and fin rot in comparison to conditions prior to treatment upgrades near the outfalls (Cross 1986).

Habitat value scores based on fish feeding guilds calculated during the regional surveys were dissimilar among years, depths, and latitudes. Temporal differences likely reflected the elevated density and larger mean size of fishes taken in 2008 compared to the other survey years. Lower habitat value scores in shallower, southern waters were likely due to less dense assemblages of smaller individuals relative to the MS and OS. The fact that the IS is in closer proximity to fishermen (commercial and sport) and stormwater discharges warrants further consideration (Dotson and Charter 2003; Allen 2006; Love 2006). With the notable exceptions of Pacific sanddab, English sole, California halibut, and Dover sole (*Microstomus pacificus*), the small otter trawls used in these regional surveys do not target harvested populations (Leet et al. 2001). The harvesting effect may be one cause of the lack of any definable relationship between Pacific sanddab abundance indices and climate indices. Further analysis is needed on this question.

Stormwater discharges are known to contain pollutants that accumulate in both nearshore and offshore sediments (Schiff and Bay 2003) and stormwater plumes are known to extend over large areas, often many kilometers from shore (Nezlin et al. 2005). However, the duration of these offshore plumes is short, at most lasting several days, and storm-discharged pollutants are rapidly diluted with most toxics comprising only a small fraction of the plume extent (Reifel et al. 2009). Thus, the relative impacts of both fishing and water quality on nearshore demersal fishes remains uncertain and cannot be accurately described by our data.

While the magnitude of current fishing and stormwater pollution impacts are uncertain, the future effects of large-scale oceanographic forces could be demonstrable. The SCB regional surveys identified substantial changes in demersal fish abundance and biomass seemingly correlated to subtle changes in climate. This is likely due to the fine-tuned bioenergetics of demersal species in response to declining food availability with increasing depth, especially those occupying the deeper habitats (Vetter and Lynn 1997). The ecological ramifications of oceanographic warming in cold-adapted fishes was reviewed by Pörtner et al. (2008) who found altered physiological performance in fishes including heart rate, fecundity, and growth rate. Therefore, the subtle changes in environmental conditions at depth in the SCB observed by CalCOFI may have reduced the demersal fish community's resiliency, perhaps manifesting itself in the significant shift in size structure observed by the Bight surveys. Ocean warming, even temporary, has been demonstrated to cause substantial faunal changes and biogeographic shifts to avoid physiological penalties, including in demersal/benthic assemblages (Genner et al. 2004; Schiel et al. 2004; Perry et al. 2005; Miller et al. 2011). Future renditions of the SCB regional demersal fish survey may provide critical data to evaluate these patterns.

ACKNOWLEDGEMENTS

This report was prepared under the auspices of the Bight'08 Regional Monitoring Program and includes data collected during the Bight '94, '98, and '03 programs. We would like to thank all the agencies participating in each regional survey for their collection efforts and their comments and discussion on this manuscript. Productive discussions with C. Thomas, J. Gully, and S. Walther helped frame this work. This manuscript was greatly improved by the comments of L.G. Allen and five anonymous reviewers.

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APPENDIX A

List of species and guild assignments per Bond et al. (1999) and Pondella (2009).

Water Column Guilds

Guild 2: Selective feeding, diurnal
Genyonemus lineatus <100 mm SL, *Seriphus politus* <100 mm SL
Guild 3: Nocturnal
Hyperprosopon argenteum <60 mm SL, *Seriphus politus* >100 mm SL, *Xenistius californiensis*
Guild 23: Pelagic mesocarnivores
Atherinopsis californiensis, *Squalus acanthias*

Substrate Associated Guilds

Guild 5: Water column foragers, schooling, selective feeding, usually benthic refugers, diurnal
Chromis punctipinnis,*Sebastes auriculatus*, *Sebastes dallii* <60 mm SL, *Sebastes miniatus, Sebastes saxicola* <100 mm SL, *Sebastes umbrosus*
Guild 6: Nocturnal, visual
Sebastes diploproa, *Sebastes saxicola* >100 mm SL
Guild 7: Non-schooling, non-visual
Porichthys myriaster, *Porichthys notatus*
Guild 8: Water column/benthic foragers, schooling, often benthic refuging, diurnal, pickers
Cymatogaster aggregata
Guild 9: Non-schooling, diurnal, engulfers
Anoplopoma fimbria, *Heterostichus rostratus*, *Paralabrax clathratus*, *Paralabrax maculatofasciatus*, *Paralabrax nebulifer*
Guild 10: Nocturnal
Cephaloscyllium ventriosum, *Scorpaena guttata*, *Sebastes atrovirens*, *Sebastes dallii* >100 mm SL, *Sebastolobus alascanus*
Guild 11: Benthic foragers, schooling/non-schooling, diurnal, generalists
Embiotoca jacksoni, *Hypsurus caryi*, *Phanerodon furcatus*, *Sebastes caurinus*, *Zalembius rosaceus*
Guild 12: Crushers
Halichoeres semicinctus, *Myliobatis californica*, *Rhacochilus vacca*, *Semicossyphus pulcher*
Guild 14: Nocturnal, generalists
Cheilotrema saturnum, *Genyonemus lineatus* >100 mm SL, *Menticirrhus undulatus*, *Rhacochilus toxotes*, *Umbrina roncador*
Guild 15: Burrowers
Chilara taylori, *Ophidion scrippsae*

Benthic Guilds

Guild 16: Water column/benthic foragers, mesocarnivores
Hippoglossina stomata, *Ophiodon elongatus*, *Paralichthys californicus*, *Scorpaenichthys marmoratus*, *Synodus lucioceps*
Guild 17: Substrate sitters, microcarnivores, diurnal
Citharichthys fragilis, *Citharichthys sordidus*, *Citharichthys stigmaeus*, *Citharichthys xanthostigma*, *Lyopsetta exilis*, *Oxylebius pictus*, *Zaniolepis frenata*
Guild 18: Nocturnal
Leptocottus armatus, *Squatina californica*, *Xeneretmus latifrons*
Guild 19: Hiders (in holes and crevices), diurnal
Lepidogobius lepidus, *Lythrypnus dalli*, *Lythrypnus zebra*, *Rhinogobiops nicholsii*
Guild 20: Benthic foragers, pickers and scrapers, diurnal
Rathbunella alleni, *Rathbunella hypoplecta*
Guild 21: Nocturnal, non-visual
Gibbonsia montereyensis, *Glyptocephalus zachirus*, *Symphurus atricaudus*
Guild 22: Diggers and extractors
Lycodes cortezianus, *Lycodes pacificus*, *Microstomus pacificus*, *Parophrys vetulus*, *Pleuronichthys coenosus*, *Pleuronichthys decurrens*, *Pleuronichthys guttulatus*, *Pleuronichthys ritteri*, *Pleuronichthys verticalis*, *Urobatis halleri*

APPENDIX B-1

Mean density (count/1000 m^2 area swept) by species for each of the four Bight surveys taken on the inner shelf. Values are not adjusted for area-weights.

Inner Shelf	1994		1998		2003		2008	
Species	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Agonopsis sterletus	—	—	—	—	—	—	0.01	0.01
Anarrhichthys ocellatus	—	—	—	—	0.01	0.01	—	—
Anchoa compressa	—	—	0.01	0.01	—	—	—	—
Anchoa delicatissima	—	—	0.17	0.11	—	—	—	—
Artedius notospilotus	—	—	—	—	—	—	0.01	0.01
Atherinopsis californiensis	—	—	<0.01	<0.01	—	—	—	—
Cheilotrema saturnum	—	—	0.08	0.03	—	—	—	—
Chilara taylori	—	—	—	—	0.01	0.01	—	—
Chitonotus pugetensis	0.01	0.01	<0.01	<0.01	0.09	0.04	0.22	0.09
Chromis punctipinnis	—	—	—	—	0.01	0.01	—	—
Citharichthys sordidus	0.09	0.05	0.06	0.04	0.3	0.09	0.39	0.19
Citharichthys stigmaeus	1.09	0.2	0.38	0.08	4.54	0.91	3.63	0.68
Citharichthys xanthostigma	0.25	0.06	0.08	0.02	0.2	0.05	0.11	0.05
Cymatogaster aggregata	—	—	0.12	0.06	0.38	0.23	0.21	0.11
Dasyatis dipterura	—	—	0.01	0.01	—	—	—	—
Embiotoca jacksoni	—	—	0.03	0.01	0.01	0.01	0.02	0.02
Enophrys taurina	—	—	<0.01	<0.01	—	—	—	—
Genyonemus lineatus	0.41	0.31	10.49	3.79	0.19	0.09	0.09	0.05
Gibbonsia metzi	—	—	—	—	—	—	0.01	0.01
Gibbonsia montereyensis	—	—	—	—	0.02	0.02	—	—
Halichoeres semicinctus	0.01	0.01	—	—	—	—	—	—
Heterostichus rostratus	—	—	<0.01	<0.01	0.01	0.01	0.04	0.02
Hexagrammos decagrammus	—	—	—	—	—	—	0.01	0.01
Hippocampus ingens	—	—	0.02	0.01	—	—	—	—
Hippoglossina stomata	0.08	0.03	0.02	0.01	0.09	0.02	0.04	0.02
Hyperprosopon argenteum	—	—	0.03	0.02	0.04	0.04	—	—
Hypsurus caryi	—	—	—	—	0.03	0.02	0.05	0.03
Icelinus cavifrons	—	—	—	—	—	—	0.03	0.02
Icelinus quadriseriatus	0.15	0.06	0.01	0.01	0.56	0.23	0.48	0.18
Lepidogobius lepidus	0.04	0.03	0.03	0.02	0.03	0.02	—	—
Leptocottus armatus	—	—	—	—	0.01	0.01	0.09	0.03
Menticirrhus undulatus	—	—	0.03	0.01	0.01	0.01	—	—
Microstomus pacificus	—	—	—	—	<0.01	<0.01	—	—
Mustelus californicus	—	—	<0.01	<0.01	—	—	—	—
Myliobatis californica	—	—	0.01	0.01	0.01	0.01	—	—
Odontopyxis trispinosa	—	—	—	—	0.04	0.02	0.09	0.05
Ophidion scrippsae	—	—	<0.01	<0.01	—	—	—	—
Ophiodon elongatus	—	—	—	—	0.05	0.02	—	—
Oxylebius pictus	—	—	—	—	—	—	0.01	0.01
Paralabrax clathratus	0.01	0.01	0.01	0.01	—	—	—	—
Paralabrax maculatofasciatus	—	—	0.12	0.04	—	—	—	—
Paralabrax nebulifer	0.05	0.02	0.28	0.06	0.01	0.01	0.02	0.01
Paralichthys californicus	0.21	0.03	0.31	0.04	0.13	0.03	0.13	0.03
Parophrys vetulus	0.14	0.04	0.06	0.02	0.38	0.08	0.41	0.15
Peprilus simillimus	0.01	0.01	0.07	0.04	0.06	0.04	—	—
Phanerodon furcatus	0.03	0.02	0.18	0.06	0.14	0.04	0.19	0.09
Platyrhinoidis triseriata	0.05	0.02	0.04	0.01	—	—	0.03	0.02
Pleuronichthys coenosus	—	—	<0.01	<0.01	0.01	0.01	—	—
Pleuronichthys decurrens	—	—	—	—	0.26	0.08	0.01	0.01

APPENDIX B-1 (continued)
Mean density (count/1000 m^2 area swept) by species for each of the four Bight surveys taken on the inner shelf. Values are not adjusted for area-weights.

Inner Shelf	1994		1998		2003		2008	
Species	**Mean**	**SE**	**Mean**	**SE**	**Mean**	**SE**	**Mean**	**SE**
Pleuronichthys guttulatus	0.01	0.01	0.07	0.03	0.02	0.01	0.03	0.02
Pleuronichthys ritteri	0.17	0.04	0.2	0.04	0.05	0.02	0.11	0.03
Pleuronichthys verticalis	0.28	0.03	0.19	0.04	0.26	0.04	0.34	0.06
Porichthys myriaster	0.04	0.02	0.16	0.04	0.07	0.02	0.05	0.02
Porichthys notatus	0.02	0.01	—	—	0.06	0.02	0.05	0.03
Prionotus stephanophrys	<0.01	<0.01	—	—	—	—	—	—
Raja inornata	0.07	0.02	0.03	0.01	0.06	0.02	0.02	0.01
Rhacochilus toxotes	0.01	0.01	—	—	0.03	0.03	0.04	0.03
Rhacochilus vacca	—	—	—	—	0.01	0.01	—	—
Rhinobatos productus	—	—	0.03	0.01	0.01	0.01	0.02	0.02
Rhinogobiops nicholsii	—	—	—	—	0.01	0.01	0.01	0.01
Rimicola muscarum	—	—	—	—	—	—	0.02	0.02
Roncador stearnsii	—	—	—	—	—	—	0.02	0.02
Ruscarius creaseri	—	—	—	—	0.01	0.01	—	—
Scorpaena guttata	0.11	0.03	0.02	0.01	0.09	0.03	0.06	0.02
Scorpaenichthys marmoratus	—	—	—	—	—	—	0.02	0.02
Sebastes atrovirens	—	—	<0.01	<0.01	—	—	0.02	0.02
Sebastes auriculatus	—	—	<0.01	<0.01	—	—	—	—
Sebastes caurinus	0.01	0.01	0.01	0.01	0.16	0.1	0.06	0.03
Sebastes constellatus	0.01	0.01	—	—	—	—	—	—
Sebastes dallii	0.02	0.02	—	—	—	—	0.02	0.01
Sebastes goodei	—	—	—	—	0.27	0.27	—	—
Sebastes miniatus	0.01	0.01	—	—	0.02	0.01	0.08	0.05
Sebastes paucispinis	—	—	—	—	0.01	0.01	—	—
Sebastes saxicola	0.02	0.02	—	—	0.02	0.02	—	—
Sebastes semicinctus	—	—	—	—	0.01	0.01	—	—
Seriphus politus	0.03	0.02	1.18	0.5	0.1	0.04	0.01	0.01
Squalus acanthias	—	—	<0.01	<0.01	—	—	—	—
Symphurus atricaudus	0.17	0.06	0.58	0.16	0.08	0.03	0.17	0.05
Syngnathus californiensis	—	—	<0.01	<0.01	—	—	—	—
Syngnathus exilis	0.01	0.01	0.01	0.01	0.01	0.01	0.07	0.03
Synodus lucioceps	0.26	0.04	0.82	0.19	0.16	0.04	0.24	0.05
Trachurus symmetricus	0.01	0.01	—	—	—	—	—	—
Trichiurus nitens	—	—	<0.01	<0.01	—	—	—	—
Umbrina roncador	—	—	0.01	0.01	—	—	—	—
Urobatis halleri	—	—	0.14	0.04	—	—	—	—
Xenistius californiensis	—	—	—	—	—	—	0.02	0.02
Xystreurys liolepis	0.18	0.03	0.13	0.03	0.08	0.02	0.12	0.03
Zalembius rosaceus	0.12	0.09	0.02	0.02	0.48	0.17	0.35	0.18
Zaniolepis latipinnis	0.06	0.04	<0.01	<0.01	0.2	0.07	0.01	0.01

APPENDIX B-2

Mean density (count/1000 m² area swept) by species for each of the four Bight surveys taken on the middle shelf. Values are not adjusted for area-weights.

Middle Shelf	1994		1998		2003		2008	
Species	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Agonopsis sterletus	—	—	0.02	0.01	0.05	0.02	—	—
Anarrhichthys ocellatus	—	—	—	—	<0.01	<0.01	—	—
Argentina sialis	0.32	0.09	0.25	0.07	0.29	0.11	—	—
Bollmannia gomezi	—	—	—	—	0.01	0.01	—	—
Brosmophycis marginata	0.01	0.01	—	—	—	—	—	—
Caulolatilus princeps	—	—	<0.01	<0.01	—	—	—	—
Cephaloscyllium ventriosum	<0.01	<0.01	0.01	0.01	<0.01	<0.01	—	—
Chilara taylori	0.07	0.02	0.03	0.01	0.09	0.02	0.08	0.03
Chitonotus pugetensis	0.1	0.03	0.13	0.04	0.55	0.09	0.86	0.21
Citharichthys fragilis	0.04	0.02	0.14	0.03	0.01	0.01	—	—
Citharichthys sordidus	2.46	0.7	0.92	0.1	3.67	0.3	2.21	0.38
Citharichthys stigmaeus	0.35	0.09	0.33	0.08	0.95	0.2	0.74	0.28
Citharichthys xanthostigma	0.59	0.09	1.22	0.13	0.57	0.08	0.55	0.11
Clupea pallasii	—	—	<0.01	<0.01	—	—	—	—
Cryptotrema corallinum	—	—	0.03	0.02	<0.01	<0.01	—	—
Cymatogaster aggregata	—	—	0.03	0.03	0.02	0.01	0.01	0.01
Engyophrys sanctilaurentii	—	—	<0.01	<0.01	—	—	—	—
Enophrys taurina	—	—	0.01	0.01	0.06	0.02	0.04	0.04
Eopsetta jordani	—	—	0.01	<0.01	<0.01	<0.01	—	—
Eptatretus stoutii	0.01	0.01	<0.01	<0.01	—	—	—	—
Genyonemus lineatus	—	—	0.17	0.06	0.01	<0.01	0.03	0.02
Glyptocephalus zachirus	0.01	0.01	—	—	0.01	0.01	—	—
Hippoglossina stomata	0.29	0.03	0.34	0.03	0.19	0.02	0.26	0.04
Hydrolagus colliei	—	—	0.01	<0.01	<0.01	<0.01	—	—
Icelinus cavifrons	—	—	0.01	<0.01	0.09	0.07	—	—
Icelinus fimbriatus	<0.01	<0.01	—	—	<0.01	<0.01	—	—
Icelinus quadriseriatus	1.7	0.37	1.6	0.21	4.64	0.73	5.41	1.26
Icelinus tenuis	0.02	0.01	0.09	0.03	0.1	0.03	0.02	0.01
Icichthys lockingtoni	—	—	—	—	<0.01	<0.01	—	—
Kathetostoma averruncus	0.01	0.01	0.01	<0.01	<0.01	<0.01	—	—
Lepidogobius lepidus	0.6	0.14	0.33	0.09	0.43	0.07	0.23	0.13
Lepidopsetta bilineata	—	—	—	—	0.01	0.01	—	—
Lycodes pacificus	0.03	0.01	0.03	0.01	0.04	0.01	0.03	0.02
Lyconema barbatum	—	—	—	—	0.01	0.01	—	—
Lyopsetta exilis	0.2	0.09	0.07	0.02	0.05	0.02	0.08	0.04
Lythrypnus dalli	—	—	0.02	0.02	—	—	—	—
Lythrypnus zebra	—	—	<0.01	<0.01	—	—	—	—
Macroramphosus gracilis	—	—	0.01	0.01	—	—	—	—
Merluccius productus	<0.01	<0.01	0.01	<0.01	—	—	0.01	0.01
Microstomus pacificus	0.4	0.05	0.34	0.1	0.73	0.11	0.3	0.06
Mustelus henlei	—	—	<0.01	<0.01	—	—	—	—
Myliobatis californica	<0.01	<0.01	—	—	—	—	—	—
Neoclinus blanchardi	—	—	<0.01	<0.01	—	—	—	—
Odontopyxis trispinosa	0.05	0.02	0.07	0.02	0.22	0.04	0.23	0.07
Ophiodon elongatus	0.02	0.01	<0.01	<0.01	0.14	0.02	0.09	0.04
Oxylebius pictus	0.01	0.01	—	—	0.01	0.01	—	—
Paralabrax clathratus	—	—	0.01	0.01	—	—	—	—
Paralabrax nebulifer	—	—	0.01	0.01	<0.01	<0.01	—	—
Paralichthys californicus	0.01	0.01	0.09	0.02	0.03	0.01	—	—
Parophrys vetulus	0.19	0.03	0.16	0.02	0.28	0.03	0.69	0.33
Peprilus simillimus	—	—	—	—	0.01	0.01	0.01	0.01
Phanerodon furcatus	—	—	—	—	—	—	0.01	0.01
Plectobranchus evides	—	—	<0.01	<0.01	0.01	0.01	0.01	0.01
Pleuronectes bilineatus	—	—	<0.01	<0.01	—	—	—	—
Pleuronectiformes	—	—	—	—	0.01	0.01	—	—
Pleuronichthys coenosus	—	—	0.01	0.01	<0.01	<0.01	—	—
Pleuronichthys decurrens	0.03	0.02	0.04	0.01	0.14	0.03	0.01	0.01
Pleuronichthys ritteri	0.01	0.01	0.01	0.01	<0.01	<0.01	0.01	0.01
Pleuronichthys verticalis	0.2	0.02	0.24	0.02	0.29	0.03	0.36	0.04
Porichthys myriaster	0.04	0.01	0.08	0.02	0.01	0.01	0.04	0.02
Porichthys notatus	0.82	0.22	0.49	0.12	0.42	0.05	0.47	0.09
Prionotus stephanophrys	—	—	0.06	0.02	<0.01	<0.01	—	—

APPENDIX B-2 (continued)

Mean density (count/1000 m^2 area swept) by species for each of the four Bight surveys taken on the middle shelf. Values are not adjusted for area-weights.

Middle Shelf	1994		1998		2003		2008	
Species	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Radulinus asprellus	—	—	—	—	<0.01	<0.01	—	—
Raja binoculata	—	—	—	—	<0.01	<0.01	—	—
Raja inornata	0.09	0.02	0.07	0.01	0.08	0.02	0.11	0.03
Raja stellulata	0.01	0.01	<0.01	<0.01	0.01	0.01	—	—
Rathbunella alleni	0.01	0.01	<0.01	<0.01	—	—	—	—
Rathbunella hypoplecta	0.02	0.01	0.01	<0.01	0.02	0.01	0.03	0.02
Rhacochilus vacca	—	—	0.01	0.01	<0.01	<0.01	—	—
Rhinogobiops nicholsii	0.02	0.02	0.02	0.01	0.08	0.05	0.02	0.01
Scorpaena guttata	0.14	0.05	0.14	0.02	0.15	0.02	0.11	0.03
Sebastes auriculatus	<0.01	<0.01	—	—	—	—	—	—
Sebastes caurinus	<0.01	<0.01	0.01	<0.01	0.02	0.01	—	—
Sebastes chlorostictus	0.03	0.02	0.03	0.01	0.02	0.01	0.06	0.03
Sebastes constellatus	—	—	0.01	0.01	0.01	0.01	—	—
Sebastes dallii	0.07	0.04	0.06	0.06	0.04	0.02	0.31	0.18
Sebastes diploproa	0.01	0.01	0.02	0.02	<0.01	<0.01	—	—
Sebastes elongatus	0.02	0.01	0.02	0.01	0.14	0.03	0.07	0.03
Sebastes eos	0.01	0.01	0.03	0.01	0.2	0.11	0.05	0.03
Sebastes goodei	—	—	—	—	0.1	0.03	—	—
Sebastes hopkinsi	<0.01	<0.01	—	—	0.05	0.04	0.05	0.03
Sebastes jordani	—	—	<0.01	<0.01	0.4	0.29	0.01	0.01
Sebastes lentiginosus	—	—	0.01	<0.01	—	—	—	—
Sebastes levis	0.03	0.01	<0.01	<0.01	0.14	0.04	0.01	0.01
Sebastes macdonaldi	—	—	<0.01	<0.01	—	—	—	—
Sebastes miniatus	0.02	0.02	0.02	0.01	0.03	0.01	0.05	0.04
Sebastes paucispinis	—	—	—	—	0.01	0.01	—	—
Sebastes pinniger	0.01	0.01	—	—	—	—	—	—
Sebastes rosaceus	0.01	0.01	—	—	0.02	0.01	0.01	0.01
Sebastes rosenblatti	0.06	0.02	0.04	0.01	0.04	0.02	0.04	0.02
Sebastes rubrivinctus	0.01	0.01	0.01	<0.01	0.01	0.01	0.02	0.01
Sebastes rufus	—	—	—	—	—	—	0.01	0.01
Sebastes saxicola	0.45	0.1	0.29	0.06	2.03	0.39	0.57	0.16
Sebastes semicinctus	0.2	0.08	0.08	0.05	3.27	1.69	1.08	0.68
Sebastes simulator	—	—	<0.01	<0.01	—	—	—	—
Sebastes sp.	0.02	0.01	0.02	0.01	—	—	—	—
Sebastes umbrosus	0.01	0.01	<0.01	<0.01	0.01	0.01	0.02	0.02
Semicossyphus pulcher	—	—	<0.01	<0.01	<0.01	<0.01	—	—
Seriphus politus	—	—	0.04	0.02	—	—	—	—
Squalus acanthias	—	—	—	—	—	—	0.01	0.01
Squatina californica	<0.01	<0.01	<0.01	<0.01	—	—	—	—
Symphurus atricaudus	0.53	0.14	0.47	0.05	0.43	0.06	0.43	0.08
Synchiropus atrilabiatus	—	—	<0.01	<0.01	—	—	—	—
Synodus lucioceps	0.21	0.03	1.66	0.28	0.1	0.02	0.2	0.04
Torpedo californica	—	—	0.01	0.01	—	—	0.01	0.01
Trachurus symmetricus	—	—	<0.01	<0.01	—	—	—	—
Trichiurus nitens	—	—	<0.01	<0.01	—	—	—	—
Xeneretmus latifrons	0.02	0.01	<0.01	<0.01	0.03	0.02	0.03	0.02
Xeneretmus triacanthus	0.01	0.01	0.01	0.01	0.03	0.01	0.02	0.01
Xystreurys liolepis	0.04	0.01	0.08	0.02	0.03	0.01	0.05	0.02
Zalembius rosaceus	0.48	0.06	0.35	0.05	0.55	0.05	1.18	0.31
Zaniolepis frenata	0.13	0.04	0.1	0.02	0.24	0.05	0.23	0.06
Zaniolepis latipinnis	0.61	0.14	0.42	0.08	1.63	0.22	0.95	0.24

APPENDIX B-3

Mean density (count/1000 m² area swept) by species for each of the four Bight surveys taken on the outer shelf. Values are not adjusted for area-weights.

Outer Shelf	1994		1998		2003		2008	
Species	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Anoplopoma fimbria	—	—	0.01	0.01	0.01	0.01	—	—
Argentina sialis	0.05	0.04	0.08	0.04	0.05	0.02	—	—
Argyropelecus sladeni	—	—	—	—	—	—	0.01	0.01
Bathyraja interrupta	—	—	—	—	—	—	0.02	0.02
Chilara taylori	0.07	0.03	0.19	0.06	0.21	0.07	0.19	0.04
Citharichthys fragilis	0.11	0.09	0.13	0.05	0.07	0.06	0.02	0.02
Citharichthys sordidus	0.78	0.14	1.49	0.31	1.69	0.31	2.13	0.75
Citharichthys stigmaeus	—	—	—	—	0.01	0.01	—	—
Citharichthys xanthostigma	—	—	0.02	0.02	0.02	0.02	0.02	0.02
Eopsetta jordani	0.02	0.02	0.02	0.01	0.01	0.01	0.07	0.03
Eptatretus stoutii	—	—	0.01	0.01	—	—	—	—
Glyptocephalus zachirus	0.39	0.07	0.13	0.03	0.34	0.1	0.21	0.07
Hippoglossina stomata	0.12	0.04	0.09	0.03	0.09	0.03	0.1	0.04
Hydrolagus colliei	—	—	0.04	0.02	0.09	0.03	0.08	0.04
Icelinus filamentosus	0.01	0.01	0.01	0.01	0.01	0.01	—	—
Icelinus oculatus	—	—	—	—	0.02	0.02	—	—
Icelinus quadriseriatus	0.02	0.02	0.02	0.02	—	—	—	—
Icelinus tenuis	—	—	0.23	0.1	0.15	0.08	0.01	0.01
Kathetostoma averruncus	0.03	0.03	—	—	0.01	0.01	—	—
Lepidogobius lepidus	—	—	0.01	0.01	—	—	—	—
Lycodes cortezianus	0.01	0.01	0.04	0.03	0.03	0.02	0.05	0.03
Lycodes pacificus	0.36	0.12	0.22	0.06	0.4	0.11	0.47	0.12
Lyconema barbatum	0.02	0.02	0.07	0.03	0.14	0.06	0.03	0.02
Lyopsetta exilis	1.59	0.32	1.99	0.37	2.87	0.77	2.69	0.49
Merluccius productus	0.85	0.37	0.09	0.03	0.16	0.04	0.13	0.04
Microstomus pacificus	0.71	0.13	0.87	0.18	0.74	0.14	0.58	0.05
Mustelus henlei	—	—	—	—	—	—	0.02	0.02
Odontopyxis trispinosa	—	—	—	—	0.01	0.01	—	—
Ophiodon elongatus	—	—	0.01	0.01	0.01	0.01	0.01	0.01
Parmaturus xaniurus	—	—	—	—	0.01	0.01	—	—
Parophrys vetulus	0.09	0.03	0.26	0.05	0.32	0.19	0.44	0.1
Physiculus rastrelliger	—	—	0.01	0.01	—	—	—	—
Plectobranchus evides	0.11	0.05	0.07	0.03	0.22	0.13	0.05	0.03
Pleuronectes bilineatus	—	—	0.01	0.01	—	—	—	—
Pleuronectiformes	—	—	—	—	0.01	0.01	—	—
Pleuronichthys decurrens	—	—	0.04	0.04	0.04	0.02	—	—
Pleuronichthys verticalis	—	—	0.01	0.01	0.04	0.03	0.1	0.05
Porichthys notatus	1.38	0.74	0.49	0.09	0.24	0.07	0.38	0.11
Radulinus asprellus	—	—	0.01	0.01	0.02	0.02	—	—
Raja binoculata	—	—	0.01	0.01	—	—	—	—
Raja inornata	0.01	0.01	0.03	0.02	0.06	0.03	0.04	0.02
Raja rhina	—	—	0.02	0.01	0.02	0.02	0.03	0.02
Raja stellulata	—	—	0.04	0.03	0.01	0.01	—	—
Rathbunella hypoplecta	—	—	—	—	0.01	0.01	—	—
Scorpaena guttata	—	—	0.01	0.01	0.03	0.02	0.01	0.01
Sebastes caurinus	—	—	0.02	0.02	—	—	—	—
Sebastes chlorostictus	0.06	0.03	0.09	0.04	0.05	0.04	0.08	0.03
Sebastes dallii	—	—	—	—	0.02	0.02	—	—
Sebastes diploproa	1.14	0.58	0.42	0.19	0.72	0.35	0.38	0.2

APPENDIX B-3 (continued)
Mean density (count/1000 m^2 area swept) by species for each of the four Bight surveys taken on the outer shelf. Values are not adjusted for area-weights.

