

**CALIFORNIA  
COOPERATIVE  
OCEANIC  
FISHERIES  
INVESTIGATIONS**

*Reports*

VOLUME 55  
JANUARY 1 TO DECEMBER 31, 2014

**Cooperating Agencies:**

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

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*Printed and distributed December 2014, La Jolla, California*  
**ISSN 0575-3317**

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Part I

## REPORTS, REVIEW, AND PUBLICATIONS

### REPORT OF THE CALCOFI COMMITTEE 2013

#### SIO HIGHLIGHTS

Four quarterly CalCOFI cruises occurred on the RV New Horizon (NH), RV Bell M Shimada (SH), and RV Ocean Starr (OS) in 2013: 1301SH (January 10–February 2), 1304SH (April 6–30), 1307NH (July 6–22), and 1311NH (November 9–26). Ancillary programs included measurement of carbon dioxide and related variables, in collaboration with the Pacific Marine Environmental Lab (NOAA) and Andrew Dickson (SIO); visual and acoustic observations of marine mammals, led by John Hildebrand (SIO); and seabird observations, led by Bill Sydeman (Farallon Institute for Advanced Ecosystem Research). CalCOFI continued to be augmented significantly by the California Current Ecosystem Long-Term Ecological Research (CCE-LTER) program led by Mark Ohman (SIO) and funded by NSF. Most data from these cruises have been rapidly made available on the Scripps CalCOFI, CCE-LTER, NOAA SWFSC, and CDF&W websites. Notable is the completion and activation of NOAA's ERDDAP website, which makes available CalCOFI hydrographic and ichthyoplankton databases from 1950 to the present in queryable form. More than 53 publications by SIO and other university scientists in 2012 were based on CalCOFI data and results, including four doctoral dissertations. Selected papers are mentioned below.

A number of papers focused on the physical oceanography and its relation to ecosystem function. High-frequency radar data were used to study subinertial currents, possibly coastally trapped waves, propagating poleward off the US West Coast (Kim et al. 2013). The California Undercurrent was the subject of two papers, one focusing on its variation in relation to temperature, salinity, and dissolved oxygen and effects on upwelled water (Meinville and Johnson 2013) and the other a numerical simulation of the coastal circulation of waters off Baja California, Mexico (Mateos et al. 2013). The timing of the spring transition and its effects on the California Current System (CCS) was modeled (Chenillat et al. 2013). General additive models were used to study the relation of nitrate concentration to temperature, salinity, and oxygen, relevant to biogeo-

chemistry and fisheries (Palacios et al. 2013). Nutrient enrichment of the subarctic Pacific pycnocline was characterized (Whitney et al. 2013).

The depth of winter mixing was shown to influence the depth of the chlorophyll maximum, with implications for assessing phytoplankton abundance and production from space (Navarro and Ruiz 2013). Dissolved oxygen and argon in the surface ocean were used to study the balance of production and respiration, and waters sampled by CalCOFI were shown to be autotrophic year-round and with an export efficiency similar to that of the open ocean (Munro et al. 2013). Particle abundance and flux in the upper 100–150m were estimated by use of the SOLOPC (Petrik et al. 2013). Midwater fish were shown to contribute significantly to the active vertical transport of carbon from the euphotic zone by the combined use of acoustics, trawling, and a bioenergetics model (Davison et al. 2013). CalCOFI data of various types were used in the Earth System Model at the NOAA's Geophysics and Fluid Dynamics Lab (Stock et al. 2014).

A number of papers were published on exploited fish, with implications for the management of their fisheries. Multivariate state-space reconstruction was used to assess the relation of sardine to the environment (Deyle et al. 2013). Earlier papers were re-examined to show that sardine dynamics are related to temperature measured at the Scripps pier but even more so to CalCOFI temperature (Jacobson and McClatchie 2013). The natural mortality rate ( $M$ ,  $y^{-1}$ ) of sardine, used in stock assessment, was characterized from past acoustic-trawl survey data, with the average value significantly higher than that generally assumed (Zwolinski and Demer 2013). Midwater trawl surveys of pelagic juvenile rockfish off the US West Coast showed 2005 and 2006 unusual in regard to both winds and rockfish distribution (Ralston and Stewart 2013). Models were used to investigate how the CCS ecosystem would respond to removal of significant portions of forage taxa, including small pelagic fish and euphausiids (Kaplan et al. 2013).

Climate effects on marine ecosystems were the subjects of a number of papers. Multivariate ocean-climate indicators were developed for north-central California

and compared with other indices of the environment (Sydeman et al. 2014). Principal components analysis of time series of CalCOFI ichthyoplankton documented major modes of variability of fish larvae and their relation to the environment (Koslow et al. 2013). Notable was PC1, representing midwater fish and related to midwater oxygen. This paper exemplifies a major strength of CalCOFI, i.e., the co-location, in time and space, of data and samples. Fluctuations of anchovy and sardine from both recent and prehistoric records was studied in relation to climate; differing life history characteristics were shown important in understanding the response of the two species to the environment (Lindgren et al. 2013). Isotopic analysis of planktonic foraminifera in sediments accumulated over the past 250y in the Santa Barbara Basin showed a range of time scales of change, including periods of enhance upwelling and subsurface equatorward flow along the Southern California Margin (Roach et al. 2013). A 24-year time series of sinking particulate organic carbon (POC) and requirements of the benthic communities, at a bottom site ~4,000m deep and west of Point Conception, showed episodes of high POC flux punctuate a common state of food deficit (Smith et al. 2013).

A commentary in *Nature* argued for the need for time series of marine biodiversity observations, citing CalCOFI as an example (Koslow and Couture 2013). An issue of *Oceanography* focused on the CCE-LTER program and its augmentation of CalCOFI (e.g., Ohman et al. 2013a,b, Franks et al. 2013). Finally, testimony was give to the California Fish and Game Commission on the value of CalCOFI to California in regard to fisheries management and education.

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## NOAA HIGHLIGHTS

### CalCOFI Ichthyoplankton Update

During the past year the SWFSC Ichthyoplankton Ecology group settled into its new laboratory and sample archive and began the task of working through the substantial sample backlog that developed during the move to the new facilities and a period of reduced staffing but high demand for time spent at sea. During that time our highest priorities in sample processing have been the spring CalCOFI, spring sardine, and SaKe surveys, and we have fallen behind in completing other cruises. However, we recently were able to hire additional plankton sorters and with the equivalent of three full time contract plankton sorters now on board in addition to NOAA staff, we are beginning to make progress in reducing the sample backlog. The ichthyoplankton group also has continued its project to retroactively update identifications of fish eggs and larvae to current standards. Identification of Pacific whiting (hake) and jack and Pacific mackerel eggs collected in the CalCOFI oblique net samples are now complete from the latter part of 1978 to the present, and larval identifications to current standards are complete from mid-1965 to present.

To enhance the increased effort directed to processing the formalin-preserved plankton samples, a substantial laboratory effort has focused on the ethanol-preserved bongo net samples (which can be used for genetic analyses) collected during Cowcod Conservation Area and CalCOFI surveys. Staff continued their collaboration with Ron Burton and his students at SIO on the development of a high-throughput system for molecular identification of ichthyoplankton, with the ultimate aim to provide accurate, near real-time identifications of fish eggs, many of which can be difficult or impossible to identify to species using traditional morphological characters. This method should ultimately enable scientists to accurately identify eggs of several taxa of sport or commercial fishery value such as Pacific hake, Pacific mackerel, white seabass, and California barracuda, and it will be applied to ethanol-preserved CalCOFI samples to develop a time series for eggs from 1997 to the present. In addition, one of Burton's students successfully defended her master's thesis from SIO that examined the distribution and abundance of genetically-identified fish eggs from CalCOFI samples between 2002 and 2004. During the past year staff finished sorting eggs and larvae from ethanol-preserved samples from winter cruises in 2004, 2011, and 2013 bringing the list of completed ethanol-preserved samples to 1998, 1999, 2002–05, 2011, and 2013. Further, we were awarded a FATE (NOAA's Fisheries and the Environment program) grant to use genetic meth-

ods to develop a time-series of rockfish species dynamics to inform rockfish stock assessment and Integrated Ecosystem Assessment. Parts of the FATE funds were used to hire a full-time technician to focus exclusively on processing the ethanol-preserved samples for the larval rockfish project. The lab has also added a master's student from University of San Diego who is working with rockfish larvae from the ethanol-preserved samples for his thesis.

To enhance understanding of how ichthyoplankton respond to environmental variability throughout the California Current system, an analysis of CalCOFI data together with ichthyoplankton and environmental data collected during IMECOCAL surveys is underway, in collaboration with Martín Hernández-Rivas and co-workers from CICIMAR. This study complements a similar, recently completed study using data collected by CalCOFI, Oregon State University and NWFSC between 1997–2011 in Oregon waters (Thompson et al. 2014, doi:10.3354/meps10801), and should help inform NOAA's California Current Integrated Ecosystem Assessment program.

Staff prepared a manuscript in collaboration with Sam McClatchie that evaluates how ichthyoplankton distributions have changed within the CalCOFI sampling frame over the past three decades. This work shows that the center of sardine spawning has shifted further offshore in recent years; the results of which have broad implications for the understanding of how the fish assemblage in the California Current system respond to climate change and the effect of these changes on population dynamics of high trophic level marine predators such as sea lions. We also prepared a manuscript examining the distribution of genetically-identified rockfish larvae collected at the relatively coarse CalCOFI spatial scale (lines separated by 74 km) and a finer scale (lines separated by 18 km) within and around the Channel Islands. Results from this work will inform placement of marine protected areas in Southern California.

Thompson A. R., T. D. Auth, R. D. Brodeur, N. M. Bowlin, and W. Watson 2014. Dynamics of larval fish assemblages in the California Current System: A comparative study between Oregon and southern California. *Marine Ecology Progress Series* 506: 193–212.

### Spring Coastal Pelagic Species Cruise

The spring Coastal Pelagic Species (CPS) cruise relies on a 25 day ship charter plus a 25–30 day commitment of NOAA vessel time, of which the first 14–17 days are typically the spring CalCOFI cruise. Observations from CalCOFI including acoustics and CUFES often guide adaptive sampling for the daily egg production method (DEPM) and the acoustic trawl method (ATM). The spring CPS cruise carries out a subset of CalCOFI measurements along with acoustics, trawling, and adaptive

sampling of eggs and larvae to provide total and spawning biomass estimates for CPS stock assessments.

The spring CalCOFI was carried out before the spring CPS cruise this year, working the 75-station pattern south to north, March 28th to April 15th on the Ocean Starr. Departure was delayed by 3 days due to a malfunctioning winch used to tow plankton nets that was detected on the first stations occupied. A repair rather than a work-around solution was determined to be necessary to ensure crew safety. After obtaining a replacement part, the winch was repaired, the vessel sailed in calm weather, and the cruise end date was extended by 3 days to April 18th. The spring CalCOFI cruise (Ocean Starr leg 1) ended in San Diego, after occupying 70 of the 75 station pattern. Most of the missed stations were due to Navy exclusion areas.

The second leg of the Ocean Starr cruise began the spring CPS cruise departing on April 20th to conduct acoustic/ trawl and DEPM coastal pelagic survey off the southern California coast. Transects were shortened to focus on stations inshore of CalCOFI station 60 since no offshore CPS were detected on the CalCOFI cruise (Ocean Starr leg 1). Meanwhile, departure of Shimada on the spring CPS cruise was delayed due to engineering staffing problems. Shimada departed San Diego on Wednesday April 15th, headed for CalCOFI line 57 just north of San Francisco to begin working from north to south, while Ocean Starr leg 2 worked the spring CPS cruise from south to north.

The spring CPS cruise continued through May 2 on Shimada, but ended on Ocean Starr in San Francisco on April 30th. Trawl sampling on Ocean Starr was limited by high winds and seas on their second leg. Amy Hays reported that they were only able to trawl nearer to shore and were not able to complete many of their allocated transects.

There was a striking absence of sardine eggs in spring 2014, despite favorable potential habitat on the central coast. Sardine eggs sampled with the Continuous Underway Fish Egg Sampler (CUFES) were found only inshore in the Southern California Bight, in good habitat as predicted by the model, even after covering the entire central California coast south of San Francisco. Most of the eggs collected were jack mackerel. Preliminary temperature surfaces from the CalCOFI cruise leg showed some indications of anomalously warm water at 10 m depth, the California Current far offshore (shown by the 100 m depth cool temperature and fresh salinity anomalies), and low fluorescence voltages, except nearshore. Warm water anomalies at 50 m were not particularly strong or consistent at the time of the cruise. Nighttime trawl catches along the central coast caught few CPS, with intermittent small catches of squid and pyrosomes. The highest catch of sardine was less than 1kg, comprising 6 sardines.

## CDFW HIGHLIGHTS

The California Department of Fish and Wildlife (CDFW) welcomed its new Marine Region Manager, Dr. Craig Shuman. Immediately before coming to CDFW, Dr. Shuman served as the Marine Advisor to the California Fish and Game Commission (FGC).

The CDFW held a Science Symposium in Sacramento in October, 2013, and staff presented papers and posters at the symposium on topics ranging from abalone translocation studies, abalone and Harmful Algal Blooms, sea cucumber research, the status of the Dungeness crab fishery, surfperch life history studies and hagfish trap study results.

### Marine Regulatory Changes

The FGC took approximately a dozen marine-related actions in 2013, including: 1) reduced the catch of red abalone in northern California for 2014 due to declines in abalone density, primarily in Sonoma County; 2) upheld abalone closure in southern California, because survey results at San Miguel Island indicated densities are below the minimum viable population size as prescribed by the Abalone Recovery and Management Plan; 3) closed a loophole in the 2-ton incidental take allowance for market squid by requiring the landing or possession with other species and setting percentage catch limits; 4) upheld the current regulations and management measures for the central coast marine protected areas (MPAs) adopted by the commission in 2007, following a symposium summarizing results after 5 years of monitoring and management; and 5) approved changes to the spiny lobster report card period and fees to better track recreational lobster harvest and increase report card return rates.

### Marine Life Protection Act

California's redesigned Marine Protected Area (MPA) network includes 124 MPAs and 15 special closures, covering approximately 16% of the state waters (over 9% are in no-take MPAs). CDFW collaborates with partners to provide oversight on all aspects of MPA monitoring to inform adaptive management. This includes developing monitoring plans that apply the statewide MPA monitoring framework, regional baseline monitoring programs, five-year monitoring and management reviews, and cost-effective continued monitoring programs based on results from baseline programs. CDFW continues to explore MPA effects on California's marine fisheries, maintains an interactive spatial marine and coastal data viewer called MarineBIOS, and conducts field investigations such as remotely operated vehicle survey projects.

In 2013, a three-day public symposium was held to present results from the central coast MPA baseline monitoring program. CDFW and California Ocean Science

Trust produced a summary report, titled *State of the California Central Coast: Results from Baseline Monitoring of Marine Protected Areas 2007–2012*. The monitoring summary report and symposium proceedings were provided to the California Fish and Game Commission to inform the management review of the central coast MPAs. In the north central coast and south coast, baseline monitoring data collection has been completed and is being analyzed. Baseline monitoring planning is nearing completion on the north coast.

### **Ocean Protection Council (OPC)**

The OPC with the aid of their Science Advisory Team, and the California Ocean Science Trust administered the baseline MPA monitoring program for the north coast, starting with evaluating proposals. The MPA implementation process continued in 2013 in the rest of the state with a conference on the results from 5 years of monitoring and management along the Central Coast.

The OPC continued to support CDFW to draft the spiny lobster Fishery Management Plan. OPC partnered with the California Sustainable Seafood Initiative, on their seafood certification and marketing program.

### **Aquaculture and Bay Management**

The Aquaculture and Bay Management Project completed its annual monitoring and assessment of the San Francisco Bay commercial Pacific herring fishery for the 2013–14 season. The spawning biomass estimate for the 2013–14 season was 60,600 tons, slightly above the historical average (1979–80 season to the present) of 52,300 tons. Over the past five seasons, the spawning biomass has steadily recovered from the historic low during the 2008–09 season of 4,800 tons. Since the fishery reopened for the 2010–11 season, harvest targets for Pacific herring have been set at less than five percent of the spawning biomass as a conservation measure to allow sustained recovery. This low level of fishing mortality allows roughly 95 percent of the spawning stock to be available as forage for a variety of species dependent on Pacific herring, and is aligned with the FGC's Forage Policy. CDFW is currently working with stakeholders to identify outside funding for the development of a Fishery Management Plan. CDFW is also working with the Centre for Environment and Fisheries Aquaculture Science to review a stock assessment model for Pacific herring.

### **Coastal Pelagic Species**

CDFW conducted a collaborative Pacific sardine survey with the California Wetfish Producers Association as a fishery-independent index of abundance for the Southern California Bight. The Pacific Fisheries Management Council reduced the harvest guideline for Pacific sardine, which was set at 57,495 mt based on a biomass estimate

of 659,539 mt. The fishery, as of June 2014, was just shy of this harvest guideline. For the fourth year in a row, the commercial market squid fishery was projected to reach the seasonal catch limit of 107,050 mt before the season's end. During the 2013–14 season the fishery was closed early on October 18, and catch totaled 104,363 mt.

### **Invertebrate Fisheries Management**

The Invertebrate Project's northern California abalone staff completed the regulation change process and began implementation of new regulations for the northern California recreational red abalone fishery. The FGC's new regulations lowered the annual limit from 24 to 18 abalone, prohibited fishing before 8AM, and closed Fort Ross to achieve catch reductions prescribed by the Abalone Management and Recovery Plan. These changes were triggered by reductions in the density of red abalone detected during fishery independent surveys at key index sites in the fishery. The FGC did not recommend opening a red abalone fishery at San Miguel Island after receiving a report from CDFW that the island's red abalone population is below the viable minimum defined in the state's Abalone Recovery Management Plan. Efforts continued toward refining management of the commercial sea cucumber fishery, with research focusing on determining the seasonal spawning cycle and determining sea cucumber age and growth. A survey was conducted with sea cucumber fishery participants to learn more about fishery practices and their concerns for fishery sustainability. Finally, this was the inaugural season of a crab trap limit program in the commercial Dungeness crab fishery.

### **Lobster**

The Lobster Fisheries Management Plan (FMP) process entered its third year in 2013. CDFW worked closely with the Lobster Advisory Committee (LAC) to develop draft harvest control rules for the lobster fishery that include threshold reference points and possible regulator options that could be selected if the threshold reference points were to be exceeded. The LAC also discussed and addressed current issues facing the fishery, and developed a series of recommendations to be considered by the FGC when the Lobster FMP moves into the regulatory phase in 2015. Working with the South Coast MPA Baseline lobster project staff analyzed results from 25,000 tagged lobster and 100 dive surveys. This effort was a collaboration between CDFW, academics (SIO and SDSU), commercial fishermen, and the San Diego Oceans Foundation. The second year of the Collaborative Fisheries Research West-funded At-Sea Sampling program was completed, involving approximately 13 commercial fishermen, and academics from Sea Grant and UCSB and CDFW.

## Ocean Salmon

The 2013 forecast of the abundance of both Sacramento River and Klamath River fall-run Chinook stocks allowed more fishing of California's commercial ocean salmon fisheries than in 2012. Commercial salmon fisheries were open for a total of 410 days, an increase of 35 days from the previous year. For the first time since 1984, commercial fishing in the Klamath Management Zone occurred during May, June, July, August and September. Total commercial landings exceeded 297,400 Chinook salmon (1,719 mt), caught in 17,300 days fished, an increase in catch of about 38% from 2012. Average nominal ex-vessel price was \$13.73/kg (\$6.23/lb), with an ex-vessel value of over \$23 million.

In order to protect ESA-listed endangered Sacramento River winter-run Chinook, California's recreational ocean salmon fisheries were more constrained than in 2012. From June 1 to July 9 in the San Francisco and Monterey port areas, recreational fishing was closed on Mondays and Tuesdays. There were a total of 729 fishing days for the season, 25 fewer than in 2012. During the 2013 recreational ocean salmon fishery, nearly 113,300 Chinook were landed in 143,800 angler-days for an 8% and 2% reduction in catch and effort, respectively, compared to 2012.

## Groundfish

The Groundfish Project prepared documents for potential modifications to federal regulations for the 2015–16 recreational fishery. Modifications may include changes to bag limits for some species and/or species groups and season lengths in the five recreational management areas. In addition, documents were prepared for proposed modifications to federal regulations for the 2014 recreational Pacific halibut fishery in California.

## California Recreational Fisheries Survey (CRFS)

Recreational finfish anglers took an estimated 5.4 million fishing trips in California's marine waters and landed about 8.2 million fish in 2013. Over 70 CRFS samplers interviewed nearly 61,000 anglers at more than 500 sites, and examined and identified roughly 223,000 fish. Additional fishing effort information was obtained from a telephone survey of licensed anglers (26,000 completed interviews) and from mandatory fishing logs

from commercial passenger fishing (CPFV) vessel operators (>30,000 logs).

The Pacific Fishery Management Council adopted provisions for adjusting mortality rates for rockfish released with a descending device in the recreational fishery. The CRFS collected species-specific data on the use of descending devices in 2013. These data will be applied retrospectively to the harvest estimates of canary rockfish (*Sebastes pinniger*) cowcod (*S. levis*) and yellow-eye rockfish (*S. ruberrimus*).

## Fisheries Independent Assessment Project

The FGC implemented new sport fishing regulations for kelp bass, barred sand bass, and spotted sand bass, increasing the minimum size limit and reducing the bag limit in March of 2013. The project continues to collect data on the number, size, and health of discarded basses to evaluate the effectiveness of these new regulations. The project has ongoing studies of age, growth and reproduction in barred sand bass and kelp bass. Preliminary results on batch fecundity, spawning frequency, and periodicity were presented at a scientific conference.

## Northern and Central California Finfish Research and Management Project

Staff in 2013 completed the sampling of commercial and recreational surfperch and California halibut fisheries for length, sex, and age composition. The commercial hagfish fishery was sampled for relative size composition. Research cruises were conducted in Monterey Bay to: 1) study bycatch and habitat impacts of light touch halibut trawl gear; and 2) the relationship of bucket trap hole diameter to percentage of immature hagfish. Staff continued a study to determine size and age at maturity and fecundity of California halibut in San Francisco Bay. There were collaborative agreements involving project staff, researchers, and commercial fishermen to: 1) sample the commercial night smelt fishery; and 2) MPA monitoring of nearshore soft bottom habitats, both along California's north coast.

### *The CalCOFI Committee*

*Dave Checkley, SIO*

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## REVIEW OF SELECTED CALIFORNIA FISHERIES FOR 2013: COASTAL PELAGIC FINFISH, MARKET SQUID, GROUND FISH, HIGHLY MIGRATORY SPECIES, DUNGENESS CRAB, BASSES, SURFPERCH, ABALONE, KELP AND EDIBLE ALGAE, AND MARINE AQUACULTURE

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### SUMMARY

In 2013, commercial fisheries landed an estimated 165,072 metric tons (t) of fish and invertebrates from California ocean waters (fig. 1). This represents an increase of almost 2% from the 162,290 t landed in 2012, but still an 11% decrease from the 184,825 t landed in 2011, and a 35% decline from the peak landings of 252,568 t observed in 2000. The preliminary ex-vessel economic value of commercial landings in 2013 was \$254.7 million, increasing once again from the \$236 million generated in 2012 (8%), and the \$198 million in 2011 (29%).