Outer Shelf	1994		1998		2003		2008	
Species	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Sebastes elongatus	0.2	0.05	0.07	0.03	0.15	0.05	0.29	0.06
Sebastes ensifer	—	—	0.03	0.02	—	—	—	—
Sebastes eos	0.06	0.03	0.06	0.03	0.05	0.02	0.19	0.05
Sebastes goodei	—	—	0.02	0.01	0.04	0.02	0.01	0.01
Sebastes jordani	0.04	0.03	0.03	0.01	0.12	0.07	0.04	0.03
Sebastes levis	0.02	0.02	—	—	0.02	0.02	0.02	0.02
Sebastes macdonaldi	—	—	0.02	0.01	0.02	0.02	—	—
Sebastes melanostomus	—	—	—	—	—	—	0.07	0.07
Sebastes rosaceus	—	—	0.03	0.03	—	—	—	—
Sebastes rosenblatti	0.14	0.04	0.04	0.02	0.1	0.04	0.11	0.04
Sebastes rubrivinctus	0.01	0.01	0.03	0.02	0.03	0.02	0.03	0.02
Sebastes saxicola	0.96	0.2	0.77	0.18	2.93	1.12	2.16	0.53
Sebastes semicinctus	0.05	0.03	0.18	0.06	0.25	0.14	0.48	0.15
Sebastes sp.	0.05	0.03	0.02	0.02	0.01	0.01	—	—
Sebastolobus alascanus	0.04	0.02	0.01	0.01	0.03	0.02	—	—
Seriphus politus	—	—	0.01	0.01	—	—	—	—
Symphurus atricaudus	0.03	0.03	—	—	—	—	0.02	0.02
Syngnathus exilis	—	—	0.01	0.01	—	—	—	—
Synodus lucioceps	0.05	0.03	0.02	0.01	—	—	—	—
Xeneretmus latifrons	0.39	0.13	0.44	0.16	0.92	0.23	0.7	0.13
Xeneretmus triacanthus	0.03	0.02	0.09	0.03	0.13	0.04	0.09	0.04
Zalembius rosaceus	0.04	0.03	0.25	0.06	0.15	0.05	0.45	0.16
Zaniolepis frenata	0.49	0.06	0.91	0.19	1.07	0.21	1.15	0.26
Zaniolepis latipinnis	0.02	0.02	0.21	0.07	0.14	0.08	0.2	0.09

APPENDIX C

Mean length and total number measured by species for each of the four Bight surveys and the grand mean across all surveys. Shaded cells indicate a value less than the grand mean.

	Abundance Weighted Mean Length (cm)					
Species	1994	1998	2003	2008	Overall	Total Measured
Citharichthys sordidus	8.97	11.91	9.28	12.48	10.21	31,924
Citharichthys stigmaeus	7.55	8.33	7.30	8.14	7.61	11,302
Icelinus quadriseriatus	6.30	6.57	6.64	6.57	6.57	8,641
Lyopsetta exilis	11.54	11.47	12.08	11.86	11.77	7,960
Genyonemus lineatus	16.87	8.80	14.31	15.33	9.64	6,642
Sebastes saxicola	9.51	9.18	8.19	9.92	8.75	5,934
Citharichthys xanthostigma	12.02	10.22	13.13	12.24	11.20	5,827
Synodus lucioceps	20.37	10.67	16.55	15.35	11.24	5,642
Zaniolepis latipinnis	13.55	13.02	10.29	12.45	11.30	4,911
Microstomus pacificus	11.03	10.08	9.52	12.83	10.29	4,614
Porichthys notatus	11.69	11.44	12.22	13.09	11.82	4,563
Sebastes semicinctus	11.48	7.69	6.82	11.95	8.46	4,179
Zalembius rosaceus	8.08	9.32	8.24	7.77	8.25	3,254
Symphurus atricaudus	10.83	11.27	13.65	11.90	11.65	2,852
Zaniolepis frenata	13.36	12.77	12.49	12.07	12.55	2,687
Parophrys vetulus	19.93	17.96	15.39	14.52	15.78	2,425
Lepidogobius lepidus	4.26	6.21	7.15	7.56	5.80	1,401
Lycodes pacificus	12.18	17.47	15.70	16.00	15.38	1,372
Pleuronichthys verticalis	14.86	13.99	14.67	14.51	14.48	1,292
Seriphus politus	15.14	8.58	12.78	13.00	8.81	1,060
Chitonotus pugetensis	7.05	7.72	8.25	8.29	8.16	1,017
Sebastes diploproa	6.64	5.45	6.83	7.17	6.51	977
Xeneretmus latifrons	11.70	12.50	12.29	12.72	12.35	893
Hippoglossina stomata	16.00	15.62	19.59	16.24	16.53	807
Argentina sialis	6.59	5.52	6.10	—	5.89	698
Glyptocephalus zachirus	13.43	16.53	11.31	14.55	12.77	456
Pleuronichthys decurrens	12.67	10.92	9.03	7.00	9.30	428
Icelinus tenuis	8.21	9.37	9.43	8.67	9.34	417
Merluccius productus	8.24	23.23	18.46	19.85	10.47	413
Scorpaena guttata	17.32	17.30	19.63	19.36	18.41	405
Paralichthys californicus	32.39	26.61	36.36	27.00	29.62	376
Cymatogaster aggregata	—	10.35	8.02	7.40	8.60	350
Sebastes jordani	15.00	12.43	8.75	13.67	9.06	346
Chilara taylori	16.00	17.24	17.65	17.19	17.35	321
Citharichthys fragilis	12.42	10.40	15.61	16.50	12.18	270
Sebastes elongatus	11.19	12.53	7.83	12.09	10.16	261
Sebastes goodei	—	24.00	7.93	14.00	8.21	247
Odontopyxis trispinosa	7.82	7.78	7.78	7.77	7.78	244
Phanerodon furcatus	13.25	11.78	11.39	11.22	11.59	228
Xystreurys liolepis	17.92	18.50	19.80	18.03	18.50	224
Sebastes dallii	12.05	5.42	7.26	10.67	8.51	212
Sebastes rosenblatti	15.13	6.64	11.31	10.20	11.20	200
Porichthys myriaster	19.86	17.84	18.43	18.79	18.25	175
Pleuronichthys ritteri	16.43	14.41	15.00	14.70	15.07	157
Ophiodon elongatus	14.60	12.50	15.16	14.11	14.84	142
Raja inornata	31.33	38.62	30.04	27.20	32.58	132
Sebastes chlorostictus	9.19	10.63	12.67	9.50	10.80	131
Sebastes eos	9.71	9.00	4.60	9.67	7.07	118
Lyconema barbatum	14.33	14.74	14.04	15.00	14.22	113
Plectobranchus evides	9.69	10.88	11.02	10.00	10.73	101
Urobatis halleri	—	25.58	—	—	25.58	101
Sebastes caurinus	10.33	6.20	5.84	7.30	6.35	100
Xeneretmus triacanthus	11.00	13.66	12.60	13.18	12.95	93
Paralabrax nebulifer	22.57	18.51	27.00	23.00	19.13	88
Rhinogobiops nicholsii	8.00	7.27	6.65	7.67	6.97	88
Sebastes levis	7.56	6.50	7.09	9.00	7.18	80
Enophrys taurina	—	7.33	8.84	9.10	8.85	74
Sebastes miniatus	11.42	9.50	8.47	8.36	9.04	74
Anchoa delicatissima	—	6.40	—	—	6.40	60
Sebastes hopkinsi	5.00	—	7.03	14.00	9.83	59
Cryptotrema corallinum	—	8.40	6.00	—	8.36	56
Icelinus cavifrons	—	5.50	5.98	7.33	6.04	50
Paralabrax maculatofasciatus	—	20.86	—	—	20.86	50
Prionotus stephanophrys	24.00	11.14	27.00	—	11.78	45

APPENDIX C (continued)

Mean length and total number measured by species for each of the four Bight surveys and the grand mean across all surveys. Shaded cells indicate a value less than the grand mean.

	Abundance Weighted Mean Length (cm)					
Species	1994	1998	2003	2008	Overall	Total Measured
Hydrolagus colliei	—	27.82	29.79	38.67	30.32	37
Peprilus simillimus	7.00	8.63	9.67	10.00	9.32	31
Agonopsis sterletus	—	11.14	10.95	10.00	10.96	27
Sebastes rubrivinctus	11.25	14.20	12.33	11.78	12.33	27
Syngnathus exilis	24.00	18.86	22.25	19.23	19.80	25
Hypsurus caryi	—	—	8.57	8.59	8.58	24
Sebastolobus alascanus	18.00	17.00	13.00	—	15.54	24
Pleuronichthys guttulatus	20.00	19.27	20.67	16.75	19.04	23
Lycodes cortezianus	22.00	10.83	21.80	15.20	15.82	22
Rathbunella hypoplecta	13.25	11.67	11.43	13.00	12.14	21
Cheilotrema saturnum	—	17.44	—	—	17.44	18
Hyperprosopon argenteum	—	8.62	9.00	—	8.72	18
Leptocottus armatus	—	—	12.33	11.67	11.78	18
Platyrhinoidis triseriata	40.00	36.80	—	26.00	35.89	18
Sebastes melanostomus	—	—	—	6.44	6.44	18
Sebastes sp.	2.75	5.38	4.00	—	4.06	17
Eopsetta jordani	32.50	37.00	29.00	28.83	32.07	15
Rhacochilus toxotes	19.50	—	8.20	8.50	9.87	15
Sebastes rosaceus	10.00	3.57	5.50	11.00	5.27	15
Pleuronichthys coenosus	—	15.50	15.67	—	15.57	14
Sebastes ensifer	—	14.14	—	—	14.14	14
Sebastes umbrosus	16.17	17.00	3.50	9.67	11.21	14
Lythrypnus dalli	—	3.46	—	—	3.46	13
Embiotoca jacksoni	—	13.50	10.33	13.00	12.67	12
Rhinobatos productus	—	44.14	41.00	23.75	37.08	12
Physiculus rastrelliger	—	13.45	—	—	13.45	11
Rhacochilus vacca	—	8.22	18.00	—	10.00	11
Paralabrax clathratus	20.00	19.67	—	—	19.70	10
Cephaloscyllium ventriosum	32.50	31.83	66.00	—	35.78	9
Raja stellulata	15.50	16.50	21.33	—	17.89	9
Heterostichus rostratus	—	8.00	8.00	8.00	8.00	8
Kathetostoma averruncus	16.50	17.00	21.00	—	17.75	8
Lepidopsetta bilineata	—	—	19.25	—	19.25	8
Macroramphosus gracilis	—	8.00	—	—	8.00	8
Menticirrhus undulatus	—	21.83	20.50	—	21.50	8
Radulinus asprellus	—	10.00	10.57	—	10.50	8
Raja rhina	—	32.50	67.50	30.50	40.75	8
Gibbonsia montereyensis	—	—	5.43	—	5.43	7
Sebastes macdonaldi	—	8.50	5.67	—	7.29	7
Sebastes constellatus	3.00	4.33	4.00	—	4.00	6
Myliobatis californica	85.00	57.00	74.00	—	69.40	5
Oxylebius pictus	14.00	—	5.33	12.00	8.40	5
Rathbunella alleni	10.00	9.00	—	—	9.20	5
Sebastes atrovirens	—	6.00	—	9.75	9.00	5
Anchoa compressa	—	11.50	—	—	11.50	4
Eptatretus stoutii	20.50	45.00	—	—	32.75	4
Pleuronectes bilineatus	—	21.50	—	—	21.50	4
Syngnathus californiensis	—	18.50	—	—	18.50	4
Torpedo californica	—	46.33	—	23.00	40.50	4
Trichiurus nitens	—	41.50	—	—	41.50	4
Umbrina roncador	—	15.25	—	—	15.25	4
Icelinus filamentosus	16.00	16.00	10.00	—	14.00	3
Mustelus henlei	—	71.50	—	51.00	64.67	3
Sebastes auriculatus	18.00	14.00	—	—	15.33	3
Sebastes paucispinis	—	—	11.33	—	11.33	3
Anoplopoma fimbria	—	18.00	26.00	—	22.00	2
Bollmannia gomezi	—	—	9.00	—	9.00	2
Caulolatilus princeps	—	16.50	—	—	16.50	2
Hippocampus ingens	—	20.00	—	—	20.00	2
Icelinus fimbriatus	16.00	—	14.00	—	15.00	2
Icelinus oculatus	—	—	13.00	—	13.00	2
Pleuronectiformes	—	—	3.00	—	3.00	2
Raja binoculata	—	60.00	17.00	—	38.50	2
Roncador stearnsii	—	—	—	27.50	27.50	2

APPENDIX C (continued)

Mean length and total number measured by species for each of the four Bight surveys and the grand mean across all surveys. Shaded cells indicate a value less than the grand mean.

	Abundance Weighted Mean Length (cm)					
Species	1994	1998	2003	2008	Overall	Total Measured
Scorpaenichthys marmoratus	—	—	—	13.50	13.50	2
Sebastes lentiginosus	—	3.00	—	—	3.00	2
Semicossyphus pulcher	—	13.00	26.00	—	19.50	2
Squalus acanthias	—	65.00	—	101.00	83.00	2
Squatina californica	85.00	27.00	—	—	56.00	2
Trachurus symmetricus	16.00	10.00	—	—	13.00	2
Anarrhichthys ocellatus	—	—	66.00	—	66.00	1
Argyropelecus sladeni	—	—	—	3.00	3.00	1
Artedius notospilotus	—	—	—	8.00	8.00	1
Atherinopsis californiensis	—	26.00	—	—	26.00	1
Bathyraja interrupta	—	—	—	8.00	8.00	1
Brosmophycis marginata	29.00	—	—	—	29.00	1
Chromis punctipinnis	—	—	12.00	—	12.00	1
Clupea pallasii	—	14.00	—	—	14.00	1
Dasyatis dipterura	—	43.00	—	—	43.00	1
Engyophrys sanctilaurentii	—	9.00	—	—	9.00	1
Gibbonsia metzi	—	—	—	6.00	6.00	1
Halichoeres semicinctus	19.00	—	—	—	19.00	1
Hexagrammos decagrammus	—	—	—	11.00	11.00	1
Icichthys lockingtoni	—	—	3.00	—	3.00	1
Lythrypnus zebra	—	3.00	—	—	3.00	1
Mustelus californicus	—	66.00	—	—	66.00	1
Neoclinus blanchardi	—	18.00	—	—	18.00	1
Ophidion scrippsae	—	19.00	—	—	19.00	1
Parmaturus xaniurus	—	—	28.00	—	28.00	1
Rimicola muscarum	—	—	—	2.00	2.00	1
Ruscarius creaseri	—	—	5.00	—	5.00	1
Sebastes pinniger	22.00	—	—	—	22.00	1
Sebastes rufus	—	—	—	13.00	13.00	1
Sebastes simulator	—	4.00	—	—	4.00	1
Synchiropus atrilabiatus	—	6.00	—	—	6.00	1
Xenistius californiensis	—	—	—	15.00	15.00	1

A TIME SERIES OF CALIFORNIA SPINY LOBSTER (*PANULIRUS INTERRUPTUS*) PHYLLOSOMA FROM 1951 TO 2008 LINKS ABUNDANCE TO WARM OCEANOGRAPHIC CONDITIONS IN SOUTHERN CALIFORNIA

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ABSTRACT

The California spiny lobster (*Panulirus interruptus*) population is the basis for a valuable commercial and recreational fishery off southern California, yet little is known about its population dynamics. Studies based on CalCOFI sampling in the 1950s indicated that the abundance of phyllosoma larvae may be sensitive to oceanographic conditions such as El Niño events. To further study the potential influence of environmental variability and the fishery on lobster productivity, we developed a 60-year time series of the abundance of lobster phyllosoma from the historical CalCOFI sample collection. Phyllosoma were removed from the midsummer cruises when the early-stage larvae are most abundant in the plankton nearshore. We found that the abundance of the early-stage phyllosoma displayed considerable interannual variability but was significantly positively correlated with El Niño events, mean sea-surface temperature, and the Pacific Decadal Oscillation, which are significantly intercorrelated. Conditions during the warm years (1950s and 1980–present) were the most productive for lobster phyllosoma in the Southern California Bight. Total lobster fishery landings show an increasing trend since 1980 due to increasing commercial landings from 1980–2000 and increased recreational landings since 2005. However, this trend is not observed in the phyllosoma time series or in the Baja California fishery, whose landings are correlated with the U.S. fishery. We suggest that the stage 1 phyllosoma may provide a useful fishery-independent index of spiny lobster spawning stock biomass and stock productivity. Due to the relationship identified here between environmental conditions and phyllosoma abundance, we suggest that this information could be used as an environmental indicator for management.

INTRODUCTION

The California spiny lobster (*Panulirus interruptus*) has been fished commercially off southern California since the late 1800s. Commercial landings peaked around 1949–55, declined in the period 1955–75, and subsequently increased, following the requirement in 1976 that commercial lobster traps be fitted with escape ports to reduce the proportion of "shorts" in the landings (fig. 1) (Neilson 2011). Since 2000, the commercial fishery has landed approximately 300 mt annually, with 319 mt landed in 2010 for an ex-vessel price of $11.13 million. While the commercial landings have been stable since 2000, recreational landings have increased considerably due to the growing popularity of hoopnet fishing, particularly since 2005. The recreational fishery now accounts for 30%–60% of the commercial fishery (fig. 1). However, the fishery was considered sustainable in a recent stock assessment (Neilson 2011), and no regulatory change is currently proposed for California.

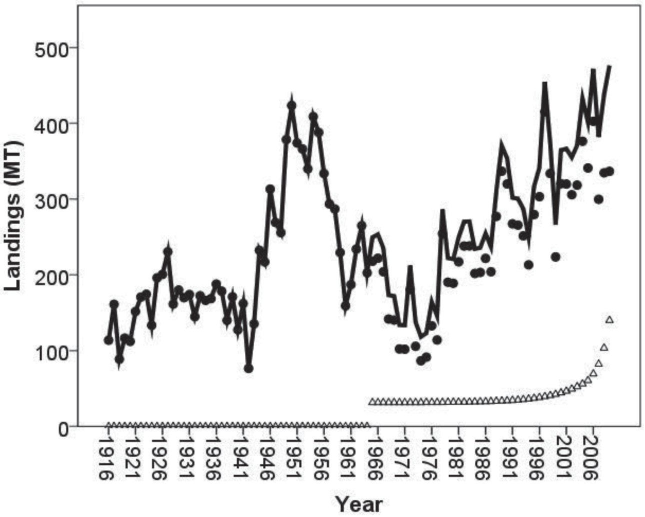

Figure 1. Commercial (solid circles), recreational (open triangles), and total landings (solid line) of spiny lobster off southern California.

Early life-history stages of marine organisms can serve as an indicator of the abundance and productivity of the adult spawning stock (Hsieh et al. 2005). Egg and larval surveys in California Cooperative Oceanic Fisheries Investigations (CalCOFI) are routinely used as indicators of spawning stock biomass for fisheries management (Moser et al. 2001; Lo et al. 2005). We suggest that the early stage phyllosoma may also be suitable as an index for the spawning biomass of spiny lobster: having been in the plankton relatively briefly, their abundance has not been greatly influenced by natural mortality. Because there are no other fishery-independent measures for the

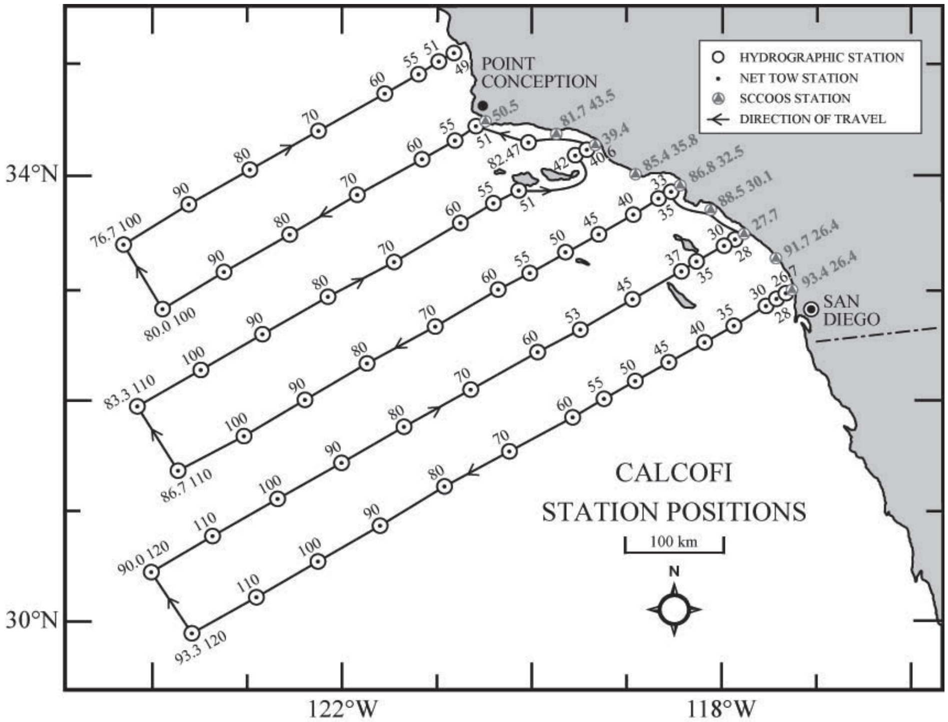

Figure 2. The core CalCOFI sampling area with six transects from the U.S./Mexico border to north of Point Conception. Only stations 60 and inshore were used in the present study because of the coastal distribution of the early-stage phyllosoma.

state of the spiny lobster population, we developed a time series of early-stage lobster from the CalCOFI sampling program, which can potentially provide further input to management of this resource. A phyllosoma time series can also be examined in relation to oceanographic parameters to determine if climate variability has a significant impact on the abundance of larval or adult lobster. Biological indices of ocean condition have provided input to management models for sardine and sablefish fisheries in the California Current (Jacobson and MacCall 1995; King et al. 2001).

The spawning and early life history of the California spiny lobster was examined in the early 1950s using CalCOFI samples (Johnson 1956, 1960a, 1960b). At that time, CalCOFI sampling extended over most of the coast of California, including Baja California (Mexico) and thus encompassed the population's distribution, which extends from Point Conception to Magdalena Bay in Baja California and is centered off central Baja (Johnson 1960a). Spawning occurs in late summer and early autumn, with peak numbers of the early-stage phyllosoma found from July to October. Remarkably, the phyllosoma drift offshore and remain in the plankton for 7–10 months until the following spring, when they metamorphose into the swimming puerulus stage, return to shore, and settle on the bottom as benthic juvenile lobsters (Johnson 1956, 1960b). Pringle 1986 re-examined the CalCOFI time series and showed that the phyllosoma abundance off southern California appeared to be enhanced during El Niño events, when there is increased northerly transport of the Davidson Current from Baja California. The lobster mature at 65–69 mm carapace length at about 5–9 years of age and recruit to the fishery at 82.6 mm, about two years later. Most recruits are removed by the fishery each year.

Our objectives are to utilize the CalCOFI sampling to 1) develop a 60-year time series of phyllosoma and 2) examine potential impacts of ocean conditions and the fishery on phyllosoma abundance.

METHODS

The CalCOFI program has consistently sampled the zooplankton, including invertebrate and fish larvae, over a core area from the U.S./Mexico border to north of Point Conception since 1951, with monthly to quarterly sampling from nearshore to several hundred kilometers offshore (fig. 2). At each station, the physical and chemical properties of the water column to 500 m depth are sampled, and at least one oblique zooplankton tow is undertaken: prior to 1969 to 140 m and subsequently to about 210 m depth. Details of the sampling protocol are found in Kramer et al. 1972 and Ohman and Smith 1995, including the change from a 1-m ring net to the 0.71 m diameter bongo net in 1977. All fish eggs and fish larvae are routinely removed from all zooplankton samples. However, until recently, invertebrate larvae,

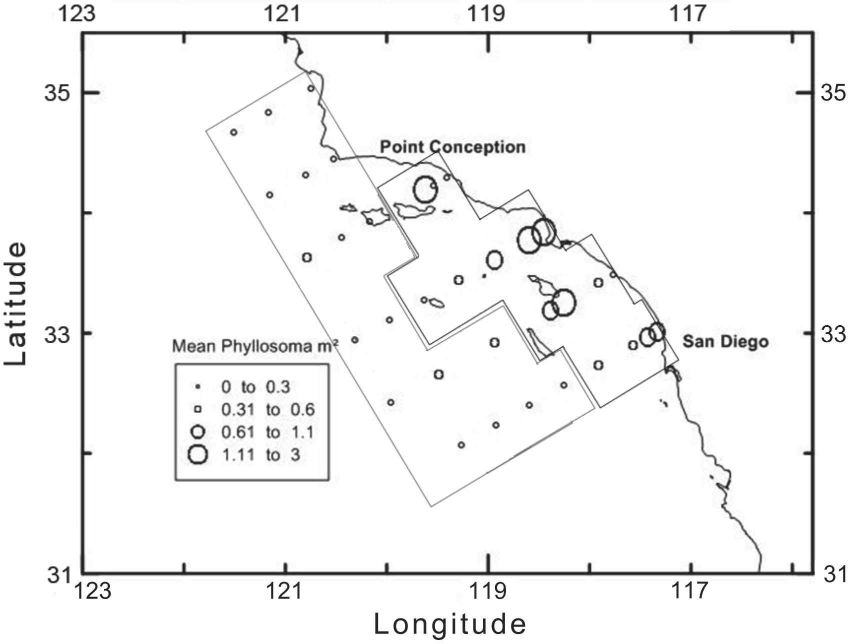

Figure 3. The CalCOFI sampling grid showing the mean abundance of phyllosoma at each station (1951–2008) and the division of the sampling area into high-abundance and low-abundance strata inshore and offshore.

including those of the spiny lobster, were only removed if undertaken by a particular investigator. Spiny lobster phyllosoma larvae are highly distinctive but also a rare component of the plankton. To re-sort all the CalCOFI samples would have been a laborious task. However, Dr. Johnson sorted the samples for the period 1951–57 and 1970–81, and the data were retrieved from the Scripps Library Archive. Since 2008, the CalCOFI program and National Marine Fisheries Service routinely sort for phyllosoma. The early-stage phyllosoma were only found in sufficiently high numbers in July/August, so we focused on the summer CalCOFI cruises from 1958–69 and 1982–2008. Phyllosoma were only rarely obtained seaward of station 60, so we only examined stations on the six core transects (lines 76 to 93) from inshore to station 60 (fig. 2). All samples were sorted under a binocular microscope, and the phyllosoma were staged using the criteria in Johnson 1956. The data are available from the CalCOFI DataZoo data repository: http://oceaninformatics.ucsd.edu/datazoo/data/calcofisio/datasets?action=summary&id=188.