Coastal pelagic species (CPS) made up four of the top five volume fisheries in 2013. California market squid continued to be the largest volume, and second highest value fishery in the state with over 104,363 t landed and an ex-vessel value of approximately \$73.7 million; an increase of 7% and 15% respectively from 2012. For the fourth season in a row, market squid landings were projected to reach the seasonal catch limit of 107,048 t. Accordingly, the Department of Fish and Wildlife (Department) closed the fishery with a total of 104,267 t landed for the open portion of the 2013–14 season. Pacific mackerel emerged as California's third largest volume fishery with 8,066 t landed worth \$1.5 million in ex-vessel revenue, which continues an increasing trend from 3,485 t in 2012 (\$872,820) and 1,357 t in 2011. For the first time since 1993, the Pacific mackerel fishery ranked as the largest among the four federally managed CPS finfish (Pacific sardine, Pacific mackerel, jack mackerel, and northern anchovy), comprising nearly 37% of the total volume and 35% of the total value. The Pacific sardine fishery has long been one of the largest in the state. However, in 2013 it dropped to the fourth largest in volume and thirteenth in value, landing 7,074 t worth \$1.6 million. In 2012 it was the second largest in volume (23,037 t) and eighth largest in value (\$5.1 million). The recommended harvest guideline (HG) for 2013 season was 66,495 t based on a biomass estimate of 659,539 t, which was a decrease from the 2012 recommended HG of 109,409 t based on a biomass estimate of 988,385 t. In 2013 northern anchovy surpassed red sea urchin as the fifth largest volume fishery. Land-

ings of northern anchovy were 6,005 t with an ex-vessel revenue of greater than \$1.0 million. When compared to landings in 2012, this represents a 141% and 191% increase in volume and value, respectively. Nearly all (93.6%; 5,621.5 t) of California's 2013 northern anchovy catch was landed in the Monterey port area. Landings of jack mackerel remained relatively low with 892 t landed; however, this represents a 515% increase over 2012 landings of 145 t.

Dungeness crab ranked as California's second largest volume fishery with 14,066 t landed, an increase from 11,696 t landed in 2012, and it continued to dominate as the highest valued fishery in the state with an ex-vessel value of over \$88.7 million, increasing from \$85.6 million in 2012. The 2012–13 season in the northern management area was the second consecutive season to be delayed as late as January 15, the maximum allowed by law. Central California coast crab usually molt earlier than northern crab, and the area is not subject to opening delays by statute. The 2013–14 season is the first season to employ trap limits, implementing a program created by Senate Bill 369 passed in 2011. The trap limit program places a cap on the number of traps a vessel can fish dependent on where the vessel places among the seven trap tiers.

More than 90 species of bottom-dwelling marine finfish are included in the federally-managed groundfish fishery. The species that comprise the groundfish fishery are diverse and complex; their primary distributions range from nearshore depths to deep offshore habitats. In 2013, California's commercial groundfish landings totaled 6,443 t, worth an estimated ex-vessel value of \$17.4 million. This represents an increase in landings (5%; 6,162 t) and a decrease in ex-vessel value (3%; \$17.9 million) compared to 2012. An estimated 2,021 t of groundfish were taken by the recreational fishery in 2013 which represents a 22% increase compared to 2012 (1,656 t). Since 2007, the Department has conducted an extensive outreach and education campaign to educate the public on the use of descending devices to minimize mortality of discarded fish and increase post release survival. In 2012, the Pacific Fishery Management Council (Council) decided to examine the issue of accounting for

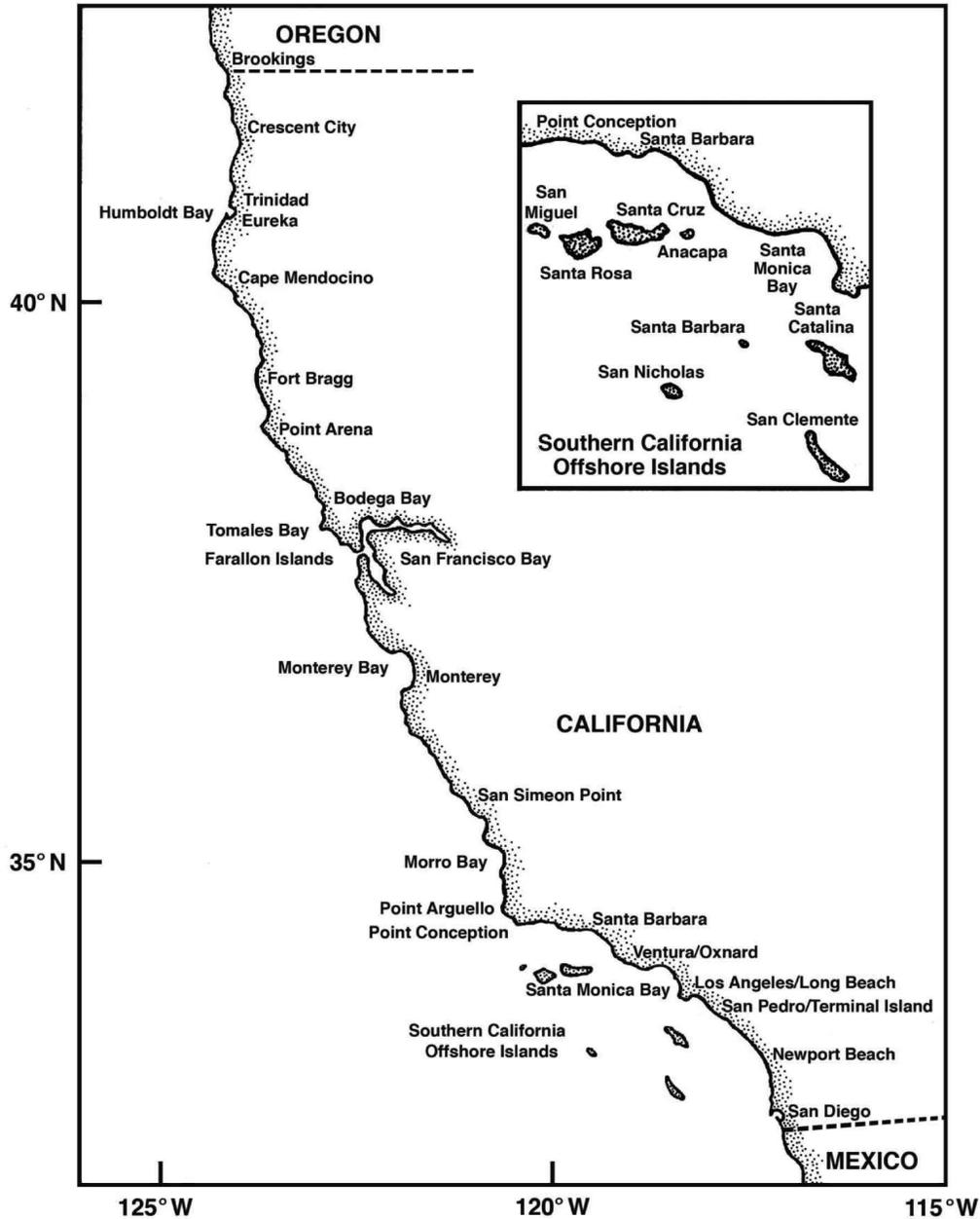


Figure 1. California ports and fishing areas.

descending devices use in groundfish management. The Council agreed that differential mortality rates for each species of rockfish associated with the use of a descending device was a priority that needed to be accounted for in modeling and management.

Highly Migratory Species fisheries (HMS) landed a total of 963 t with a combined ex-vessel value of nearly \$4.1 million. Of all species that are federally regulated under the West Coast Highly Migratory Species Fishery Management Plan (HMS FMP), swordfish commands the highest price-per-pound and brings in the highest total revenue of all HMS species landed in California.

In 2013, there were 525 t of swordfish landed with an ex-vessel value of nearly \$2.7 million.

During the first half of the twentieth century, kelp bass, barred sand bass, and spotted sand bass were targeted by both recreational and commercial fishermen. In 1953, due to concerns regarding declining catch, commercial take of these basses was prohibited and a minimum size limit was established for recreational take. Bag limits for the basses first began in 1939 and have fluctuated over the years, but have remained the same since 1975. Due to concerns from the Department and the public regarding the continued declining catch, a thorough analysis of the

saltwater bass fishery was recently conducted. In March 2013, the Commission implemented new size and bag limits for all three species.

The surfperch assemblage includes seaperch and perch, and encompasses 24 species. Many of California's marine surfperch are the target of a modest commercial fishery in central and northern California (11.6 t in 2013) and a sizable recreational fishery throughout the state. The surfperch fisheries in California are solely managed by the Department. No formal stock assessments have been completed for surfperch and the fisheries are considered data-poor; however, there is no indication that surfperch stocks are in decline based on the best available data. Although surfperch stocks do not appear to be declining, their low fecundity and mating and spawning aggregations may cause them to be more vulnerable to fishing. Water pollution and changing sea temperature can also cause vulnerability.

The recreational red abalone fishery in northern California is the largest in the world, with over 30,000 participants annually. The average annual take between 2002 and 2012 was approximately 254,000 red abalone, with fishing effort centered on the coastal counties of Sonoma and Mendocino. The fishery is actively managed by the state under the Abalone Recovery and Management Plan (ARMP) using traditional fishery management strategies as well as an innovative adaptive management approach incorporating density survey data in decision making. In northern California, fishery-independent density surveys are conducted triennially at eight (fished) index sites to assess whether fishing regulations are maintaining densities through time. Catch from these sites accounts for ~48% of the total fishery catch. These index sites were chosen to provide early warning for declines in density in the fishery overall. The ARMP harvest control rules provide for reductions in take and site closures if overall densities across the index sites fall below established baselines.

There are 87 administrative kelp beds located offshore of California's mainland and surrounding the Channel Islands. The administrative kelp beds contain giant or bull kelp or a combination of both. Along the California coast perennial giant kelp is most abundant south of San Francisco (San Mateo County). Bull kelp is an annual alga found offshore from central to northern California, with greater amounts of bull kelp in northern California. Giant kelp harvested during the January 1–December 31, 2013 harvest season was 3,305 t (reported landings include a nominal amount of bull kelp). During this time the majority of giant kelp was harvested from boats using small mechanized harvesters or by hand to provide food for aquacultured abalone. Commercial edible algae harvesting includes a variety of marine algae. In 2013, the total reported commercial harvest of edi-

ble algae was 17 t, up slightly from the annual average of 14 t reported from 1997 to 2013. The commercial harvest of edible algae is regional, with 90% of the harvest occurring along the north coast (Alder Creek in Mendocino County to the California/Oregon border) during 2000–13. Recreational harvest of giant and bull kelp and other edible algae for personal use is also permitted. Amendments to the regulations governing the commercial harvest of giant and bull kelp were implemented in 2013. The regulation amendments were Phase One of a three phase process. Phase Two will address commercial marine algae license fees and royalty rates. Phase Three will follow with a focus on marine algae management policies including marine algae harvest methods.

California's commercial marine aquaculture industry consists of the production of five oyster species, clams, mussels, and abalone. In California, the Department manages 21 state water bottom leases for marine aquaculture, totaling 1,952 acres. Additional marine aquaculture operations occur on granted or privately owned tidelands, adding an additional 3,948 acres for a statewide total of 5,900 acres of water bottoms utilized for marine aquaculture. There are also marine aquaculture facilities established on privately owned uplands along the California coastline. Total shellfish production in 2013 (January through December) had the second highest recorded harvest in the 42 year history of landings, reaching a total of 828 t, all species combined. This resulted in a value of \$24.2 million. Compared to 2012, there was a 19% increase in production in 2013, all species combined. The culture of Pacific oysters represented the largest production for the industry, resulting in 73% of the total production, and 70% of the total value in 2013.

### Coastal Pelagic Finfish

Pacific sardine (*Sardinops sagax*), Pacific mackerel (*Scomber japonicus*), jack mackerel (*Trachurus symmetricus*), and northern anchovy (*Engraulis mordax*) form a finfish complex known as coastal pelagic species (CPS). These species are jointly managed by the Pacific Fishery Management Council (Council) and the National Marine Fisheries Service (NMFS) under the Coastal Pelagic Species Fisheries Management Plan (CPS FMP). In 2013, total commercial landings for these species equaled 22,036 t (table 1), with a combined ex-vessel revenue of over \$4.3 million. When compared to landings in 2012, this represents a 25% and 23% decrease in volume and value, respectively. For the first time since 1993, the Pacific mackerel fishery ranked as the largest among these four species in 2013, comprising 36.6% of the total volume and 35% of the total value.

**Pacific Sardine.** The Pacific sardine fishery in California has long been one of the largest in the state. In 2013 it was the fourth largest in volume and thirteenth largest

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	0		1,566	121,556	154,874
2012	23,037	2,488	3,485	145	0		1,482	97,078	127,715
2013	7,074	6,005	8,066	892	1	0	2,086	104,404	128,528

Data Source: Commercial Fisheries Information System (CFIS)

TABLE 2  
 Landings (metric tons) of Pacific sardine (*Sardinops sagax*) and Pacific mackerel (*Scomber japonicus*), jack mackerel (*Trachurus symmetricus*), and northern anchovy (*Engraulis mordax*) at California port areas for 2013.

Area	Pacific sardine		Pacific mackerel		Jack mackerel		Northern anchovy	
	Landings	% Total	Landings	% Total	Landings	% Total	Landings	% Total
Monterey	823.2	11.7	0.1	0.0	0.0	0.0	5621.5	93.6
Santa Barbara	221.5	3.2	0.4	0.0	0.0	0.0	201.2	3.4
Los Angeles	5,987.9	85.1	7,226.2	100.0	889.1	100.0	180.9	3.0
Total	7,032.7	100	7,226.6	100	889.2	100	6,003.6	100

\*Monterey totals include San Francisco landings; Los Angeles totals include Oceanside landings.

in value, landing 7,073.5 t and generating an ex-vessel revenue of \$1.6 million (fig. 2). This was a 69% decrease from 2012 (23,003 t). Commercial landings of sardine averaged 42,280 t over the thirteen year period from 2001–13. Nearly all (96.8%) of California’s 2013 sardine catch was landed in Los Angeles (85.1%, 5,987.9 t) and Monterey (11.7%, 823.2 t) port areas (table 2). California exported 5,679.1 t of sardine product worth over \$5.1 million. Twenty-six countries received sardine prod-

uct from California; Australia and Thailand received the majority at 30% and 15%, respectively.

While the fishery ranges from Baja California, Mexico, north to British Columbia, Canada, the majority of landings have occurred in southern California and northern Baja California since the 1980s. Landings of sardine have steadily increased in the Pacific Northwest and Canada since the recent expansion of the sardine fishery in 1999. Combined landings of Pacific sardine for

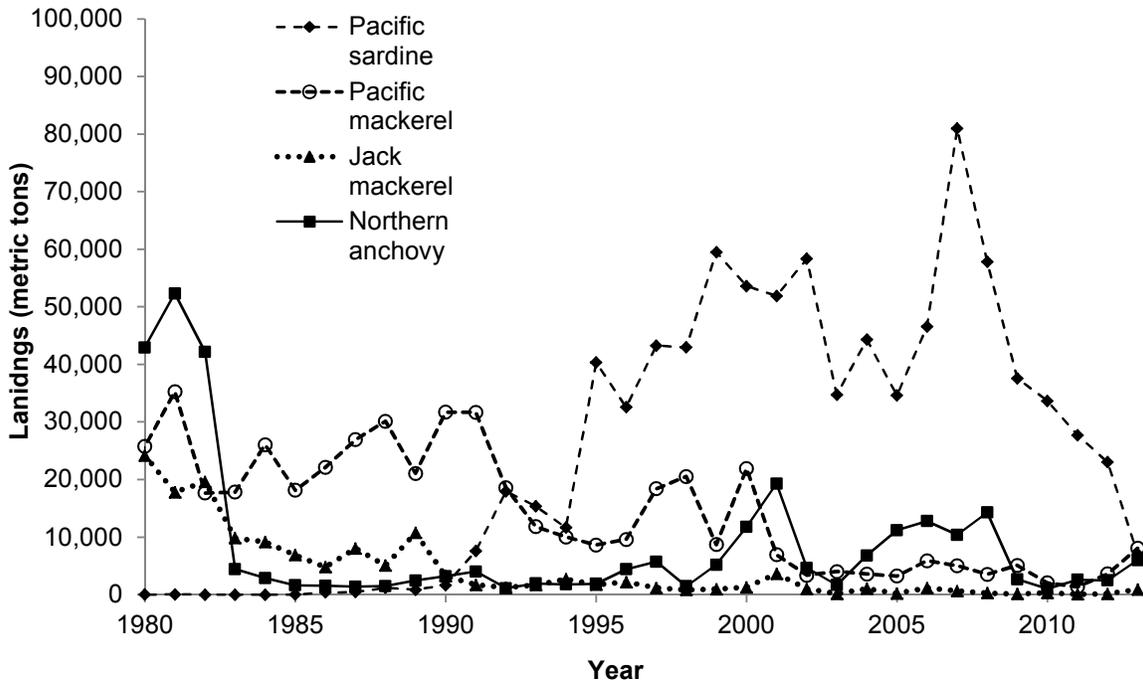


Figure 2. California commercial landings of Pacific sardine (*Sardinops sagax*), Pacific mackerel (*Scomber japonicus*), jack mackerel (*Trachurus symmetricus*), and northern anchovy (*Engraulis mordax*), 1980–2013.

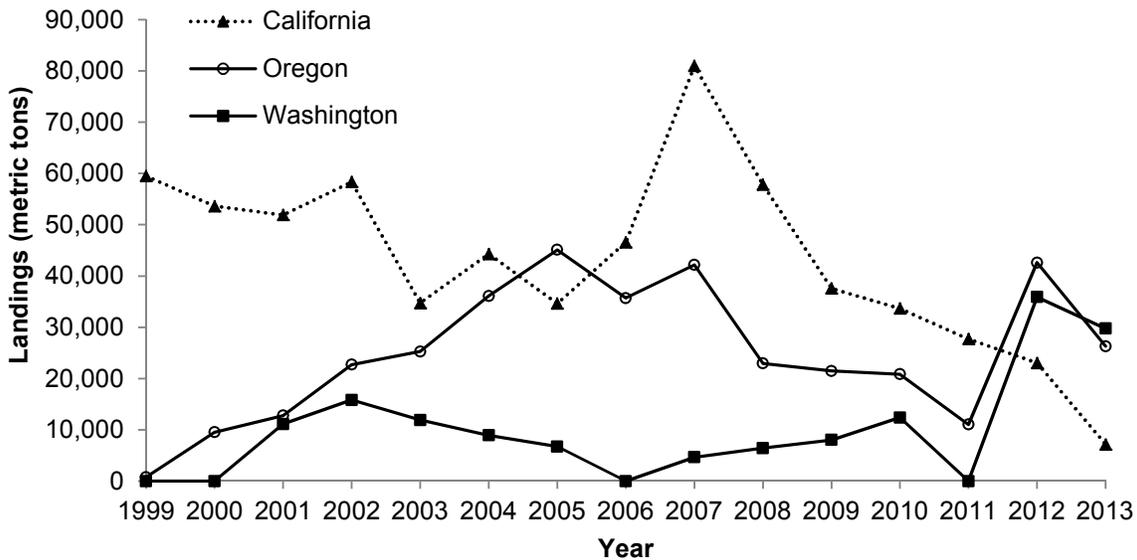


Figure 3. Commercial landings of Pacific sardine (*Sardinops sagax*) in California, Oregon, and Washington, 1999–2013.

California, Oregon, and Washington totaled 63,181.9 t, a 37.8% decrease from the 101,553.7 t landed in 2012 (fig. 3). The Pacific sardine harvest guideline (HG) for each calendar year is determined from the previous year’s stock biomass estimate (of  $\geq 1$ -year-old fish on 1 July) in US and Mexican waters. The recommended HG for 2013 season was 66,495 t based on a biomass estimate of 659,539 t. The Pacific sardine HG was apportioned coast-wide through the year with a 35% allocation of

the annual HG from 1 January through 30 June, 40% (plus any portion not harvested) allocated from 1 July through 15 September, and the last 25% (plus any portion not harvested from the first two allocations) released on 15 September.

In 2013, the US West Coast fisheries harvested a large portion (95%) of the HG. The first allocation period (1 Jan–30 Jun) lasted through the entire allocation period, 180 days. The second period (1 Jul–14 Sep) lasted

52 days; the fishery was officially closed on 22 August. The third allocation period (15 Sep–31 Dec) also lasted the entire allocation period, 107 days.

Oregon landings appeared to be leveling off since 2008, experienced a large jump in 2012 and decreased in 2013. Landings of Pacific sardine totaled 26,288.4 t, a 38% decrease from 2012 (42,618.4 t). In 2013, Oregon exported 3,722 t of sardine product to 3 countries (Malaysia, Thailand, and China) worth \$2.9 million.

Washington landings of Pacific sardine totaled 29,747.7 t in 2013, a decrease of 17% from 2012 (35,891.5 t). They exported 44,740.2 t of sardine product to 26 countries, totaling \$39.9 million in revenue.

The recreational Pacific sardine catch as sampled from the California Recreational Fisheries Survey (CRFS) was 77 t (731,170 fish). The majority (99%) of the fish landed were from manmade structures, such as piers. While the tonnage was slightly larger than the 74 t caught in 2012, there was a 29% decrease in the number of fish.

In November 2013, the start date of the 12 month Pacific sardine fishery was changed from 1 January to 1 July; this changed the fishing season from one based on a calendar year (1 January–31 December) management cycle to a fishing season (1 July–30 June) cycle. This change will better align the timing of the research and science required for annual stock assessments with the annual management schedule. A one-time interim harvest period from 1 January 2014 through 30 June 2014 was established with an allocation of 5,446 t to allow targeted fishing to continue during the transition to the new management cycle.

**Pacific Mackerel.** In 2013, 8,065 t of Pacific mackerel were landed in California (table 1, fig. 2) generating over \$1.5 million in ex-vessel revenue, and making it California's third largest volume fishery. This is a 124% increase in volume and a 67% increase in ex-vessel revenue from 2012. Industry exported 2,040.9 t of mackerel product, valued at \$1.9 million, mainly for human consumption, to 16 countries. Australia (898.9 t) and the Philippines (625.1 t) received over 74% of this product.

Oregon reported landing 439.3 t of Pacific mackerel in 2013, with an ex-vessel revenue of \$79,831. This is a 75% decrease from the 2012 catch of 1,779.2 t. No exports were reported for Oregon. Washington did not report any landings of Pacific mackerel in 2013.

At the start of the 2013–14 season, which runs from 1 July to 30 June the following year, the PMFC set the HG at 39,268 t, including a 13,089 t set-aside for incidental landings in other fisheries. Landings above the HG would be constrained by an incidental catch rate of 45% by weight when landed with other CPS.

The 2013 recreational Pacific mackerel catch as sampled from CRFS was 159 t (902,882 fish), a 21.5%

decrease (27% by number of fish) from 2012. The majority (66%, 595,456 fish) of fish landed were from manmade structures; 29% of fish were landed on CPFVs.

**Jack Mackerel.** Jack mackerel has long been the smallest of the federally managed CPS finfish fisheries and represented 4% of the total landings of these fisheries in California for 2013. Landings of jack mackerel totaled 892 t in 2013, with an ex-vessel revenue of \$178,686 for California (table 1, fig. 2). Landings in Oregon jumped dramatically in 2012 (95.5 t) and increased by 29% in 2013 (123.2 t), bringing an ex-vessel revenue of \$12,358. Washington reported no landings of jack mackerel during 2013.

The 2013 recreational jack mackerel catch as sampled from CRFS was 4.25 t (22,208 fish), a 43.75% decrease (53% by fish) from 2012. A total of 16,466 fish were landed on manmade structures.

**Northern Anchovy.** Composed of three stocks, southern, central and northern, landings of northern anchovy in California have been reported since the early 1900s. Currently, northern anchovy are a monitored species under the CPS FMP. Studies of scale deposits on the sea floor suggest that their abundance has historically been quite large. Now used for animal food, live bait, and human consumption, anchovy was used mainly in a reduction industry to produce oil and fish meal in the 1900s. From the 1900s to the late 1970s, northern anchovy was a major component of California's commercial CPS fisheries. During periods of low sardine abundance, anchovy landings have increased, hitting a peak in the mid-1970s at over 100,000 t. However, commercial landings of northern anchovy have remained relatively low since the 1980s due to market constraints. Presently, landings of northern anchovy are modest, averaging 7,682 t per year over the last 13 years. Only occasionally landed in Oregon and Washington, the California fishery is harvested from the central stock, which ranges from San Francisco to northern Baja California.

Landings of northern anchovy in California for 2013 were 6,005 t with an ex-vessel revenue of greater than \$1.0 million (table 1, fig. 2). When compared to landings in 2012, this represents a 141% and 191% increase in volume and value, respectively. Nearly all (93.6%; 5,621.5 t) of California's 2013 northern anchovy catch was landed in the Monterey port area (table 2). Exports of northern anchovy product from California totaled 268.3 t for an export value of \$589,597. Five countries received anchovy product from California; Australia received the majority at over 87%. In 2013, Oregon and Washington reported landing 13 t and 116 t of anchovy, respectively (NOAA West Coast Region). Oregon did not report any anchovy exports in 2013. Washington exported 10 t of anchovy product to Canada, totaling \$65,694 in revenue.

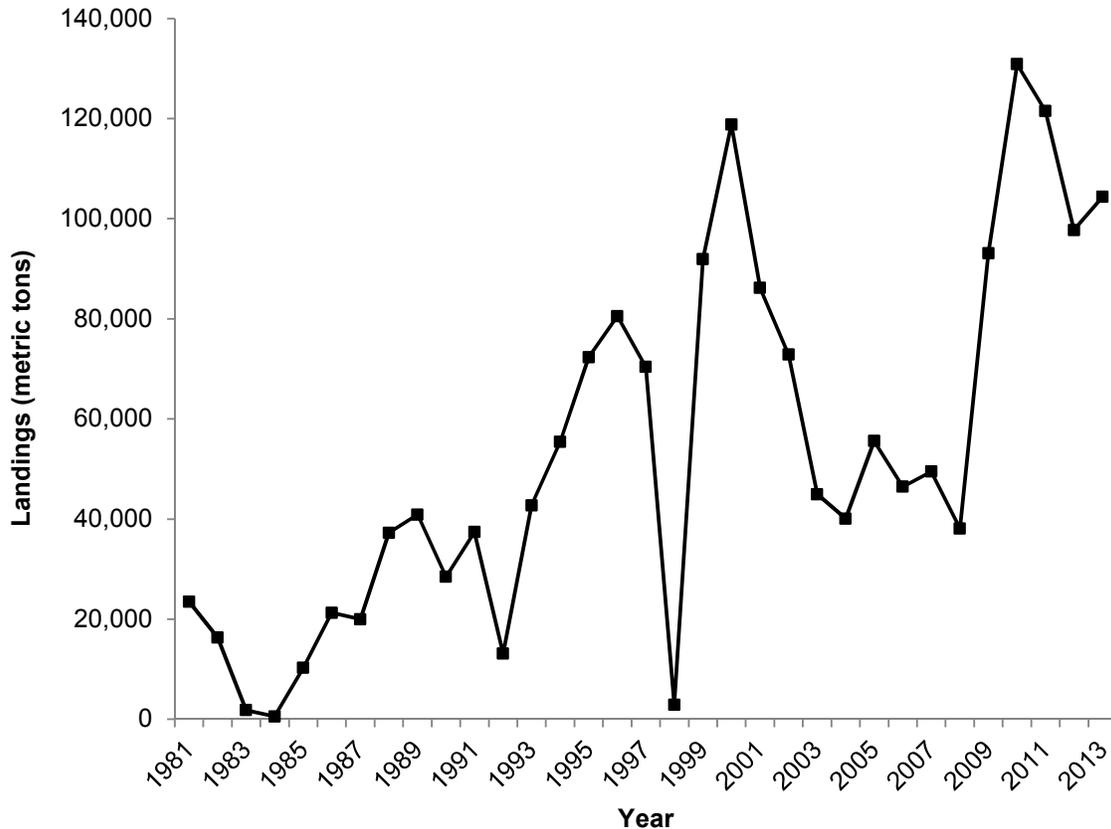


Figure 4. California commercial market squid (*Loligo (Doryteuthis) opalescens*) landings, 1981–2013.

The 2013 recreational northern anchovy catch as sampled from CRFS was 5 t (456,087 fish), a 765% increase (769,000% by fish) from 2012. The majority (98%) of the fish landed were from manmade structures, the remaining 2% of fish were landed from CPFVs.

### California Market Squid

In 2013, market squid (*Loligo (Doryteuthis) opalescens*) continued to dominate commercial landings of marine species in California, contributing about 63% of the total tonnage and 29% of total ex-vessel value of all species landed. Landings of market squid in 2013 increased 7% compared to 2012 landings, from 97,733 t to 104,363 t (fig. 4). Ex-vessel value in 2013 increased 15% compared to 2012, from \$63.9 million to \$73.7 million. California fish businesses exported 71,452 t of market squid to 35 countries for a value of \$104 million in 2013. The majority (86%) was shipped to just 3 countries but most (73%) went to China.

For the fourth season in a row, since the inception of the Market Squid Fishery Management Plan (MS FMP) in 2005, market squid landings were projected to reach the seasonal catch limit of 107,048 t. Accordingly, the Department of Fish and Wildlife (Department) closed the fishery on 18 October 2013, with a total of 104,267 t landed for the open portion of the 2013–14 season.

Commercial fishing for market squid is limited by fishery control rules set forth in the MS FMP. Vessels are required to have a permit to commercially fish for market squid. In 2013, there were 76 market squid vessel (purse or drum seine), 34 light boat (attracting), and 44 brail (or dip net) permits issued. Of the 76 vessel permits issued, 68 vessels were active in the fishery with 47 vessels contributing 95% of the landings. Other fishery control rules include a seasonal catch limit that starts April 1 and ends March 31 of the following year, weekend closures, spatial closures, and lighting restrictions.

Although the fishery has its historical origins in Monterey Bay, the fishery has been dominated by southern California landings (fig. 5). Of note is the increase in landings for Monterey, which has seen over 14,000 t in each of the last four seasons.

Market squid live less than a year and have been found in nearshore waters of the eastern Pacific Ocean from Baja California to the Gulf of Alaska. The population appears to fluctuate widely in abundance in response to short-term oceanographic events, like the El Niño Southern Oscillation. Ecologically, they are considered important as forage for other species, including predatory fishes, marine mammals, and seabirds.

A live bait fishery exists for market squid, largely to supply recreational fishing in southern California. The live bait fishery is a low-volume, high-value endeavor,

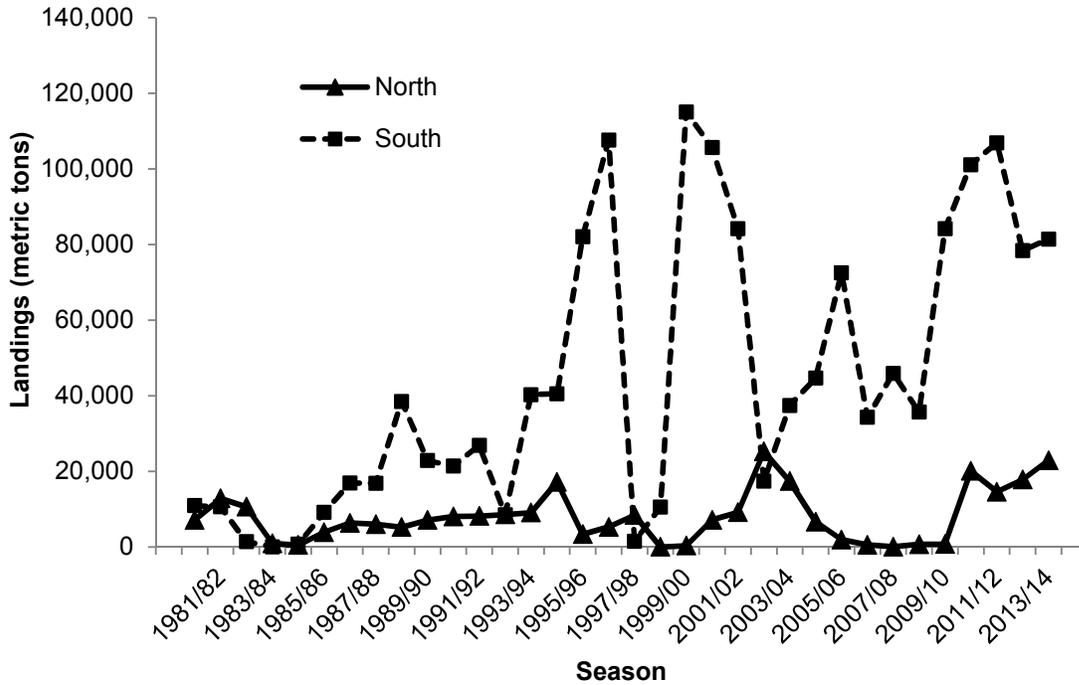


Figure 5. Comparison of market squid (*Loligo (Doryteuthis) opalescens*) landings for northern and southern fisheries by fishing season (1 April–31 March), from 1980/81 to 2013/2014 seasons.

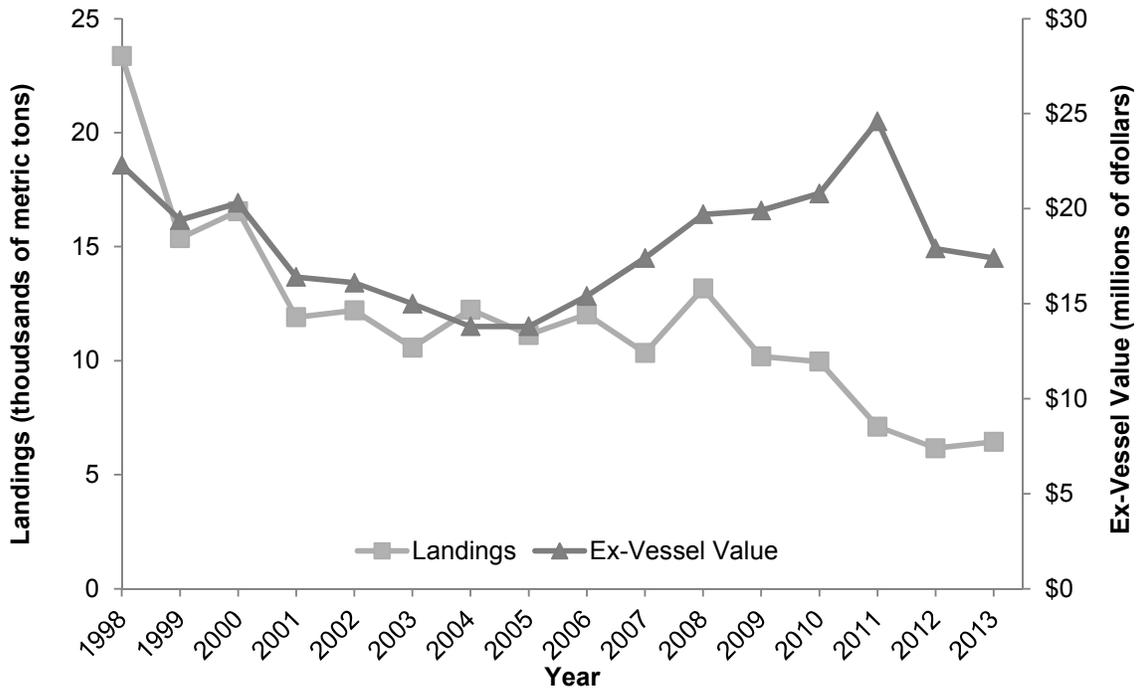


Figure 6. California commercial groundfish landings, 1998–2013.

as recreational anglers are willing to pay up to \$60 for a “scoop” of live squid, which averages 10 lbs.

**Groundfish**

More than 90 species of bottom-dwelling marine finfish are included in the federally-managed ground-

fish fishery. The species that comprise the groundfish fishery are diverse and complex; their primary distributions range from nearshore depths to deep offshore habitats. “Groundfish” species include all rockfishes in the Scorpaenidae family, flatfishes such as Dover sole (*Microstomus pacificus*) and petrale sole (*Eopsetta jordani*),

TABLE 3  
 California commercial groundfish landings (in metric tons) and ex-vessel value in 2013 with comparisons to 2012.  
 The top species by weight for the Flatfishes and Rockfishes are represented in the table.

	2013		2012		% change from 2012 (mt)	% change from 2012 (\$)
	Harvest (mt)	Value (\$)	Harvest (mt)	Value (\$)		
<b>Flatfishes</b>						
Dover sole	2,218	\$2,143,990	2,151	\$1,936,707	3%	11%
Petrale sole	470	\$1,321,525	222	\$697,277	112%	90%
Arrowtooth flounder	118	\$26,824	99	\$23,815	19%	13%
English sole	49	\$39,777	23	\$21,091	112%	89%
Rex sole	45	\$42,920	48	\$40,913	-5%	5%
Sand sole	15	\$37,774	18	\$49,233	-13%	-23%
Other flatfishes	28	\$24,679	24	\$48,743	15%	-49%
Total Flatfishes	2,944	\$3,637,489	2,585	\$2,817,779	14%	29%
<b>Rockfishes</b>						
Chilipepper	322	\$472,897	236	\$362,174	37%	31%
Blackgill rockfish	72	\$146,033	127	\$369,358	-43%	-60%
Bank rockfish	52	\$110,088	11	\$23,480	370%	369%
Black rockfish	36	\$159,878	24	\$105,557	48%	51%
Brown rockfish	28	\$422,334	26	\$363,624	8%	16%
Vermilion rockfish	23	\$142,335	17	\$103,475	36%	38%
Gopher rockfish	23	\$392,733	23	\$370,588	1%	6%
Other rockfishes	100	\$751,094	179	\$821,693	-44%	-9%
<b>Overfished species</b>						
Bocaccio	16.5	\$39,700	12.37	\$28,765	33%	38%
Canary rockfish	1.6	\$3,474	0.56	\$817	190%	325%
Cowcod	0.2	\$191	0.08	\$74	131%	159%
Darkblotched rockfish	4.2	\$6,204	6.51	\$9,602	-36%	-35%
Pacific ocean perch	0.05	\$56	0.07	\$67	-22%	-17%
Yelloweye rockfish	0.01	\$30	0.003	\$3	337%	1006%
Total Rockfishes	679	\$2,647,047	663	\$2,559,276	2%	3%
<b>Roundfishes</b>						
Sablefish	1,375	\$7,014,561	1,627	\$9,007,673	-15%	-22%
Lingcod	64	\$294,396	48	\$208,735	34%	41%
Cabezon	29	\$361,832	31	\$363,917	-5%	-1%
Kelp greenling	5	\$70,790	5	\$68,598	8%	3%
Pacific whiting	4	\$212	4	\$1,876	3%	-89%
Total Roundfishes	1,478	\$7,741,790	1,714	\$9,650,799	-14%	-20%
Scorpionfish, California	3	\$28,399	4	\$41,671	-32%	-32%
Sharks & Skates	172	\$145,009	184	\$161,885	-6%	-10%
Thornyheads	1,085	\$3,114,120	914	\$2,641,905	19%	18%
Other Groundfish	84	\$68,466	99	\$52,604	-15%	30%
Total Groundfish	6,443	\$17,382,320	6,162	\$17,925,918	5%	-3%

\*Petrale sole was declared overfished in 2009

Data Source: CFIS (CMASTR) Extraction Date: 04/28/2014

roundfishes such as sablefish (*Anoplopoma fimbria*) and lingcod (*Ophiodon elongatus*), and various sharks and skates. These groundfish species are distributed between 39 federal 'management units,' consisting of species or species groups, to help facilitate management measures that balance biological and economical goals.

**Commercial Fishery.** In 2013, California's commercial groundfish landings totaled 6,443 t, worth an estimated ex-vessel value of \$17.4 million. This represents an increase in landings (5%; 6,162 t) and a decrease in ex-vessel value (3%; \$17.9 million) compared to 2012. During the last decade, groundfish landings declined by 39% (6,443 t in 2013 versus 10,573 t in 2003); yet the ex-vessel value increased nearly 16% (\$17.4 million in 2013 versus \$15.0 million in 2003). Although annual

landings declined, the fishery experienced an increase in value over the past decade (fig. 6). The majority (80%) of groundfish landed in California, worth 57% of the ex-vessel value, was landed between the California/Oregon border and the Monterey Bay area. In the groundfish fishery the majority (77%) of landings by weight were made by trawl gear, followed by hook and line and trap gear (23%). However, hook and line and trap gear generated 57% of the ex-vessel value. The majority (86%) of trips were made with hook and line and trap gear while trawl gear was used to a lesser extent (13%); other gears comprised the remainder. In 2013, landings of Dover sole, sablefish, thornyheads (*Sebastobus altivelis* and *S. alascanus*), petrale sole and chilipepper (*Sebastes goodei*) continued to be the top

species by weight, with 2,218 t, 1,375 t, 1,079 t, 470 t and 322 t landed respectively. These species comprised 85% of the groundfish landings. Groundfish landings in 2013 were mostly comprised of flatfishes (46%), followed by roundfishes (23%), thornyheads (17%) and rockfish (11%). The “other” groundfish species category was comprised of grenadier (Macrouridae) which accounted for 83 t (table 3). Chilipepper was the top rockfish species by weight in 2013, with landings of 322 t worth an ex-vessel value of \$472,962. Unlike high-volume, high-value species such as sablefish, nearshore rockfishes are generally a low-volume, high-value commodity in California—brown rockfish (*S. auriculatus*), gopher rockfish (*S. carnatus*) and grass rockfish (*S. rastrelliger*) were worth a combined ex-vessel value of \$1,079,359 with landings of 28 t, 23 t and 13 t respectively. Restricted access and the live fish market are primarily responsible for the high market value of the nearshore fishery. In 2013 the top grossing nearshore species were grass rockfish, black-and-yellow rockfish (*S. chrysomelas*) and gopher rockfish; valued at approximately \$21,100/t, \$17,200/t and \$17,000/t, respectively. By contrast, chilipepper (a non-nearshore rockfish) was valued at approximately \$1,500/t.

Landings of overfished rockfish species, which accounted for <1% of the groundfish landings in 2013, increased compared to 2012 (23 t versus 20 t). In both years the predominant specie was bocaccio (*S. paucispinis*), which accounted for 73% and 63% of the total overfished rockfish species landings in 2013 and 2012, respectively. Strong year classes and an increase in abundance are likely causes of the increased bocaccio encounters in recent years. Management measures to protect overfished species have greatly reduced landings over the past decade.

**Recreational Fishery.** The Recreational Fisheries Information Network (RecFIN) Program stores recreational data from California, Oregon, and Washington. RecFIN incorporates data from two recreational fishery sampling programs in California—the Marine Recreational Fisheries Statistical Survey (MRFSS), which operated from 1980 to 2003, and the California Recreational Fisheries Survey (CRFS) initiated by the Department of Fish and Wildlife (Department) in 2004. These data, which are available from 1980 to the present, represent the best available information on recreational catch in California. CRFS data indicate that California anglers targeting groundfish participated in an estimated 863,000 trips in 2013, a small decrease (<1%) from 2012 (867,000 trips). The predominant gear type used in the California recreational groundfish fishery is hook and line.

An estimated 2,021 t of groundfish were taken by the recreational fishery in 2013 (table 4), which represents a 22% increase compared to 2012 (1,656 t). The

TABLE 4  
 Comparison of recreational groundfish catch in California in 2013 and 2012 (does not include discards and only includes catch greater than 5 mt).

Species	2013 Harvest (mt)	2012 Harvest (mt)	% Change from 2012
Lingcod	433	281	54%
Black rockfish	363	210	73%
Vermilion rockfish	211	220	-4%
Bocaccio	131	125	5%
California scorpionfish	112	116	-3%
Blue rockfish	106	52	104%
Copper rockfish	99	80	24%
Pacific sanddab	86	66	30%
Brown rockfish	82	70	17%
Yellowtail rockfish	56	53	6%
Gopher rockfish	41	52	-21%
Cabezon	39	43	-9%
Starry rockfish	24	23	4%
Olive rockfish	20	32	-36%
Kelp rockfish	19	19	1%
Widow rockfish	18	5	257%
Squarespot rockfish	17	4	314%
Speckled rockfish	16	10	55%
Flag rockfish	14	14	1%
Leopard shark	14	35	-60%
Kelp greenling	14	13	5%
Treefish	13	11	19%
Canary rockfish	13	13	-4%
Greenspotted rockfish	11	18	-38%
China rockfish	10	14	-28%
Grass rockfish	10	21	-53%
Honeycomb rockfish	9	6	53%
Chilipepper	7	8	-9%
Spiny dogfish	7	3	134%
Black-and-yellow rockfish	6	5	16%
Rosy rockfish	6	6	-8%
Other groundfish	16	28	-43%
Total Groundfish	2,021	1,656	22%
<b>Angler Trips</b>			
Bottomfish Effort	863,339	867,096	0%

Data source: RecFIN Date Extracted: 04/24/2011

top five species were lingcod, black rockfish (*S. melanops*), vermilion rockfish (*S. miniatus*), bocaccio, and California scorpionfish (*Scorpaena guttata*), which accounted for approximately 62% of the groundfish catch by weight; in 2012, the same five species comprised 57% of the catch. In 2013, the majority (51%) of groundfish catches occurred in Central California (Point Conception to Cape Mendocino), where lingcod was the most frequently encountered. In southern California (south of Point Conception), anglers took 40% of the groundfish catch with California scorpionfish being the most frequently encountered. Lastly, northern California (Cape Mendocino to the California/Oregon border) accounted for 9% of the catch, with black rockfish being the most frequently encountered.

**Barotrauma.** Barotrauma is a pressure-related injury that occurs in fish due to the inability to release gasses

that expand in the swim bladder when brought up from depth. Some visible symptoms of barotrauma include a swollen or tight belly, an everted stomach and/or rectum, and distended and/or “crystallized” eyes; non-visible symptoms may include hemorrhaging and tearing of the swim bladder. Research has shown that symptoms of barotrauma (e.g., everted stomachs, eyes) can be reversed when the fish is returned to depth; many of these symptoms disappear and internal injuries can heal allowing the fish to survive.

Among groundfish, rockfish (*Sebastes* spp.) are especially susceptible to barotrauma and as a result can suffer high mortality rates. When released at the surface, excessive buoyancy caused from gas expansion diminishes the fish’s ability to submerge on its own. Often these fish are left floating on the surface where they may succumb to thermal shock, suffocation, and/or predation.