Because of minor changes in station locations over the period of the CalCOFI program, the area was divided into low-abundance offshore and high-abundance coastal strata (fig. 3). Annual mean abundance was first estimated for each stratum and then summed. For statistical analyses, the phyllosoma abundance data were square-root transformed to achieve an approximately normal distribution. Statistical analyses were carried out using standard statistical routines in SPSS®.

We examined relationships between annual mean phyllosoma abundance and environmental variables sampled on CalCOFI cruises and indices for several large-scale environmental features. Sea-surface temperature (SST) was based on the mean annual temperature measured at 10 m from CalCOFI cruises. The Multivariate ENSO (El Niño Southern Oscillation) Index (MEI) (Wolter and Timlin 1998) was obtained from the National Oceanic and Atmospheric Administration (NOAA) Earth System Research Laboratory MEI Web page: http://www.esrl.noaa.gov/psd/enso/mei; the Pacific Decadal Oscillation (PDO) (Mantua et al. 1997) from the University of Washington: http://jisao.washington.edu/pdo/PDO.latest; the North Pacific Gyre Oscillation (NPGO) (Di Lorenzo et al. 2008) from the website of E. Di Lorenzo: http://www.o3d.org/npgo/data/NPGO.txt; and upwelling was based on offshore Ekman transport at 33°N and 119°W (Pacific Fisheries Environmental Laboratory: http://las.pfeg.noaa.gov/las6_5/servlets/dataset).

Commercial lobster landings data from the California Department of Fish and Game (DFG) were obtained from the California Fisheries Information System (CFIS). Landings are recorded by fishers on landing receipts which are input into the CFIS as pounds per landing by DFG block (10 × 10 min blocks). Landings were combined for each year and converted to metric tonnes.

The time series of recreational landings was based on a reconstruction for the years 1965 to the present

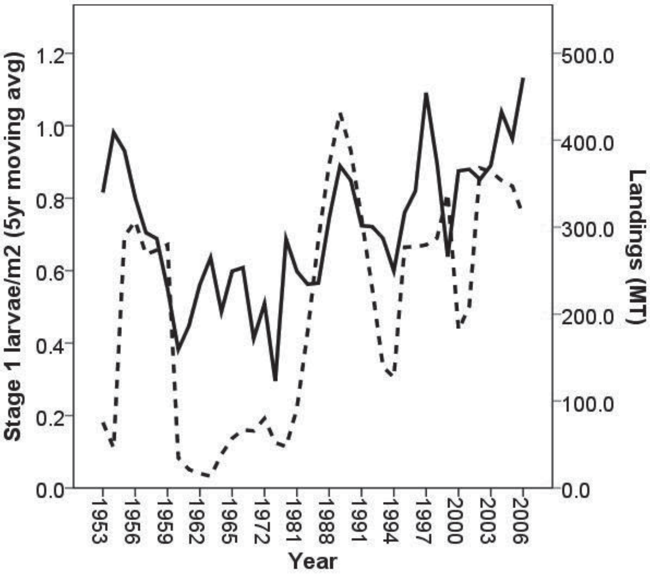

Figure 4. Time series for the abundance of stage 1 phyllosoma of the California spiny lobster (dashed line) and of combined commercial and recreational spiny lobster landings (solid line) off southern California. There is a significant increasing trend in the total landings of lobster since 1981 but not of phyllosoma.

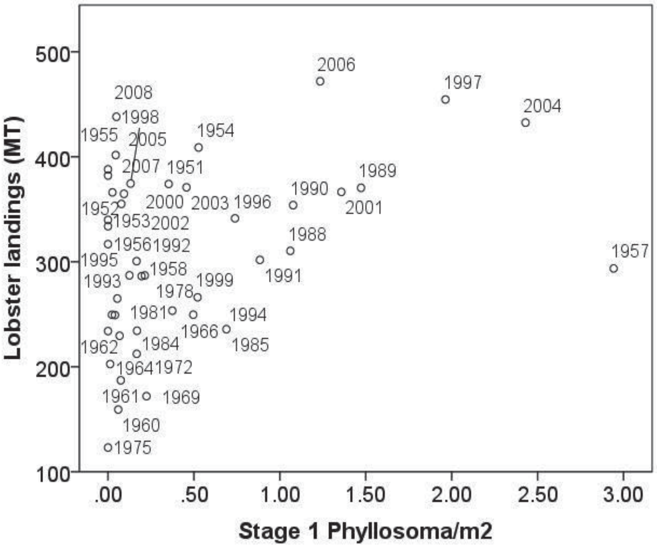

Figure 5. A scatterplot of phyllosoma stage 1 abundance per m² and total lobster landings (in metric tonnes).

adopted in the recent stock assessment (Neilson 2011). This reconstruction is based on DFG creel surveys in 1992 and 2007, hoopnet marketing observations for the past decade, spiny lobster report card data from 2008 to the present, and the observation from report card data that the recreational fishery is comprised of separate hoopnet and diving fisheries. Hoopnetting became popular in about 2005 with the majority of the recreational catch prior to that made by diving. Recreational lobster fishing is assumed to have begun in 1965 with constant dive-based catches and gradually increasing hoopnet catches to the value observed in 1992. The interpolation of recreational catch to 2005 again assumes constant dive-based catch but an exponential increase in hoopnet catch to 2005. The rate of exponential increase in hoopnet catch since 2005 was estimated by fitting an exponential relationship from 2005 to the levels observed in the 2008 report cards returns, passing through the levels observed during the 2007 creed survey. Since 2008, the catch has been determined from report card data. This reconstruction assumes that dive catches remained relatively stable over time and that the increase in catch since 2005 was the result of the popularization of fishing with hoopnets.

RESULTS

The phyllosoma stage 1 time series from 1951–2008 is highly variable, but like the landings is characterized by relatively high abundance in the 1950s and from about 1980 to the present, with a period of low abundance in the 1960s and 1970s (fig. 4). There is a significant positive correlation between the two time series ($r = 0.35$, $p < 0.05$). However, the landings time series exhibits a significant positive trend since 1981 ($r = 0.53$, $p < 0.01$), which is not reflected in the stage 1 phyllosoma time series. Examination of the scatterplot between these variables indicates that most years since 2000 appear in the upper left quadrant, indicating relatively high catch relative to the abundance of stage 1 phyllosoma (fig. 5). The plot seems to indicate generally little relationship between landings and phyllosoma abundance at low levels of phyllosoma abundance, but a reasonably linear relationship at moderate to high levels of phyllosoma abundance (≥1 stage-1 phyllosoma m^{-2}), with only one outlier at the far right side of the plot, the 1957 El Niño year, when phyllosoma abundance was very high and landings were only moderate.

We examined the potential stock-recruitment relationship for spiny lobster and whether phyllosoma abundance might be used to predict recruitment to the fishery, using the abundance of stage 1 phyllosoma as an index of spawning stock size. Spiny lobsters are generally caught within a year or two of recruitment to the fishery (Neilson 2011), but the age of maturity and age of recruitment to the fishery are not precisely known. Estimates for the age of maturity range from 3 to 9 years, with 5 years adopted in recent assessments (Serfling and Ford 1975; Engle 1979; Chavez and Gorostieta 2010; Neilson 2011). The age of recruitment to the California fishery is estimated to be approximately 7 years (Neilson 2011). Landings to the California fishery were significantly correlated with the abundance of stage 1 phyllosoma at lags of 7 and 8 years ($r = 0.39$ and $r = 0.37$, respectively, $p < 0.05$) (fig. 6), but not at other lags. A potential stock-recruitment relationship was plotted

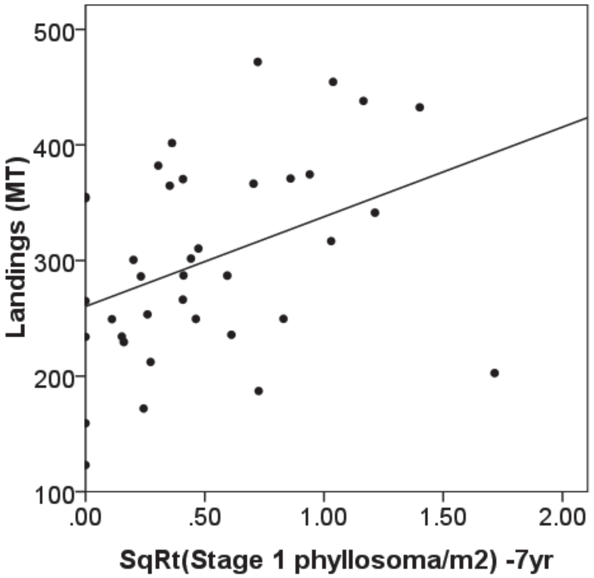

Figure 6. Spiny lobster landings (combined recreational and commercial) plotted against the abundance of stage 1 phyllosoma (numbers per m² square-root transformed) lagged by 7 years. The correlation, r = 0.39, p < 0.05.

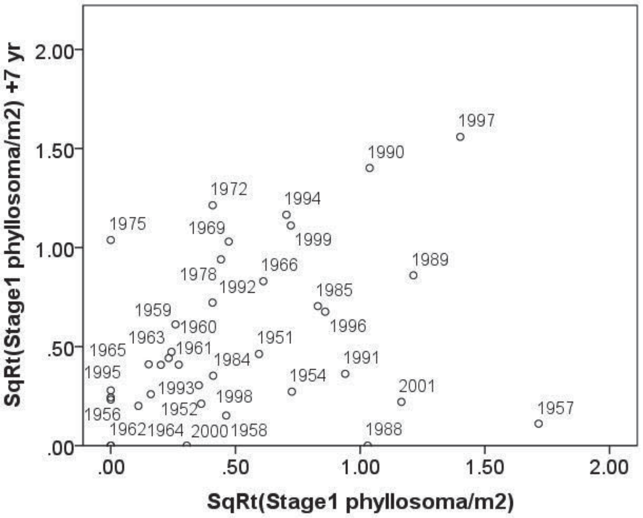

Figure 7. The abundance of stage 1 phyllosoma, an index of spawning stock size, plotted against their abundance 7 years hence, an index of recruitment. Both indices have been square-root transformed.

based on the abundance of stage 1 phyllosoma (a proxy for stock size) and their abundance 7 years hence (a proxy for their recruits) (fig. 7). No clear relationship is seen, although an asymptotic (Beverton-Holt) or dome-shaped (Ricker) relationship could potentially be drawn through the cloud of points. However, the data indicate that while there is considerable variability, good levels of recruitment seem to require at least moderate levels of spawners and initial phyllosoma abundance. There was a comparable correlation between the abundance of stage 1 phyllosoma, an index of stock size, and the abundance of stage 1 phyllosoma 7 years hence (correlation based on square-root transformed variables, r = 0.31, p = 0.06).

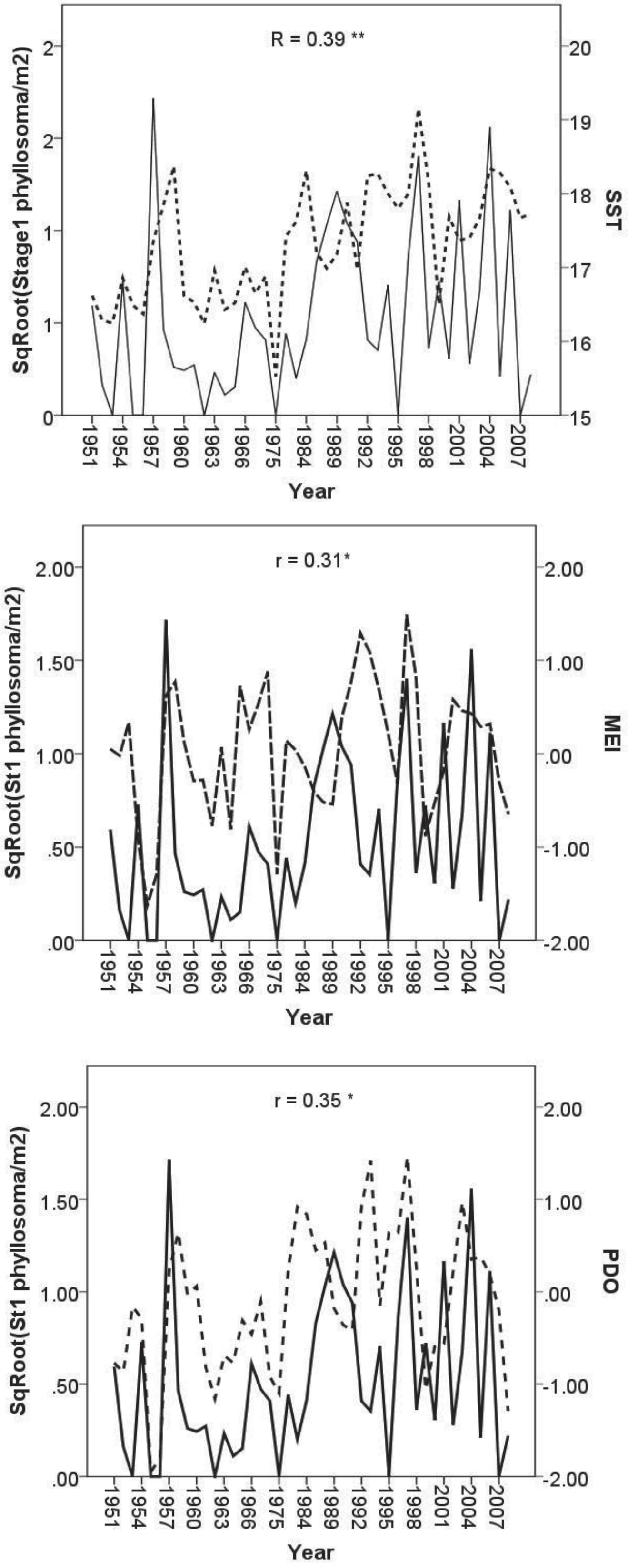

Figure 8. The time series of stage 1 phyllosoma abundance (solid lines) plotted with mean SST, the Multivariate ENSO Index (MEI), and the Pacific Decadal Oscillation (PDO) (dashed lines).

TABLE 1
Pearson correlations of sea-surface temperature (SST), the Multivariate ENSO Index (MEI), and Pacific Decadal Oscillation (PDO) with landings from the California lobster fishery at lags of 0–8 years. ★: $p < 0.05$; ★★: $p < 0.01$; ?: $p < 0.10$; df = 44 at 0 lag.

Correlations	Landings	Landings +1 year	Landings +2 years	Landings +3 years	Landings +4 years	Landings +5 years	Landings +6 years	Landings +7 years	Landings +8 years
SST	.46 ★★	.19	.23	.37★	.50★★	.43★★	.35★	.43★★	.46★★
MEI	.10	–.14	–.04	.17	.26	.37★	.25	.22	.22
PDO	.11	.15	.14	.29?	.44★★	.48★★	.21	.17	.34★

The stage 1 phyllosoma time series was significantly correlated with several time series related to ocean temperature: the sea-surface temperature (SST) time series averaged from the CalCOFI surveys ($r = 0.39$, $p < 0.01$), the MEI ($r = 0.30$, $p < 0.05$), and the PDO ($r = 0.35$, $p < 0.05$) (fig. 8). All correlations indicate that relatively warm ocean conditions, including El Niño events and the warm phase of the PDO, are positively associated the abundance of phyllosoma. Because of the intercorrelations between SST, the MEI, and the PDO, stepwise regression analysis was carried out. SST was most highly correlated with the abundance of stage 1 phyllosoma, so it entered the regression first, at which point neither the MEI nor the PDO contributed significantly to explaining the remaining variance. The NPGO was not significantly correlated with the abundance of stage 1 phyllosoma.

Correlations of landings were examined with the environmental variables lagged up to eight years. The SST time series was significantly correlated with the total landings 3–8 years hence (table 1). The PDO was significantly correlated with the landings 4, 5, and 8 years later, and the MEI was significantly correlated with landings 5 years later (table 1). Again, the NPGO was not significantly correlated with the landings at any lag.

DISCUSSION

The consistent positive correlation of stage 1 phyllosoma with several indicators of warm ocean conditions such as sea-surface temperature, El Niño events, and the warm phase of the PDO is consistent with earlier studies (Johnson 1960a; Pringle 1986). This relationship led some earlier workers to hypothesize that the relationship was based on the influence of advection, with cool conditions indicative of enhanced southward transport of the California Current and warm conditions (and El Niños, in particular) indicative of enhanced northerly transport by the Davidson Countercurrent. Pringle 1986 and Johnson 1960a noted there were enhanced concentrations of phyllosoma off California and reduced concentrations off Baja during the 1957 El Niño, with the opposite distribution in 1975, when there was strong southward flow of the California Current. Pringle 1986 hypothesized that early-stage phyllosoma produced in California waters were mostly advected south to the waters off central Baja, with recruitment to the California fishery dependent on pueruli advected northward by the Davidson Current. However, this implies that recruitment to the Mexican and U.S. fisheries should be inversely correlated, with a negative correlation between El Niños and recruitment to the Mexican fishery, since enhanced northward transport would result in depletion from the more southerly component of the population. However, Phillips et al. 1994 found that the Baja fishery was positively correlated with El Niño events lagged by four years, similar to our finding for the California fishery. More generally, the California and Baja fisheries are significantly positively correlated (fig. 9). These relationships indicate that larval survival and subsequent recruitment throughout the Pacific west coast fishery are positively associated with warm ocean conditions, including the occurrence of El Niño. We observed an anomalously high abundance of phyllosoma relative to the fishery landings off California only during the 1957 El Niño event, suggesting that Pringle's 1986 observation

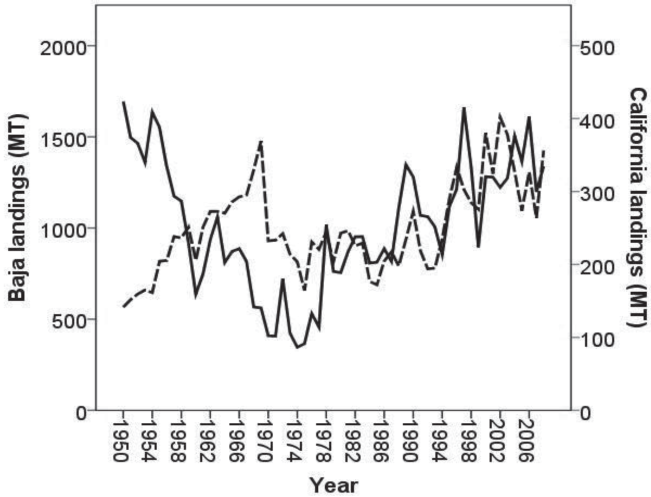

Figure 9. Time series (1956–2008) for landings (in metric tonnes) from the U.S. California (solid line) and Baja California (dashed line) commercial spiny lobster fisheries. Data prior to 1956 are not shown due to limited fishing effort in the Baja fishery. The correlation between the time series is 0.49, $p < 0.01$. (Data for the Baja fishery courtesy of E. Chavez.)

of an inverse relationship in the phyllosoma distribution in U.S. and Mexican waters during that El Niño was anomalous (fig. 5). Thus, the mechanism underlying the correlations between ocean temperature conditions and lobster recruitment remains unclear. However, our findings do not support the hypothesis that enhanced northward or southward transport of the California Current is a primary driver underlying this relationship.

The requirement introduced in 1976 for an escape port in commercial lobster traps closely coincides with the transition in 1978–79 to warm PDO conditions. This raises the possibility that the correlation between phyllosoma abundance and temperature conditions may be spurious, possibly related to coincident changes in the fishery. However, phyllosoma abundance appears to be significantly correlated with SST, the PDO, and ENSO at interannual time scales (fig. 8) and not dependent on a single change in management of the fishery. These correlations are also significant without any lag, indicating that these correlations are based at least in part on enhanced phyllosoma survival.

The correlation between the time series of stage 1 phyllosoma abundance and spiny lobster landings suggests that the landings are correlated with lobster spawning stock biomass. This is consistent with the apparently high levels of exploitation in the fishery, such that most new recruits are removed each year. The fishing season follows the spawning season, so a large proportion of the spawning stock is presumably removed each year. This leads us to speculate why the trend of increasing landings since about 2000 is not reflected in either the phyllosoma time series (fig. 4) or the Baja California fishery, whose landings are significantly correlated with U.S. lobster landings ($r = 0.49$, $p < 0.01$) (fig. 9). This disparity potentially reflects an increasing exploitation rate on spiny lobster. However, we note that the apparent increase in lobster landings is attributable to a substantial increase in recreational landings (fig. 1), whose time series has been reconstructed from only a few years of recreational landings data. There is thus some uncertainty about the recent increasing trend. This merits further attention, given its possible implications for the sustainability of the present fishery.

We suggest that the abundance of stage 1 phyllosoma in the CalCOFI collections may be useful as a fishery-independent index for spiny lobster spawning stock biomass in the waters off California. In addition, SST, the MEI, and the PDO may be used to enhance the index for lobster stock productivity, with warm periods being more productive than cool periods. Stepwise regression analysis and lagged correlation analysis indicated that local SST was most closely related to phyllosoma survival and subsequent recruitment; the broader MEI and PDO climate indices did not significantly contribute to further explaining variance in the time series. There is growing recognition that local and large-scale environmental processes significantly influence the productivity of various exploited populations inhabiting the California Current ecosystem (and elsewhere) and that sustainable management can be enhanced by taking these influences into account, either formally or through the use of more informal "environmental report cards." The sardine, sablefish, and halibut fisheries off the west coast of North America are several fisheries in which exploitation rates are managed with reference to environmental conditions (Jacobson and MacCall 1995; McCaughran 1997; King et al. 2001). Since the phyllosoma time series is now maintained as part of CalCOFI, it represents a low-cost, efficient tool that could help monitor this population, given its susceptibility to variable oceanographic conditions and lack of other fishery-independent measures of its status. The ability to predict lobster recruitment to the fishery would be further enhanced through use of puerulus collectors to monitor juvenile settlement, which has proven an effective means to predict future fishery recruitment in other spiny lobster fisheries (Caputi et al. 1997). A recent trial use of puerulus collectors in the Baja California fishery appears to have been successful (Arteaga-Ríos et al. 2007). The apparent close relationship between landings in the Alta and Baja California lobster fisheries and their similar relationships to environmental conditions suggest that greater data sharing, collaborative research and management between the U.S. and Mexico should be considered to further the sustainable management of this transnational population.

ACKNOWLEDGMENTS

We gratefully acknowledge the support from the Joint Ocean Protection Council and California Dept. Fish and Game Project (A-6) for their funding of this work. We thank Emily Jones, Mindy Kelly, and Bryan Overcash for their technical support in sorting the samples; Karen Baker, Mason Kortz, and James Conners, who assisted with data management; and Mark Ohman, Annie Townsend, and Linsey Sala, who assisted with providing historical CalCOFI samples from the Scripps Pelagic Invertebrate Collection. Ernesto Chavez kindly provided effort and landings data for the Baja California fishery. We are grateful to the Archive at the Scripps Library for their thoughtful preservation of Martin Johnson's data and their assistance in retrieving it. Reviews by Kevin Hovel and two anonymous reviewers improved the manuscript. Finally, we gratefully acknowledge the many participants in the CalCOFI program and Martin Johnson's laboratory who collected and sorted the samples over the years.

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CALIFORNIA SEA LIONS: AN INDICATOR FOR INTEGRATED ECOSYSTEM ASSESSMENT OF THE CALIFORNIA CURRENT SYSTEM

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ABSTRACT

We examined the annual number of pups born, pup mortality, and pup weights of California sea lions (*Zalophus californianus*) at San Miguel Island, California, and related them to large and small-scale oceanographic indices in the central California Current System (CCS) between 1997 and 2011. Annual variability in the number of pups born and pup mortality was best explained by the mutlitvariate ENSO index (MEI) that tracks the El Niño/La Niña cycle. Annual variability in average pup weights was best explained by a sea surface temperature anomaly index (SSTA); average pup weights were lower in years when the SSTA was greater than 1°C above normal. We demonstrated that California sea lions are sensitive to large and small-scale changes in ocean conditions through changes in their reproductive success, pup growth, and pup mortality. Therefore, California sea lions are an ideal indicator species for the IEA of the CCS.

INTRODUCTION

Integrated ecosystem assessment (IEA) is the scientific foundation that supports ecosystem-based management (Levin et al. 2009). A central component of IEA is the identification of indicator species that respond to changes in the ecosystem. In the California Current System (CCS), large-scale global processes like the Pacific Decadal Oscillation (PDO), North Pacific Gyre Oscillation (NPGO), and El Niño Southern Oscillation (ENSO) as well as small-scale processes like localized disruption of seasonal upwelling can alter the trophic dynamics on time scales of months, years, or decades (Hayward 1997; McGowan et al. 2003; Goericke et al. 2007; Bjorkstedt et al. 2010; King et al. 2011). In the CCS, the atmospheric forcing associated with the PDO and NPGO controls decadal patterns in upwelling and results in regionally variable coastal upwelling conditions that affect primary and secondary marine productivity and consequently, the distribution of fishes and other higher trophic level marine organisms. Thus, suitable indicator species for the CCS must be sensitive to marine ecosystem changes at various spatial and temporal scales. An indicator species should be directly observable, have a historical time series of data that includes periods of large- and small-scale environmental changes, be sensitive to changes in the ecosystem, and have traits that respond to and that can be measured in relation to the ecosystem processes of interest (Rice and Rochet 2005). Upper trophic level marine predators often make good indicator species because annual changes in population parameters, such as births, mortality, and growth, are often linked to oceanographic changes (e.g., production of chlorophyll and zooplankton) that affect the distribution and availability of lower trophic level prey (e.g., euphausiids, fishes, cephalopods) (Ainley et al. 2005; Beauplet et al. 2005; Foracada et al. 2005; Reid and Forcada 2005; Reid et al. 2005; Wells et al. 2008).

California sea lions (*Zalophus californianus*) are upper trophic level marine predators that are abundant and permanent residents of the CCS. Their range extends from northern Mexico to Canada and much of their life history has evolved to take advantage of the high ocean productivity in the CCS. Weaning and reproduction occur during late spring and early summer, respectively, during the peak upwelling period in the CCS when primary productivity is at its maximum (Bograd et al. 2009). California sea lion females give birth to a single pup between May and June that they provision through lactation. Lactation usually lasts 11 months during which time females are central-place foragers, alternating 2–5 day foraging trips to sea with 1–2 day nursing visits to the colony (Melin et al. 2000). Lactating females exploit the continental shelf, slope, and offshore regions of the central and southern CCS throughout the year (Kuhn 2006; Melin et al. 2008), making more than 60 foraging trips between the California Channel Islands and Monterey Bay, California. Their large foraging area and diving capabilities give them access to a diverse prey assemblage resulting in a diet that includes over 30 taxa of fish and cephalopods (Antonelis et al. 1990; Lowry et al. 1990; Melin et al. 2010).

Over the past 40 years, population parameters of California sea lions have shown annual variability associated with large- and small-scale oceanographic events. The populations breeding in the California Channel Islands off the southern coast of California experienced significant declines in births, increased pup mortality, lower mean pup weights, and changes in the diet in response to the warm oceanographic conditions associated with the El Niño phase of ENSO events in 1982–83 (DeLong et al. 1991), 1992–93 (DeLong and Melin 2000), and 1997–98 (Weise and Harvey 2008; Melin et al. 2010). The population effects lasted for 1 to 4 years (Lowry and Maravilla-Chavez 2005). Furthermore, California sea lions are also sensitive to regional and localized changes in their foraging environment that affect their prey base (Weise et al. 2006; Weise and Harvey 2008). In 2009, a brief collapse of the summer seasonal upwelling along the central California coast (Bjorkstedt et al. 2010) resulted in an unprecedented level of California sea lion pup mortality, a dramatic change in the adult female diet, and contributed to a reduction in the number of births in the following year (Melin et al. 2010). The impact of these anomalous oceanographic events on the California sea lion population are presumably meditated through their affect on sea lion prey availability (i.e., distribution, abundance), but it is difficult to measure prey availability directly. Therefore indices of ocean conditions like the PDO, NPGO, upwelling, and sea surface temperatures that affect distribution and abundance of prey can be used as proxies for prey availability to California sea lions and consequently, may explain annual variability in California sea lion population indices.