Not all species are affected by barotrauma equally. Factors such as morphology (e.g., elasticity or thickness of swim bladder) and position in the water column (midwater versus benthic) may affect the severity of barotrauma injury. Depth of capture, however, appears to be the most likely factor affecting the severity of injury. Returning fish to depth as quickly as possible has been shown to increase survival compared to those released at the surface.

Devices that release fish at depth are known as ‘descending devices’ and many types are available. These devices can either be purchased or fabricated out of inexpensive materials such as a weighted milk crate tied to a rope or a sinker with an upturned barbless hook attached. While each device may look different, they all function similarly by securing a fish until it can be returned to depth, thereby allowing the gases inside the body to recompress and equalize so that the fish can swim away on its own. Although the use of descending devices is not mandatory, many anglers currently use them. The use of these devices has become more popular as information on their benefits and angler awareness has spread. This is in large part due to outreach programs conducted by a number of organizations, institutions, and agencies.

Since 2007, the Department has conducted an extensive outreach and education campaign to educate the public on the use of descending devices to minimize mortality of discarded fish and increase post-release survival. Some of these efforts involve distribution of donated descending devices and barotrauma informational fliers which recommend proper recompression techniques. While there are clear conservation benefits of using descending devices, mitigating barotrauma-induced mortality by using a descending device also has management implications.

**Barotrauma in Management.** Recreational groundfish seasons are structured to maximize fishing opportu-

nities for healthy stocks while keeping within allowable limits for overfished species. Allowable limits for canary rockfish, cowcod, and yelloweye rockfish are low and constrain fishing opportunities in California. To ensure that catches stay within allowable limits for all species, all fish encountered in the recreational fishery (both taken and discarded) must be accounted for by fishery managers. The mortality rates used in catch forecasting and accounting models assumed the same mortality rates for fish released at the surface, regardless of whether or not a descending device was used. Although it had been acknowledged that descending devices reduce mortality of discarded rockfish, few data had been available to inform a lower mortality rate that could be used by fishery managers in estimating mortality of released fish.

In 2012, the Pacific Fishery Management Council (Council) decided to examine the issue of accounting for descending device use in groundfish management. The Council agreed that differential mortality rates for each species of rockfish associated with the use of a descending device was a priority that needed to be accounted for in modeling and management. Following extensive scientific scrutiny, revised mortality rates based on the most recent research were adopted in 2013 for use in management for canary rockfish, cowcod and yelloweye rockfish. These rates account for both short and long-term mortality and include buffers to accommodate unaccounted mortality. When a fish is released at depth using a descending device, mortality rates can be reduced by as much as one half depending on species and depth of capture. Therefore, applying depth dependent mortality rates which reflect the use of descending devices for these particular species will likely have the greatest management implications.

Data on descending devices use are collected by CRFS. In 2013, CRFS samplers began collecting data on descending device use for all rockfish discarded in boat fishing modes (private and charter). Effort is largely focused on boat based modes because they account for the majority of recreational encounters.

As overfished stocks continue to rebuild and encounters become more frequent, it becomes increasingly important that anglers use descending devices to return fish to depth. Increased survivorship from descending device use may help stocks rebuild more quickly and could result in increased fishing opportunities. However, any realized benefits from using descending devices ultimately depend on the number of anglers who use them properly. Although revised depth-dependent mortality rates are only applicable to a canary rockfish, cowcod, and yelloweye rockfish at this time, they could be expanded to include additional species in the recre-

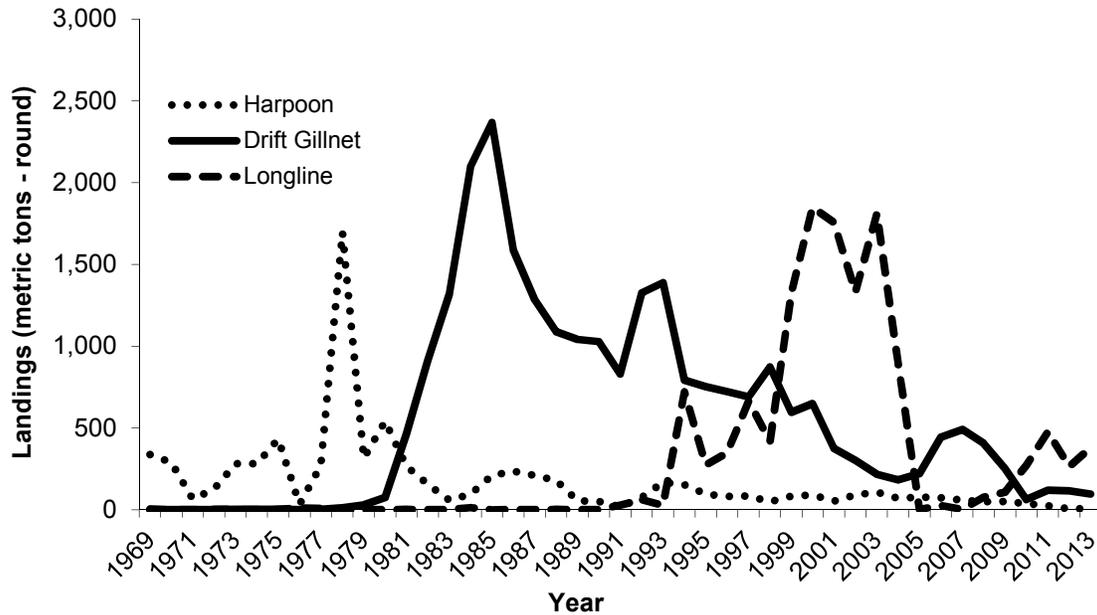


Figure 7. California swordfish (*Xiphias gladius*) landings by gear type, 1968–2013.

ational fishery and/or commercial fishery as more data becomes available.

### Highly Migratory Species

Highly migratory species (HMS) encompass a suite of large, pelagic fishes which are generally targeted by multiple fisheries and desired for their high market value. Species that are federally regulated under the West Coast Highly Migratory Species Fishery Management Plan (HMS FMP) include swordfish, albacore tuna, yellowfin tuna, skipjack tuna, bluefin tuna, common thresher shark, shortfin mako shark, and dorado.

**Swordfish.** Swordfish (*Xiphias gladius*) is commercially harvested off of California with multiple gear types. It commands the highest price-per-pound and brings in the highest total revenue of all HMS species landed in California. While the majority of California-based vessels target swordfish with drift gill nets (DGN), fish landed by harpoon or handheld hook and line sell at a higher price. In 2013, 525.4 t of swordfish were landed in California at an overall ex-vessel average price of \$7.33/kg (\$3.33/lb); 1.2% by harpoon, 75.8% by hook and line and longline gears (the majority of which comes from Hawaiian longline vessels fishing outside of the US EEZ; only 1.2% were hand held hook and line), 18.5% by drift gill net (DGN) gear, and 4.6% by other miscellaneous gears (fig. 7). The average ex-vessel price by gear type was \$19.84/kg (\$9.02/lb), \$7.41/kg (\$3.37/lb), and \$9.59/kg (\$4.36/lb), for harpoon, hook-and-line/longline, and DGN, respectively. Ex-vessel revenue of California landed swordfish totaled almost \$3.9 million (fig. 8). While there were no exports

of swordfish, California alone imported almost 2,016 t of swordfish product from 14 countries, worth almost \$16 million. There was no record of swordfish recreationally landed off California in 2013, and no records have been documented since 2007, according to data collected by the California Recreational Fishing Survey (CRFS) and Commercial Passenger Fishing Vessel (CPFV) logbooks.

Import levels are high despite the Eastern Pacific Ocean swordfish population being under fished and at levels above the minimum required to achieve maximum sustainable yield, mainly due to the numerous temporal and spatial regulations placed on the fishery. While DGN and longline gear types are efficient at catching marketable numbers of swordfish, their rate of bycatch has been highly scrutinized. Shallow-set longline is not an authorized gear type off of the West Coast, but the Hawaiian fishery has been reopened with the introduction of modified gear and bait configurations which have shown to reduce bycatch. Similarly, the DGN fishery has undergone multiple gear modifications such as net extenders to lower nets below the level most cetaceans travel at, as well as acoustic pingers which have proven to greatly reduce the interactions with marine mammals. While alternative gear types, such as harpoon, are as capable of landing swordfish, they are more artisanal in nature and cannot supply the domestic demand. Additionally, they use considerably more fuel than DGN and longline gears, introducing a different type of environmental impact. Research on other gear types such as buoy gear and deep set longline is being conducted, but as of yet, does not provide an efficient alternative to DGN and longline gear. The

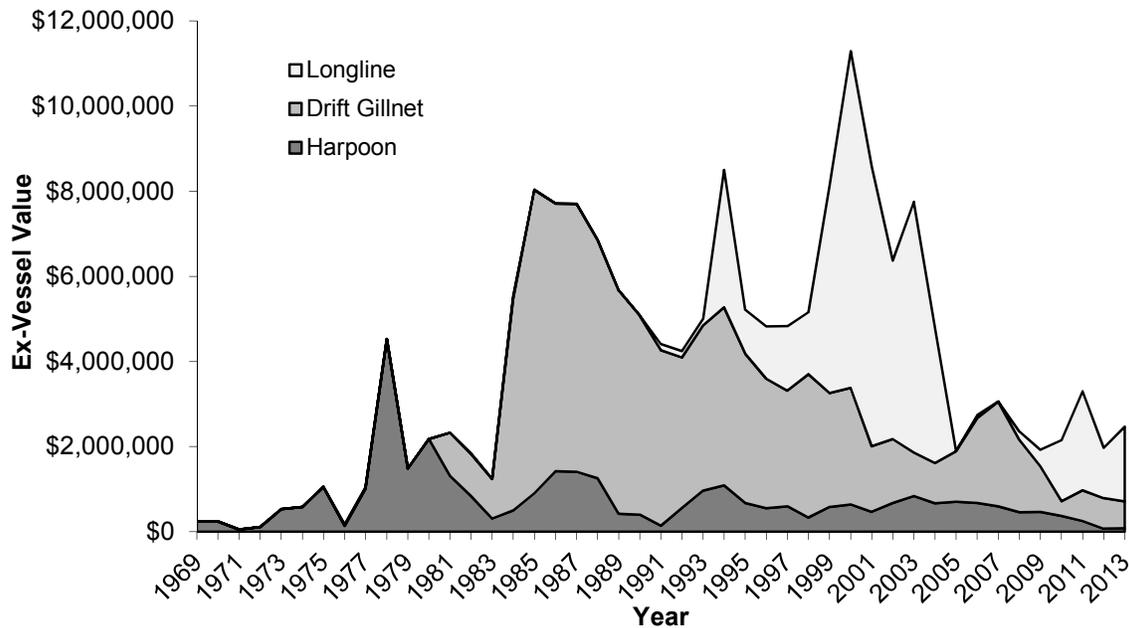


Figure 8. Annual ex-vessel value of California swordfish (*Xiphias gladius*) by gear type, 1969–2013.

“transfer effect” has been cited as a concern, in that while domestic swordfish fisheries may have bycatch, they are highly regulated to reduce the incidence of unintended catch, but the countries of imports may not manage their fisheries with the bycatch standards the US does. As a result, incidence of bycatch may in fact be higher for imported swordfish products than it is for the California fishery.

The Pacific Fisheries Management Council (PFMC) had directed the Highly Migratory Species Management Team (HMSMT) to evaluate the potential modification of the boundaries of the Pacific Leatherback Conservation Area (PLCA) to allow for additional fishing grounds for the DGN swordfish fleet. This Area Under Consideration (AUC), as it was termed, would open an area at the southeastern border of the PLCA, allowing for greater opportunity to target swordfish in a highly frequented area.

**Albacore.** Targeted by commercial and recreational fisheries off California, Washington, and Oregon, albacore tuna (*Thunnus alalunga*) comprises more than 95% of all HMS landed commercially on the West Coast, taken most often with troll and jig and bait gears. In 2013, commercial landings in California decreased by 50%, from 649 t in 2012 to 324 t valued at just over \$1.1 million, at an average of \$3.41/kg (\$1.55/lb). This represented only 2.5% of the coast-wide total. Washington landings comprised 62%, with 7,983.3 t averaging \$3.08/kg (\$1.40/lb) and having an ex-vessel value of over \$24.7 million, and Oregon landings were 4,629 t at \$3.48/kg (\$1.58/lb), valued at over \$16 million. CPFV logs indicated 2,832 fish taken by party boats off of Cali-

fornia, and CRFS recorded 303 landed by private vessels. Over 388 t of fresh and frozen albacore tuna was exported to ten different countries from California in 2013; the majority of fresh to Mauritius and the majority of frozen to Spain.

**Yellowfin Tuna.** In 2013, yellowfin tuna (*Thunnus albacares*) commanded the second highest average price-per-pound of all HMS, at \$6.95/kg (\$3.16/lb). Mainly taken by purse seine, commercial landings in California experienced a notable increase, as 6.2 t were landed this year alone, but <7 t had been landed the three previous years combined. Ex-vessel revenue for yellowfin tuna was \$42,930. Around 71 t of fresh yellowfin tuna was exported in 2013, largely to Thailand, but also to Mexico and Canada. Opposite the increase in commercial landings, CPFV logbooks indicated that recreational catch decreased with 3,462 yellowfin landed by anglers on party boat vessels, representing an decrease of 21% the amount landed in 2012. CFRS estimated that no yellowfin tuna were landed by private vessels off of California in 2013, but the survey is for US waters only.

**Skipjack Tuna.** Both commercial and recreational landings of skipjack tuna (*Kastuwonus pelamis*) have been minimal for several years. In 2013, 0.5 t of skipjack was landed mainly by purse seine vessels, with an ex-vessel value of only \$813. Frozen exports of skipjack to Thailand and China totaled around 542 t this year. The last three years saw no skipjack tuna caught off California by private boats, and only one was estimated to be landed this year from US waters based off CRFS. CPFV logs reported an estimated 59 fish; a 12% decrease from the 66 landed in 2012.

**Bluefin Tuna.** Off California, commercial landings of bluefin tuna (*Thunnus thynnus*) continued to decline in 2013. Taken by multiple gear types such as purse seine and periodically in DGN, bluefin landings decreased 92% from 118 t in 2011 and 43 t in 2012, down to 9.9 t landed in 2013. However, the ex-vessel price jumped dramatically from \$2.24/kg (\$1.02/lb) to \$6.84/kg (\$3.11/lb), making bluefin the third highest priced of commercial HMS landings. Conversely, CPFV logbook data indicated an increase in recreational landings, as 6,504 bluefin were reported as taken in California waters in 2013 (5,627 taken in 2012), with CRFS estimating only an additional 27 fish landed in US waters by private vessels, although this represents an increase from the 10 taken in 2012. California exported almost 10 t of fresh and 6 t of frozen bluefin products to Canada in 2013.

**Common Thresher Shark.** Common thresher shark (*Alopias vulpinus*) is the most valuable shark species taken in commercial HMS fisheries off of California. It is targeted in the DGN fishery and often landed incidentally in other gears. Landings in 2013 slightly decreased from those in 2012 from 66 t to 65.8 t. However, ex-vessel value increased, bringing in \$200,190 at an average of \$3.04/kg (\$1.38/lb), increasing from \$2.93/kg (\$1.33/lb) in 2012. CPFV logs reported 37 threshers landed in 2013, while estimates from CRFS indicated private boat anglers landed around 77 common threshers from US waters, down from 372 in 2012.

**Shortfin Mako Shark.** Shortfin mako shark (*Isurus oxyrinchus*) is the second most commonly landed shark in commercial HMS fisheries. Landings increased to 30.6 t in 2013, nearly an 18% increase from the previous year. Shortfin mako are taken incidentally by many gear types, but are not directly targeted commercially. The average dressed weight price increased from \$1.94/kg (\$0.88/lb) in 2012 to \$2.88/kg (\$1.31/lb) in 2013, resulting in an ex-vessel value of \$88,375. There were 128 shortfin mako sharks reported taken by party boat anglers on CPFV logs, which is consistent with numbers landed in 2012. CRFS reported an estimated 508 sharks taken by private sportfishing boats in US waters, a 22% decrease from 2012.

**Dorado (dolphinfish).** While 2012 saw a three-fold increase in commercial landings of dorado (*Coryphaena hippurus*) from the previous year, 2013 landings were a substantial 90% decrease from 2012, with only 1 t landed, all on the US West Coast in California ports. Dorado is not generally targeted, but caught incidentally by long-line gear, hook and line, and occasionally in DGN. Ex-vessel revenue from California caught dorado was just under \$6,000, commanding \$5.92/kg (\$2.69/lb). Similar to the decrease in commercial landings, CPFV logs showed a decrease in landings as well, from 6,337 fish

landed in 2012 to 1,807 fish in 2013; a 71% decrease. CRFS reported an estimated 133 fish landed by private vessels in US waters.

**HMS Management.** In 2012 the California Department of Fish and Wildlife (Department) responded to a petition to list the northeastern Pacific (NEP) population of great white sharks as endangered or threatened under California's Endangered Species Act (CESA). Department staff spent over a year reviewing the best available literature and research. In early 2014, the Department presented its evaluation to the California Fish and Game Commission (Commission) with the recommendation that listing under CESA was not warranted.

### Dungeness Crab

The Dungeness crab, *Metacarcinus magister* (formerly *Cancer magister*), trap-based fishery spans the West Coast of North America from Alaska to central California. In California there are two distinct management areas, the northern and central, demarcated by the Sonoma/Mendocino county line. 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, depending on the condition of the crab.

The Dungeness crab fishery, in recent years, has secured its place among California's most valued fisheries, being the highest valued fishery again in 2013 (\$88.7 million) and second in volume to the market squid fishery (14,066 t) in volume. The fishery has brought in record landings in recent seasons including both the 2010–11 and 2011–12 seasons, with 12,497 t and 14,465 t landed, respectively (fig. 9). Although not record breaking, the 2012–13 crab season remained relatively high compared to the 10-season average of 9,060 t, with 11,054 t landed statewide. Generally the northern area contributes to the majority of total crab landed statewide and the 2012–13 season was no exception with 68% derived from the northern ports from Crescent City to Fort Bragg, and 32% landed from Bodega Bay south to Morro Bay. Four of the five highest recorded seasons for the entire fishery dating back to the 1915–16 season have occurred in the last eight seasons, starting with the 2004–05 season, ranking fourth at 11,445 t, and include this most recent 2012–13 season, ranking fifth in total Dungeness crab catch.

This past season also ranks second for the fishery in ex-vessel value of \$68.9 million. Average ex-vessel value from the past 10 seasons of \$44 million (not inflation-adjusted) has been steadily increasing over time during this period of high landings. The average price paid to fishers of \$6.29/kg (\$2.85/lb), is also higher than the 10-season moving average of \$4.89/kg (\$2.22/lb), and coupled with higher than average landings has resulted

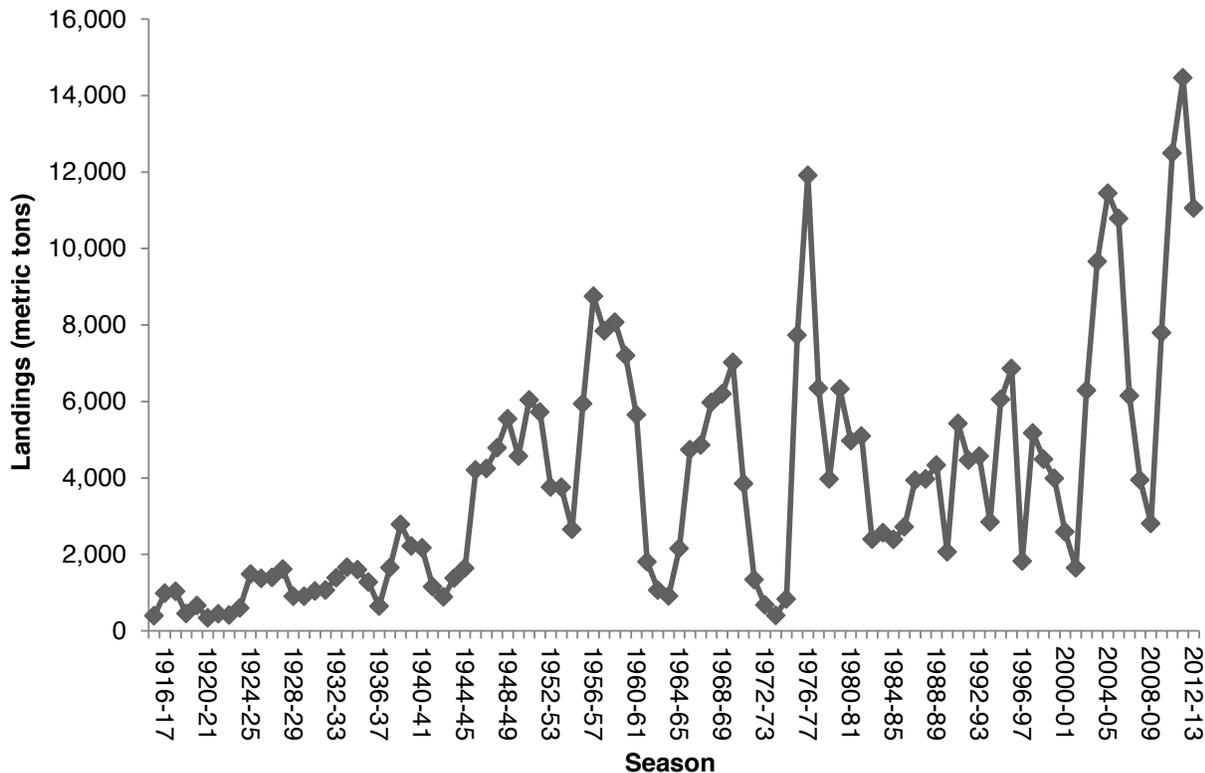


Figure 9. California commercial Dungeness crab (*Metacarcinus magister*) landings, 1912/13 season–2012/13 season.

in one of the highest total ex-vessel values for the fishery on record, at \$95.5 million during the 2011–12 season.

Preliminary data from the 2013–14 season shows state landings exceeding 7,000 t (through March 2014), with the majority of crab coming from the central area. Although landings are lower than past seasons, the record high average price of \$7.30/kg (\$3.31/lb) has contributed to over \$50 million brought in by that date.

The 2013–14 season is the first season to employ trap limits, implementing a program created by Senate Bill 369 passed in 2011. The trap limit program places a cap on the number of traps a vessel can fish dependent on where the vessel places among the seven trap tiers. Placement is based on historical landings during a ‘window’ period by the vessel. The highest tier is set at a maximum of 500 traps while the lowest tier is set at 175 traps. Permit holders were required to purchase Department-issued trap tags for each trap in their tier and an additional biennial permit before the start of the season. If they fail to do so their commercial Dungeness crab permit will no longer be valid, potentially removing latent permits from the fishery. With trap limits in place there may be an observable effect to the derby style nature of the fishery, the rush at the start of the season to catch as much crab as possible, when about 80% of the catch occurs in the first six to eight weeks of the fishery. From a fishery management perspective, trap limits will be a

useful tool in tracking effort among fishery participants whereas before, the total number of traps in the fishery was not known.

The commercial fishery is regulated through the state legislature and is managed primarily 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 with similar 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 sport fishing, 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. Data from the recreational take is limited or nonexistent but sampling from the California Recreation Fisheries Survey (CRFS) concentrated in Bay Area ports from November and December 2013 suggests that total take is less than 5% of the commercial fishery take.

Mature males typically molt on an annual basis 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 (Tri-State), on whether to delay the opening of the season in order to let the crabs reach a standard body meat relative weight.

The 2012–13 season in the northern management area was the second consecutive season to be delayed as late as January 15, the maximum allowed by law. Central California coast crab usually molt earlier than northern crab, and the area is not subject to opening delays by statute. In the 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 2012 commercial Dungeness Crab Vessel Permit, 444 vessels made at least one landing in the 2010–11 season. Less than a quarter of these total 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. Even with trap limits in place, 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 overcrowding on crab fishing grounds.

In 2008, legislation created the Dungeness Crab Task Force (task force), an advisory group comprised of Dungeness crab fishers from the major fishing ports, members from the Department, and nongovernmental organizations. The task force was reinstated with SB 369 and several meetings will take place between 2014 and 2016 to further discuss the future of Dungeness crab fishery management such as evaluating the trap limit program and whether to include the central management area in the Tri-State Committee process by adopting the preseason testing protocol. The task force is set to report initial recommendations to the Joint Committee on Fisheries and Aquaculture and the Department by January 2015, with final recommendations set for January 2017.

### Basses

Three salt water bass species from the genus *Paralabrax* represent a few of the most important nearshore, target species for anglers fishing in the waters off of southern California. These fish are caught year-round, but the highest catch occurs from June through August which also corresponds with the peak of their spawn-

ing season. All three species are managed together under the same regulations.

During the first half of the twentieth century, kelp bass (*Paralabrax clathratus*), barred sand bass (*Paralabrax nebulifer*) and spotted sand bass (*Paralabrax maculatofasciatus*) were targeted by both recreational and commercial fishermen. Due to concerns regarding declining catch, commercial take of these basses was prohibited in 1953 and a 26.7 cm (10.5 in) total length (TL) minimum size limit was established. The minimum size limit was gradually increased to 30.5 cm (12 in) TL in 1959, and remained in effect until March 1, 2013. Bag limits for the basses first began in 1939 and have fluctuated over the years at 10, 15, and 20 fish aggregate limits with no more than 10 per species. The bag limit has remained at 10 fish in aggregate since 1975, until its recent change in March 1, 2013.

Due to concerns from the Department and the public regarding the continued declining catch, a thorough analysis of the saltwater bass fishery was recently conducted. Results from several fishery-independent and fishery-dependent data sets indicated that fishing pressure and unfavorable oceanographic conditions have contributed to declining bass populations. The Department recommended management changes, and in 2013, the Commission implemented a five fish aggregate bag limit as well as increasing the minimum size limit from 30.5 cm (12 in) to 35.6 cm (14 in) TL for all three *Paralabrax* species.

**Kelp Bass.** Kelp bass, often referred to as calico bass, are found in the nearshore habitat and have historically ranged from the Washington/Oregon border south to Bahia Magdalena Bay, Baja California, Mexico (BCM), but rarely occur north of Point Conception. Kelp bass typically inhabit shallow waters from the surface to 50 m (164 ft) and are often associated with high relief structures, including kelp. The breeding season for kelp bass occurs from April through November, with the peak in the summer months around the full moon. Kelp bass grow to 721 mm (28.4 in) and weigh up to 6.6 kg (14.5 lb).

Commercial Passenger Fishing Vessel (CPFV) catch records have been available since 1935, but all records before 1975 grouped all of the *Paralabrax* species into a single “rock bass” category. Based on recent information, it is highly likely that kelp bass made up most of the catch early on. Catch-per-unit-effort (CPUE), calculated from CPFV logbook data as the number of fish kept divided by the number of anglers on boats where at least one kelp bass was caught, fluctuated considerably from 1980 to 2013. From 1992 to 1999 CPUE decreased by 57% falling from 1.69 fish per angler to 0.72 fish per angler; the lowest level since 1984. Following this decline, CPUE increased to a peak of 1.51 fish per angler in 2004. Another negative trend occurred

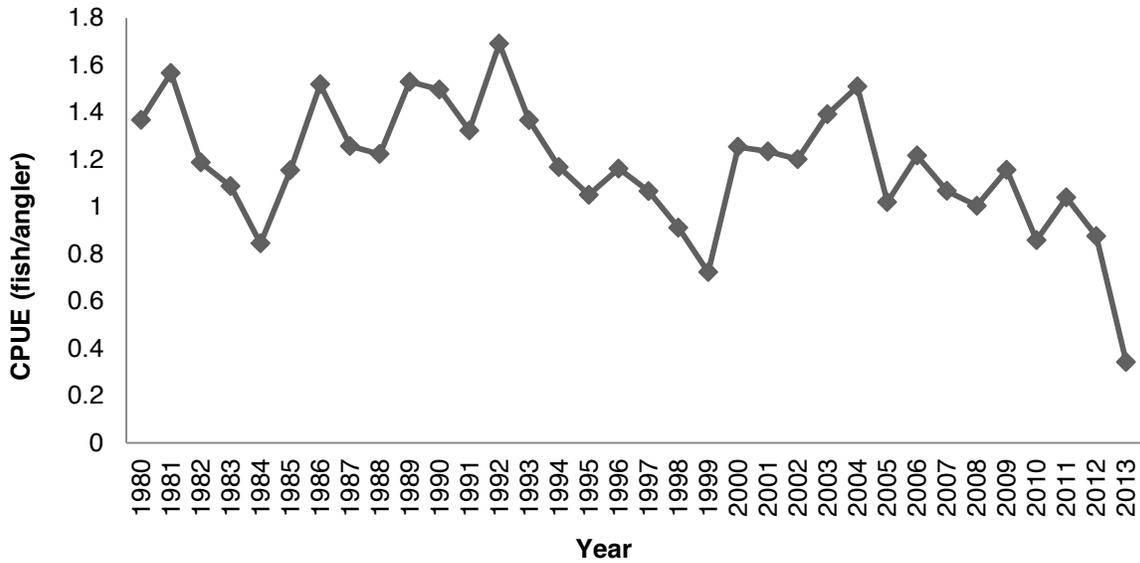


Figure 10. Catch-per-unit effort (CPUE) for kelp bass (*Paralabrax clathratus*) caught by CPFVs in southern California for trips where barred sand bass were caught. Data are based on CPFV logbooks (1980–2013) for fish caught in U.S. waters.

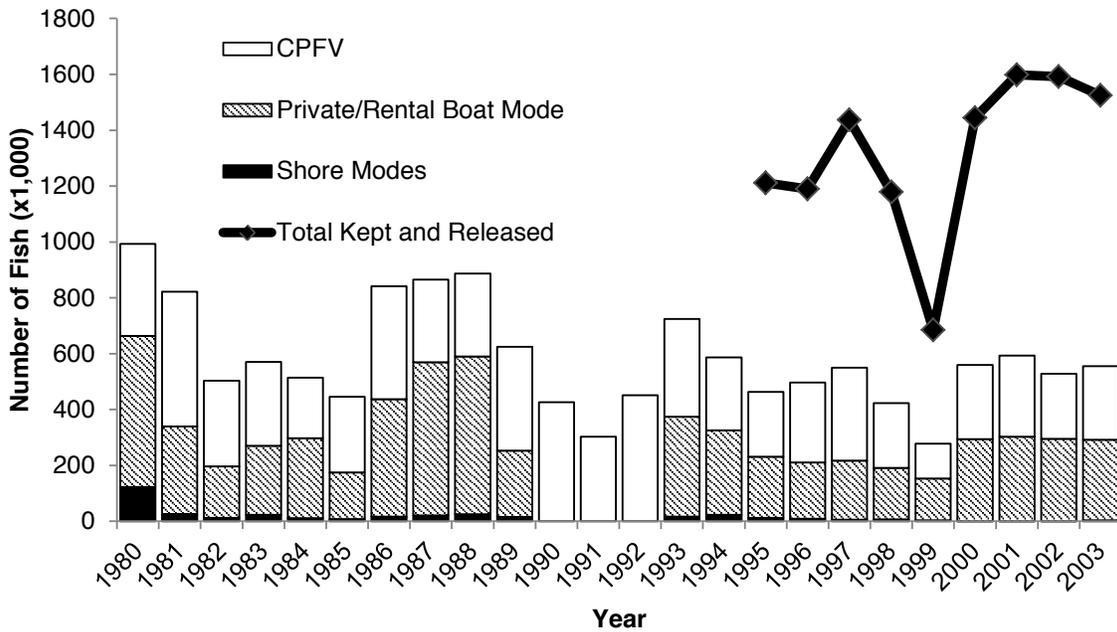


Figure 11. Recreational catch estimates of kelp bass (*Paralabrax clathratus*) in southern California in thousands of fish as reported by MRFSS for private/rental boats and shore modes, and by CPFV logbooks, 1980–2003. No recreational data from MRFSS were available from 1990–92 and for Jan–Feb 1995. Data for total combined catch with fish released alive were only available from 1995–2003.

between 2004 and 2012 with CPUE declining by 42% to 0.88 fish per angler. Declining CPUE continued into 2013 with CPUE declining by 61% to 0.34 fish per angler and reaching the lowest value since 1980 (fig. 10). The decline from 2012 to 2013 can be partially attributed to the increase in size limit for the basses.

Kelp bass are also targeted and caught by anglers fishing from shore modes as well as from private/rental

boats. From 1980 to 2004, the Marine Recreational Fisheries Statistical Survey (MRFSS) collected historical size and total estimated catch data for kelp bass from beach/bank, manmade structures and private/rental boat modes, and historical size data from the CPFV fishery. In 2004, the California Recreational Fisheries Survey (CRFS) replaced MRFSS. Estimated catch data for CPFVs is available from the CPFV logbooks, however

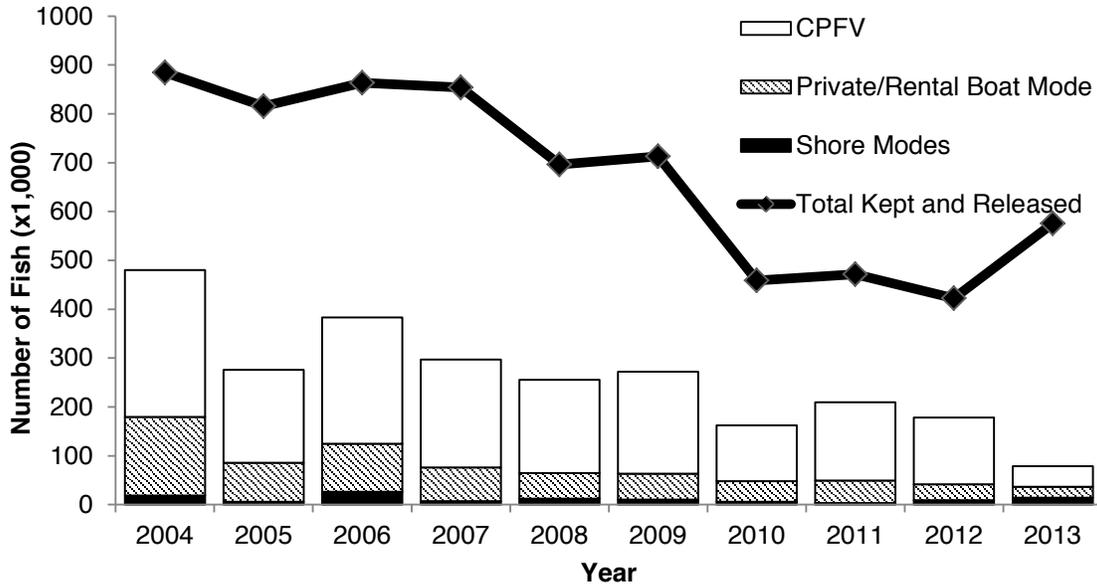


Figure 12. Recreational catch estimates of kelp bass (*Paralabrax clathratus*) in southern California in thousands of fish as reported by CRFS for private/rental boats and shore modes, and by CPFV logbooks for party/charter boats, 2004–13.

TABLE 5  
 Number of kelp bass (*Paralabrax clathratus*) kept by California commercial passenger fishing vessels (CPFVs) in southern California by port for 2012 and 2013 and 10-year average (2004–13).  
 Data were taken from CPFV logbooks for fish caught in US waters.

CA ONLY Port Name	2012		2013		10-Year Average (2004–13)	
	No. Fish Caught	% Total	No. Fish Caught	% Total	No. Fish Caught	% Total
Oxnard/Channel Islands	13,328	10%	5,177	12%	15,041	8%
Redondo Beach	3,825	3%	265	1%	12,137	7%
San Pedro	19,551	14%	7,919	19%	28,970	16%
Long Beach	10,443	8%	5,607	13%	23,143	13%
Newport/Balboa	14,639	11%	3,405	8%	21,802	12%
Dana Point	27,460	20%	6,003	14%	27,801	15%
Oceanside	6,192	5%	1,553	4%	6,562	4%
Mission Bay	15,263	11%	4,446	11%	22,204	12%
San Diego	17,630	13%	4,283	10%	17,357	10%
Other	8,102	6%	3,599	9%	7,292	4%
Total CPFV Catch	136,433	100%	42,257	100%	182,308	100%

due to survey differences, MRFSS and CRFS party/charter estimates are not directly comparable. From 1980 to 2003, MRFSS data indicate that shore modes made up only 4% of the catch while private/rental boats and CPFVs made up 96% of the catch (fig. 11). More recent CRFS data indicate that shore modes made up a slightly greater percentage (14%) with private/rental boats and CPFV's accounting for 86% of the catch between 2004 and 2013 (fig. 12). Combined MRFSS and CPFV logbook data show a decrease of 44% from 992,900 fish in 1980 to 555,650 fish in 2003 (fig. 11). This decline continued between 2004 and 2012 as the number of fish kept showed a decrease of 63% from 480,500 fish in 2004 to 178,200 fish in 2012 (fig. 12). A 56% decrease in catch occurred from 2012 to 2013,

partly due to the new regulation changes. CRFS samplers measured 37,786 kept kelp bass with an average TL of 356 mm (14 in) from 2004–13. Prior to 2013, the average TL was steadily decreasing to its lowest point in 2012 of 346.9 mm (13.7 in); the average TL increased to 389.8 mm (15.3 in) in 2013. This increase can be attributed to the new minimum size limit that went into effect in 2013.

Kelp bass have consistently been in the top ten species or species groups caught per year by southern California CPFV anglers during the past 20 years. Based on landings in 2013, kelp bass ranked tenth among all finfish species reported by CPFVs. This ranking comes even after regulatory changes in 2013 that limited kelp bass catch. On average, over the past 10 years, San Pedro

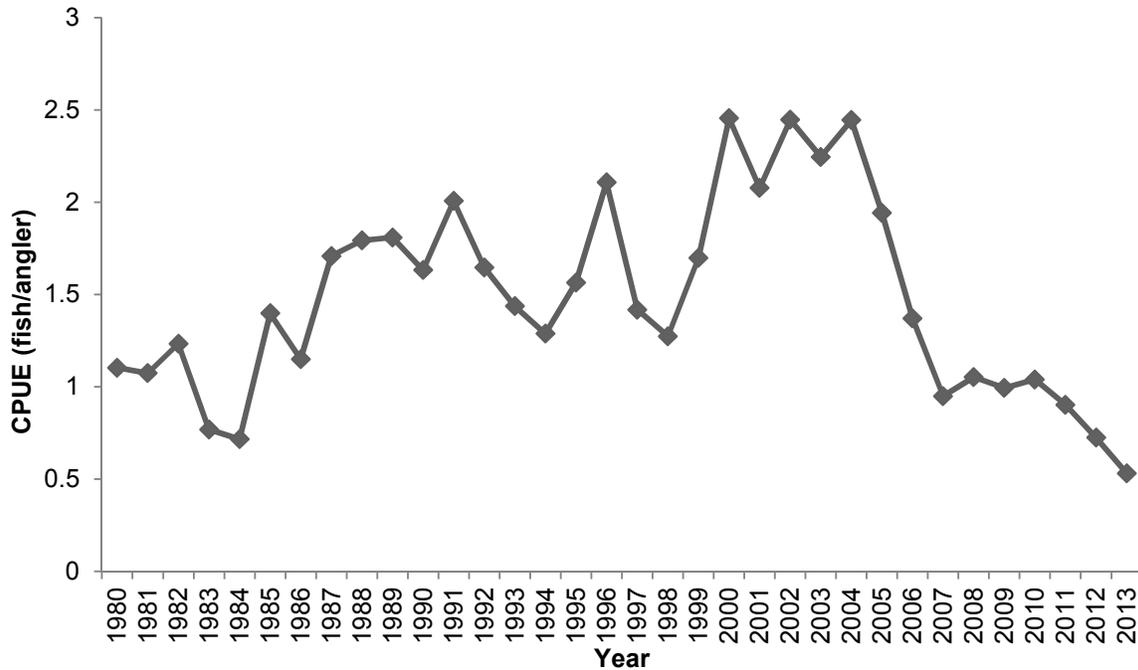


Figure 13. Catch-per-unit effort (CPUE) for barred sand bass (*Paralabrax nebulifer*) caught by CPFVs in southern California for trips where barred sand bass were caught. Data are based on CPFV logbooks (1980–2013) for fish caught in U.S. waters.

ranks first with 16% of total fish caught (table 5). The ports of Dana Point and Long Beach rank second and third with 15% and 13% of the catch, respectively. Other landings reporting substantial catch include Newport/Balboa with 12%, Mission Bay with 12%, and San Diego with 10%. While a majority of fish overall are caught in California waters, between 2004 and 2013 21% of fish kept by CPFVs from San Diego were taken from Mexican waters. From 2012 to 2013, there was an increase in Mexican caught fish from 14% to 36% for San Diego CPFVs.

**Barred Sand Bass.** Barred sand bass range from Santa Cruz, California south to Bahia Magdalena Bay, BCM; however, they are rarely found north of Point Conception. They inhabit waters from the shallow subtidal to 183 m (600 ft), but are most common in waters less than 30 m (100 ft) and are usually associated with sand/rock interfaces of deep reefs and artificial structures. The breeding season occurs between April and November, with July being the peak month of spawning. During the summer months sand bass form large breeding aggregations over sandy bottoms at depths of 15–30 m (~50–100 ft). They can grow to 647.7 mm (25.5 in) and 6 kg (13.2 lb).

Barred sand bass catch estimates are available from 1935 to present, but they were not differentiated until 1975. Prior to 1975, all three *Paralabrax* species were grouped into a single “rock bass” category. CPFV logbook data from 1980 to present show that barred sand bass CPUE has fluctuated, showing a steady increase

starting in the mid-1980s increasing from 1.15 fish per angler in 1986 and peaking in 2000 with 2.46 fish per angler (fig. 13). From 2004 to 2012 CPUE substantially declined, decreasing by 70% from 2.45 fish per angler in 2004 to 0.72 fish per angler in 2012. From 2012 to 2013, CPUE decreased another 27% reaching a new low of 0.53 fish per angler. This decrease in 2013 is partly attributable to the increase in the minimum size for the basses.

In addition to CPFVs, barred sand bass are also caught by anglers fishing from other modes including shore (piers, jetties, and beach/bank) and private/rental boats. MRFSS data from 1980–2003 indicate that CPFVs made up 58% of the catch, with private/rental boats making up 41%, and shore modes making up 1%. CRFS data from 2004–13 indicate a similar trend, with shore modes making up 3% of the catch and CPFVs making up 70% of the catch. Combined MRFSS and CPFV logbook data representing all modes from 1980–2003 show a fluctuating trend with peak catches for kept fish in 1988 and 2002, with 1,295,022 and 1,253,900 fish, respectively (fig. 14). From 1995 to 2003 a large number of fish were released, which resulted in a peak total of kept and released fish of 2,893,476 in 2002; prior to 1995 CPFV logbook data do not include releases. The proportion of fish released differed by fishing mode with 80% for shore-based fishing, 63% for private/rental boats, and 12% for CPFVs. Combined CRFS and CPFV logbook data show a substantial decline between 2004 and 2013 of total kept and released fish for all modes.

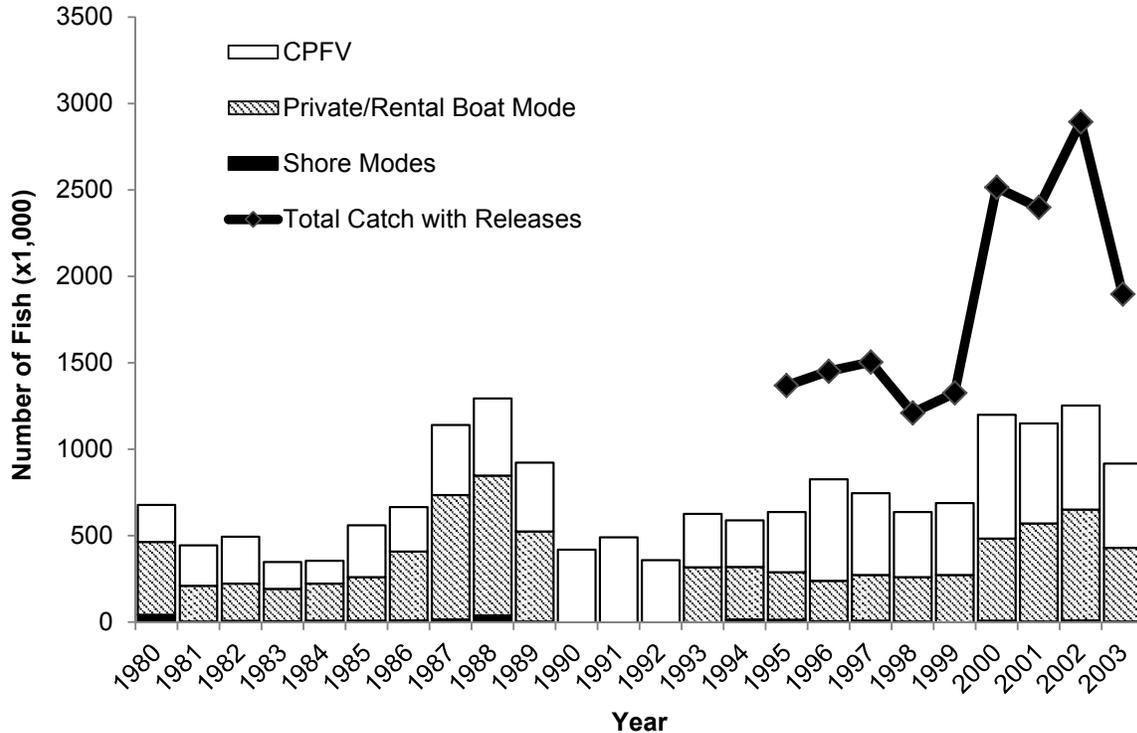


Figure 14. Recreational catch estimates of barred sand bass (*Paralabrax nebulifer*) in southern California in thousands of fish as reported by MRFSS for private/rental boats and shore modes, and by CPFV logbooks, 1980–2003. No recreational data from MRFSS were available from 1990–92 and for Jan–Feb 1995. Data for total combined catch with fish released alive were only available from 1995–2003.