A reduction in prey available to lactating California sea lion females has the greatest population effect because it affects reproduction and survival of pups. When prey is scarce, lactating females expend more energy to meet the demands of reproduction by foraging farther from the colony and/or diving deeper presumably in response to changes in the spatial distribution of their prey (Melin et al. 2008). More importantly, movement of prey outside the normal adult female foraging range results in longer foraging trips (Melin et al. 2008), which may result in slower growth or starvation of the pup if the foraging trip durations exceed the pup's fasting capability. In addition, because lactating females are usually also pregnant during nine months of the 11-month lactation period, a diet that is insufficient to support both lactation and gestation may result in the resorption of the fetus or a premature birth. Given the relationships between ocean conditions, prey availability, and California sea lion behavior, we used regional and local oceanographic and adult female diet indices as explanatory variables in models of the annual number of pups born, pup mortality, and pup weight (as an index of growth) of California sea lions at San Miguel Island, California to 1) describe the relationship between annual variability in the marine environment and California sea lion population indices, and 2) determine if California sea lions could be used as an indicator species in the IEA of the CCS.

METHODS

Oceanographic Indices

PDO, NPGO, and ENSO. The PDO signal is strongest north of 38°N, the NPGO is strongest south of 38°N (Di Lorenzo et al. 2008), and the ENSO signal varies depending on the strength of the event at the equator (King et al. 2011) but all three indices are related and affect the CCS (King et al. 2011). So, we explored relationships between these indices and California sea lion population parameters. For each year between 1997 and 2011, monthly values for the PDO (http://jisao.washington.edu/pdo/PDO.latest), NPGO (http://www.o3d.org/npgo/npgo.php), and ENSO (multivariate ENSO index (MEI), http://www.esrl.noaa.gov/psd/enso/mei/table.html) were averaged for: 1) October through the following June (average gestation period) for models explaining trends in pup births, 2) June and July for models evaluating pup mortality up to 5 weeks of age, and 3) June through September for models exploring variability in pup mortality and pup weights at 14 weeks of age. Because the MEI is measured at the equator, the index was lagged 3 months, after testing lags of 0 to 6 months, based on the highest positive correlation between the average MEI values and local sea surface temperatures in lactating female sea lion foraging areas in the CCS (e.g., MEI value at the equator in January was assigned the CCS MEI value in April).

Local Upwelling and Sea Surface Temperature. Large-scale oceanographic patterns affect local ocean conditions in the CCS through changes in the timing, strength, and characteristics of upwelling and changes in sea surface temperature that affect the distribution of sea lion prey over shorter time periods (i.e., weeks or months) and may have more immediate effects on California sea lion population indices than large-scale processes. We used upwelling and sea surface temperature indices to investigate the effect of small-scale oceanographic conditions on California sea lion population and diet indices. The monthly coastal upwelling index at 33°N 119°W (UWI33) and 36°N 122°W (UWI36) (http://www.pfeg.noaa.gov/products/PFEL/modeled/indices/upwelling/NA/data_download.html) between 1997 and 2011 was used as an index of regional monthly ocean productivity along the central California coast (Schwing et al. 2006). These two locations were the centers of 3 x 3 degree grids for which the upwelling index was computed and encompassed the foraging range of lactating female California sea lions (Melin and DeLong 2000) (fig. 1). Positive values of the UWI are generally associated with higher than normal ocean productivity and negative values are associated with lower than normal productivity in the CCS (Schwing et al. 1995). The baseline index was calculated from monthly means of

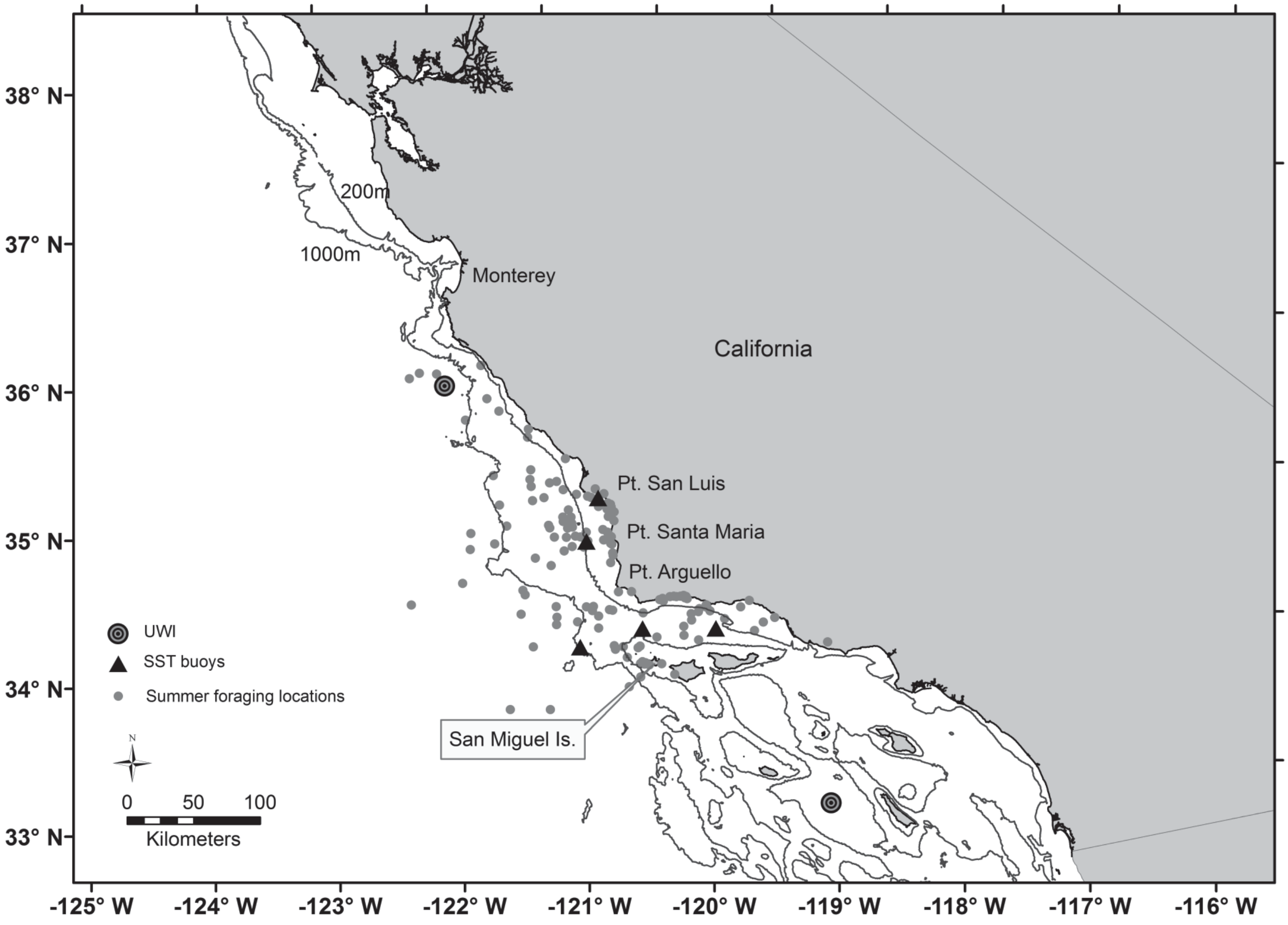

Figure 1. Locations of upwelling anomaly index sites and sea surface temperature buoys used for upwelling index (UWI) and sea surface temperature anomaly index (SSTA) within the summer foraging range of California sea lions from San Miguel Island, California. Data are from Melin and DeLong 2000 for California sea lion females in June–August 1995.

upwelling between 1946 and 1986. The monthly upwelling anomalies within each year between 1997 and 2011 were the difference between the baseline mean and the annual monthly mean.

For a more localized indicator of environmental conditions, we used sea surface temperature (SST) as a proxy for ocean productivity. Warmer SSTs are usually associated with low ocean productivity and cool SSTs with high productivity. We calculated a daily mean SST from five buoys (http://www.ndbc.noaa.gov/rmd.shtml) along the central California coast that overlapped with the foraging range of lactating female sea lions (fig. 1). A monthly baseline SST was calculated from the daily mean values for each buoy for the periods 1994 to 1996 and 1998 to 2011. Data for 1997 were not available for many of the months at several buoys, so it was excluded from the baseline calculation. For each buoy, we subtracted the baseline monthly SST from the mean SST value for each month to construct a time series of monthly anomalies (SSTA). As for the large-scale indices, the monthly UWI and SSTA indices were averaged for: 1) November to the following June (average gestation period) for models explaining trends in pup births, 2) June and July for models evaluating pup mortality up to 5 weeks of age, and 3) June to September for models exploring variability in pup mortality and pup weights at 14 weeks of age.

California Sea Lion Population Indices

Study Site. San Miguel Island, California (34.03˚N, 120.4˚W), is one of the largest colonies of California sea lions, representing about 43% of the U.S. breeding population (calculated from Caretta et al. 2007). As such, it is a useful colony to measure trends and population responses to changes in the marine environment. The Point Bennett Study Area (PBSA) represents about 50% of the births that occur on San Miguel Island and provides a good index of trends for the entire colony. This site has been used as a long-term index site since the 1970s for measuring population parameters and we used this site for data on the number of pups born, pup mortality, and weights of pups between 1997 and 2011. We limited our data set to 1997–2011 and to the PBSA because this study area within this time series has the most complete data for all the parameters of interest for this study.

Pup Mortality. Pup mortality was assessed to calculate morality at 5 weeks of age, 14 weeks of age, and the total number of pups born. Pup mortality surveys conducted every 2 weeks from late June to the end of July were used as an index of pup mortality at 5 weeks of age and to calculate total births for the PBSA. A final survey was conducted the last week of September to estimate pup mortality at 14 weeks of age. On each survey, dead pups were removed from the breeding areas as they were counted so they would not be recounted on subsequent surveys. The total number of observed dead pups for each survey described the temporal trend in pup mortality and was an estimate of the cumulative mortality of pups at 5 weeks or 14 weeks of age. Cumulative pup mortality rate was calculated as the proportion of the number of pups born in each year that died by 5 weeks of age or 14 weeks of age of the total number of pups born in each year.

Number of Births. Live pups were counted after all pups were born (between 20–30 July) each year. Observers walked through the PBSA, moved adults away from pups, and then counted individual pups. A mean of the number of live pups was calculated from the total number of live pups counted by each observer. The total number of births was the sum of the mean number of live pups and the cumulative number of dead pups counted up to the time of the live pup survey.

Pup Weights. Between 310 and 702 pups were selected from large groups of California sea lions hauled out in Adams Cove (part of the PBSA) over 4–5 days in September or October in each year (when about 14 weeks old). Pups were sexed, weighed, tagged, branded, and released. Because the weighing dates were not the same in each year, we standardized the weights to a 1 October weighing date. A mean daily weight gain rate times the number of days from the weighing date to 1 October was added or subtracted from the pup weight based on the number of days before (–) or after (+) 1 October that the pup was weighed. The number of days between 1 October and the actual weighing day was included as a parameter (days) in models to describe annual variability in pup weights.

Adult Female Diet. We collected fecal samples from adult female California sea lion haul out areas in the PBSA in June through September in 2000–03, 2005, and 2009–11 to examine the diet and develop diet indices to include in the models of pup weights. Sample processing followed Orr et al. 2003. Fish bones, fish otoliths, and cephalopod beaks were recovered from the samples and identified to family, genus, or species. Rockfish (*Sebastes* spp.) otoliths were from juvenile fish and badly eroded with no identifiable fine structures to reliably determine species, so to be conservative with identification they were identified to the genus level. When only upper cephalopod beaks were present in the sample, they were only identified to genus because many upper beaks within a genus are too similar to identify to species. We used three indices to describe diet: 1) frequency of occurrence (FO) is a measure of the percentage of fecal samples in which a prey taxon occurred, 2) split-sample frequency of occurrence (SSFO) is a measure of the percentage of occurrences for each prey taxon from the total count of all prey taxa found in a sample year; this index was used in the Principal Components Analysis (PCA), and 3) species richness is a measure of diet diversity based on the number of species present within each scat. All the diet indices are based on the presence or absence of a taxon in a fecal sample and are only a relative measure of prey occurrence because of biases associated with extrapolating from fecal contents to meal contents, biomass, or percent biomass of prey consumed by pinnipeds (Laake et al. 2002; Joy et al. 2006). The SSFO were used in PCA in R (R Core Development Team 2009) to develop a diet type index to explore if there were annual patterns in prey taxa found in the diet. The two diet indices, diet type and species richness, were used in models of pup weight at 14 weeks of age from the years for which diet data were available (2000–03, 2005, and 2009–11) to determine if adult female diet explained annual variability in pup weight.

Models

We used general linear models (pup births, 5-week pup morality, and 14-week pup mortality) and linear mixed-effects models (pup weights) in R (R Core Development Team 2009) to develop models to explore relationships between oceanographic and California sea lion population indices. A sequence of models was developed for each population index that included year and one or more of the oceanographic indices: PDO, NPGO, MEI (ENSO index), UWI33, UWI36, or SSTA. Pup weight models also included pup sex, days (days prior or after 1 October of actual weighing date), and cohort as explanatory fixed-effect variables. To accommodate potential random variation in mean pup weights within years and growth rates over the sampling period within each year, random effects of cohort (year) and batch (weighing dates within each year) on average weights (intercept) and growth rates (slope of batch) were included in the models. The best random effects model included a cohort and batch effect, so these random effects were included in all of the mixed-effects models.

A mean value was used for each oceanographic index that summarized the index values over the different seasonal periods because pup births (October to following June), pup weights (June through September), and pup mortality (June to July and June to September) are related to the cumulative energy transfer from mother to pup from birth to the time of weighing or death. Following Zuur et al. 2008, the Akaike Information Criterion adjusted for small sample sizes (AICc) was used to select the best model for each population parameter. We chose a model selection approach rather than a traditional step-wise hypothesis testing approach because it allows for a more objective process of inference that evaluates sources of variability in a biological context based on well-defined criteria and a strong fundamental basis (Burnham and Anderson 1998). Models separated by less than 4 in their AICc values were considered plausible for a given set of candidate models.

RESULTS

California Sea Lion Population Indices

Number of Births. Annual births in the PBSA at San Miguel Island between 1997 and 2011 ranged from a low of 8,603 to a high of 17,203 (table 1). The greatest annual declines occurred in 1998 (–44.1%), 2003 (–27.3%), and 2010 (–41.3%). We evaluated 11 models; the model with year and MEI_{OJ} was the best model to describe annual variability in pup births (B5; table 4). There was a negative trend in pup births over the time series (slope = –301.3, SE = 113.7) and a negative relationship between the number of births and average MEI between October and June the following year (slope = –2471.1, SE = 567.9). MEI_{OJ} values that were greater than 0.5 or less than 0.5 tended to be associated with the lowest and highest pup births, respectively (table 1). The next best models included two additive models with MEI_{OJ} and UWI36_{OJ} (B10) or UWI33_{OJ} (B11), and one model with year and SSTA_{OJ} (B2) as variables (table 1). All of these models had very similar AICc values that were larger than the best model but also represent plausible explanations for the variability in the number of births among years (AICc values <4 from the best model).

Pup Mortality. Pup mortality that occurs in the first 5 weeks (early season mortality) is usually related to trauma or starvation. Mortality of 5-week-old pups was highest in 2009 (74%) and 1998 (40.9%) and lowest in 2008 (11.4%) (table 2). We evaluated 10 models for pup mortality at 5 weeks of age. The best model included only SSTA_{JJ} as an important effect explaining year-to-year variation (EM4; table 4). Average pup mortality was 21.9% (SE = 6.6%) and a 1°C increase in the SSTA_{JJ} increased mortality an average of 12% (SE = 5.4%). Other competitive models included models with UWI36_{JJ} (EM6 and EM7), UWI33_{JJ} (EM5 and EM8), alone or in combination with SSTA_{JJ} (table 4).

Starvation and trauma continue to be major factors of mortality for older pups but disease becomes a significant mortality factor for pups 6 weeks and older (Lyons et al. 2005; Spraker et al. 2007). High pup mortality by 14 weeks of age occurred in 1998 (50.3%), 2001 (52.6%), and 2009 (80.3%) (table 3). Of 10 models, the best model estimated an average pup mortality of 35.3% (SE = 8.6%) and most of the variability was explained by a positive relationship between pup

TABLE 1

Total number of California sea lion pups born in the PBSA, San Miguel Island, California, 1997–2011, and mean values of oceanographic indices from October (year – 1) to the following June (year) (denoted with subscript OJ) used in models to evaluate annual variability in pup births. PDO_{OJ} = Pacific Decadal Oscillation, NPGO_{OJ} = North Pacific Gyre Oscillation, MEI_{OJ} = multivariate ENSO index, UWI33_{OJ} = Upwelling anomaly at 33°N 119°W, UWI36_{OJ} = Upwelling anomaly at 36°N 122°W, SSTA_{OJ} = Sea surface temperature anomaly.

		Oceanographic indices					
Year	Number of births	PDO_{OJ}	NPGO_{OJ}	MEI_{OJ}	UWI33_{OJ}	UWI36_{OJ}	SSTA_{OJ}
1997	16,670	0.61	–1.02	0.29	0	33	0.43
1998	9,325	1.02	0.58	2.24	–34	–17	2.40
1999	17,203	–0.78	1.50	–0.89	30	71	–0.64
2000	17,106	–1.07	1.84	–0.78	–19	2	–0.27
2001	15,333	–0.23	2.36	–0.39	–16	28	–0.05
2002	16,220	–0.74	1.67	0.19	5	44	–0.40
2003	11,819	1.24	1.44	0.68	13	16	0.02
2004	12,474	0.41	0.32	0.30	–35	–7	–0.09
2005	11,343	0.53	–0.93	0.65	–20	–9	0.48
2006	14,723	0.00	–0.28	–0.31	–3	1	–0.27
2007	15,557	–0.14	0.41	0.47	43	57	–0.27
2008	11,492	–1.20	1.45	–0.92	13	36	–0.79
2009	14,651	–1.36	1.07	–0.29	–16	–2	0.16
2010	8,603	0.25	1.86	0.89	14	3	0.43
2011	15,925	–0.89	1.24	–1.25	–6	–5	–0.52

TABLE 2

Pup mortality rate at 5 weeks of age of California sea lion pups born in the PBSA, San Miguel Island, California, 1997–2011, and mean values of oceanographic indices from June through July (denoted with subscript JJ) used in models to evaluate annual variability in mortality. PDO$_{JJ}$ = Pacific Decadal Oscillation, NPGO$_{JJ}$ = North Pacific Gyre Oscillation, MEI$_{JJ}$ = multivariate ENSO index, UWI33$_{JJ}$ = Upwelling anomaly at 33°N 119°W, UWI36$_{JJ}$ = Upwelling anomaly at 36°N 122°W, SSTA$_{JJ}$ = Sea surface temperature anomaly.

		Oceanographic indices					
Year	Pup mortality rate	PDO$_{JJ}$	NPGO$_{JJ}$	MEI$_{JJ}$	UWI33$_{JJ}$	UWI36$_{JJ}$	SSTA$_{JJ}$
1997	18.9	2.34	–0.86	2.48	–10	47	1.38
1998	40.9	–0.03	0.26	0.74	–88	–31	1.52
1999	17.5	–1.19	1.64	–0.46	30	92	–0.24
2000	22.9	–0.76	1.88	–0.24	–21	29	0.35
2001	25.0	–1.10	1.92	0.07	–18	83	0.59
2002	13.9	–0.54	1.49	0.70	23	115	–0.14
2003	26.8	0.61	0.99	0.02	79	102	–0.10
2004	24.8	0.03	0.59	0.36	–83	–64	–0.08
2005	15.4	0.70	–1.14	0.44	–71	–52	–0.78
2006	16.0	0.48	0.05	0.55	–86	–24	0.07
2007	13.4	0.22	1.50	–0.30	–41	–41	–0.47
2008	11.4	–1.72	1.61	0.06	–78	–62	0.05
2009	74.0	–0.63	0.71	0.88	–97	–113	0.83
2010	23.8	–0.85	1.39	–0.79	12	33	–0.84
2011	15.5	–1.49	1.33	–0.19	–14	–6	–0.32

TABLE 3

Pup mortality rate and mean pup weight at 14 weeks of age of California sea lion pups born in the PBSA, San Miguel Island, California, 1997–2011 and mean values of oceanographic and diet indices from June through September (denoted with subscript JS) used in models to evaluate annual variability in mortality and weight. PDO$_{JS}$ = Pacific Decadal Oscillation, NPGO$_{JS}$ = North Pacific Gyre Oscillation, MEI$_{JS}$ = multivariate ENSO index, UWI33$_{JS}$ = Upwelling anomaly at 33°N 119°W, UWI36$_{JS}$ = Upwelling anomaly at 36°N 122°W, SSTA$_{JS}$ = Sea surface temperature anomaly, sprich = Species richness in diet, diet4 = Four diet types. A '–' indicates no data for that year.

		Pup weight													
		Females			Males			Oceanographic Indices						Diet indices	
Year	Pup mortality rate	n	Mean (kg)	SE	n	Mean (kg)	SE	PDO$_{JS}$	NPGO$_{JS}$	MEI$_{JS}$	UWI 33$_{JS}$	UWI 36$_{JS}$	SSTA$_{JS}$	sprich	diet type
1997	29.6	347	14.4	0.14	194	17.2	0.15	2.38	–0.74	2.67	–9	24	2.17	–	–
1998	50.3	409	12.6	0.16	293	15.3	0.17	–0.41	0.21	0.18	–72	–18	1.98	–	–
1999	23.7	302	18.3	0.14	200	21.0	0.14	–1.25	1.51	–0.63	26	55	–0.72	–	–
2000	33.7	324	17.1	0.14	183	19.8	0.14	–1.02	1.62	–0.22	–18	27	0.25	2.80	2
2001	52.6	329	15.9	0.12	206	18.6	0.12	–1.12	1.91	0.05	5	75	0.02	2.51	2
2002	32.8	334	17.0	0.12	180	19.7	0.12	–0.05	1.16	0.76	17	75	–0.79	2.87	1
2003	41.8	393	18.4	0.11	275	21.1	0.12	–0.49	0.91	0.19	93	86	–0.45	4.00	3
2004	46.4	304	20.9	0.18	198	23.6	0.18	0.38	0.56	0.47	–84	–63	0.29	–	–
2005	37.6	301	20.2	0.18	199	22.9	0.18	0.26	–1.09	0.38	–42	–25	–0.55	2.61	1
2006	25.6	275	19.0	0.16	231	21.7	0.16	–0.19	–0.01	0.68	–48	–16	0.22	–	–
2007	25.1	308	19.1	0.16	204	21.8	0.17	0.11	1.41	–0.54	–33	–42	–0.35	–	–
2008	14.8	195	17.8	0.24	115	20.5	0.24	–1.71	1.97	–0.16	–65	–57	0.47	–	–
2009	80.3	298	14.8	0.19	216	17.5	0.19	–0.20	0.87	0.87	–66	–79	0.39	1.99	4
2010	30.2	234	17.1	0.17	190	19.8	0.17	–1.18	1.30	–1.34	0	21	–1.39	3.04	2
2011	24.8	239	14.8	0.16	108	17.5	0.17	–1.66	1.39	–0.41	–8	12	–0.51	3.08	2

mortality rates and MEI$_{JS}$ (LM2; table 4), with positive MEI values associated with the higher pup mortality. However, models with SSTA$_{JS}$ (LM4), UWI33$_{JS}$ (LM5), UWI36$_{JS}$ (LM6), and PDO$_{JS}$ (LM1) were also considered plausible models for this parameter (table 4). SSTA$_{JS}$ had a positive relationship with pup mortality; SSTA$_{JS}$ greater than 1°C were associated with the highest pup mortality. The UWI models showed a negative relationship between pup mortality and average UWI values with negative UWI values being associated with higher pup mortality.

Pup Weights. Average weights of 14-week-old pups were quite variable over the 15-year period (table 3). Of 38 models evaluated for annual variability in pup weights, the best model included random intercepts for cohort and batch (day of weighing), and fixed sex-specific intercepts for growth rates (sex:days) and average SSTA$_{JS}$ (sex:SSTA$_{JS}$) (PW6; table 4). The aver-

TABLE 4
Models evaluating the relationships between California sea lion population indices and oceanographic indices in the CCS between 1997 and 2011. 'np' is the number of parameters in the model, AICc is the Akaike Information Criterion corrected for small sample size (n=15).

California sea lion population index	Model #	Model Parameters[1]	np	AICc
Total births	B5	Year+MEI$_{OJ}$	3	274.82
	B10	Year+MEI$_{OJ}$+UWI36$_{OJ}$	4	277.46
	B11	Year+ MEI$_{OJ}$+UWI33$_{OJ}$	4	277.65
	B2	Year+SSTA$_{OJ}$	3	277.83
Pup mortality at 5 weeks old				
	EM4	SSTA$_{JJ}$	2	–8.61
	EM7	SSTA$_{JJ}$+UWI36$_{JJ}$	3	–7.79
	EM6	UWI36$_{JJ}$	2	–6.34
	EM8	SSTA$_{JJ}$+UWI33$_{JJ}$	3	–6.00
	EM5	UWI33$_{JJ}$	2	–5.65
Pup mortality at 14 weeks old				
	LM2	MEI$_{JS}$	2	–5.22
	LM4	SSTA$_{JS}$	2	–4.91
	LM5	UWI33$_{JS}$	2	–4.76
	LM6	UWI36$_{JS}$	2	–4.74
	LM1	PDO$_{JS}$	2	–4.72
Pup weight at 14 weeks old	PW6	sex+days+SSTA$_{JS}$+sex:days+sex:SSTA$_{JS}$	6	38963.28
Pup weight 14 weeks old and adult female diet				
	PWD30	sex+days+SSTA$_{JS}$+sex:days+sex:SSTA$_{JS}$	6	20477.06
	PWD13	sex+days+SSTA$_{JS}$+sprich+sex:days+sex:SSTA$_{JS}$	7	20484.25

[1] Model parameter definitions: Year=data collection year, SSTA$_{OJ}$ =Sea Surface Temperature Anomaly between October and June of the following year, SSTA$_{JJ}$ =Sea Surface Temperature Anomaly between June and July, SSTA$_{JS}$ =Sea Surface Temperature Anomaly between June and September, PDO$_{JS}$ =Pacific Decadal Oscillation between June and September, MEI$_{OJ}$ =Multivariate El Niño Southern Oscillation between October and June the following year, MEI$_{JS}$ =Multivariate El Niño Southern Oscillation between June and September, UWI33$_{OJ}$ =Upwelling at 33°N 119°W between October and June of the following year, UWI33$_{JJ}$ =Upwelling at 33°N 119°W between June and July, UWI33$_{JS}$ =Upwelling at 33°N 119°W between June and September, UWI36$_{OJ}$ =Upwelling at 36°N 122°W between October and June of the following year, UWI36$_{JJ}$ =Upwelling at 36°N 122°W between June and July, UWI36$_{JS}$ =Upwelling at 36°N 122°W between June and September, sex=sex of pup, days=number of days from weighing date to 1 October, sprich=species richness of the adult female diet. Model notation: '+' is an additive effect, ':' is a full interaction effect between the variables.

age weight was 17.1 kg for females (SE = 0.60; range 12.6 kg – 20.9 kg) and 19.9 kg for males (SE = 0.60; range 15.3 kg – 23.6 kg); male pups were 2.6 kg (SE = 0.06) heavier than female pups. There was a negative relationship between average SSTA$_{JS}$ and mean pup weights; an increase of 1°C in SSTA$_{JS}$ resulted in 1.0 kg (SE = 0.55) decrease in mean weight of female pups and a 1.4 kg (SE = 0.08) decrease in the average weight of male pups (fig. 2). Average pup weights were the lowest in 1997, 1998, and 2009 when SSTA$_{JS}$ was warmer than normal but in 2011, when SSTA$_{JS}$ was cooler than normal, average pup weights were also low, similar to 1997 and 2009 averages. The inconsistencies in the relationship between SSTA$_{JS}$ and average pup weights indicate that other factors besides oceanographic conditions may contribute to the variability in this parameter.

Adult Female Diet. California sea lions consumed 13 cephalopod taxa and 45 fish taxa (table 5). Pacific hake (*Merluccius productus*), northern anchovy (*Engraulis mordax*), Pacific sardine (*Sardinops sagax*), rockfish (*Sebastes* spp.), Pacific saury (*Cololabis saira*), jack mackerel (*Trachurus symmetricus*), California smoothtongue (*Leuroglossus stilbius*), market squid (*Loligo opalescens*), and East Pacific red octopus (*Octopus rubescens*), were the most common prey throughout the time series with FO greater than 10% in at least one of the years.

The first three components of the PCA represented 95% of the variance in the prey composition of the diet. The first component was SSFO of market squid (52% of the variance), the second component was Pacific hake (29% of the variance), and the third component was Pacific sardine (14% of the variance). The PCA identified four diet types: 1) Diet 1 occurred in 2002 and 2005 and had a low SSFO of market squid and a high SSFO of Pacific sardine, 2) Diet 2 occurred in 2000, 2001, 2010, and 2011 and was dominated by market squid and Pacific hake, 3) Diet 3 occurred only in 2003 and was comprised mostly of northern anchovy and Pacific sardine, and 4) Diet 4 occurred in 2009 and was dominated by market squid and rockfish (fig. 3).