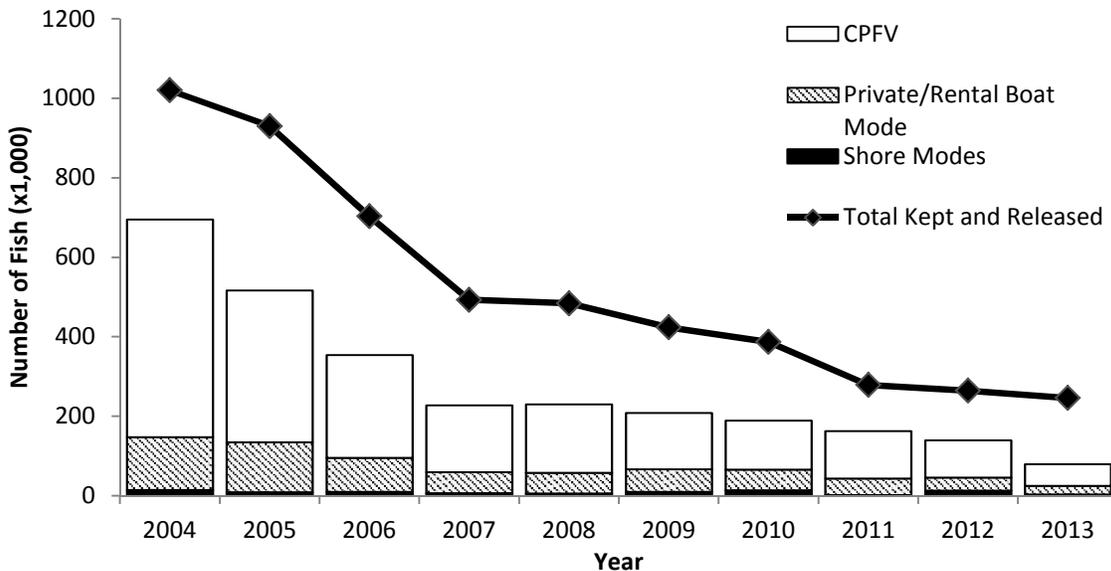


Figure 15. Recreational catch estimates of barred sand bass (*Paralabrax nebulifer*) in southern California in thousands of fish as reported by CRFS for private/rental boats and shore modes, and by CPFV logbooks for party/charter boats, 2004–13.

Between 2004 and 2012 the number of fish kept showed an 80% decrease from 694,900 in 2004 to 139,145 in 2012 (fig. 15). The increase in size limit between 2012 and 2013 resulted in a 43% decrease in catch. From 2004 to 2013, the number of kept and released fish also showed a substantial decline from the 2004 peak of

1,020,400 fish to 246,200 fish for all modes. The proportion of fish released between 2004 and 2013 was similar to 1980–2003 with shore modes releasing 86%, private/rental boats releasing 71% and CPFVs releasing 14%.

Between 2004 and 2013, CRFS samplers measured 43,476 kept barred sand bass with an average TL of

TABLE 6  
 Number of barred sand bass (*Paralabrax nebulifer*) kept by California commercial passenger fishing vessels (CPFVs) in southern California by port for 2012 and 2013 and 10-year average (2004–13).  
 Data were taken from CPFV logbooks for fish caught in US waters.

CA ONLY	2012		2013		10-Year Average (2004–2013)	
Port Name	No. Fish Caught	% Total	No. Fish Caught	% Total	No. Fish Caught	% Total
Santa Barbara/Ventura	1,116	1%	405	1%	824	0%
Marina Del Rey	8,184	8%	5,529	10%	14,513	7%
Redondo Beach	2,741	3%	330	1%	13,864	7%
San Pedro	14,468	15%	7,130	13%	25,218	12%
Long Beach	29,213	30%	13,180	23%	48,945	24%
Newport/Balboa	17,057	17%	10,039	18%	38,888	19%
Dana Point	8,026	8%	3,616	6%	23,470	11%
Oceanside	1,998	2%	1,669	3%	8,451	4%
San Diego	8,685	9%	8,404	15%	14,842	7%
Other	6,768	7%	6,059	11%	19,124	9%
Total CPFV Catch	98,256	100%	56,361	100%	208,139	100%

374 mm (14.7 in). From 2004 to 2011, the average TL of fish fluctuated with peaks of 375 mm (14.8 in) in 2005 and 376 mm (14.8 in) in 2007 before reaching the highest point of 378 mm (14.9 in) in 2012. The 2013 TL size limit increase resulted in the largest TL of the ten year period with an average TL of 409 mm (16 in).

During the last 20 years, barred sand bass have consistently ranked among the top species caught per year by southern California CPFV anglers. Based on 2013 landing records, barred sand bass ranked fifth overall among all finfish species reported by CPFVs. This ranking comes after regulatory changes in 2013 that limited barred sand bass catch, and shows an improvement from the ranking of sixth overall in 2012. On average, over the past ten years, Long Beach ranks first with 24% of the total catch (table 6). The ports of Newport/Balboa and San Pedro ranked second and third with 19% and 12% of total catch, respectively. Other landings reporting substantial catch include Dana Point with 11% and Marina del Rey and San Diego with 7% each. A large number of kept fish on San Diego CPFVs come from Mexican waters. Between 2004 and 2013, 43% of the kept fish reported for the port of San Diego were taken from Mexican waters. When comparing catch data for 2013 with that of 2012, an increase in catch from Mexico can be seen, especially for CPFVs fishing out of San Diego. Overall, the catch taken from Mexican waters increased from 3% in 2012 to 17% in 2013, and for the port of San Diego increased from 43% to 50% from 2012 to 2013.

**Spotted Sand Bass.** Spotted sand bass range from Monterey, California to Mazatlán, Mexico including a substantial population located in the Gulf of California; however, this species is rarely found north of Santa Monica Bay. Populations in southern California are typically restricted to sandy or muddy bottom habitat within shallow bays, harbors, and lagoons that contain eelgrass, surf grass and rock relief for shelter. Adults are usually

found to occupy waters ranging in depth from .6 m to 9.1 m (2–30 ft), but specimens have been taken from as deep as 70 m (200 ft) in the Gulf of California. Spotted sand bass are primarily fished in Mission and San Diego Bays (San Diego County) and Newport and Anaheim Bays (Orange County). These areas provide a sheltered warm water habitat necessary for this generally subtropical species. Spotted sand bass grow to 560 mm (22 in) and 3.1 kg (6.8 lb).

Spawning typically begins in May and continues through early September, when spotted sand bass aggregate at or near the entrances of bays in southern California. Reproductive strategies of spotted sand bass are complex, with individuals from different regions employing different strategies such as protogynous hermaphroditism. Significant genetic and morphological differences have been found between the Gulf of California and southern California populations.

The spotted sand bass fishery has been popular with recreational shore and private skiff anglers beginning in the mid-1950s due to the fish's aggressive behavior and fighting ability. Accurate landings data were not available until the mid-1970s as a result of being grouped together with other *Paralabrax* species or not adequately reported. Surveys conducted by the Department on skiff fishing estimated that the annual catch of spotted sand bass in southern California ranged from 12,790 to 23,933 fish between 1976 and 1981. MRFSS estimates from 1980–2003 show that an average of 368,500 spotted sand bass were caught annually. During this time period peak catch (kept and released) occurred in 1986 with 603,950 fish and 2002 with 646,530 fish. The majority of the fish (91%) were caught by private/rental boats with shore based anglers catching 8% and CPFVs catching 1% (fig. 16). Estimates obtained from CRFS from 2004–13 show that an average of 294,600 fish were caught annually. During this period of time

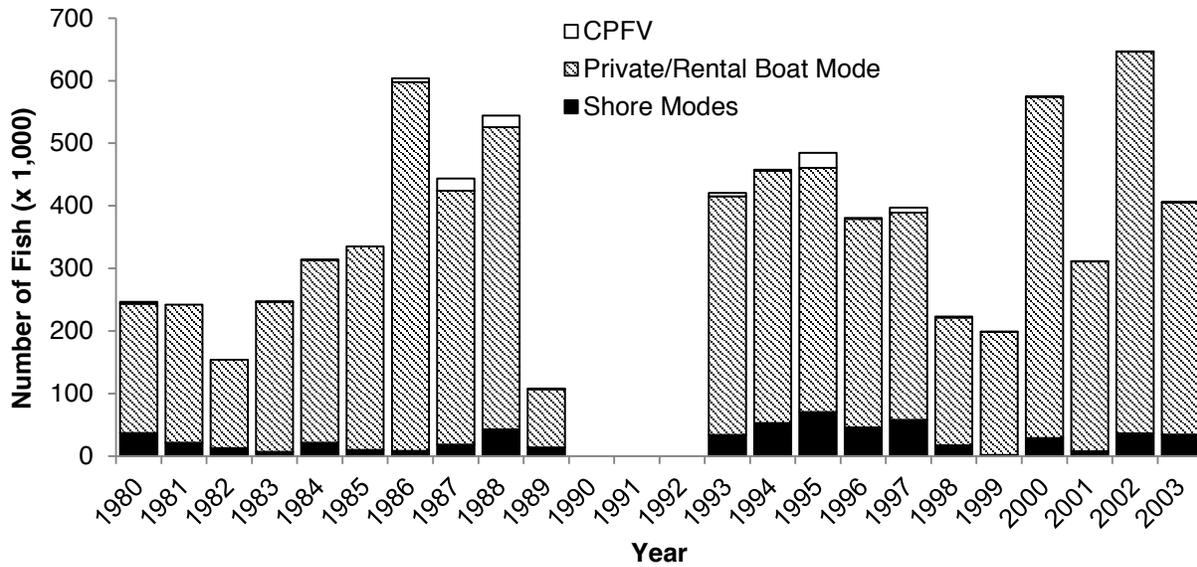


Figure 16. Recreational catch estimates of spotted sand bass (*Paralabrax maculatofasciatus*) in southern California in thousands of fish as reported by MRFSS for private/rental boats and shore modes, and by CPFV logbooks, 1980–2003. No recreational data from MRFSS were available from 1990–92 and for Jan–Feb 1995.

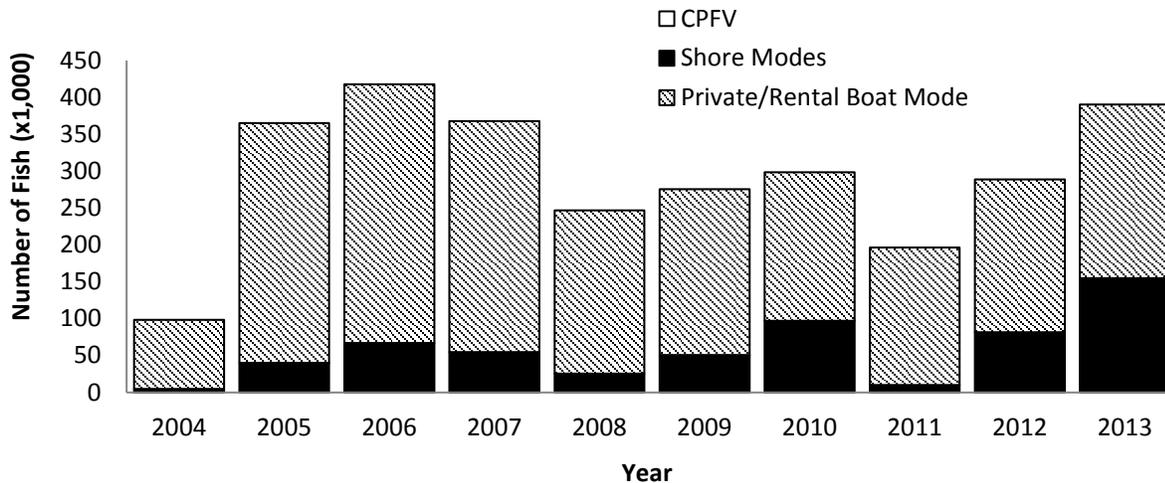


Figure 17. Recreational catch estimates of spotted sand bass (*Paralabrax maculatofasciatus*) in southern California in thousands of fish as reported by CRFS for private/rental boats and shore modes, and by CPFV logbooks for party/charter boats, 2004–13. CPFV catch is not apparent due to the small contribution to the total catch (<1%).

peak catch occurred in 2006 with 417,700 fish caught (kept and released) (fig. 17). CRFS data show a similar trend with private/rental boats comprising 80% of the catch and shore-based anglers and CPFVs comprising 20% and less than 1%, respectively. When looking at MRFSS catch estimates for the basses (kept and released) for all modes in California, spotted sand bass made up the smallest percentage of catch (8%); barred sand bass and kelp bass, made up 43% and 49%, respectively. CRFS catch estimate data show an increase in spotted sand bass catch (19%) relative to barred sand bass (36%) and kelp bass (45%). Although over the past two decades there has been increased fishing pressure put on spotted sand

bass, a majority of fish caught are released. From 1980–2003, release rates from MRFSS data for spotted sand bass, kelp bass, and barred sand bass were 78%, 66%, and 54%, respectively. CRFS data from 2004–13 show that release rates have increased in more recent years with spotted sand bass having the highest release rate (95%) of the three *Paralabrax* species followed by kelp bass (73%) and barred sand bass (55%).

### Surfperch

The surfperch assemblage is comprised of the family Embiotocidae, includes seaperch and perch, and encompasses 24 species. The complete assembly, collectively

known as surfperch, contains four species only found in waters around Japan and one species only found in freshwater and estuarine habitats in California. There are 19 species of marine surfperch inhabiting California's temperate coastal waters, representing the majority of the assemblage. The island perch (*Cymatogaster gracilis*) is now considered to be synonymous with the shiner perch (*C. aggregata*). The Guadalupe perch (*Brachyistius aletes*) is included in this count; however, it is very similar and possibly synonymous with the kelp perch (*B. frenatus*).

Extensive life history variation exists within the surfperch assemblage. However, all surfperch are viviparous—which means that the live young are retained until birth, all young are highly developed at parturition, and all adults have internal fertilization. There are specific mating and birthing seasons for surfperch, the timing of which depends on the species and often the latitude, and may be linked to water temperature. In general, mating occurs in the fall and parturition occurs in the summer. Many species aggregate to mate and to give birth and some species move inshore for these events. By definition, viviparous fish have low fecundity; however, fecundity increases with the length of the female.

Many of California's marine surfperch are the target of a modest commercial fishery in central and northern California and a sizable recreational fishery throughout the state. The surfperch fisheries in California are solely managed by the California Department of Fish and Wildlife (Department). Both the commercial and recreational fisheries are primarily shore-based and typically use similar hook and line gear, although there is a boat based hook and line commercial fishery in San Francisco Bay. Surfperch, depending on the species, are found in a variety of habitats; however, the fisheries mainly target surfperch on sandy beaches. Landings are highest when the surfperch are aggregated during the mating and parturition seasons.

No formal stock assessments have been completed for surfperch and the fisheries are considered data-poor; however, there is no indication that surfperch stocks are in decline based on the best available data. The Department has analyzed fishery trends such as catch-per-unit-effort (CPUE) and the average length at capture over time. In addition, the Department collects data on life history through fishery-independent surveys (FIS) and monitors the commercial and recreational fisheries.

Although surfperch stocks do not appear to be declining, their low fecundity and mating and spawning aggregations may cause them to be more vulnerable to fishing. Water pollution and changing sea temperature can also cause vulnerability.

**Commercial Fishery.** The commercial surfperch season is closed May 1 through July 31 statewide. This excludes shiner perch, which may be taken at any time

of the year. The seasonal closure is intended to protect aggregating females during the parturition season and the end of the closure was extended in 2002 from July 14 to July 31 for this reason. Barred surfperch (*Amphistichus argenteus*), calico surfperch (*A. koelzi*), and redbtail surfperch (*A. rhodoterus*) may not be fished commercially south of Point Arguello (redtail surfperch rarely occur there). There are no minimum size limits or bag limits for the commercial fishery.

The fishery primarily uses hook and line gear from shore, however, other gear types are occasionally used which include fish traps, A-frame dip nets, and beach seines. Redtail surfperch is the primary surfperch species landed from shore in Humboldt and Del Norte counties and barred surfperch is the primary surfperch species landed from shore in Monterey and San Luis Obispo Counties. The San Francisco Bay fishery is primarily conducted using skiffs to fish hard-bottom near-shore habitat and habitat near manmade structures. A wide variety of species commercially landed in this area includes, but is not limited to, striped seaperch, rainbow seaperch, rubberlip seaperch, black perch, pile perch, and shiner perch.

Surfperch are sold for human consumption within the US mainly in ethnic food markets. Some species of surfperch, mainly shiner perch, are used as live bait for California halibut (*Paralichthys californicus*) and striped bass (*Morone saxatilis*). Surfperch are landed live or dead, with the live fishery generally fetching a higher price per pound. In 2013, the commercial fishermen were paid an average of \$2.00/lb for surfperch. The rainbow seaperch (*Hypsurus caryi*) averaged the highest price in 2013 at \$4.50/lb, followed by the striped seaperch (*Embiotoca lateralis*) at \$4.49/lb, then the rubberlip seaperch (*Rhacochilus toxotes*) at \$3.38/lb, the black perch (*E. jacksoni*) at \$3.17/lb, the barred surfperch at \$2.91/lb, the pile perch (*Damalichthys vacca*) at \$2.50/lb, the calico surfperch at \$2.25/lb, and finally the redbtail surfperch at \$1.21/lb.

The Department mainly collects data on commercial landings through the monitoring of landing receipts. Prior to 1927, surfperch landings were grouped on the receipts with similar species such as blacksmith (*Chromis punctipinnis*), halfmoon (*Medialuna californiensis*), opal-eye (*Girella nigricans*), and sargo (*Anisotremus davidsonii*). After 1927, these similar species were excluded from the surfperch category; however, the majority of surfperch landings still did not identify surfperch to species. Some surfperch landings are still not sorted to species. However, due to continuing Department efforts, the percentage of surfperch receipts that include unspecified surfperch has decreased in recent years. In 2013, 80% of landing receipts recorded surfperch landings to species.

The ports of San Francisco, Avila/Port San Luis, and Eureka had the most commercial landings in 2013 with

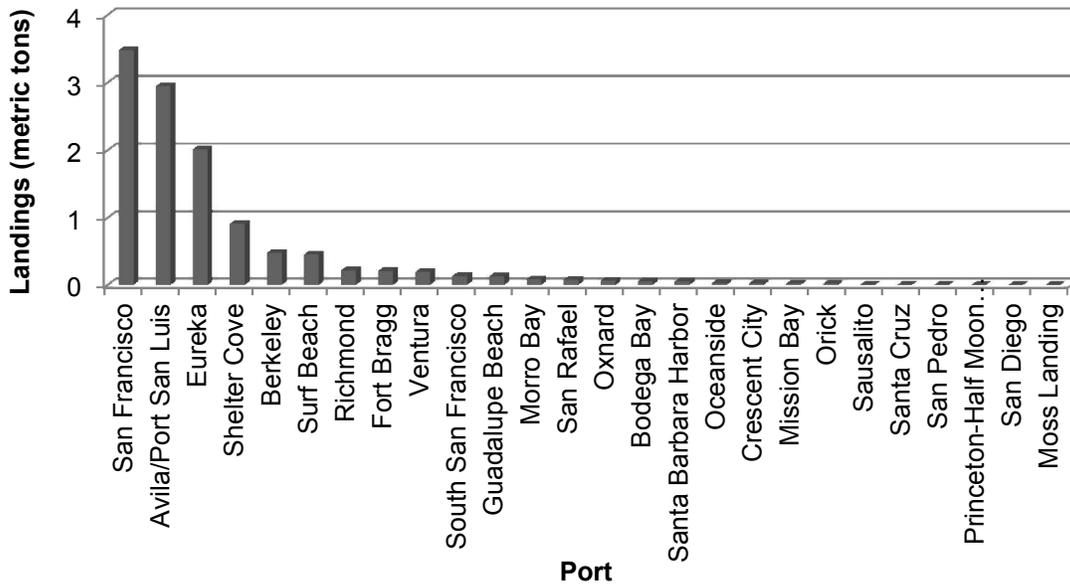


Figure 18. Commercial surfperch landings for all species by port, 2013.

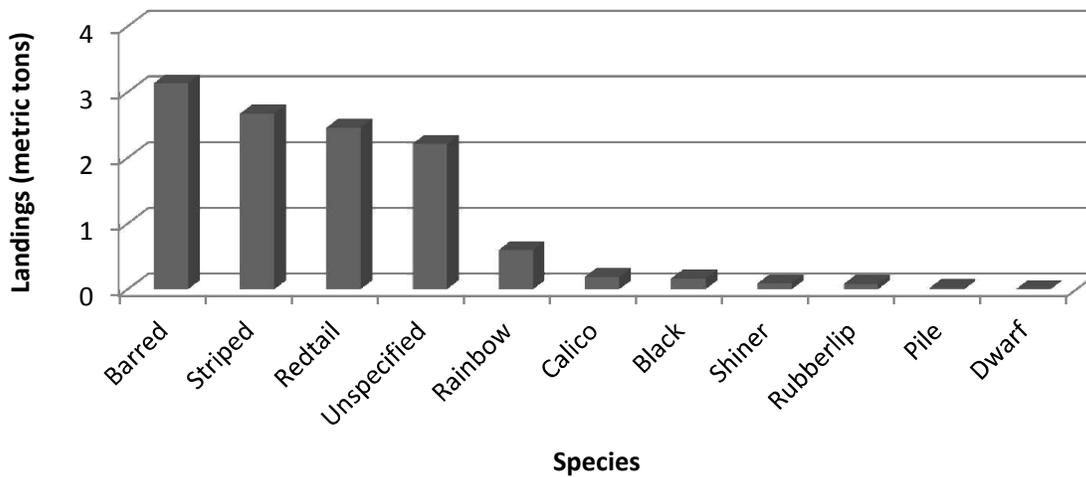


Figure 19. Statewide commercial surfperch landings by species, 2013.

total landings >1 t per port (fig. 18). Since the 1990s these ports account for 42% of all commercial surfperch landings by weight. There were 23 other ports with reported surfperch landings in 2013 that totaled <1 t per port (fig. 18). San Francisco area ports had the most landings for 2013 with a total of 4.4 t, northern California ports (Oregon/California border to Fort Bragg) followed with a total of 3.2 t, central California ports (Half Moon Bay to Avila/Port San Luis) totaled 3 t, and southern California ports (Santa Barbara county to the California/Mexico border) totaled 1 t.

The surfperch species with the most commercial landings (by weight) statewide in 2013 were the barred surfperch (27%), striped seaperch (23%), and redbtail surfperch (21%) (figs. 19, 20). Since the 1990s these species

have composed 64% of all commercial surfperch catch by weight, including those landings which were not identified to species. In 2013, 75% of commercial landings in ports in northern California (Oregon/California border to Fort Bragg) consisted of redbtail surfperch, 61% of commercial landings in ports in the San Francisco Area consisted of striped seaperch, 82% of commercial landings in ports in central California (Half Moon Bay to Avila/Port San Luis) consisted of barred surfperch, and 63% of commercial landings in ports in southern California (Santa Barbara county to the California/Mexico border) consisted of barred surfperch (fig. 21). It is likely that the percentages of these primary species were actually higher due to the use of the “unspecified” market category.

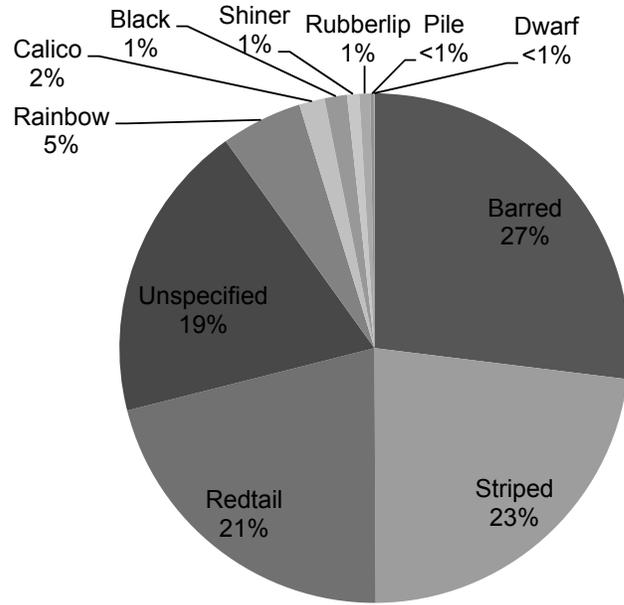


Figure 20. Statewide commercial surfperch landings shown as percentage of species by weight, 2013.

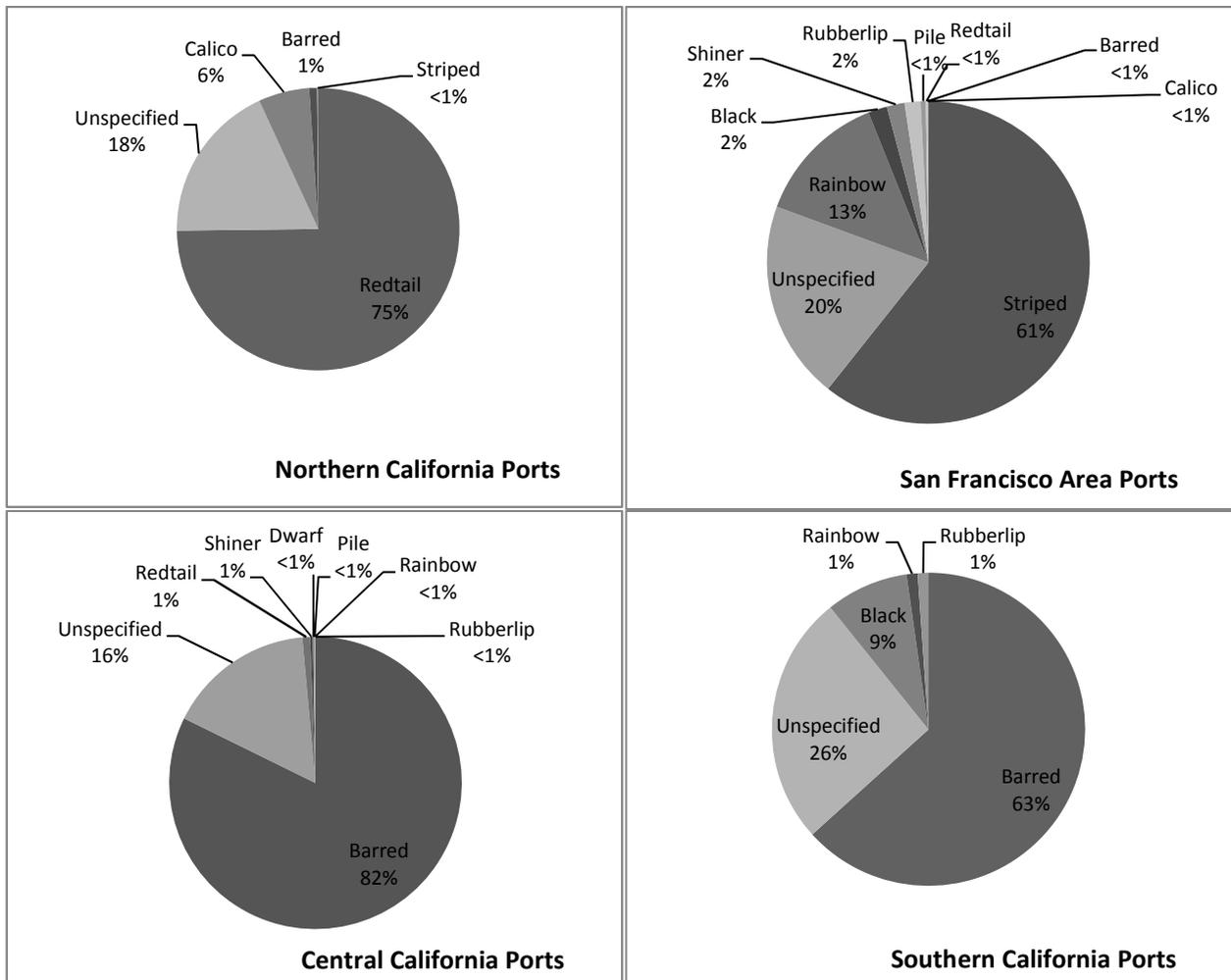


Figure 21. Commercial surfperch landings by port areas shown as percentage of species by weight, 2013.

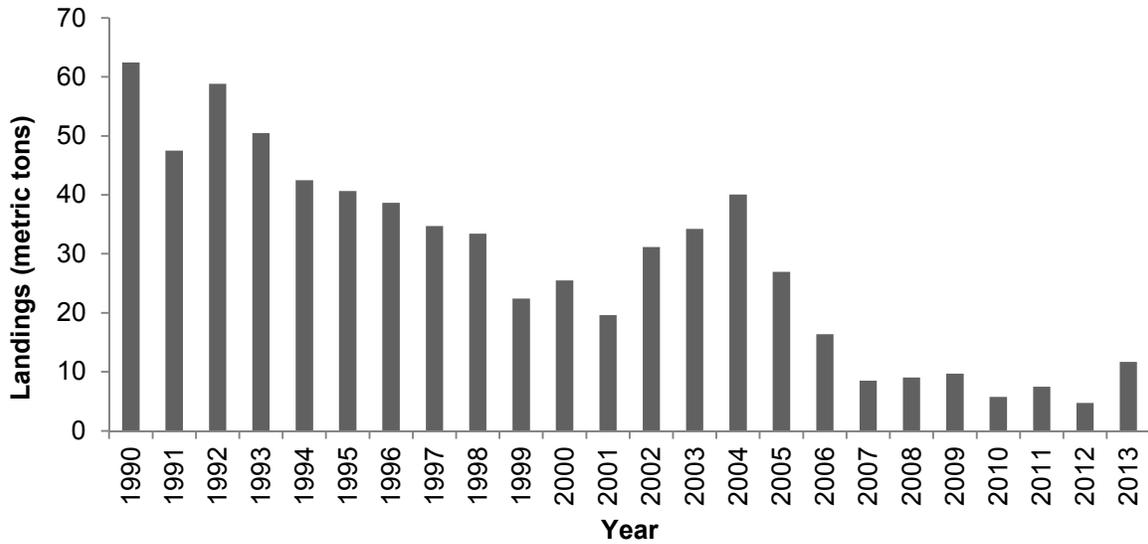


Figure 22. Historic commercial landings for all species of surfperch, 1990–2013.

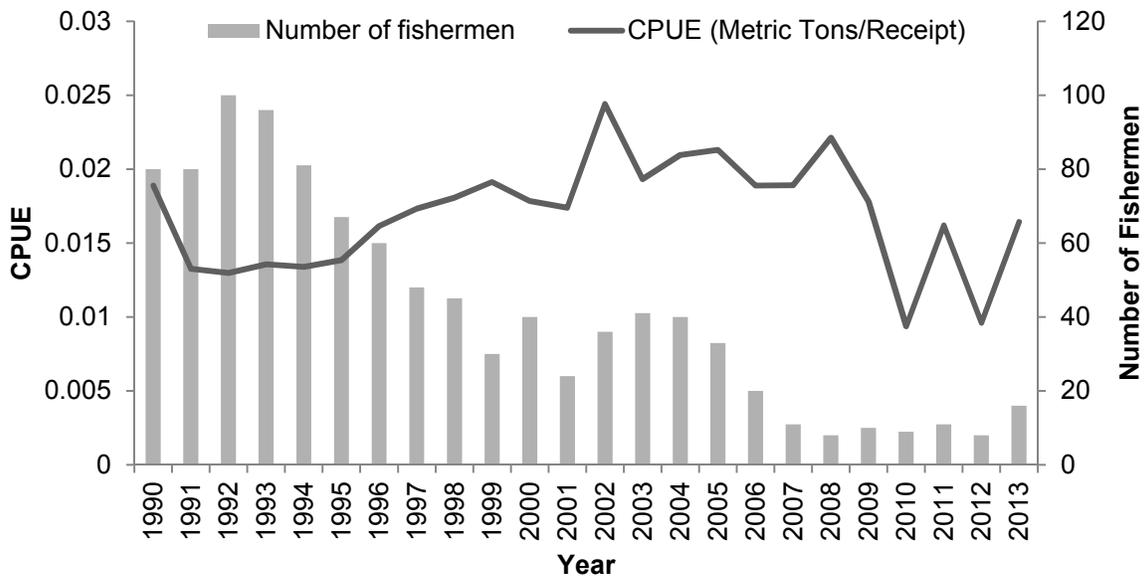


Figure 23. Annual CPUE (metric tons landed per receipt) for all species of surfperch compared with the number of commercial surfperch fishermen who made 10 or more landings per year, 1990–2013.

The total amount of surfperch landed commercially in 2013 was 11.6 t (fig. 22). The commercial surfperch fishery has shown a declining trend in the number of participants and overall annual landings over the last few decades, however, CPUE has remained relatively stable indicating that the decline in landings and participants (fishermen making 10 or more landings annually) is likely not due to a decline in surfperch stocks (fig. 23). The decline may be due to decreasing market demand, restrictions to the fishery such as the ban of vehicle use on most beaches, and possibly displacement of local fishermen due to recently implemented MPAs.

**Recreational Fishery.** The recreational surfperch season is open all year, except in San Francisco and San Pablo Bays where the season is closed April 1 through July 31. This excludes shiner perch which may be taken at any time of the year. The seasonal closure is intended to protect aggregating females during the parturition season. In San Francisco and San Pablo Bays, the daily bag limit is five surfperch, not including shiner perch. In all other areas, the daily bag limit is 20 surfperch; however, no more than 10 surfperch may be of any one species. This also excludes shiner perch. The daily bag limit for shiner perch is 20, and they may be taken

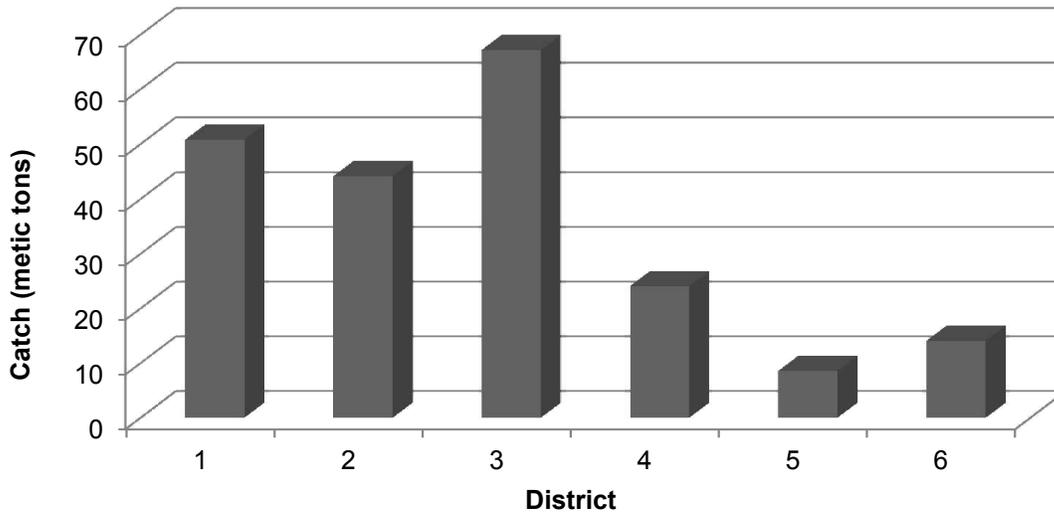


Figure 24. CRFS recreational catch estimates for all species of surfperch by District, 2013.

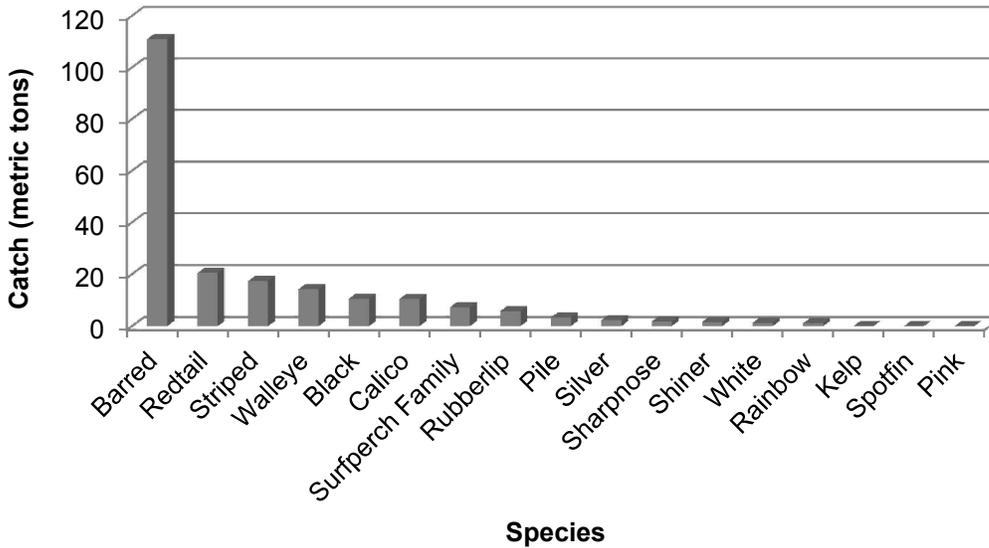


Figure 25. Statewide CRFS recreational surfperch catch weight estimates by species, 2013.

or possessed in addition to the overall daily bag limit of 20 finfish specified in the CCR, Title 14 §27.60(a). Only the redbtail surfperch has a minimum size limit in the recreational fishery, which is 10.5 inches total length (TL).

Surfperch are valued by the recreational fishery for both consumption and catch-and-release fishing. The fishery primarily uses hook and line gear from shore on sandy beaches and rocky banks. Manmade structures such as piers, private or rental boats, and CPFVs also account for a small portion of surfperch caught using hook and line. There is also harvest by scuba and free divers using pole spear or spear gun.

Since 2004, the Department has mainly collected data on recreational surfperch catch through the Cal-

ifornia Recreational Fisheries Survey (CRFS). Previously, from 1981–89 and 1993–2003, recreational catch was monitored by the Marine Recreational Fisheries Statistics Survey (MRFS). The CRFS has an improved sampling design, however, CRFS and MRFS are sufficiently different surveys and catch estimates between them cannot be compared. Both CRFS and MRFS are surveys which intercept recreational anglers during or after their fishing trips to determine species composition and catch rates. A telephone survey is used to estimate fishing effort for shore-based modes (beach/bank and manmade structures); these modes are responsible for the overwhelming majority of the catch of barred, redbtail, calico, silver, and walleye surfperches. The CRFS separates California into six marine districts with the

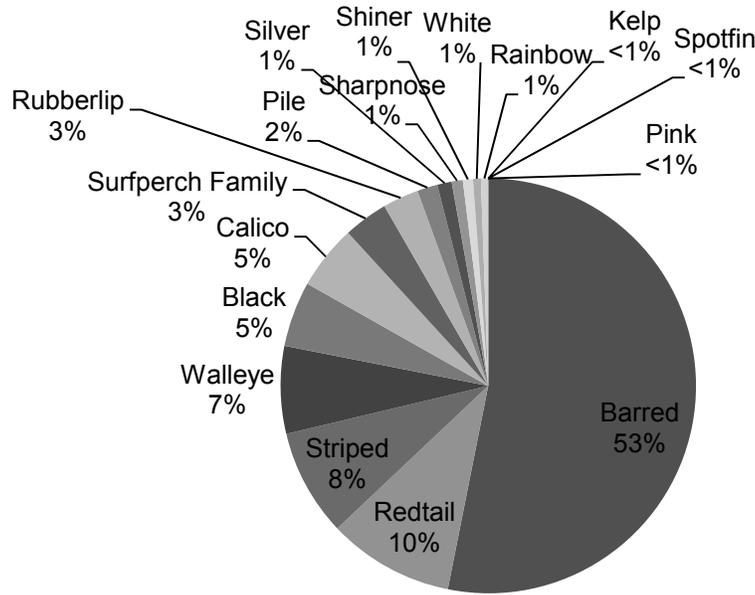


Figure 26. Statewide CRFS recreational surfperch catch estimates shown as percentage of species by weight, 2013.

following boundaries: District 1—Los Angeles, Orange, and San Diego counties; District 2—Ventura and Santa Barbara counties; District 3—Santa Cruz, Monterey, and San Luis Obispo counties; District 4—Marin, San Mateo, and the San Francisco Bay Area counties; District 5—Mendocino and Sonoma counties; and District 6—Del Norte and Humboldt counties. The districts with the highest estimated recreational catch for all surfperch species combined in 2013 were District 3 (67.19 t), District 1 (50.80 t), and District 2 (44.16 t) (fig. 24). Since 2004, these districts account for 75% of all recreational surfperch catch estimates. The catch for the remaining districts in 2013 were estimated as follows: District 4 (24.06 t), District 6 (14.09 t), and District 5 (8.58 t).

The surfperch species with the highest estimated recreational catch (by weight) statewide in 2013 were the barred surfperch (53%), redbtail surfperch (10%), and striped seaperch (8%) (figs. 25, 26). Since 2004, these species have composed 66% of all recreational catch estimates. The primary species taken by District are as follows: barred surfperch (Districts 1, 2, and 3); redbtail surfperch (Districts 4 and 6); and striped surfperch (District 5) (fig. 27). It should be noted that these figures display the recreational catch estimate percentage of each surfperch species caught by weight instead of by number of fish, so that the results can be compared to the commercial data, for which number of fish landed is not available. This is important because there are differences in size distribution among landed species of surfperch and therefore percentages by weight might be lower than percentages by number for small species. Smaller species include the silver surfperch, walleye surfperch, shiner

perch, spotfin surfperch, kelp perch, sharpnose seaperch, and pink seaperch.

The total estimated recreational catch of surfperch far surpassed the total landings of the commercial surfperch fishery in 2013. The recreational catch estimate for 2013 was 208.9 t while the commercial fishery landings totaled 11.6 t. Since 2004, CRFS recreational catch estimates have been much higher than commercial landings every year (fig. 28).

Recreational CPUE north of Point Conception for barred surfperch, redbtail surfperch, and striped seaperch varied in the beach and bank fishing mode from 2004 to 2013 with no trend (fig. 29). Similarly, recreational CPUE south of Point Conception for barred surfperch varied from 2004 to 2013 with no trend. Redtail surfperch and striped seaperch were not included in analyses south of Point Conception due to their low sample size. The average CPUE from 2004–13 for surfperch north of Pt. Conception are as follows: barred surfperch (.26), redbtail surfperch (.09), and striped seaperch (.10). The average CPUE for barred surfperch south of Pt. Conception was (.34). CPUE for barred surfperch in both regions has been above average since 2011. The lack of downward trends in CPUE indicates that stocks for these important surfperch species are not declining, at least on the regional level for areas north and south of Point Conception.

Length frequency data are available for species of surfperch encountered during recreational data collection surveys. Barred surfperch length frequency distributions for shore based fishing modes north of Pt. Conception from CRFS measurements (fig. 30) have shown no trend and have been relatively consistent since 2004.

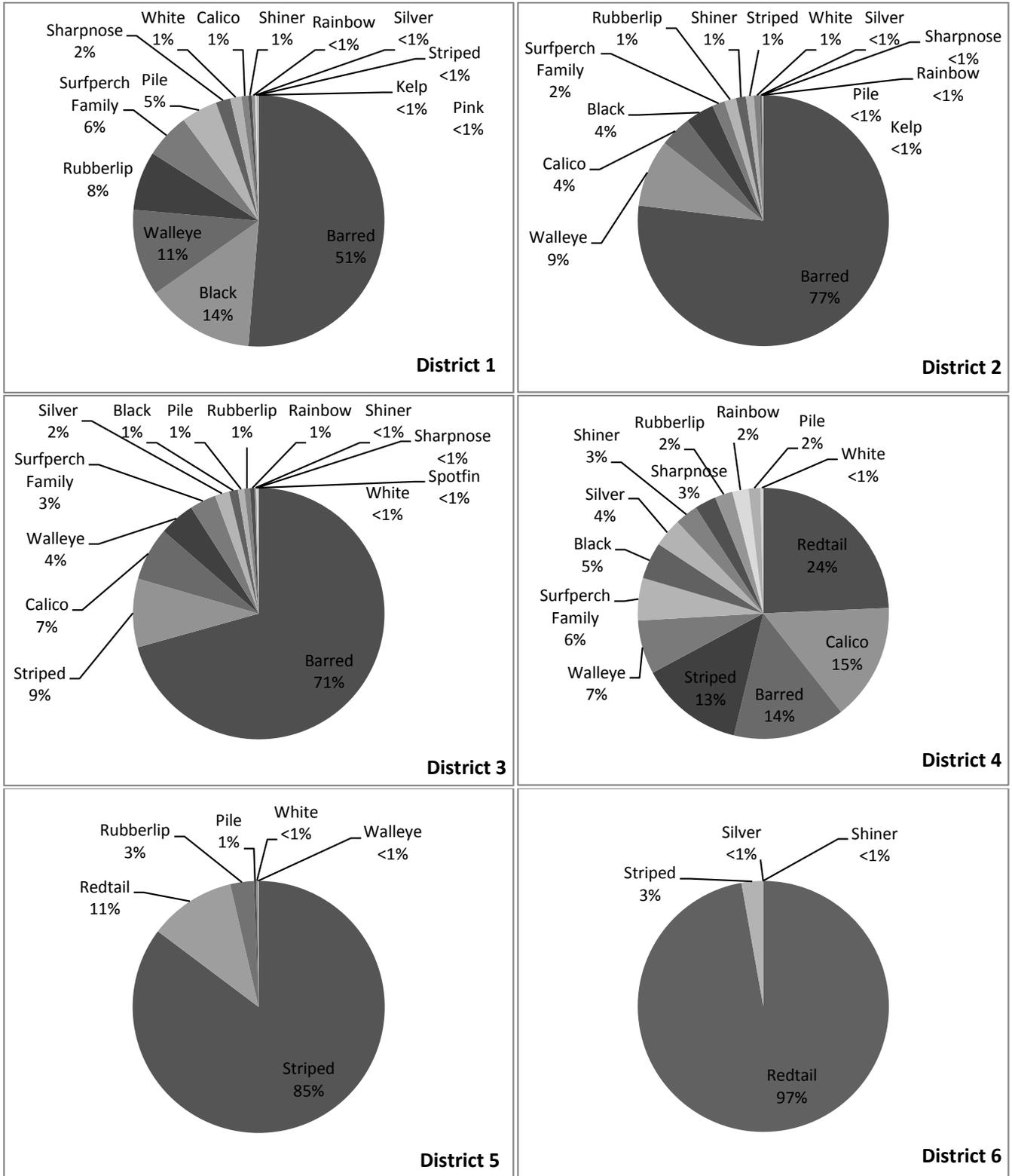


Figure 27. CRFS recreational catch estimates by district, shown as percentage of species by weight, 2013.