Average pup weights tended to be heavier in years represented by Diets 1 and 3, average in years with Diet 2, and the lightest pups occurred in 2009 with Diet 4 (fig. 4). Because diet data were only available for 8 of the 15 years, the best model for pup weights (PW6) was run for the reduced time series and then the AICc was compared to 30 models with diet indices added to determine if adult female diet explained additional variability in pup weights. However, the best model for pup weight

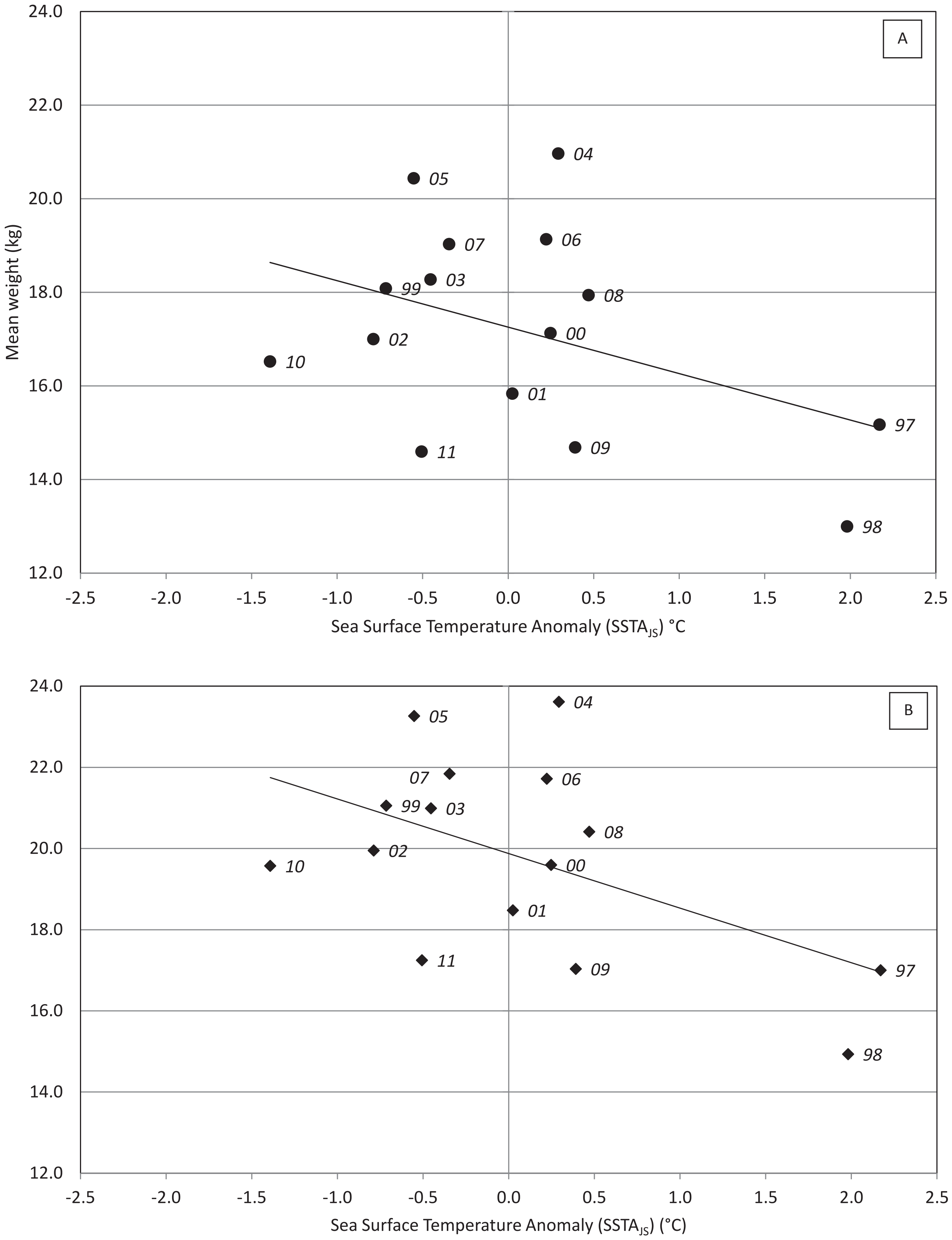

Figure 2. Relationship between the sea surface temperature anomalies ($SSTA_{JS}$) averaged between June and September each year and estimated average mean pup weights of 14-week-old female (A) and male (B) California sea lion pups at San Miguel Island, California.

TABLE 5

Frequency of occurrence (FO) of prey taxons identified from hard parts recovered from fecal samples of adult female California sea lions at San Miguel Island, California. Fecal samples were collected from breeding sites between June and September over 8 years. Taxon code is an abbreviation of the scientific name that was used in Principal Components Analysis (PCA). 'n' is the number of fecal samples collected in each year.

			Year							
			2000	2001	2002	2003	2005	2009	2010	2011
Taxon code	Scientific name	Common name	n = 154	n = 61	n = 98	n = 96	n = 62	n = 64	n = 57	n = 44
Fish										
MERPRO	*Merluccius productus*	Pacific hake	51.3	80.3	42.9	11.5	41.9	15.6	43.9	40.9
ENGMOR	*Engraulis mordax*	Northern anchovy	34.4	23.0	28.6	54.2	37.1	31.3	1.8	0.0
COLSAI	*Cololabis saira*	Pacific saury	24.7	6.6	26.5	13.5	24.2	7.8	0.0	0.0
SEBSPP	*Sebastes* spp.	Rockfish	11.0	13.1	22.4	20.8	16.1	54.7	36.8	18.2
SARSAG	*Sardinops sagax*	Pacific sardine	9.1	1.6	63.3	62.5	61.3	28.1	12.3	6.8
LEUSTI	*Leuroglossus stilbius*	California smoothtongue	5.2	0.0	0.0	0.0	3.2	0.0	15.8	0.0
TRASYM	*Trachurus symmetricus*	Jack mackerel	2.6	9.8	3.1	29.2	12.9	9.4	0.0	0.0
GENLIN	*Genoymemus lineatus*	White croaker	1.9	0.0	0.0	1.0	0.0	0.0	0.0	0.0
SCOJAP	*Scomber japonicus*	Pacific mackerel	1.9	6.6	1.0	1.0	0.0	1.6	0.0	4.5
PEPSIM	*Peprilus simillimus*	Pacific pompano	1.3	1.6	0.0	0.0	0.0	0.0	0.0	0.0
SERPOL	*Seriphus politus*	Queenfish	1.3	1.6	4.1	0.0	0.0	0.0	0.0	0.0
SQUACA	*Squalus acanthias*	Spiny dogfish	1.3	0.0	0.0	1.0	0.0	0.0	0.0	0.0
ATHSTO	*Atheresthes stomias*	Arrowtooth flounder	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CHITAY	*Chilara taylori*	Spotted cuskeel	0.6	0.0	2.0	1.0	0.0	3.1	1.8	0.0
CYMAGG	*Cymatogaster aggregata*	Shiner perch	0.6	0.0	0.0	2.1	0.0	0.0	0.0	0.0
HIPELA	*Hippoglossoides elassodon*	Flathead sole	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LYOEXI	*Lyopsetta exilis*	Slender sole	0.6	1.6	0.0	0.0	0.0	0.0	0.0	0.0
MAGATL	*Magnisudis atlantica*	Duckbill barracudina	0.6	0.0	3.1	0.0	0.0	0.0	3.5	0.0
PORNOT	*Porichthys notatus*	Plainfin midshipmen	0.6	0.0	0.0	0.0	0.0	0.0	3.5	0.0
SEBALT	*Sebastolobus altivelis*	Longspine thornyhead	0.6	0.0	0.0	0.0	0.0	0.0	1.8	0.0
STELEU	*Stenobrachius leucopsarus*	Northern lampfish	0.6	0.0	0.0	1.0	0.0	9.4	1.8	2.3
TARCRE	*Tarletonbeania crenularis*	Blue lanternfish	0.6	3.3	1.0	1.0	0.0	3.1	1.8	0.0
ANOFIM	*Anoplopoma fimbria*	Sablefish	0.0	0.0	0.0	0.0	0.0	1.6	0.0	0.0
BATPAC	*Bathylagus pacificus*	Pacific blacksmelt	0.0	0.0	0.0	0.0	1.6	0.0	0.0	0.0
CITSOR	*Citharichthys sordidus*	Pacific sanddab	0.0	0.0	1.0	2.1	0.0	4.7	0.0	0.0
CLUPAL	*Clupea pallasi*	Pacific herring	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0
CLUSPP	*Clupeid* spp.	Herring	0.0	1.6	0.0	0.0	1.6	0.0	0.0	0.0
COTSPP	*Cottid* spp.	Sculpin	0.0	0.0	0.0	0.0	0.0	3.1	0.0	0.0
EMBSPP	*Embiotocid* spp.	Surfperch	0.0	0.0	1.0	0.0	0.0	1.6	0.0	0.0
EPTSTO	*Eptatretus stoutii*	Pacific hagfish	0.0	1.6	0.0	0.0	0.0	0.0	0.0	0.0
GLYZAC	*Girella nigricans*	Opaleye	0.0	0.0	0.0	0.0	0.0	1.6	0.0	0.0
GOBSPP	*Gobid* spp.	Goby	0.0	0.0	0.0	0.0	0.0	1.6	0.0	0.0
HEXSPP	*Hexagrammid* spp.	Greenling	0.0	1.6	0.0	1.0	0.0	0.0	0.0	0.0
LEPLEP	*Lepidogobius lepidus*	Bay goby	0.0	0.0	0.0	0.0	0.0	4.7	1.8	0.0
LUMSAG	*Lumpenus sagitta*	Snake prickleback	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.3
LYCPAC	*Lycodes pacificus*	Blackbelly eelpout	0.0	0.0	0.0	0.0	0.0	3.1	1.8	2.3
MICPAC	*Microstomus pacificus*	Dover sole	0.0	0.0	1.0	0.0	0.0	3.1	0.0	0.0
MYCSPP	*Myctophid* spp.	Laternfish	0.0	1.6	0.0	1.0	0.0	0.0	0.0	0.0
OSMSPP	*Osmerid* spp.	Smelt	0.0	1.6	0.0	0.0	0.0	0.0	0.0	0.0
OXYCAL	*Oxyjulis californica*	Senorita	0.0	0.0	0.0	0.0	0.0	0.0	1.8	0.0
PARSPP	*Paralepid* spp.	Barrcudina	0.0	0.0	0.0	0.0	0.0	1.6	0.0	0.0
PLESPP	*Pleuronectid* spp.	Righteye flounder	0.0	0.0	0.0	1.0	0.0	0.0	1.8	0.0
PSEMEL	*Psettichthys melanostictus*	Sand sole	0.0	1.6	0.0	0.0	0.0	0.0	0.0	0.0
STISPP	*Stichaeid* spp.	Prickleback	0.0	1.6	0.0	0.0	0.0	0.0	0.0	0.0
SYMCAL	*Symbolophorus californiensis*	California laternfish	0.0	3.3	5.1	4.2	3.2	7.8	1.8	0.0
Cephalopods										
LOLOPA	*Loligo opalescens*	Market squid	68.2	83.6	62.2	34.4	37.1	53.1	75.4	47.7
OCTRUB	*Octopus rubescens*	East Pacific red octopus	6.5	0.0	5.1	1.0	8.1	7.8	17.5	20.5
ONYBOR	*Onychoteuthis borealijaponicus*	Boreal clubhook squid	5.2	0.0	6.1	0.0	6.5	6.3	5.3	0.0
GOTSPP	*Gonatopsis* spp.	Armhook squid	3.2	1.6	1.0	0.0	0.0	0.0	0.0	0.0
GONSPP	*Gonatus* spp.	Armhook squid	1.3	1.6	2.0	2.1	0.0	1.6	8.8	2.3
DOSGIG	*Dosidicus gigas*	Humbolt Squid	0.6	0.0	0.0	0.0	0.0	1.6	0.0	0.0
MORROB	*Moroteuthis robusta*	North Pacific giant squid	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ABRFEL	*Abraliopsis felis*	Enope squid	0.0	0.0	1.0	0.0	1.6	1.6	0.0	0.0
GONBER	*Gonatus berryi*	Berry armhook squid	0.0	0.0	0.0	0.0	0.0	1.6	0.0	0.0
GONBOR	*Gonatopsis borealis*	Boreopacific armhook squid	0.0	0.0	0.0	0.0	0.0	9.4	7.0	4.5
GONONY	*Gonatus onyx*	Clawed armhook squid	0.0	0.0	0.0	0.0	0.0	10.9	19.3	2.3
OCTSPP	*Octopus* spp.	Octopus	0.0	0.0	0.0	0.0	0.0	9.4	0.0	20.5
OMMSPP	*Ommasteuthid* spp.	Flying squid	0.0	0.0	3.1	2.1	0.0	0.0	0.0	0.0

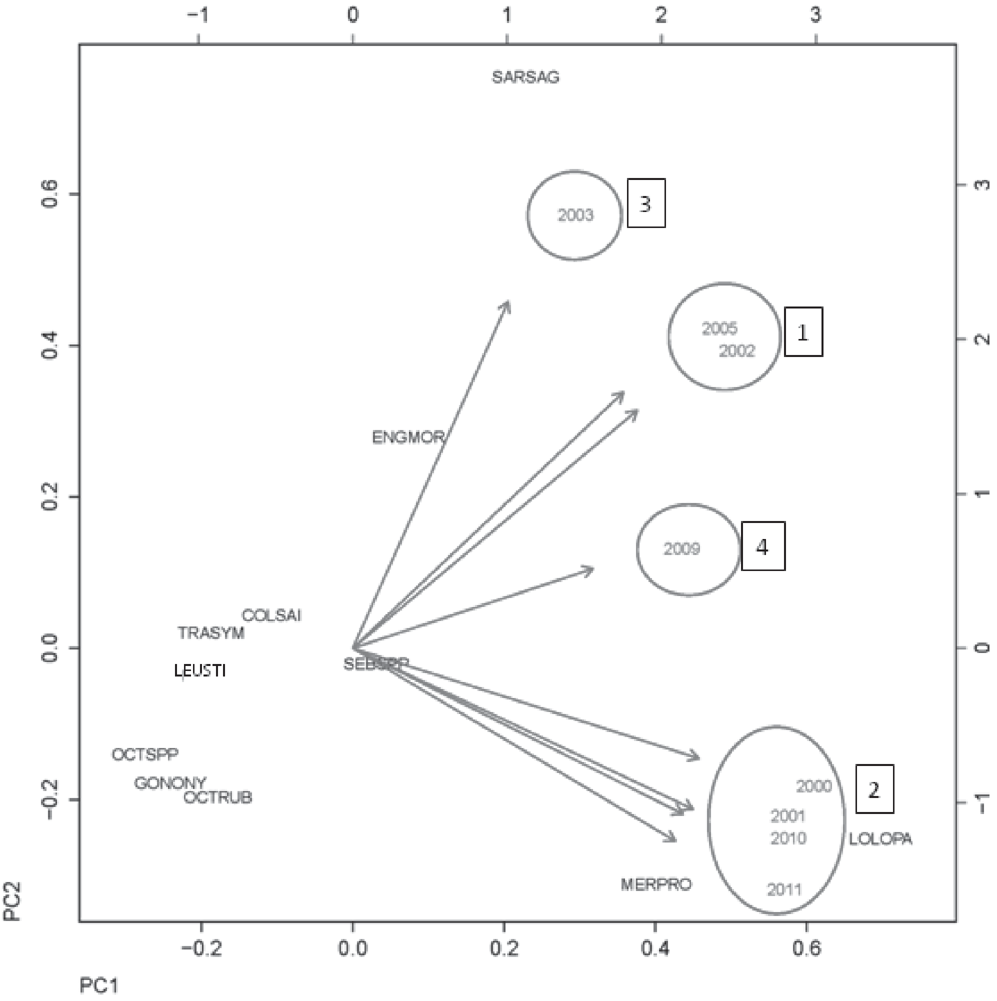

Figure 3. Principal components analysis (PCA) of annual differences of adult female California sea lion prey based on split-sample frequency of occurrence (SSFO) of prey taxa in fecal samples collected at San Miguel Island, California. PC1 represents the annual variation in SSFO of market squid and PC2 represents annual variation in SSFO of Pacific hake relative to other prey taxa in the diet. For clarity, only the prey taxa occurring in SSFO greater than 10% in at least one year are included in the figure but all identified taxa were included in the PCA. Numbers 1–4 indicate unique diet types used in models of pup weights. Taxa codes are listed in Table 5.

during the diet time series (PWD30; table 4) was the same model for the full time series. The best model with diet indices included species richness (sprich) (PWD13; table 4) but was inferior to the model without diet indices included.

DISCUSSION

Reproduction indices of number of pup births and pup mortality at 5 weeks or 14 weeks of age for California sea lions were most sensitive to large scale oceanographic indices, in particular, the MEI. Positive MEI values are associated with El Niño conditions and in years where this occurred, we observed the lowest number of births and highest pup mortality. Negative values of the MEI indicate La Niña conditions and these were generally associated with years of high births but not as consistently as the relationship with El Niño. Variability in the relationships stems from the different characteristics of three ENSO events that occurred during the study (1997–99, 2002–03, and 2009–10). The El Niño phase of these events lasted for several months (Schwing et al. 2006; Bjorkstedt et al. 2011). But the greatest oceanographic changes occurred at different times of the year during each event which resulted in some sea lion population indices being more affected by the events than others (e.g., total births in 1998 vs. 2003). The different impacts of the two phases of ENSO on California sea lion population indices occur because El Niño conditions temporarily reduce the carrying capacity of the CCS and lactating females can only compensate for this with behavioral changes (e.g., longer foraging trips, deeper diving, prey shifting). If the behavioral changes are not sufficient to sustain lactation or gestation, reproductive failure occurs. In contrast, La Niña conditions tend to create a more productive CCS with more abundant sea lion prey and so a greater

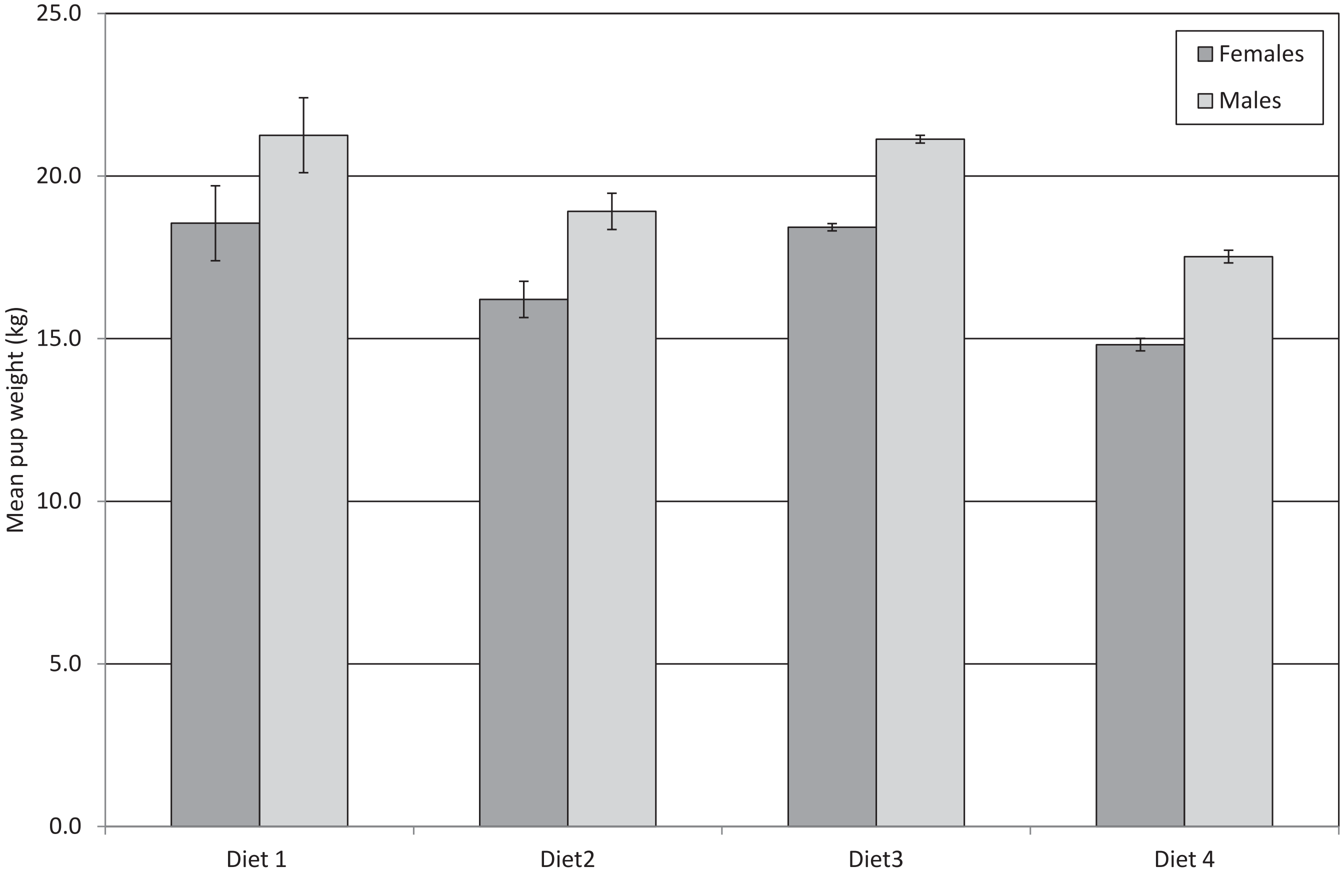

Figure 4. Comparison of four diet types from Principal Components Analysis of adult female California sea lion prey to average weights of 14-week-old California sea lion pups at San Miguel Island, California. Diet 1: high occurrence of Pacific sardine and low occurrence of market squid; Diet 2: high occurrence of market squid and Pacific hake; Diet 3: high occurrence of Pacific sardine and northern anchovy; Diet 4: high occurrence of market squid and rockfish.

number of adult females reproduce and rear their pups successfully.

Small-scale environmental events were also detected by the population indices. Most notably, the sudden collapse of upwelling and productivity as well as elevated sea surface temperatures in the central CCS in May and June 2009 resulted in 74% mortality of 5-week-old pups and highlights the importance of the evolution and timing of local oceanographic events relative to the California sea lion reproductive cycle. The rapid onset of poor foraging conditions at a time when reproductive females were giving birth resulted in high mortality of pups due to starvation (Melin et al. 2010) and failed breeding or pregnancies that contributed to a 41.3% decline in births the following year. Although this event was considered a relaxation event separate from the 2009–10 ENSO, by October 2009 El Niño conditions dominated the CCS (Bjorkstedt et al. 2010). The 2009–10 ENSO was not considered strong compared to historical events (e.g., 1982–84 or 1997–99) and did not follow the normal evolution of these events (Bjorkstedt et al. 2010; Bjorkstedt et al. 2011), but the combination of the relaxation of upwelling in May and June, followed by El Niño conditions from the autumn to spring 2010, had the greatest impact of any event since studies began on the San Miguel California sea lion population in 1972. Thus, the changes in population indices of California sea lions indicated an extreme change in the marine environment that disrupted prey dynamics but that was not interpreted by traditional oceanographic indices until much later. Similarly, in 2004 and 2005, the number of births was lower than average due to localized strong negative upwelling that was not associated with El Niño conditions or regional oceanographic anomalies (Goericke et al. 2005).

Pup weight by 14 weeks of age was perhaps the most sensitive index, responding to relatively small changes in local sea surface temperature with warmer temperatures resulting in lower pup weights. The negative relationship between SSTA and average pup weights was most apparent when SSTs were significantly warmer than normal, 1˚C or greater. Presumably this relationship stems from changes in the availability of sea lion prey to lactating females which results in their inability to fully meet the energetic demands required to nutritionally support their pups. Though we did not find a strong relationship between pup weight and adult female diet, a trend was apparent and a larger data set of diet and pup weight measurements may expose the links between adult female diet, pup growth, and oceanographic indices. Indeed, in Monterey Bay, the diet of California sea lions that were not rearing pups was associated with different ocean conditions (Weise et al. 2006; Weise and Harvey 2008).

Seabird reproductive success has long been considered an indicator of environmental changes because of a relatively direct link between local oceanographic conditions in the CCS, prey availability to adult birds, and success of laying or rearing chicks (Ainley et al. 1995; Abraham and Sydeman 2004; Sydeman et al. 2001; Sydeman et al. 2009). California sea lions range over a greater geographic area of the CCS, measure environmental changes throughout the year, and are sensitive to large and small-scale oceanographic changes, making them an ideal complimentary indicator species for the IEA of the CCS.

ACKNOWLEDGEMENTS

We thank all the field personnel who assisted with pup surveys and weighing activities. Channel Islands National Park and Channel Islands Aviation provided logistical support for the field work. We appreciate the reviews by R. Towell, P. Gearin, H. Huber, J. Lee, and three anonymous reviewers. This project was funded by the National Marine Fisheries Service, Alaska Fisheries Science Center and was conducted under Marine Mammal Protection Act Permit Numbers 977, 1613, 782–1812, and 16087 issued to the National Marine Mammal Laboratory.

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THE SPATIAL STRUCTURE OF COASTAL ICHTHYOPLANKTON ASSEMBLAGES OFF CENTRAL AND SOUTHERN CALIFORNIA

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ABSTRACT

We examined the assemblage structure of the coastal ichthyoplankton off central and southern California in relation to depth and region, based on data from the California Cooperative Oceanic Fisheries Investigations (CalCOFI), the Los Angeles County Museum, monitoring of coastal power plants, and other sources. Point Conception was a transition region for ichthyoplankton from San Francisco to San Diego, with distinct depth-related ichthyoplankton assemblages north and south of Point Conception. Northern and southern shallow assemblages were dominated by larval gobies (Gobiidae), with *Acanthogobius flavimanus* and *Lepidogobius lepidus* more important in the north and *Gillichthys mirabilis* in the south. The more offshore assemblage north of Point Conception was dominated by a variety of larval sculpins (Cottidae), while there was greater influence from several croaker species (Sciaenidae) in the Southern California Bight (SCB). There was a faunal transition zone at 15–22 m depth in the SCB. The shallow larval assemblages were primarily characterized by demersally spawning species, while species with planktonic eggs were generally found more offshore. Analysis of several coastal data sets suggested that ichthyoplankton programs may target distinct larval assemblages even within the relatively narrow coastal zone and that such differences may be more pronounced during certain seasons. Our results have important implications for marine spatial planning and for monitoring coastal marine protected areas.

INTRODUCTION

A growing interest in ecosystem management based on marine spatial planning—in particular the design, establishment, and monitoring of representative systems of marine protected areas (MPAs)—has led to the need to better understand biogeographic patterns and their underlying physical and biological processes. California initiated a process of marine spatial planning based on the Marine Life Protection Act (MLPA) of 1999, which directed the state to re-evaluate and redesign its system of MPAs using the best available science. Fundamental to this process is an understanding of the spatial structure of marine ecological communities along the California coast, as well as historical baselines for the composition of these communities.

One of the oldest and richest data sets for California's coastal communities is for the ichthyoplankton. Ichthyoplankton data have been systematically collected off California since 1949 as part of the California Cooperative Oceanic Fisheries Investigations (CalCOFI) program. CalCOFI sampling has been carried out mostly seaward of about 35–50 m depth, with most studies centering primarily on the offshore larval fish assemblages (Loeb et al. 1983; Moser and Smith 1993; Hsieh et al. 2005). However, sampling within California's coastal zone has also been carried out by government and academic institutions, most notably the National Marine Fisheries Service (NMFS) and the Los Angeles County Museum (LACM). Further ichthyoplankton sampling has been carried out by industry as part of environmental impact assessment and monitoring studies of power generating stations situated along California's coast.

Synthesis of these various data sets is hindered by the varied temporal and spatial scales of the studies. However, these studies mostly adopted a common sampling gear: the CalCOFI bongo net towed obliquely through the upper water column. In addition, the taxonomic knowledge of the ichthyoplankton has improved considerably since the inception of CalCOFI and the taxonomic expertise developed largely at NMFS through the CalCOFI program is well disseminated (e.g., Moser 1996) and adopted by all agencies.

Since the mid-1970s, many studies have examined the coastal ichthyoplankton within the Southern California Bight (SCB), focusing on their horizontal (Gruber et al. 1982; Barnett et al. 1984; Lavenberg et al. 1986; Walker et al. 1987; McGowen 1993; Watson et al. 2002) and vertical distributions (Barnett et al. 1984; Schlotterbeck and Connally 1982; Brewer and Kleppel 1986; Moser and Pommeranz 1999) as well as some rarely sampled habitats (Jahn and Lavenberg 1986). Although most of these works displayed very different temporal and spatial coverage, they often reported similar patterns of cross-shelf change in species composition as well as pronounced seasonal differences in the abundance of dominant taxa.

Several studies have adopted a community approach, using multivariate techniques to assess the ichthyoplankton assemblages within various regions of the SCB (McGowen 1993; Walker et al. 1987; Watson et al. 2002). These community-based studies identified "season" as an important factor structuring larval fish assemblages in the area. In addition, McGowen (1993) indicated distinct cross-shelf assemblage structure for different icthyoplankton groups but no significant alongshore variation in assemblage composition within the SCB. In contrast, Watson et al. (2002) found little evidence for cross-shelf zonation, but noted certain assemblage differences alongshore, primarily because they covered the transitional region off Point Conception—a well-known zoogeographical boundary (Horn and Allen 1978).

Ichthyoplankton studies off the central California coast (from Point Conception to Monterey Bay) have mostly centered on a few selected taxa, such as larval rockfishes (*Sebastes* spp.) (Larson et al. 1994; Sakuma and Ralston 1995; Yocklavich et al. 1996; Bjorkstedt et al. 2002; Wilson et al. 2008), sanddabs (Paralichthyidae) (Sakuma and Larson 1995; Sakuma and Ralston 1995; Sakuma et al. 1999) or Pacific hake (*Merluccius productus*) (Sakuma and Ralston 1995; Sakuma et al. 2007). The only study to assess the entire nearshore ichthyoplankton assemblage in central Californian waters was the 15 month study off Diablo Canyon, which documented the species composition and seasonal abundances of eggs and larvae at two stations at 20 and 60 m depth (Icanberry et al. 1978).

The objectives of this paper are: 1) conduct a community-based analysis of the composition and variability of coastal ichthyoplankton assemblages over the region from San Francisco to San Diego; 2) examine cross-shelf changes in the coastal ichthyoplankton on different spatial and temporal scales in several hydrologically different regions off central and southern California; and 3) compare larval fish assemblages sampled by different ichthyoplankton programs in the area.

MATERIALS AND METHODS

Data sources

Several coastal ichthyoplankton data sets from government, academic, and private industry sources were used in our analysis (table 1). The Tenera Environmental Inc. (further referred to as Tenera) data set is based on biological monitoring of twelve power plants/generating stations

TABLE 1
Coastal ichthyoplankton data sets used in this study.

Coastal ichthyoplankton data set	Coverage (year, month)	Depth range (m)	Stations	Samples	Taxa recorded	Type of bottom	Coastline
Los Angeles County Museum	1978–85	8–75	73	1450	172	sand	open coast
LACM 1978	6–7, 9–12	8–36	39	231	91	sand	open coast
LACM 1979	1–5, 8–12	8–36	65	409	107	sand	open coast
LACM 1980	1–7	8–36	47	322	86	sand	open coast
LACM 1981	8	8–36	12	12	42	sand	open coast
LACM 1982	1–6, 8–10,12	8–75	20	116	97	sand	open coast
LACM 1983	2,4,6,8,10,12	8–75	20	115	95	sand	open coast
LACM 1984	1–4, 6,8,10,12	8–75	20	125	84	sand	open coast
LACM 1985	2,4,6,8,10,12	8–75	20	120	69	sand	open coast
Tenera Environmental Inc.							
Alamitos Bay Generating Station	2006	2–14	6	72	69	sand, mud	embayment
Diablo Canyon Power Plant	1997–99	4–72	64	1535	114	rocks	open coast
Encina Power Plant	06.2004–05.2005	4–35	5	65	81	sand	open coast
Harbor Generating Station	2006	10–29	2	24	55	sand, mud	embayment
Huntington Beach Generating Station	09.2003–08.2004	8–24	7	116	58	sand	open coast
Morro Bay Power Plant	06.1999–12.2000	2–4	5	121	72	sand, mud	embayment
Moss Landing Power Plant	03.1999–05.2000	2–5	1	45	43	sand, silt	open coast embayment
Potrero (San Francisco Bay) Power Plant	01.2001–02.2002	1–14	9	224	81	soft mud	Bay
Redondo Beach Generating Station	2006	5–26	7	84	100	sand, silt, clay	open coast embayment
San Onofre Nuclear Generating Station	04.2006–01.2007	8–10	1	10	41	sand, cobble, rocks	open coast embayment
Santa Monica Bay Power Plant	2006	7–31	10	120	108	sand, silt, clay	open coast embayment
South Bay (San Diego Bay) Power Plant	01.2001–10.2003	1–9	5	95	40	sand, silt, clay	Bay
MERRP (Big Sycamore Canyon)	1998–99	12–370	60	240	88	Sand	open coast
MERRP (Vandenberg Ecological Reserve)	1998–99	12–210	60	232	79	Sand, rocky headlands & outcrops	open coast
SCCOOS	2004–07	6–25	9	107	61	sand	open coast
CalCOFI (innermost stations)	1978–85	40–151	23	23	59	sand	open coast

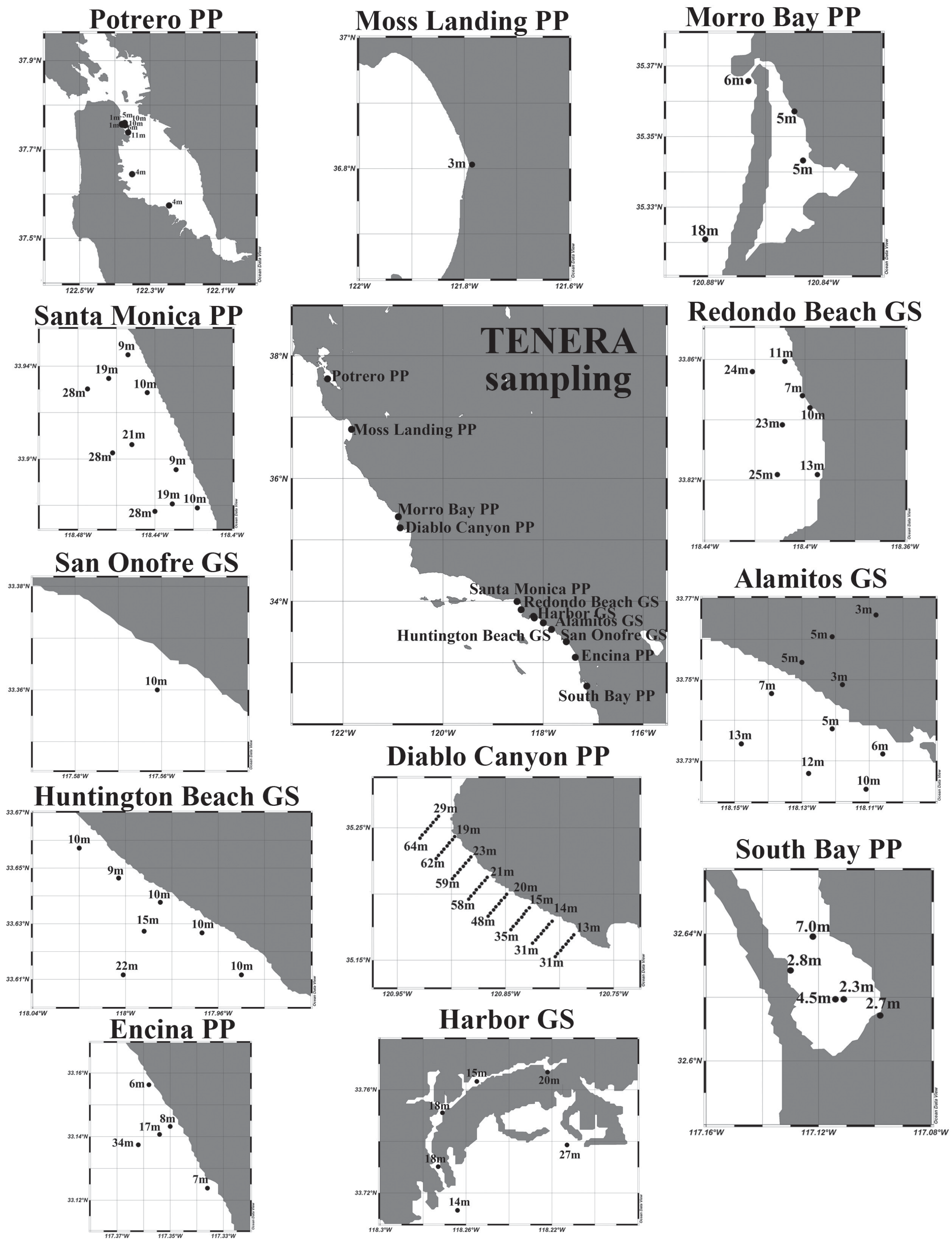

Figure 1a. Ichthyoplankton sampling locations from Tenera Environmental Inc., PP/GS – power plant/generating station.

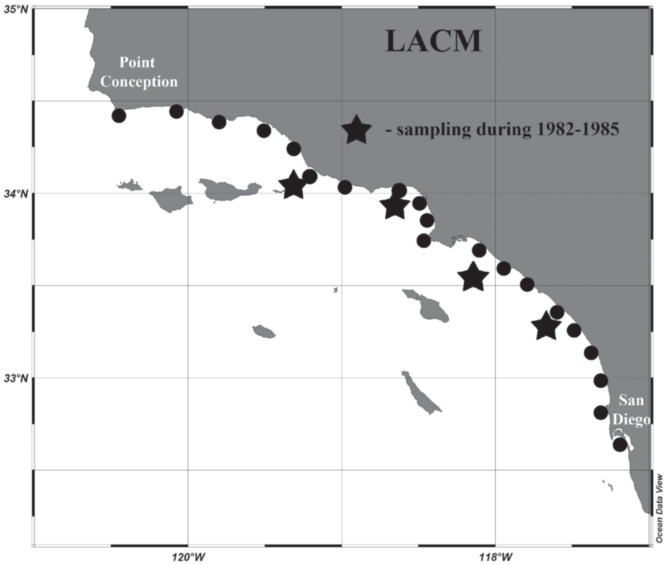

Figure 1b. Ichthyoplankton sampling locations of the Los Angeles County Museum.

located along the coast of central and southern California (fig. 1a), extending from San Francisco Bay to San Diego Bay and covering a variety of habitats from large bays to small coastal enclosures and from nearshore to ~50 m depth. Sampling effort varied considerably between these sites, from one station off Moss Landing and San Onofre Generating Station to 64 stations along eight transects off Diablo Canyon. These locations were sampled throughout the year, thus covering the entire spawning season of the various species. Sampling was carried out over somewhat varying years from 1997 to 2007 (table 1).

The Los Angeles County Museum (LACM) data are from ichthyoplankton sampling carried out during 1978–85 (fig. 1b). Collections from 1978–80 covered 20 transects along the entire SCB with typically four stations on the 8, 15, 22, and 36 m isobaths. Ichthyoplankton data for 1981 was omitted from the analysis because it was confined to only three transects in the central portion of the SCB and was conducted during a single month. Sampling during 1982–85 was confined to four lines spanning the area from Ormond Beach to San Onofre. At the same time, sampling lines during this period were extended offshore to include additional stations along the 75 m isobath (Lavenberg et al. 1986; McGowen 1993).

Among smaller areas within and just outside the SCB, we examined larval fish and egg data from the two coastal areas surveyed as part of the National Marine Fisheries Service Marine Ecological Reserves Research Program (MERRP) off Big Sycamore Canyon Ecological Reserve and Vandenberg Ecological Reserve (fig. 1c). These data were collected during four cruises in late winter-summer 1998–99 (Watson et al. 2002) (table 1). However, we only present data for Big Sycamore Canyon, since no meaningful patterns were found for ichthyoplankton collected off Vandenberg Ecological Reserve.

In recent years, nine nearshore stations were added to the CalCOFI grid as part of the SCCOOS (Southern California Coastal Ocean Observing System) program (fig. 1d). We used data from three years of sampling (2004–07) to compare the ichthyoplankton assemblage from the SCCOOS stations with that found at other coastal CalCOFI stations and from nearby Tenera sampling sites (Alamitos, Encina, Harbor, Santa Monica, and San Onofre).

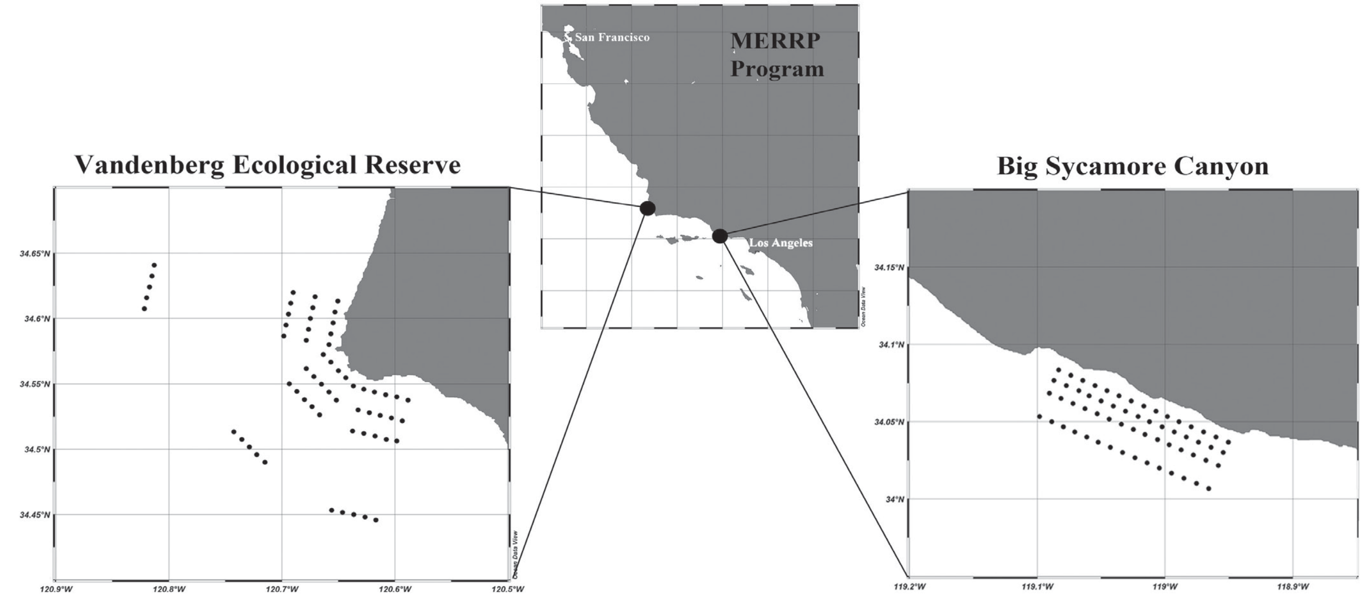

Figure 1c. Ichthyoplankton sampling locations from MERRP program.

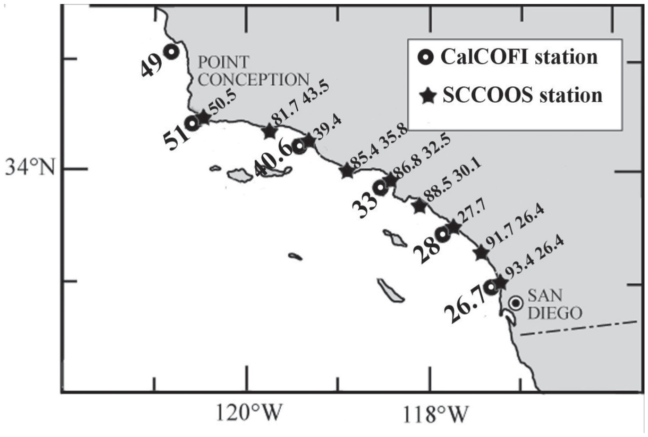

Figure 1d. Ichthyoplankton sampling locations from CalCOFI (inshore stations) and SCCOOS programs.

Due to temporal and spatial overlap between some of these data sets, it was possible to combine several (or components of them) to obtain a broader view of ichthyoplankton community structure and cross-shelf variability in the region. Thus, we compared larval fish assemblages present in the SCB during the late 1970s–early 1980s based on the LACM and CalCOFI data sets (innermost stations of the sampling grid), and during the most recent decade using data from the innermost CalCOFI, Tenera, and SCCOOS stations (sampling during 2004–07). For this purpose, we averaged ichthyoplankton data over monthly sampling periods (LACM + innermost CalCOFI stations) or over the entire period of sampling (5 Tenera locations + innermost CalCOFI + SCCOOS stations).

The coastal data sets were collected during different periods, often characterized by different oceanographic regimes, and generally in different locations, depths and distances offshore. We therefore analyzed them separately or in particular combinations in order to avoid artifacts due to differences in sampling period or location. However, the distinct characteristics of these data sets also enabled us to examine distinct biogeographic issues related to alongshore and onshore-offshore variability in the ichthyoplankton assemblages along the southern and central California coasts.

Ichthyoplankton samples in these data sets were collected using similar sampling procedures and gear. CalCOFI and Tenera used bongo nets with 0.505 mm mesh, while LACM and MERRP used bongos with 0.333 mesh. All programs carried out oblique tows to sample the water column to 200 m maximum depth. However, the LACM study was conducted with a wheeled bongo net, designed to sample the epibenthic layer as well as the water column (Lavenberg et al. 1986), because several nearshore fishes have a preferentially epibenthic distribution (Barnett et al. 1984). The MERRP study used a vertically towed bongo that covered the same depth range but with a smaller sampling volume (Watson et al. 2002). Detailed information on sampling procedures, sample sorting, processing, and preservation for the CalCOFI program is available (Kramer et al. 1972; Ohman and Smith 1995). Procedures for the other sampling programs were generally similar; technical information can be found in references describing the original studies and listed above. In our description of ichthyoplankton assemblages and cross-shelf changes, "depth" always refers to bottom depth. Prior to the analysis, larval abundances were standardized to numbers/10 m^2.

Data analysis

To examine spatial variation in ichthyoplankton assemblages off central and southern California, we first normalized larval abundance within the Tenera data sets over the seasonal cycle by averaging larval fish abundances (numbers/10 m^2) over the sampling period at each station. For Diablo Canyon, which had more extensive sampling (64 stations on eight transects, fig. 1a), larval abundances at each transect were averaged, reducing the number of samples to eight.

To investigate cross-shelf changes in ichthyoplankton assemblages, we averaged larval abundances from each depth stratum over each year for the 1978–85 LACM data set, which provided 33 stations for analysis. For the MERRP sampling off Vandenberg and Big Sycamore Ecological Reserves, we used larval abundances without further normalization. For the 64 Tenera Diablo Canyon stations, we averaged monthly larval abundances over the two-year sampling period.

We used Primer-5 (Clarke and Gorley 2001) to examine ichthyoplankton assemblage structure. Agglomerative hierarchical cluster analysis was carried out using the Bray-Curtis similarity coefficient on fourth-root transformed data. Nonmetric multidimensional scaling (MDS) analysis was carried out as well, based on the same Bray-Curtis similarity matrices, to examine the robustness of groups defined by classification and to observe possible further structure within the ichthyoplankton assemblages not revealed in a one-dimensional classification. Univariate indices such as Shannon-Weaver diversity (H') and Pielou evenness (J') were calculated for ichthyoplankton groups, as well as mean larval abundances and number of taxa at particular locations, using the Primer-5 routine, DIVERSE.

The statistical significance of the groups delineated by our classification procedure was tested using a series of "similarity profile" (SIMPROF) permutation tests (significant at $p < 0.01$, indicated by dotted branches on dendrograms). Groups were examined with the Similarity Percentage (SIMPER) procedure to identify within-group sample similarity and the spe-

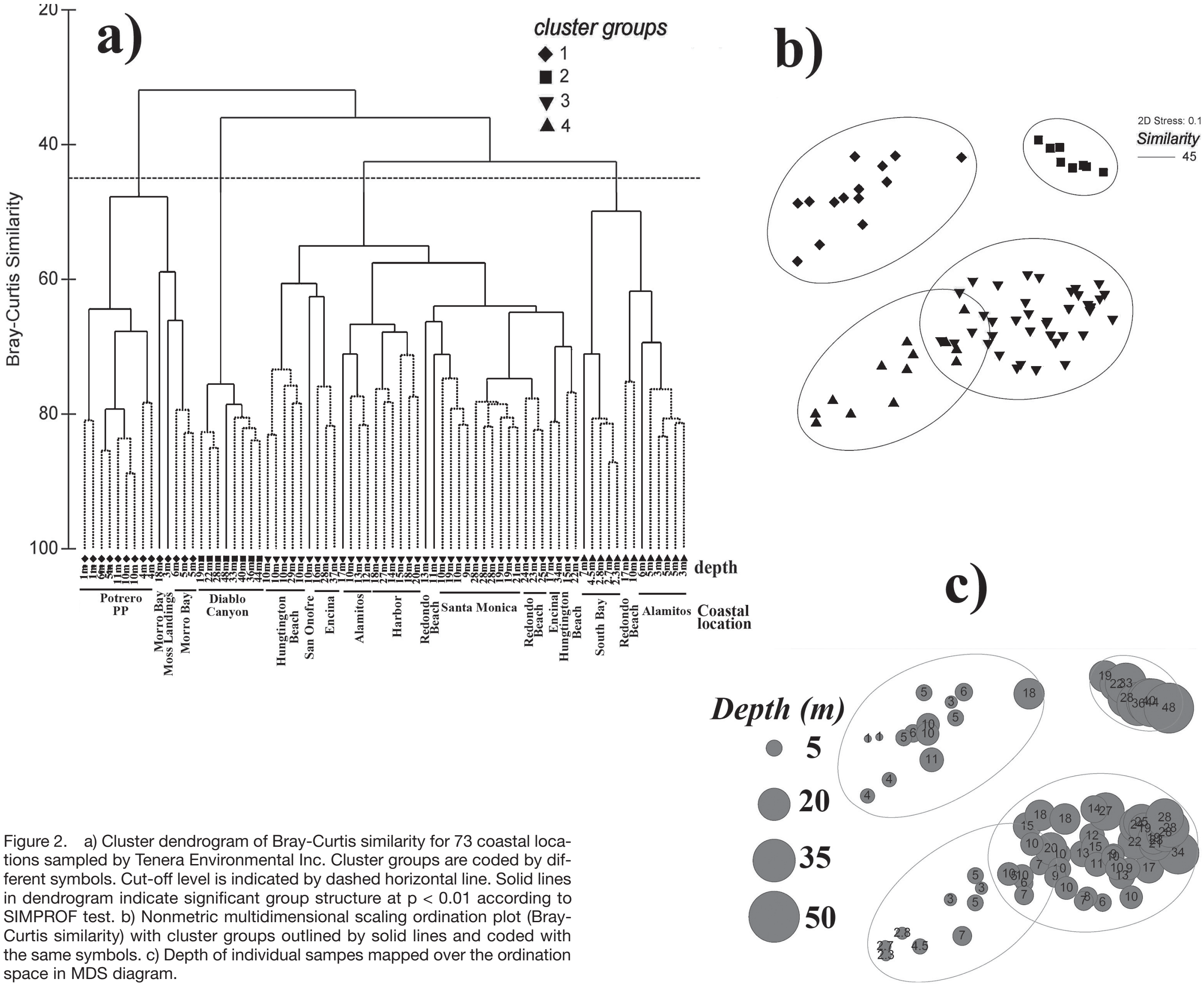

Figure 2. a) Cluster dendrogram of Bray-Curtis similarity for 73 coastal locations sampled by Tenera Environmental Inc. Cluster groups are coded by different symbols. Cut-off level is indicated by dashed horizontal line. Solid lines in dendrogram indicate significant group structure at $p < 0.01$ according to SIMPROF test. b) Nonmetric multidimensional scaling ordination plot (Bray-Curtis similarity) with cluster groups outlined by solid lines and coded with the same symbols. c) Depth of individual sampes mapped over the ordination space in MDS diagram.

cies numerically responsible for group identity. Dominating species defined by SIMPER are those with the highest contribution to the average similarity within particular groups.

We also used Indicator Species Analysis (ISA; Dufrêne and Legendre 1997) to identify taxa indicative for each group outlined in cluster analysis (PC-ORD software, McCune and Mefford 1999). ISA is helpful in examining the fidelity of occurrence of a particular taxon within a certain group. The calculations in ISA are based on the abundance of particular taxa in a group relative to their abundance in all groups and the percent frequency of that taxon in each group. Indicator values range from 0 (no indication) to 100 (perfect indication). Monte-Carlo procedures were used to evaluate the statistical significance of the maximum indicator value recorded for particular species (Dufrêne and Legendre 1997).

RESULTS

Biogeography

The Tenera data set was characterized by the broadest geographic ambit, with 73 stations from 12 coastal locations ranging from San Francisco Bay to San Diego Bay (table 1). Classification revealed four large groups at the level of 45% similarity (fig. 2a). The two most distinct groups (I) and (II) are from the area north of Point Conception, while two others (III) and (IV) were within the SCB. The larval fish assemblages can be further separated based on depth, with shallow (I, IV) and deep assemblages (II, III) forming distinct clusters.

The northernmost assemblage (group I) includes nine stations within San Francisco Bay, four stations within or just outside Morro Bay, and one shallow station at the entrance to Moss Landing Harbor. All of these shallow

TABLE 2

Results of SIMPER and Indicator Species Analysis (ISA) for Tenera coastal ichthyoplankton data. Only top 8–9 taxa in each analysis are shown for each group. Taxa are arranged in descending order of indicator value. Av. Abund. – average abundance of species in the group, Av. Sim. – average similarity of species in the group, S(i) – average contribution (%) of species to overall similarity within the group, IndVal – indicator value, N, H', J' – mean number of species, Shannon-Weaver diversity and Pielou evenness indices for a particular group. NS – non significant

Group	Species	Av. Abund	Av. Sim	S(i)	Ind Val	N	H'	J'
I central California shallow waters, embayments	*Clupea pallasii*	1.47	4.53	7.66	93	41	3.42	0.92
	Leptocottus armatus	0.86	3.18	5.39	80			
	Lepidogobius lepidus	1.39	4.52	7.65	79			
	Acanthogobius flavimanus	1.23	2.99	5.05	58			
	Ammodytes hexapterus	0.37	0.70	1.19	57			
	Gobiidae spp.	2.15	7.63	12.91	24 (NS)			
	Engraulis mordax	1.43	4.29	7.26	22 (NS)			
	Genyonemus lineatus	0.96	3.24	5.48	3 (NS)			
II central California offshore	*Rathbunella* spp.	0.71	1.01	1.29	100	95	4.43	0.97
	Gadidae spp.	0.49	0.68	0.88	98			
	Cebidichthys violaceus	1.10	1.46	1.87	97			
	Sebastes spp.	2.09	3.18	4.07	97			
	Scorpaenichthys marmoratus	1.12	1.66	2.12	97			
	Sardinops sagax	1.77	2.53	3.24	96			
	Bathymasteridae spp.	1.36	2.03	2.60	92			
	Stenobrachius leucopsarus	1.68	2.47	3.16	89			
III southern California offshore	*Seriphus politus*	1.31	2.43	4.02	96	53	3.84	0.97
	Pleuronichthys ritteri	0.82	1.38	2.29	95			
	Paralabrax spp.	1.08	1.76	2.92	90			
	Sciaenidae spp.	1.44	2.85	4.73	90			
	Paralichthys californicus	1.27	2.32	3.85	85			
	Genyonemus lineatus	2.16	3.92	6.49	81			
	Engraulis mordax	1.96	3.69	6.12	46 (NS)			
	Hypsoblennius spp.	1.70	1.14	5.21	38 (NS)			
	Gobiidae spp.	1.57	2.86	4.75	10 (NS)			
IV southern California shallow waters, embayments	Gobiidae spp.	2.94	11.24	18.55	66	33	3.26	0.93
	Labrisomidae spp.	0.78	2.21	3.65	65			
	Syngnathus spp.	0.61	2.03	3.36	62			
	Atherinops affinis	0.55	1.70	2.81	59			
	Hypsoblennius spp.	1.91	6.36	10.49	52			
	Atherinopsis californiensis	0.74	2.88	4.75	34 (NS)			
	Engraulidae spp.	1.15	3.92	6.48	21 (NS)			
	Genyonemus lineatus	1.00	2.70	4.46	7 (NS)			

central California locations are within coastal enclosures/bays or near the entrances to such features.

SIMPER analysis indicated that group I was dominated by typical inshore and embayment species, such as Bay goby (*Lepidogobius lepidus*), yellowfin goby (*Acanthogobius flavimanus*), and some unidentified gobies (most likely species of genera *Clevelandia*, *Ilypnus*, and *Quietula*) (McGowen 1993; Moser and Watson 2006), common coastal pelagics such as Pacific herring (*Clupea pallasii*) and northern anchovy (*Engraulis mordax*), as well as white croaker (*Genyonemus lineatus*) and Pacific staghorn sculpin (*Leptocottus armatus*), together contributing to 51% of the average similarity of 59.1 for this group. However, some of those dominant taxa had less than significant ($p > 0.05$) Indicator Values (IndVal). Species with the highest IndVal included: Pacific herring, Pacific staghorn sculpin, Bay goby, yellowfin goby, and Pacific sand lance (*Ammodytes hexapterus*) (table 2).

The deeper-water assemblage north of Point Conception (group II) included all samples collected off Diablo Canyon. Larval rockfishes, northern anchovy, Pacific sardine (*Sardinops sagax*) and northern lampfish (*Stenobrachius leucopsarus*) were the key species here, contributing 15% to the average similarity of 78.1 within this group. Group II showed the least dominance by individual species, with 65 species making up 90% of the average similarity between samples, and it had highest values for the mean number of species and diversity and evenness indices. Indicator species analysis identified 78 species with significant IndVal, with deeper-water and rocky bottom taxa including larval ronquils (*Rathbunella* spp.), unidentified codfishes (Gadidae), monkeyface prickleback (*Cebidichthys violaceus*), rockfishes and cabezon (*Scorpaenichthys marmoratus*) having the highest IndVal (table 2).

The deeper-water assemblage south of Point Conception (group III) included 38 samples taken at vari-

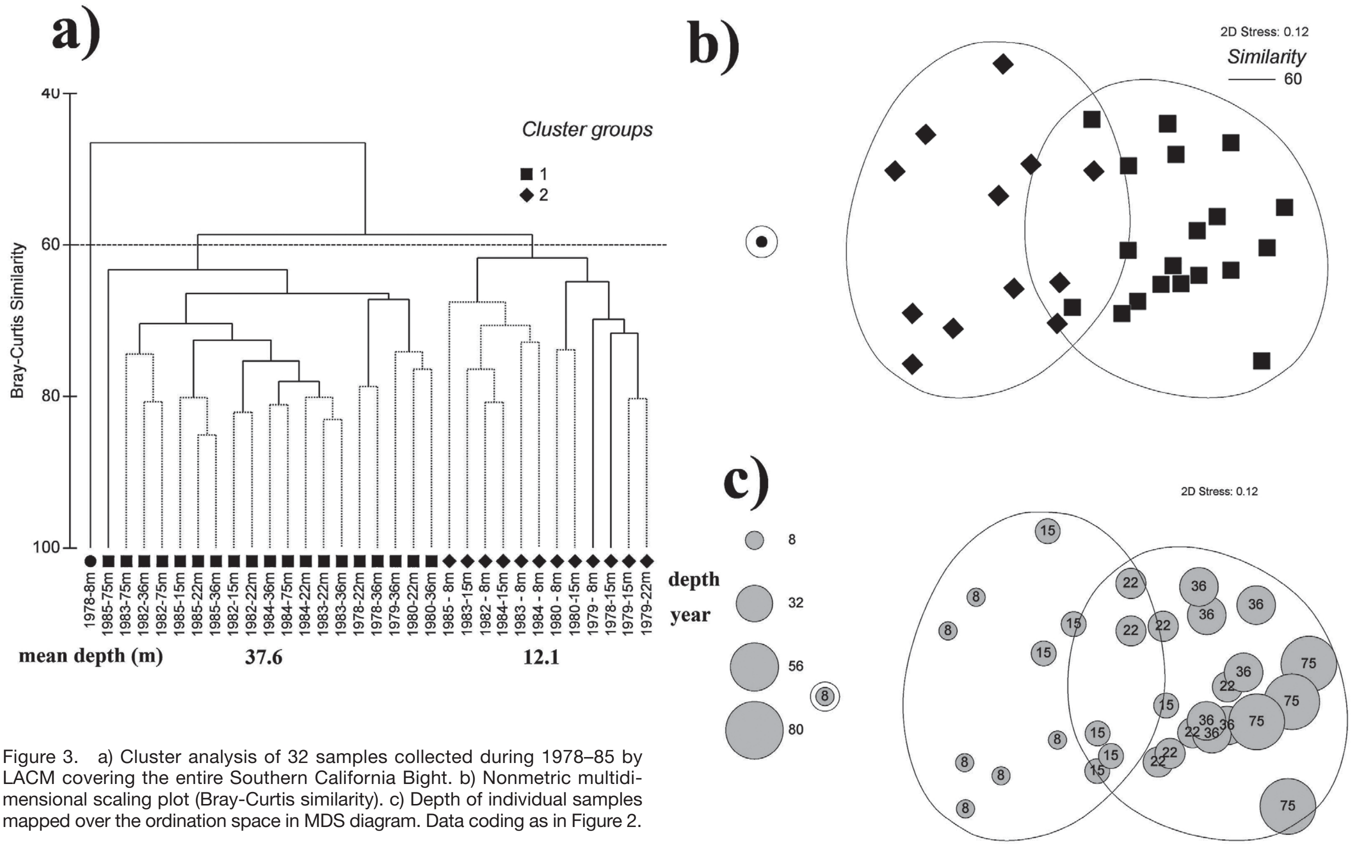

Figure 3. a) Cluster analysis of 32 samples collected during 1978–85 by LACM covering the entire Southern California Bight. b) Nonmetric multidimensional scaling plot (Bray-Curtis similarity). c) Depth of individual samples mapped over the ordination space in MDS diagram. Data coding as in Figure 2.

ous locations within the SCB (with the exception of the shallowest stations inside the enclosed channels leading to the Redondo Beach and Alamitos generating stations). Overall, this group can be described as a primarily croaker-flatfish assemblage, with queenfish (*Seriphus politus*), unidentified croakers (Sciaenidae), seabass (*Paralabrax* sp.), white croaker, and several flatfish species displaying highest group fidelity (table 2). Species contributing the most to the average similarity of 60.3 were white croaker, northern anchovy, unidentified combtooth blennies (*Hypsoblennius* sp.), and unidentified gobies and croakers.

The shallow-water assemblage from the SCB (group IV) is composed of fish larvae collected from stations within San Diego Bay, and the shallow channels leading to Redondo Beach and Alamitos generating stations. Compared to other groups, this assemblage displayed the highest abundances of unidentified larval gobies and combtooth blennies, together contributing to 30% of the average similarity of 60.6 between samples, and both identified as significant indicator species for this group. In addition, larval labrisomid kelpfishes (Labrisomidae), pipefishes (Syngnathidae) and topsmelt (*Atherinops affinis*) were also top indicator species for this assemblage (table 2). Overall, this group displayed the lowest mean number of species, as well as low diversity and evenness values.

Distinct assemblages based on geographic location (north and south of Point Conception) and depth also form clear groups on the MDS plot. The first axis represents a depth gradient, separating embayment/shallow and coastal/deep coastal assemblages in two biogeographically different regions (group I and IV), while the second axis separates assemblages north and south of Point Conception (II and III) (figs. 2b,c).

Onshore-offshore variation and depth-related gradients

To further analyze potential faunistic boundaries related to depth in the coastal zone of southern California, we first assessed broad patterns of cross-shelf variation based on the extensive sampling of the LACM ichthyoplankton program which spanned the entire SCB. We further refined this analysis by centering on larval assemblages sampled on smaller spatial and temporal scales, based on sampling within the SCB (Big Sycamore Canyon), near Point Conception (Vandenberg), and off central California (Diablo Canyon).

Southern California Bight. Classification and ordination of 33 samples representing averaged depth strata of the LACM sampling resulted in two large groups, based on depth (figs. 3a–c).

The deeper-water assemblage (I) was comprised of 19

TABLE 3

Results of SIMPER and ISA for LACM (Los Angeles County Museum) ichthyoplankton data. Sim/SD – Similarity/Standard deviation, other abbreviations and data structure as in Table 2.

Group	Species	Av. Abund	Av. Sim	Sim/SD	S(i)	Ind Val	N	H'	J'
I deep	*Stenobrachius leucopsarus*	1.7	1.98	3.75	2.84	95	61	1.7	0.4
	Citharichthys spp.	1.68	2.02	6.61	2.91	93			
	Engraulidae sp.	3.37	4.04	5.94	5.8	88			
	Oxyjulis californica	1.07	1.29	4.9	1.86	87			
	Icelinus quadriseriatus	0.98	1.01	1.79	1.45	86			
	Engraulis mordax	5.13	6.46	9.46	9.29	84			
	Clupeiformes spp.	2.79	3.4	6.01	4.89	70			
	Sardinops sagax	2.27	2.55	2.71	3.67	76			
	Genyonemus lineatus	3.05	3.68	3.94	5.28	57 (NS)			
II shallow	*Gobiesox rhessodon*	0.89	1.39	4.75	2.13	93	58	2.1	0.5
	Heterostichus rostratus	0.76	1.06	1.82	1.63	91			
	Paraclinus integripinnis	0.52	0.71	1.3	1.08	80			
	Hypsypops rubicundus	0.65	0.76	1.26	1.17	79			
	Leuresthes tenuis	0.92	1.55	3.97	2.37	77			
	Gobiidae spp.	2.09	3.7	5.95	5.66	67			
	Genyonemus lineatus	2.79	4.52	5.53	6.92	43 (NS)			
	Seriphus politus	2	3.27	5.6	5	42 (NS)			
	Engraulis mordax	3.3	5.48	6.65	8.38	16 (NS)			
	Engraulidae sp.	2.01	3.22	5.02	4.92	12 (NS)			

TABLE 4

Results of SIMPER and ISA analysis for ichthyoplankton data collected off Big Sycamore Canyon by MERRP (Marine Ecological Reserves Research Program). Abbreviations and data structure as in Table 2, 3. Groups I and III are shallower assemblages from 1998 and 1999, respectively; groups II and IV are deeper assemblages from those years.

Year	Group	Species	Av. Abund	Av. Sim	Sim/SD	S(i)	Ind Val	N	H'	J'
1998	I	*Engraulis mordax* (larvae)	1.89	16.85	2.16	25.07	67	5	1.18	0.78
		Paralichthys californicus (eggs)	2.55	25.53	5.93	37.97	29 (NS)			
		Engraulis mordax (eggs)	0.80	3.52	0.58	94.54	8 (NS)			
		Genyonemus lineatus (eggs)	1.89	17.66	2.24	64.23	6 (NS)			
	II	*Argentina sialis* (eggs)	1.35	9.47	5.30	14.00	59	11	2.00	0.85
		Argentina sialis (larvae)	0.88	4.24	1.06	6.27	58			
		Engraulis mordax (eggs)	1.58	10.88	6.15	16.08	35			
		Merluccius productus (eggs)	1.41	10.04	6.05	45.94	21 (NS)			
		Engraulis mordax (larvae)	1.25	8.49	5.76	72.48	12 (NS)			
		Paralichthys californicus (eggs)	1.55	10.17	4.48	31.10	5 (NS)			
1999	III	*Genyonemus lineatus* (eggs)	3.55	16.9	5.57	26.02	63	10	1.41	0.63
		Citharichthys stigmaeus (eggs)	2.19	9.62	5.30	14.81	61			
		Pleuronichthys verticalis (eggs)	1.45	5.00	1.32	7.69	57			
		Atherinopsis californensis (larvae)	0.47	0.40	0.24	0.62	27			
		Genyonemus lineatus (larvae)	3.07	13.43	10.99	46.70	36 (NS)			
		Paralichthys californicus (eggs)	2.10	9.67	6.34	61.59	13 (NS			
	IV	*Parophrys vetulus* (eggs)	1.54	5.77	2.30	8.71	67	14	1.90	0.73
		Merluccius productus (eggs)	1.76	6.70	2.86	10.12	62			
		Leuroglossus stilbius (larvae)	1.42	3.94	1.23	5.95	62			
		Merluccius productus (larvae)	1.38	4.96	2.23	7.49	44			
		Leuroglossus stilbius (eggs)	1.04	2.36	0.76	3.56	60			
		Citharichthys stigmaeus (eggs)	1.87	7.26	4.15	25.63	34 (NS)			
		Paralichthys californicus (eggs)	1.93	6.83	2.78	35.94	24 (NS)			
		Genyonemus lineatus (eggs)	2.56	9.71	3.64	14.66	1 (NS)			

samples, mostly from the 22, 36, and 75 m depth strata (average station depth 37.6 m). Twelve shallow samples (8 and 15 m depth, with one sample from 22 m, average depth: 12.1 m) formed the shallow assemblage (II). Overall, both assemblages displayed similar dominant species, such as the common coastal pelagics, northern anchovy, and Pacific sardine, and the croakers, white croaker and queenfish, with higher abundances more

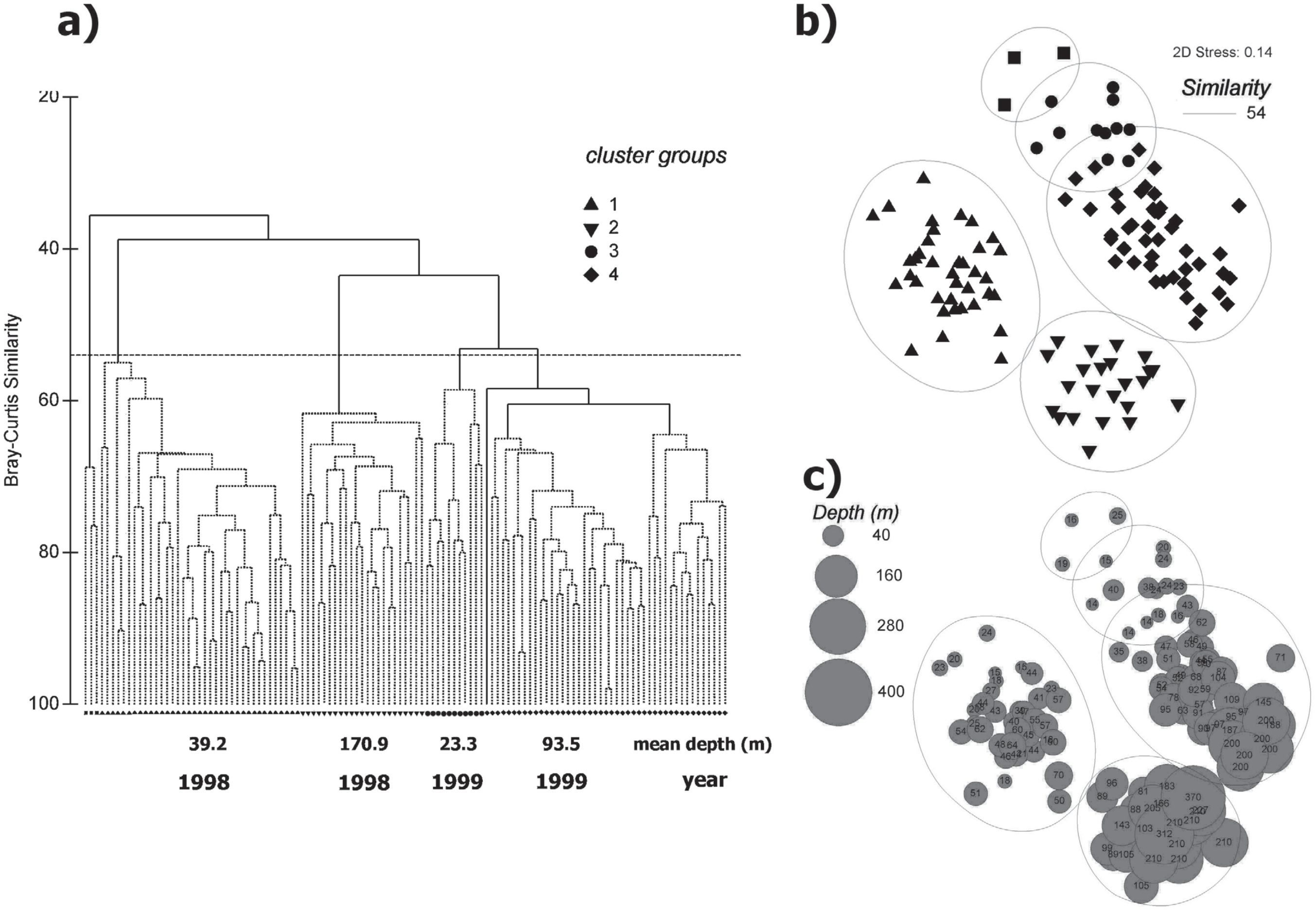

Figure 4. a) Classification of 119 samples obtained during 1998–99 sampling off Big Sycamore Canyon Ecological Reserve. b) Nonmetric multidimensional scaling plot (Bray-Curtis similarity) with cluster groups outlined by solid lines and coded with the same symbols. c) Depth of individual samples mapped over the ordination space in MDS diagram. Data coding as in Figure 2.

offshore. However, ISA suggested distinct sets of indicator species—northern lampfish, sanddabs (Paralichthyidae), señorita (*Oxyjulis californica*), and northern anchovy for the deeper assemblage and larval clingfishes (Gobiesocidae), clinid kelpfishes (Clinidae), labrisomids, garibaldi (*Hypsypops rubicundus*), and grunion (*Leuresthes tenuis*) for more inshore waters (table 3). Both groups had similar average species richness and evenness, but the shallow group was characterized by higher Shannon-Weaver diversity values (table 3).

Big Sycamore Canyon Ecological Reserve. Classification of 119 samples collected during winter in 1998–99 off Big Sycamore Canyon revealed one small and four large groups (I–IV) at a similarity level of 54% (fig. 4a). The four principal groups displayed very close Bray-Curtis similarities ranging from 64.9 to 67.6 and can be described as shallow and deep larval fish assemblages of 1998 (El Niño year) and 1999 (La Niña year).

The shallow assemblage of 1998 (group I) is composed of 37 samples collected over depths of 15–70 m (mean depth: 39 m), while the deep group (II) included 23 samples from depths of between 81 and 370 m (mean depth: 171 m). These assemblages were mainly discriminated by the relative abundance of eggs of offshore and inshore spawning species. Thus, eggs and larvae of mesopelagic, e.g., North-Pacific argentine (*Argentina sialis*), California smoothtongue (*Leuroglossus stilbius*), and northern lampfish and offshore species such as Pacific hake (*Merluccius productus*), showed much higher abundances at deeper stations, while shallow samples had higher contributions from eggs and larvae of typical coastal benthic species, such as croakers and flatfishes (fig. 5). Larval northern anchovy was a significant indicator species for the shallow group, while eggs and larvae of North-Pacific argentine and eggs of northern anchovy were significant indicators for the deep assemblage.

Depth was also important in structuring the ichthyoplankton assemblages in 1999, although these differences were less distinct compared with the previous year. Similar to 1998, the shallow larval assemblage (III) of 1999 displayed somewhat higher abundances of eggs and larvae of croakers and flatfishes, while the deeper group

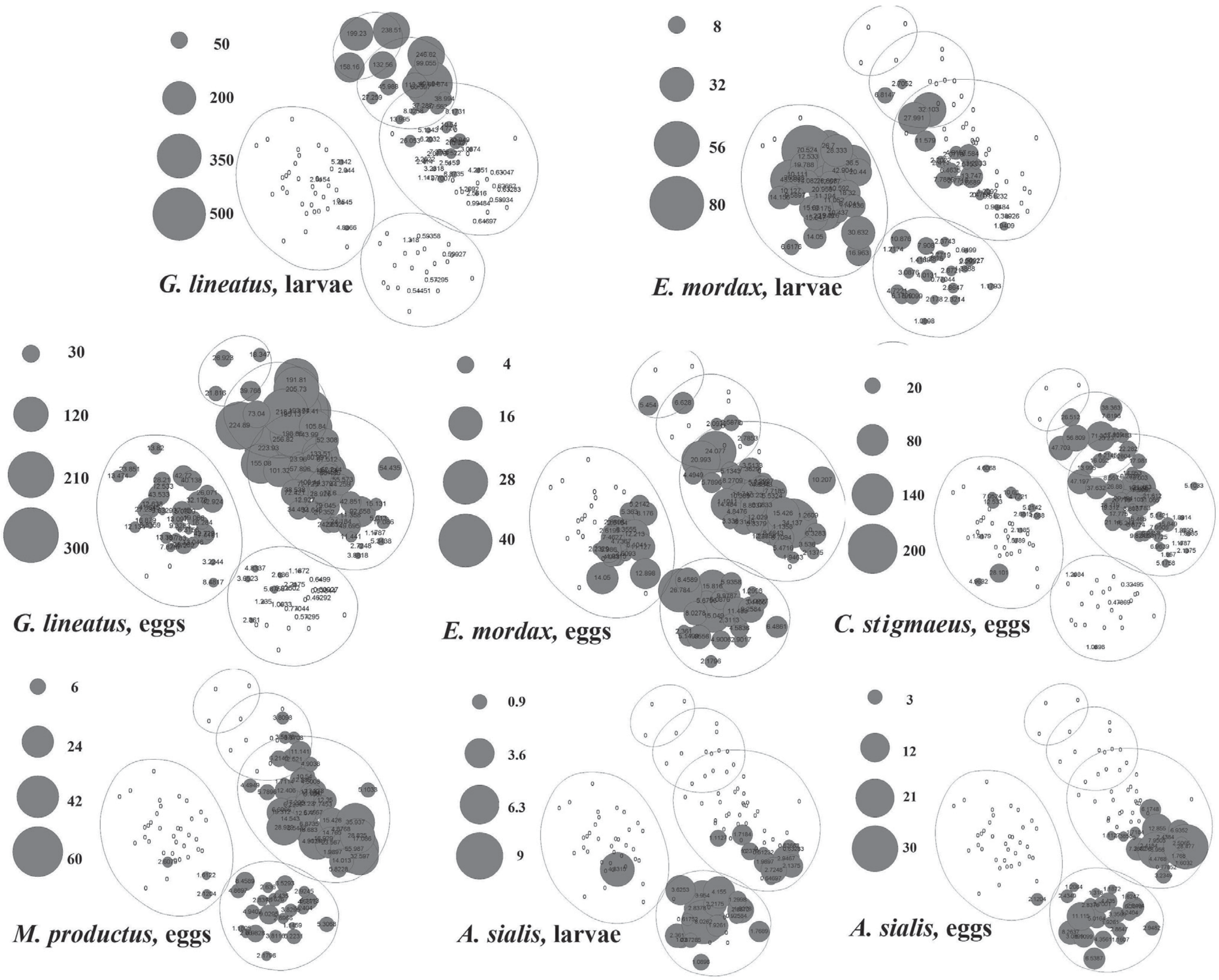

Figure 5. a) Abundances (spec./10 m^2) of most significant species according to SIMPER results and Indicator Species Analysis mapped in ordination space of two first axes on MDS plot.

(IV) was influenced by oceanic species such as deep-sea smelts and Pacific hake (table 4, fig. 5). Eggs of white croaker, speckled sanddab (*Citharichthys stigmaeus*), and hornyhead turbot (*Pleuronichthys verticalis*) and larvae of jack silverside (*Atherinopsis californensis*) were significant indicators for the shallow La Niña assemblage, while eggs and larvae of California smoothtongue and Pacific hake and eggs of English sole (*Parophrys vetulus*) were characteristic of the deeper assemblage.

North-Pacific argentine, a species with southerly affinities, was more abundant during the El Niño. Several species, however, were more abundant in 1999: white croaker, Pacific hake, and speckled sanddab.

Ordination analysis revealed similar groupings based on the first two MDS axes (fig. 4b). The first horizontal axis primarily separates the El Niño from La Niña assemblages, while the second axis separates the shallow and deep assemblages. Mapping the depths of the individual samples clearly shows the dominant depths associated with these assemblages (fig. 4c).

We did not find clear assemblages related to depth off Big Sycamore Canyon during summer. There was also no significant effect of depth on assemblage structure off Vandenberg Ecological Reserve, just north of Point Conception, which was sampled during the same MERRP ichthyoplankton surveys. Strong currents and intense sand transport apparently create poor fish habitat at this site, possibly eliminating potential faunistic boundaries in the pelagic environment.

Diablo Canyon. Classification of 64 samples from Diablo Canyon based on averaged larval abundances over a two year sampling period revealed three groups of samples at a 64.7% similarity level (fig. 6a). The MDS plot indicates a depth gradient in the ichthyoplankton assemblages (figs. 6b, c).

The more offshore assemblages (groups I and III in

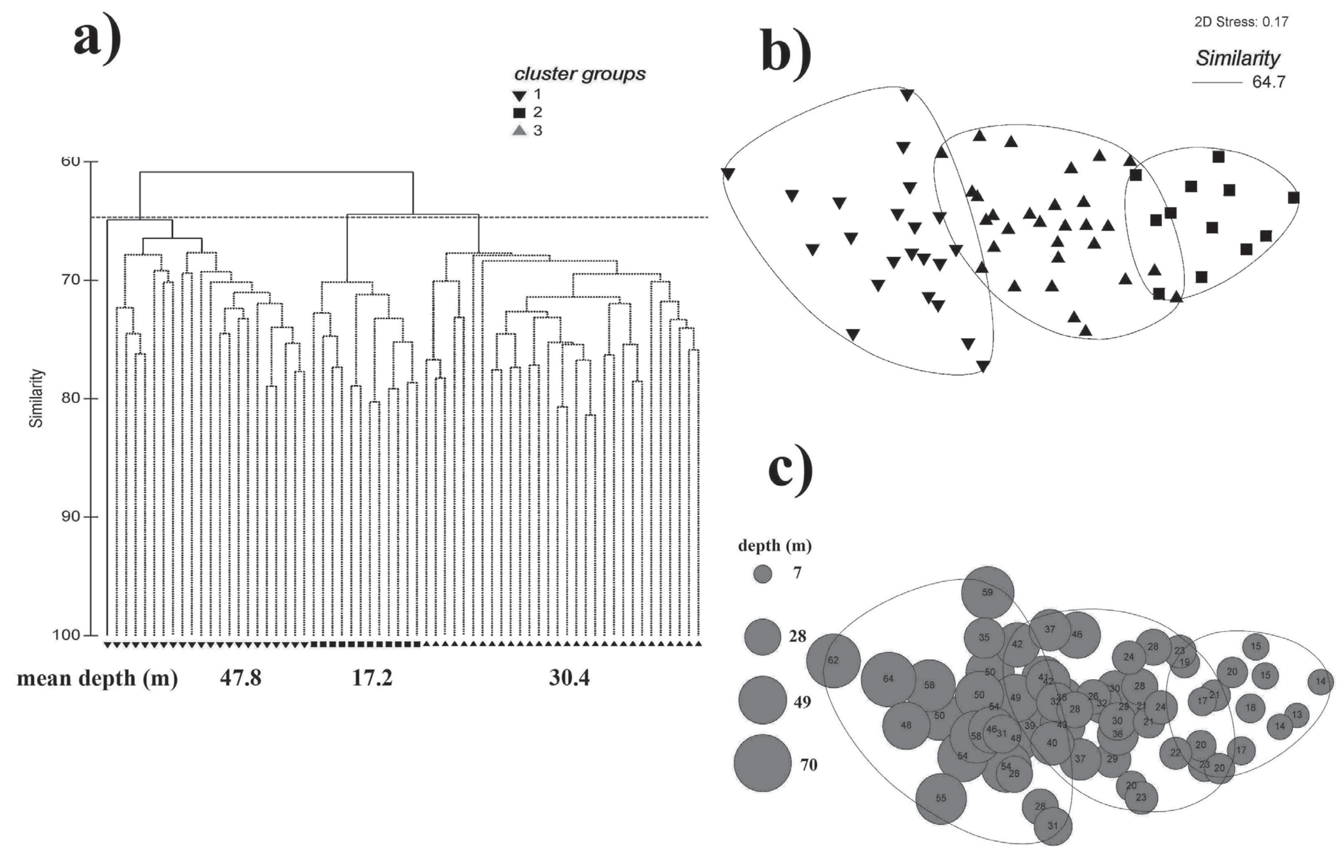

Figure 6. a) Cluster dendrogram of 64 coastal stations performed in the vicinity of Diablo Canyon Power Plant. b) Non-metric multidimensional scaling plot (Bray-Curtis similarity) with cluster groups outlined by solid lines and coded with the same symbols. c) Depth of individual samples mapped over the ordination space in MDS diagram. Data coding as in Figure 2.

the dendrogram), were characterized by similar dominant species (northern anchovy, Pacific sardine, various rockfishes, and northern lampfish), with higher abundances more offshore. Most important indicator species for the deepest assemblage (I) were Pacific hake, mesopelagic blue lanternfish (*Tarletonbeania crenularis*), and *Nannobrachium* spp., and also Pacific sanddab (*Citharichthys sordidus*) and slender sole (*Lyopsetta exilis*). The top indicator species for the intermediate-depth assemblage (III) were the ronquils (Bathymasteridae), sculpins (smoothhead sculpin *Artedius lateralis*, and unidentified sculpin species), gadids, and sand sole (*Psettichthys melanostictus*) (table 5). The shallowest assemblage (group II) was primarily characterized by several typical nearshore groups: clinids (*Gibbonsia* spp.), sculpins (tidepool sculpin *Oligocottus maculosus*, *Oligocottus* spp.), monkeyface prickleback, and blind goby (*Typhlogobius californiensis*). This group had the lowest species richness and abundances (table 5).

Larval fish assemblages as revealed by different studies

Inshore CalCOFI stations and LACM data set, 1978–85. Because of the infrequent sampling in late 1970s-early 1980s by the CalCOFI program, we limited the analysis to geographic locations and months sampled by both LACM and CalCOFI. Classification of larval fish data from these samples resulted in three large groups, revealing patterns of seasonality and distance from shore (fig. 7). The first group (I) was comprised of 16 LACM samples obtained primarily during spring (but with two winter and two fall samples as well) from 20–30 m station depth. The top five indicator species were white croaker, jack silverside, unidentified clinids, turbot (*Pleuronichthys* sp.) and English sole. The second group (II) represented a mixture of LACM (n=7) and CalCOFI (n=6) locations sampled during the summer (plus one fall sample) mainly at depths of 45 m or less with important indicator species: chub mackerel (*Scomber japonicus*), seabasses, Pacific barracuda (*Sphyraena argentea*), Mexican lampfish (*Triphoturus mexicanus*), and reef finspot (*Paraclinus integripinnis*). The final group (III) comprised 13 CalCOFI winter-spring samples from approximately 40–100 m (fig. 7a). The deeper CalCOFI winter-spring assemblage (group III) was strongly dominated by northern anchovy and was characterized by low species richness and larval abundances (fig. 7, table 6). No statistically significant indicator species were found

TABLE 5
Results of SIMPER and ISA analyses (top 8–10 indicator species) for ichthyoplankton data collected off Diablo Canyon by Tenera. Abbreviations and data structure as in Tables 2, 3.

Group	Species	Av. Abund	Av. Sim	Sim/SD	S(i)	Ind Val	N	H'	J'
I	*Citharichthys sordidus*	0.76	1.29	1.93	1.89	70			
deep	*Tarletonbeania crenularis*	0.93	1.84	6.58	2.7	68			
	Merluccius productus	0.84	1.49	2.59	2.19	68			
	Nannobrachium spp.	0.92	1.75	2.86	2.57	66			
	Sardinops sagax	2.06	4.25	12.36	6.24	66	113	2.4	0.62
	Engraulis mordax	2.23	4.63	14.48	6.8	52			
	Stenobrachius leucopsarus	1.92	3.93	9.65	5.76	63			
	Rhinogobiops nicholsii	1.41	2.89	9.51	4.24	57			
	Lyopsetta exilis	0.7	1.12	1.35	1.64	64			
	Sebastes spp.	2.14	4.54	12.95	6.65	39 (NS)			
II	*Gibbonsia* sp.	1.33	3.64	8.25	5.06	80			
shallow	*Oligocottus maculosus*	0.5	1.02	1.08	1.42	70			
	Oligocottus sp.	0.57	1.09	1.06	1.52	66			
	Cebidichthys violaceus	1.44	4.02	6.46	5.58	66	56	2.74	0.77
	Typhlogobius californensis	1.06	2.81	4.11	3.9	53			
	Genyonemus lineatus	1.22	3.28	5.79	27.31	27 (NS)			
	Sebastes spp.	1.8	4.72	7.72	6.56	24 (NS)			
	Engraulis mordax	1.54	3.99	5.35	17.69	14 (NS)			
III	Bathymasteridae spp.	1.45	2.97	6.04	4.24	59			
intermediate	Cottidae spp.	0.98	1.93	2.87	2.76	51			
	Gadidae spp.	0.41	0.54	0.8	0.77	40			
	Psettichthys melanostictus	0.37	0.45	0.67	0.64	33			
	Artedius lateralis	1.15	2.35	7.17	3.35	46	89	2.63	0.68
	Engraulis mordax	1.98	4.23	9.74	6.04	33 (NS)			
	Sebastes spp.	2.03	4.19	7.06	5.98	37 (NS)			
	Sardinops sagax	1.63	3.33	6.46	4.75	28 (NS)			
	Stenobrachius leucopsarus	1.53	3.2	8.13	4.57	27 (NS)			

for this group. Northern anchovy was the dominant species in all three assemblages, which differed from one another due to input from other taxa (table 6). A number of nearshore taxa contributed to the primarily spring LACM group (I): croakers, flatfishes (Pleuronectidae and Paralichthyidae), gobies, sculpins, lanternfishes, rockfishes, and clinids (fig. 7b). The summer assemblage (II) was strongly influenced by chub mackerel and seven species of right-eyed flounders (Pleuronectidae), with smaller contributions from croakers, seabasses, lanternfishes, and blennies (fig. 7b).

Inshore CalCOFI stations, SCCOOS stations, and Tenera data sets, 2004–07. Classification of 38 samples collected by SCCOOS, Tenera, and CalCOFI programs produced two principal groups (fig. 8a). The first assemblage included all the nearshore Tenera locations (mostly shallower than 25 m), with the second group comprising the six coastal CalCOFI stations and seven SCCOOS stations (mostly offshore of 25 m). The first, more inshore group had 20 significant indicator species, with unidentified larval gobies, diamond turbot (*P. guttulatus*), unidentified croakers, queenfish, and combtooth blennies being most important, while the second group had only two significant indicator species: unidentified rockfishes and mussel blenny (*Hypsoblennius jenkinsi*). Croakers were the dominant taxon in the first group, while northern anchovy was dominant in the second (table 7). In general, however, similar taxa were found in the two groups, although their contribution to average similarity differed somewhat: pleuronectid and paralichthyid flatfishes, blennies, and myctophids (fig. 8b). The stations in the Tenera group on average contained twice as many species and had greater larval abundances.

DISCUSSION

It has been hypothesized that ichthyoplankton assemblages represent an adaptive feature, resulting from similar responses of different species to selective pressures in the pelagic environment (Frank and Leggett 1983). Understanding spatio-temporal patterns of such multispecies associations is important to gaining insight into specific niches during early ontogeny, resource utilization, and optimal environmental conditions for growth and survival.

Our study examined the biogeography of coastal ichthyoplankton in the region from San Francisco Bay to San Diego Bay. Alongshore within this region, the major breakpoint was Point Conception, with distinct assemblages north and south. This is in agreement with many previous studies, which emphasized the importance of Point Conception as a major zoogeographical

TABLE 6
The results of SIMPER and ISA analyses for classification of inshore CalCOFI stations and LACM dataset. Abbreviations and data structure as in Tables 2, 3.

Group	Species	Av. Abund	Av. Sim	Sim/SD	S(i)	Ind Val	N	H'	J'
I	*Genyonemus lineatus*	2.91	6.24	2.92	11.76	76			
LACM	Clinidae spp.	0.89	1.55	1.28	2.92	56			
spring	*Atherinopsis californiensis*	0.68	1.00	0.87	1.88	55			
	Pleuronichthys sp.	0.8	1.57	1.24	2.95	54	31	3.2	0.9
	Parophrys vetulus	0.73	0.83	0.71	1.57	54			
	Gobiidae spp.	1.58	3.06	1.66	5.76	52			
	Paralichthys californicus	1.34	2.49	1.51	4.69	48			
	Sebastes spp.	1.53	2.56	1.41	4.82	39 (NS)			
	Engraulis mordax	5.01	11.08	4.13	20.88	37 (NS)			
II	*Scomber japonicus*	2.26	4.75	3.17	10.41	94			
LACM + CalCOFI	*Paralabrax* spp.	1.69	3.46	2.48	7.58	91			
summer	*Sphyraena argentea*	1.10	1.67	1.07	3.66	74	31	3.2	1
	Triphoturus mexicanus	1.45	2.98	1.93	6.54	67			
	Hypsoblennius spp.	1.62	2.79	1.36	6.11	58			
	Paraclinus integripinnis	0.37	0.30	0.58	0.67	54			
	Engraulis mordax	3.41	8.06	3.24	17.67	25 (NS)			
III	*Engraulis mordax*	5.12	47.28	2.66	87.02	38 (NS)			
CalCOFI	*Merluccius productus*	0.72	3.17	0.46	5.84	28 (NS)			
winter-spring	*Sebastes* spp.	0.84	1.58	0.38	2.90	9 (NS)	4.1	1	0.9
	Stenobrachius leucopsarus	0.52	0.64	0.27	1.18	7 (NS)			
	Genyonemus lineatus	0.62	1.20	0.37	2.20	6 (NS)			

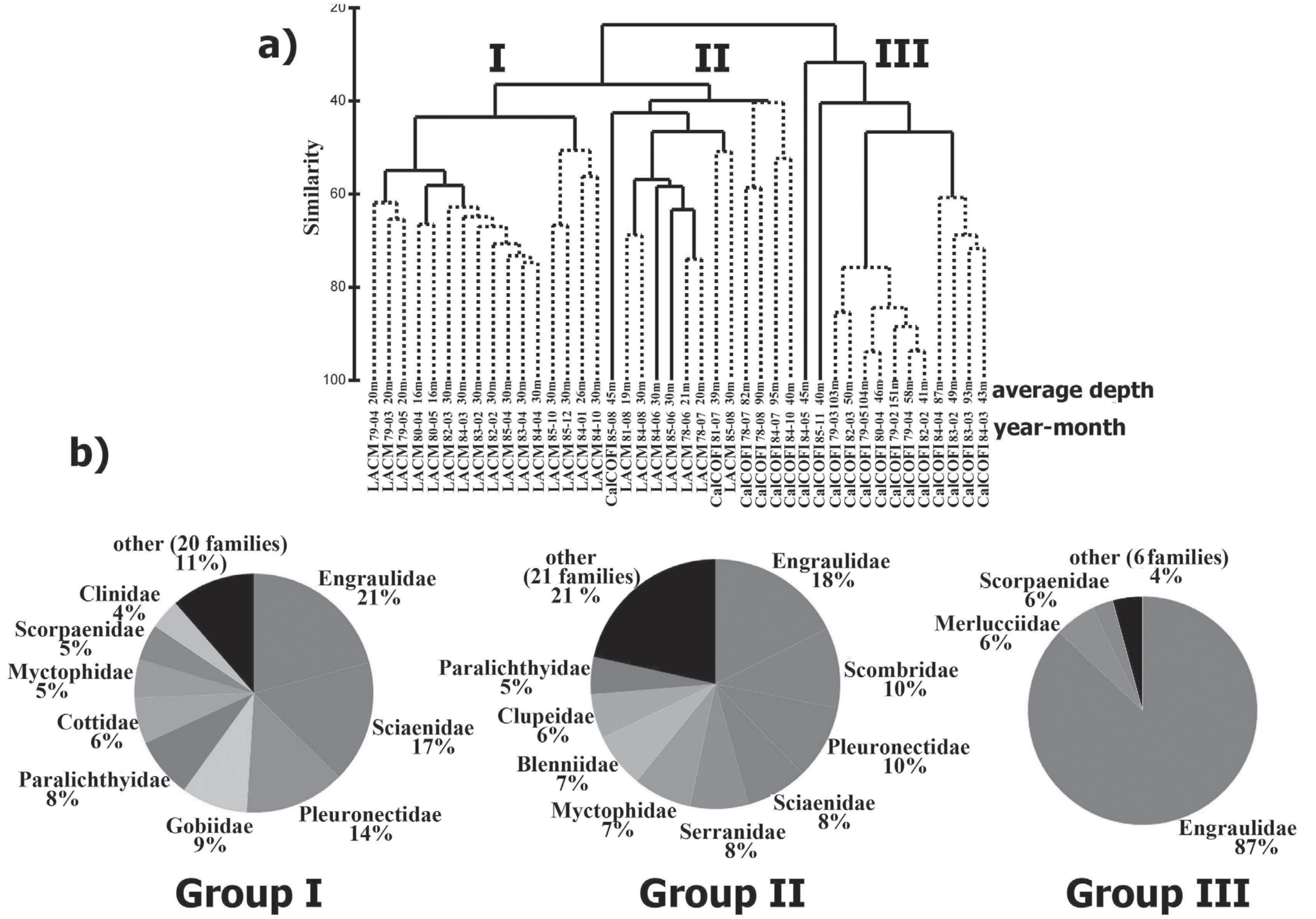

Figure 7. a) Cluster dendrogram of larval assemblages observed at five inshore CalCOFI stations and from the LACM data set, based on similar months and areas sampled during 1978–85. b) Contribution of different fish families (based on pooled species contributions) to the average similarity between cluster groups.

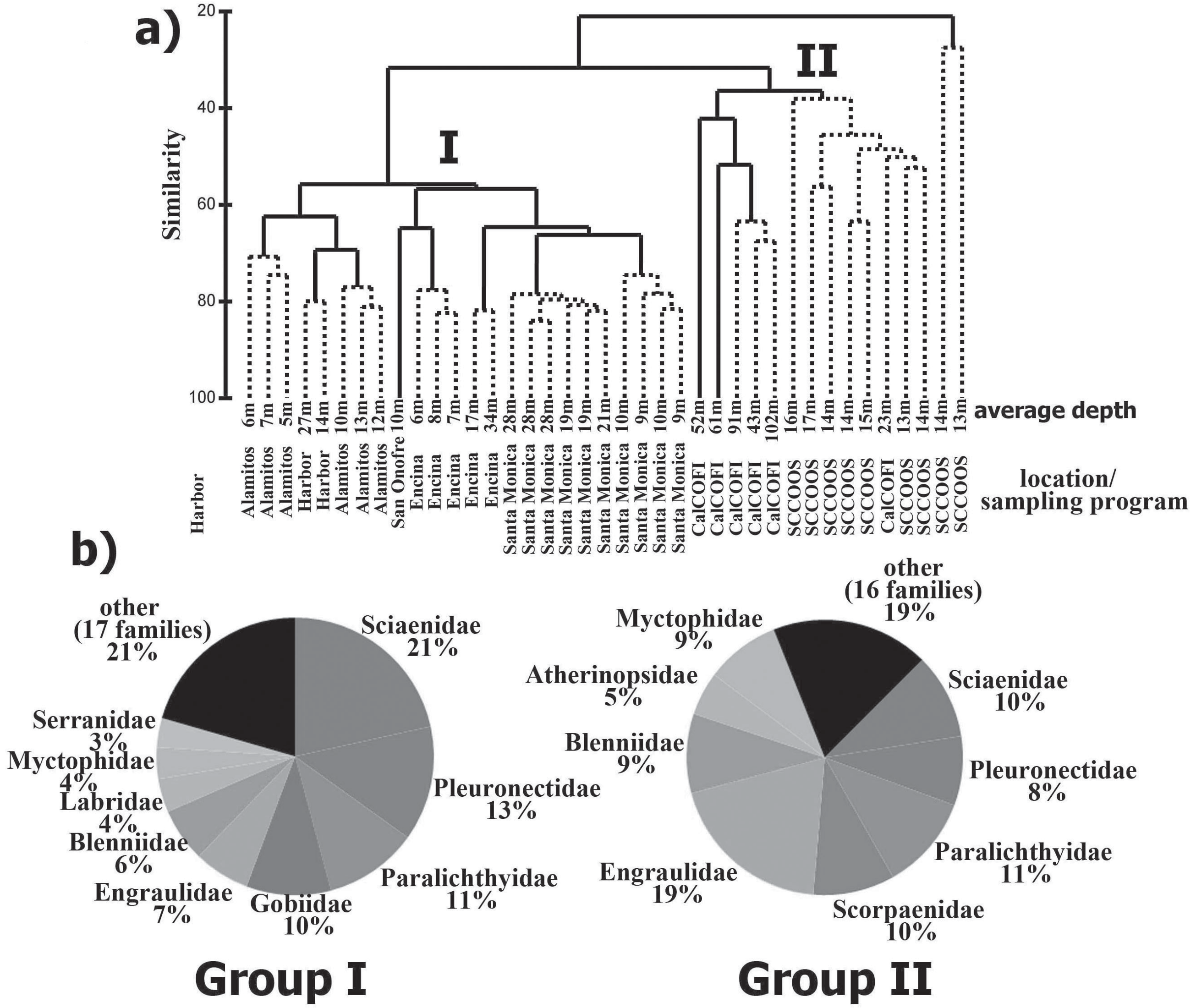

Figure 8. a) Cluster dendrogram of larval assemblages observed at inshore CalCOFI station, coastal SCCOOS stations and power plant locations sampled by Tenera during 2004–07. b) Contribution of different fish families (based on pooled species contributions) to the average similarity between cluster groups.

boundary in the region, separating the Oregonian faunal province from the San Diegan or Californian (Briggs 1974; Horn et al. 2006). This faunal break was found for assemblages in nearshore and embayment habitats and for those found more offshore on the continental shelf.

We also observed a strong nearshore gradient in ichthyoplankton assemblages off both central and southern California. Northern and southern shallow coastal/embayment larval assemblages were dominated by larval gobies, a typical demersally spawning coastal family. However, different gobiid species were more important north of Point Conception (*A. flavimanus*, *L. lepidus*) and south of it (*G. mirabilis*) within the SCB. The northern and southern shallow assemblages displayed pronounced differences in the dominance of other families as well, consistent with the distribution of adult fishes (Horn and Allen 1978; Horn et al. 2006). Thus, when SIMPER values of particular species are combined into family contributions, bays and shallow open coastal habitats off central California appeared more influenced by larval sculpins, clupeids (mainly Pacific herring), flatfishes (left and right flounders combined), stichaeids, rockfishes, sand lances, and ronquils; while southern shallow assemblages in the SCB were structured by larval silversides, combtooth blennies, clinids, labrisomids, and clingfishes (*Gobiesox* spp.). However, a number of taxa, such as the jack silverside, northern anchovy, croakers, combtooth blennies, and pipefishes, were important in both northern and southern shallow assemblages.

Estuarine fish assemblages in California have relatively low species diversity, a pattern observed in other temperate zones worldwide (Allen et al. 2006). We found

TABLE 7

Results of SIMPER and ISA for classification of inshore CalCOFI (California Cooperative Fisheries Investigations) stations, SCCOOS (Southern California Coastal Ocean Observing System) stations and power plant locations sampled by Tenera during 2004–07. Abbreviations and data structure as in Table 2.

Group	Species	Av. Abund	Av. Sim	S(i)	Ind Val	N	H'	J'
I	Gobiidae spp.	1.55	2.92	4.79	100			
Tenera	*Pleuronichthys guttulatus*	0.89	1.84	3.03	100			
	Sciaenidae spp.	1.48	3.08	5.07	100			
	Seriphus politus	1.25	2.17	3.56	96			
	Hypsoblennius spp.	1.79	3.64	5.97	96	50	3.8	0.97
	Genyonemus lineatus	2.26	4.38	7.19	81			
	Engraulis mordax	2.08	4.00	6.57	37 (NS)			
	Gobiidae spp.	1.55	2.92	4.79	30 (NS)			
	Sciaenidae spp.	1.48	3.08	5.07	25 (NS)			
	Hypsoblennius spp.	1.79	3.64	5.97	20 (NS)			
II	*Sebastes* spp.	1.09	3.25	7.76	87			
CalCOFI	*Hypsoblennius jenkinsi*	1.16	3.35	8.01	81			
SCCOOS	*Engraulis mordax*	2.40	8.17	19.52	61	24	3.06	0.97
	Paralichthys californicus	0.99	3.48	8.31	21 (NS)			
	Genyonemus lineatus	1.34	3.79	9.04	15 (NS)			

a similar pattern in the ichthyoplankton, with embayment/estuarine assemblages north and south of Point Conception having lower species richness and diversity values compared with more offshore larval assemblages.

Pronounced differences were also evident in the open coastal assemblages north and south of Point Conception. The northern open coast assemblage was dominated by a variety of larval sculpins in comparison with the SCB, which was dominated by larval croakers. Typical offshore families, such as myctophids, bathylagids, and argentinids all had higher influence in structuring northern open coast larval assemblages. Oceanic larval fishes are more easily advected into shallow coastal habitats off the central California coast than within the SCB, where the coast is further from the main axis of the California Current. In addition, engraulids, gobiids, blenniids, labrids, and silversides were more important groups in the SCB, while larval greenlings, ronquils, and clupeids were more important for offshore assemblages in the north.

The lack of significant alongshore variation in the larval assemblages within the SCB based on our analysis of the LACM data is consistent with the gyral circulation in this region, with poleward flow nearshore dominating in fall and winter and equatorward flow in spring and summer (Lynn and Simpson 1987). The region has generally been recognized as forming a single biogeographic province, and previous studies of coastal ichthyoplankton in the area have reached similar conclusions (Lavenberg et al. 1986; McGowen 1993).

Several earlier studies of the shallow habitats in the region reported cross-shelf patterns in larval distribution, although without specifying the precise boundaries (Gruber et al. 1982; Barnett et al. 1984; Lavenberg et al. 1986; McGowen 1993). Our data for the SCB based on averaged annual ichthyoplankton abundances suggested a faunal transition zone between 15–22 m, separating inshore and more offshore assemblages. Due to the fluid nature of the pelagic environment and rather small spatial scale of this boundary, there was considerable overlap in the species that dominate these assemblages, such that they are characterized primarily by differences in relative abundance. Interestingly, a more localized study off San Onofre reported a very similar transitional zone (or ecotone) located between the 12 and 22 m isobaths (Marine Review Committee 1977). A similar pattern was noted for the coastal zooplankton community in the region, with the inshore-offshore boundary in the vicinity of the 30 m isobath (Barnett and Jahn 1987).

We found that our assemblages were often characterized by distinct sets of indicator species, which indicate there are micro-faunal zones in coastal waters. Thus, larval silversides, clinids, gobiesocids, labrisomids, and stichaeids were indicators for the shallow assemblages, while clupeids, engraulids, hexagrammids, labrids, merlucciids, myctophids, paralichthyids, pleuronectids, and sphyraenids characterized more offshore habitats. Some families spanned these faunal zones, such as the sculpins and gobies, with Pacific staghorn sculpin and longjaw mudsucker (*Gillichthys mirabilis*) characteristic of the shallow assemblage and yellowchin sculpin (*Icelinus quadriseriatus*) and Bay goby of deeper water. Notably, indicator species of the shallow assemblage are characterized by demersal spawning, either depositing small numbers of eggs in the substratum or attaching them to seaweeds or rocks, thus reducing planktonic dispersal, a pattern observed in temperate (Marliave 1986; Suthers and Frank 1991), as well as tropical regions (Leis and Miller 1976). Larvae of demersal spawners are also relatively more developed and have greater sensory and swimming capability and thus are more capable of choosing a particular habitat (Suthers and Frank 1991). On the other hand, indicator species for more offshore assemblages spawn large quantities of planktonic eggs with a long larval duration and often have multiple spawnings through the year (Moser 1996). Distinct onshore-offshore gradients in larval distribution have been described for coastal regions worldwide, including upwelling areas, such as the Benguela (Olivar 1990) and Humboldt Currents (Suntsov 2000; Hernandez-Miranda et al. 2003), and northern California Current (Richardson et al. 1980; Doyle et al. 1993).

The importance of depth in structuring the coastal assemblages was also evident on a more restricted temporal and spatial scale off Big Sycamore Canyon (SCB) and Diablo Canyon (central California). In addition, these two areas provided information on the persistence and structure of the assemblages throughout the year, in different habitats as well as during large environmental disturbances such as El Niño/La Niña. We found distinct ichthyoplankton assemblages off Big Sycamore only during winter months; there were no clear depth-related assemblages during summer. Many coastal species off the U.S. West Coast spawn during winter-spring, when coastal upwelling is minimal, thereby maximizing larval retention nearshore; offshore Ekman transport apparently precludes the formation of persistent larval assemblages during summer months.

The strong El Niño of 1998 and ensuing La Niña in 1999 significantly affected the structure of the coastal assemblages sampled off Big Sycamore Canyon. Although distinct inshore/offshore groups were present both years, they were characterized by different indicator species, with certain sciaenids, pleuronectids, and paralichthyids more abundant in 1999, and engraulids and argentinids more prevalent during the El Niño. In addition, the coastal assemblage observed in 1999 had more offshore affinities and was also restricted to nearshore stations centering around the 20 m isobath, whereas during the warmer conditions of 1998 the inshore assemblage expanded offshore. Our data for differential cross-shelf distributions of larvae and eggs of northern anchovy is in good agreement with some previous studies, where the shallow water zone was hypothesized as a larval nursery area for this species (Barnett et al. 1984).

Compared to the Big Sycamore Canyon area, the ichthyoplankton assemblages off Diablo Canyon were less distinct, although these two regions were sampled over a similar depth range. Big Sycamore Canyon is characterized by soft bottom substrates and relatively quiet hydrological conditions (Watson et al. 2002), while Diablo Canyon is a turbulent rocky habitat, characterized by dense kelp beds and is well exposed to northeasterly winds and large ocean swells (Icanberry et al. 1978), which likely contribute to greater mixing of assemblages. However, onshore-offshore structure was also evident here. Again, the more offshore assemblage was characterized by oceanic species or families with planktonic eggs (e.g., Myctophidae, Merlucciidae, Pleuronectidae, Paralichthyidae), whereas the more inshore assemblage was characterized by species with demersal eggs (e.g., Cottidae, Clinidae, Stichaeidae, Gobiesocidae). However, the numerically dominant species in both of these assemblages were northern anchovy and rockfishes, consistent with observations in Monterey Bay (Yoklavich et al. 1996).

Significant cross-shelf structure in the ichthyoplankton assemblages implies that different coastal ichthyoplankton programs target distinct larval communities. In the SCB, there were few differences between the ichthyoplankton at the innermost CalCOFI and SCCOOS stations, although the SCCOOS stations are somewhat further inshore because the large vessels conducting the CalCOFI and SCCOOS programs cannot work within the 10–12 m isobaths where the nearshore ichthyoplankton assemblage is found. The distinct nearshore and embayment assemblages were sampled by Tenera in its monitoring of coastal power plants. The Tenera stations had higher contributions from coastal families such as croakers, right-eyed flounders, gobies, wrasses, and sea basses, and lesser input from anchovies or lanternfishes. These differences may be less distinct during certain seasons. For example, the assemblages at the innermost CalCOFI stations and LACM data differed most in winter-fall (due to the dominance of northern anchovy), while forming a mixed group later in the year.

In conclusion, the results of this study suggest that nearshore habitats off central and southern California host distinct and diverse ichthyoplankton assemblages, with differences related to local geomorphology, hydrology and season. This information has important implications for future ichthyoplankton monitoring of nearshore coastal habitats as a means to assess the impact of establishing a network of marine protected areas along the California coast.

ACKNOWLEGEMENTS

This study was funded by a grant from the California Conservancy and Ocean Protection Council. We gratefully acknowledge the cooperation and support from Tenera Environmental, in particular John Steinbeck, Richard Feeney (Los Angeles County Museum, Ichthyology Section), and from Russ Vetter, Richard Charter, Sam McClatchie, Ed Weber and others from the Southwest Fisheries Science Center (NMFS/NOAA). We thank Karen Baker, J. Conners, and M. Kortz for assistance with database operations.

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The CalCOFI Editorial Board will consider for publication in the "Scientific Contributions" section manuscripts not previously published elsewhere that address the following in relation to the North Pacific, the California Current, and the Gulf of California: marine organisms; marine chemistry, fertility, and food chains; marine fishery modeling, prediction, policy, and management; marine climatology, paleoclimatology, ecology, and paleoecology; marine pollution; physical, chemical, and biological oceanography; and new marine instrumentation and methods.

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The manuscript should contain the following parts:

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3. Body of the text, including any footnotes
4. Literature cited, in alphabetical order
5. Acknowledgments, if any
6. Tables
7. Figures and captions

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Text. Double-space all elements of the text, allow margins of at least 1 inch on all sides, and use a standard font (such as Times or Times New Roman) no smaller than 12 points. Number the pages consecutively. Eliminate all nonessential formatting. Indicate subordination of heads consistently; for example, use all caps for the main heads, boldface for the next level, and italics for the third level. To indent paragraphs, use the tab key, not the space bar or a "style" feature of any sort. Never use letters for numbers or vice versa; in other words, do not type the lowercase "el" for the number "one" or the capital letter "oh" for zero. Use your word-processor's automatic footnoting feature to insert footnotes. Acknowledgments, if included, should be placed at the end of the text and may include funding sources. Place the entire text (title page, abstract, text body, footnotes, acknowledgments, and literature cited) in one document file, and label it with your name—for example, "Smith text.doc."

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