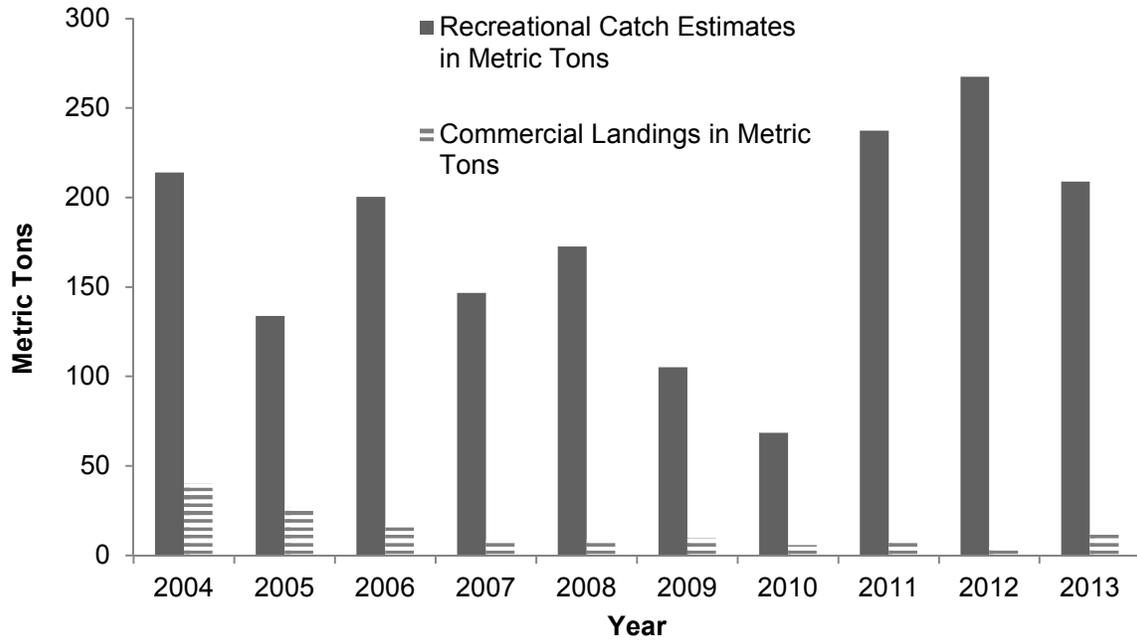


Figure 28. Annual CRFS recreational catch estimates or all species of surfperch compared to commercial landings for all species of surfperch, 2004–13.

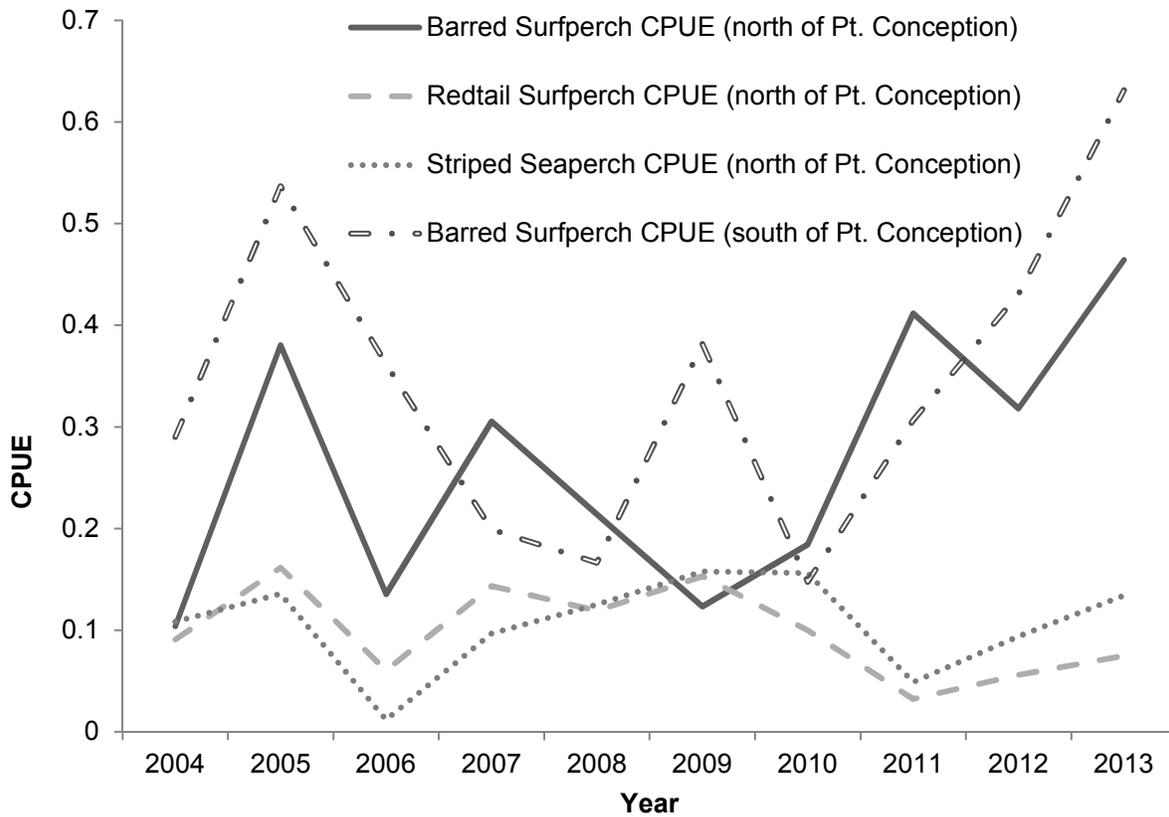


Figure 29. Recreational CPUE for barred surfperch, redbtail surfperch, and striped seaperch north of Pt. Conception and barred surfperch south of Pt. Conception, in beach and bank fishing modes, 2004–13.

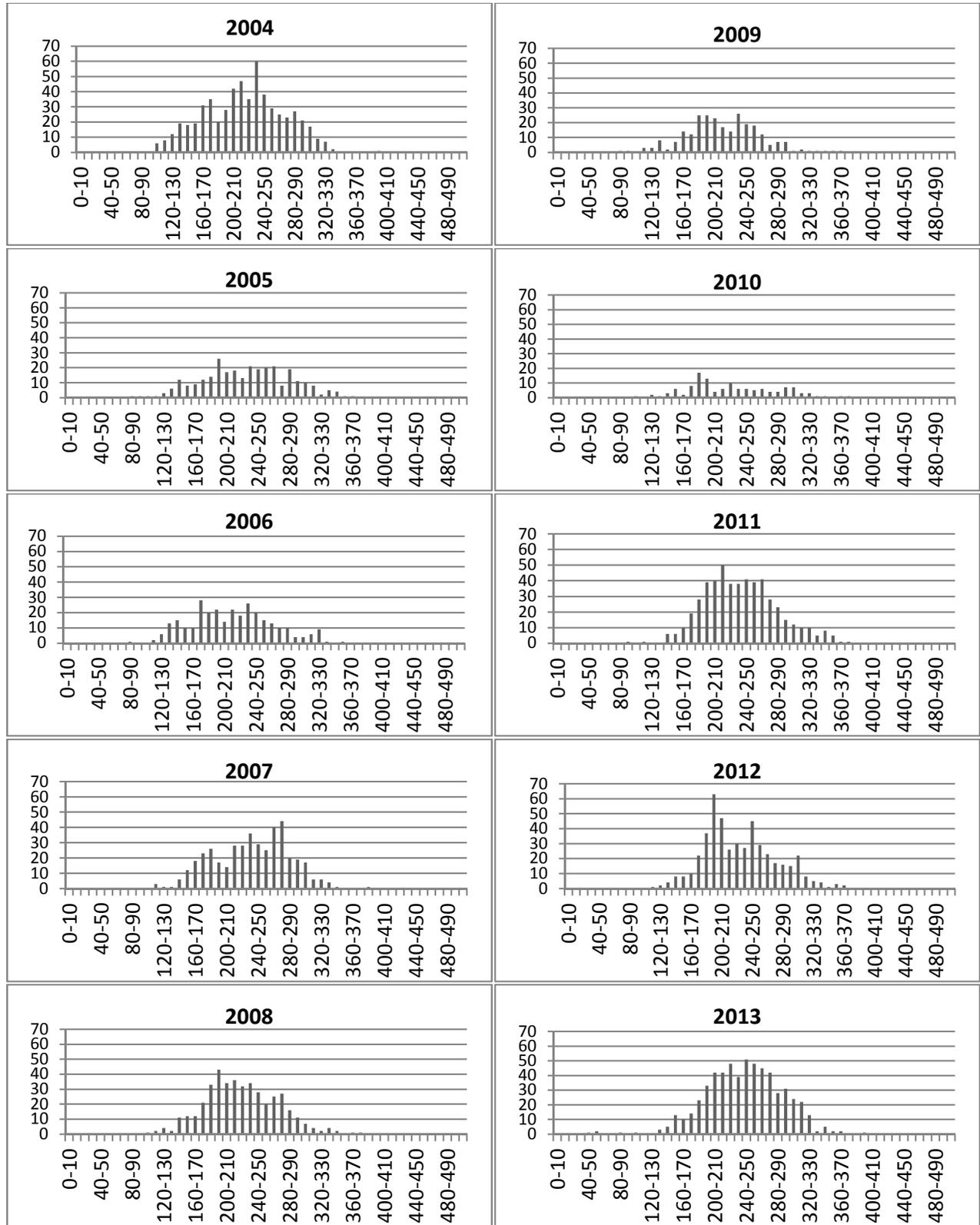


Figure 30. Length frequency distribution for barred surfperch caught from shore-based modes north of Pt. Conception, CRFS measurements, 2004–13. Length frequency bins are in 10 mm increments (X-axis) and the Y-axis shows the number of surfperch measured in each bin. Surfperch are displayed in fork length.

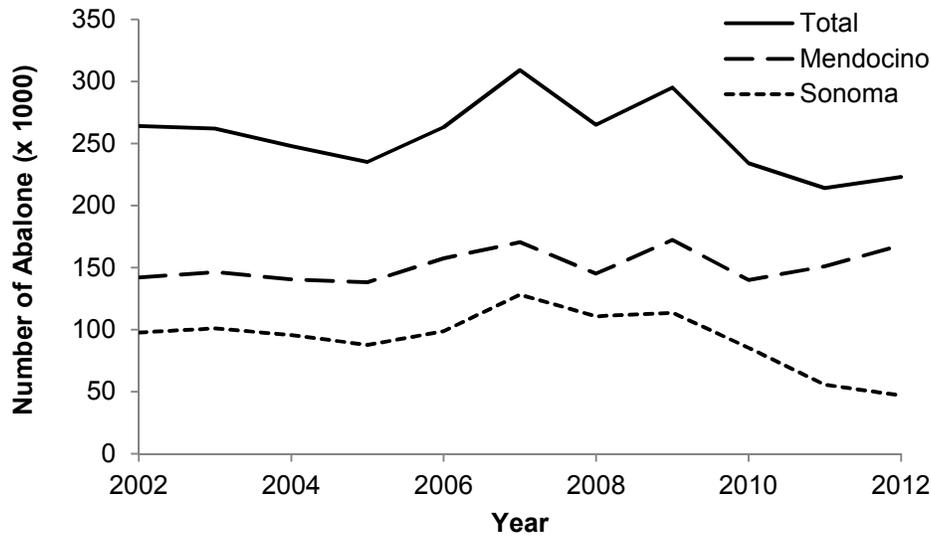


Figure 31. California recreational red abalone (*Haliotis rufescens*) catch, 2002–12.

### Red Abalone

The recreational red abalone (*Haliotis rufescens*) fishery in northern California is the largest in the world, with over 30,000 participants annually. The average annual take between 2002 and 2012 was approximately 254,000 red abalone, with fishing effort centered on the coastal counties of Sonoma and Mendocino. Given the importance of this fishery to the local coastal economy, as well as to California’s natural heritage, the state is actively managing the fishery to ensure the long-term sustainability of the resource. The fishery is managed under the Abalone Recovery and Management Plan (ARMP) using traditional fishery management strategies as well as an innovative adaptive management approach incorporating density survey data in decision making. The fishing season extends from April 1 to November 30, with an interim closure during the month of July. Only abalone >178 mm (>7 in) may be taken, either at low tide or by free diving. These regulations are designed to allow multiple years of reproduction prior to entering the fishery while also maintaining a depth refuge of abalone in deeper areas. Higher densities of abalone on the fishing grounds are also particularly important to maintain in order to avoid reduction in reproductive potential at low densities.

In northern California, fishery-independent density surveys are conducted triennially at eight (fished) index sites to assess whether fishing regulations are maintaining densities through time. Catch from these sites accounts for ~48% of the total fishery catch. These index sites were chosen to provide early warning for declines in density in the fishery overall. The ARMP harvest control rules reduce the take by 25% if the average density across the index sites drops 25% below the established baseline of 0.66 abalone m<sup>2</sup>. Furthermore, a site closure and fish-

ery reduction trigger was established at 0.25 abalone m<sup>2</sup> to avoid local impacts to reproduction due to low densities. Reductions in fishing pressure across the fishery are designed to lessen the impacts of potential shifts in fishing effort and to maintain a sustainable fishery.

Recently, densities at the index sites have declined due to a combination of fishing and non-fishing impacts. The catch in Sonoma and Mendocino counties was unusually high from 2006 to 2009, averaging 274,000 abalone, with a peak of 309,000 abalone in 2007 (fig. 31). Much of the increased fishing effort was directed at Fort Ross in Sonoma County, which peaked at >62,000 abalone in 2007. The average catch at Fort Ross prior to this period was almost half this level at 36,000 abalone. By 2009, surveyed densities in Fort Ross were reflecting this impact (density: 0.37 abalone m<sup>2</sup>—a 36% decline from 2006 estimate). In response to concerns over declining densities at Fort Ross due to increased fishing pressure, Fort Ross was closed to abalone fishing during the first two months of the season (implemented in 2012).

In August 2011, a Harmful Algal Bloom (HAB) resulted in high abalone mortalities along the Sonoma County coast, further reducing densities of red abalone. In response, the Fish and Game Commission instituted an emergency closure of the fishery in Sonoma County in October. Following the HAB, surveys revealed that the abalone density (2009–12) had dropped to 0.47 abalone m<sup>2</sup>, which is below the management trigger of 0.5 abalone m<sup>2</sup>. The decline in red abalone density was driven by the decline in the Sonoma County portion of the fishery where the HAB event occurred (fig 32). In Sonoma County, the average abalone density at the four sites declined by 60% from 0.79 abalone m<sup>2</sup> (2003–07) to 0.31 abalone m<sup>2</sup> (2009–12) (ANOVA:  $p < 0.001$ ). There was no significant decline in Men-

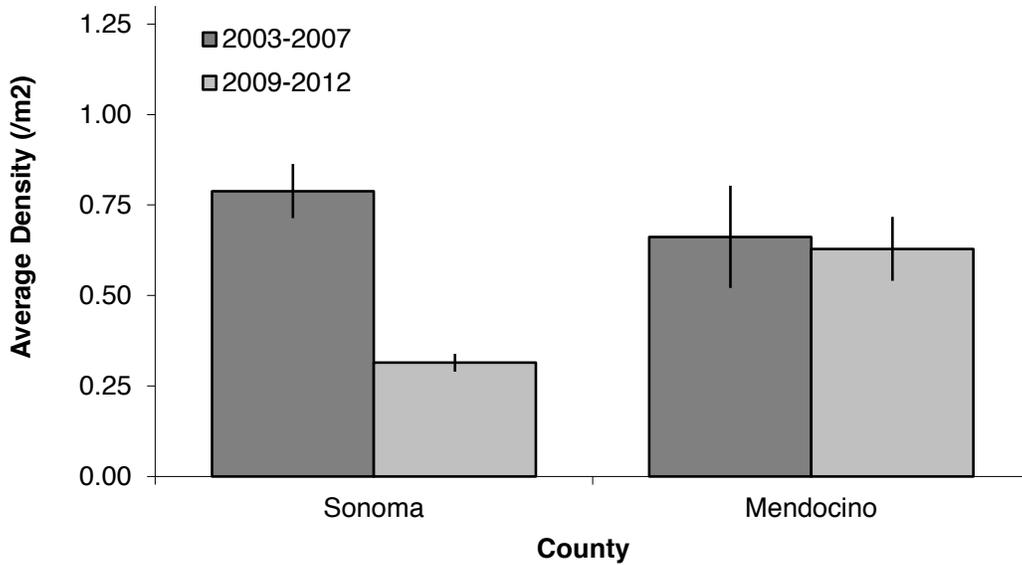


Figure 32. Average density of red abalone (*Haliotis rufescens*) from index site surveys in Sonoma and Mendocino counties, 2003–07 and 2009–12.

docino County, with average densities near 0.6 abalone m<sup>2</sup> in both time periods.

The decline in the fishery overall triggered management action to reduce the annual take from 24 to 18 abalone, with additional limitations in Sonoma County and south, where only 9 out of the 18 abalone may be taken. The daily start time was also delayed to 8:00 am, which reduces access during extreme low tide events. Fort Ross, historically the most popular abalone fishing site, was closed because the density had declined below the site closure trigger after the HAB event.

Report card data show reductions in overall take after the 2009 season, with effort shifting away from Sonoma County, prior to implementation of regulation changes in the 2014 season. The overall catch from 2012 (223,000 abalone) was 13% lower than the average catch from the prior 10 years (fig. 31). The 2012 catch in Mendocino County (152,000 abalone) was 11% higher than the prior 10-year average, while the catch in Sonoma County (82,000 abalone) was 50% lower. The proportion of the catch from Sonoma County has been steadily declining since 2010, from an average of 39% (2002–09) to 21% in 2012. Conversely, the proportion of the catch in Mendocino has been increasing, from an average of 57% (2002–09) to 75% in 2012.

These reductions in take in Sonoma County resulted from a combination of the heavy fishing pressure and HAB impacts on densities, as well as other circumstances that limited opportunities for abalone fishing in the county. Many popular state parks in Sonoma County reduced operations and closed parking access areas in 2010 due to budget cuts, reducing access to sites during popular low tide events in the spring. Newly adopted

Marine Protected Areas (May 2010) also prohibited abalone take at a few sites in Sonoma County. In 2011, the adoption of the Automated License Data System (ALDS) for sales and reporting of abalone report cards limited individuals to purchasing only one card, resulting in fewer card sales and a reduction in catch. Abalone card sales dropped by 2,800 cards during the first year of the ALDS implementation, potentially indicating the number of illegal duplicate cards purchased in prior years. Adoption of the ALDS has also resulted in greater compliance with timely returns of report cards, so that catch estimates may be more quickly available than in years past.

The apparent shift in fishing effort toward Mendocino is concerning for future sustainability of those sites, although overall fishing pressure may drop in response to the most recent regulation changes in the 2014 season. The more rapid assessment of catch statistics as well as the continued density surveys will provide important insight into the future dynamics of this vital abalone fishery.

### Kelp and Edible Algae

Perennial giant kelp (*Macrocystis pyrifera*) forests can be found worldwide in nearshore temperate oceans. On the West Coast of North America, giant kelp forests range from southeast Alaska to Baja California, Mexico. Along the California coast, giant kelp is most abundant south of San Francisco (San Mateo County) and generally grows attached to rocky substrate in depths from 6 meters (m) to more than 30 m. Bull kelp (*Nereocystis leutkeana*) is an annual alga that ranges offshore of the Pacific coast of North America and Asia. Along California, bull kelp can

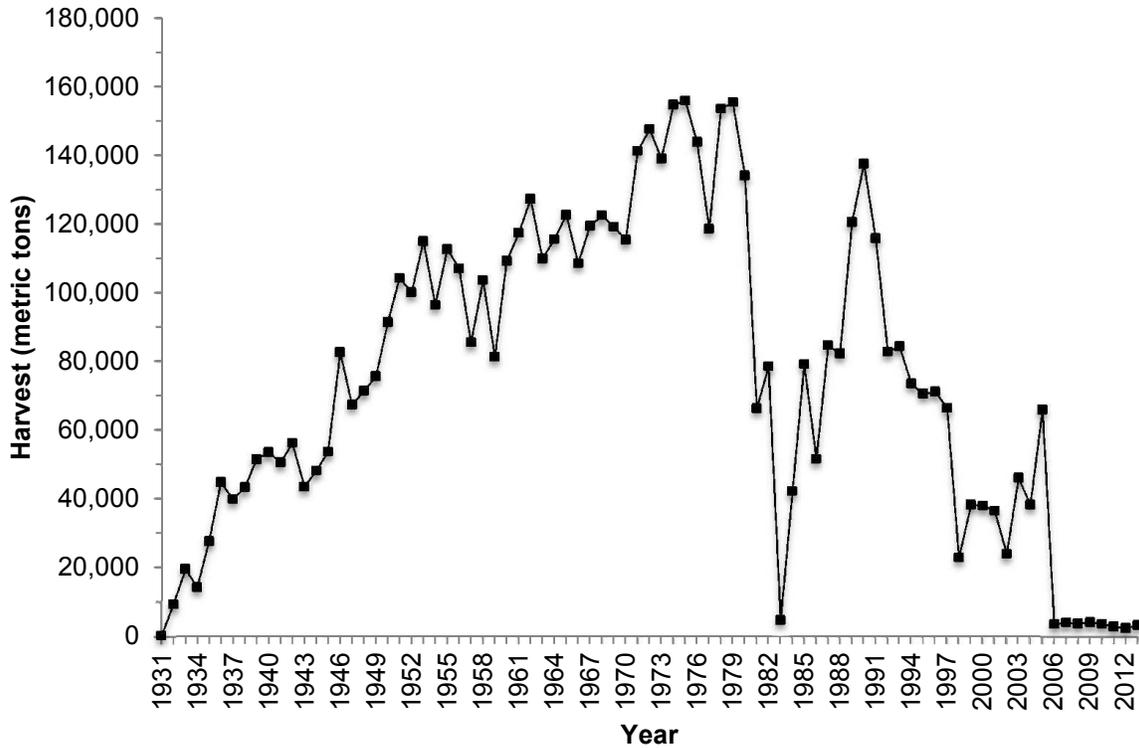


Figure 33. Commercial kelp harvest logbook data for giant and bull kelp, 1931–2013.

be found offshore from central to northern California, with greater amounts of bull kelp in northern California. Bull kelp attaches to rocky substrate in depths of 4 to 22 m.

Optimal conditions for giant kelp growth include cool ocean temperatures of 10° to 16° C and high nutrient availability. Bull kelp optimal growing conditions include high light availability (including intensity of light and photoperiod), nutrient availability, and water clarity. In general, both giant and bull kelp are affected negatively during El Niño events due to warm-water stress, along with reduced nutrient availability and large swells. Anthropogenic disturbances that inhibit giant and bull kelp growth include coastal development resulting in pollution, increased water turbidity which reduces light availability for photosynthesis, siltation which can hinder growth or bury young kelp, turbid warm water outflows from power plants, and wastewater discharges. As typical with other environments, the reduction of kelp forests is usually due to a combination of factors. While urchins can coexist in a thriving ecosystem with giant and bull kelp, the combination of poor kelp growing conditions and an increase in urchin populations can result in the formation of “urchin barrens,” which can remove large amounts of kelp through overgrazing. The removal of urchin predators, such as the southern sea otter (*Enhydra lutris nereis*) in southern California has upset the giant kelp ecosystem balance. Furthermore, fishing activities

have reduced urchin predators like the California sheep-head (*Semiossyphus pulcher*) and California spiny lobster (*Panulirus interruptus*), and abalone, an urchin competitor.

There are 87 administrative kelp beds located offshore of California’s mainland and surrounding the Channel Islands. The administrative kelp beds contain giant or bull kelp or a combination of both. The term “kelp” refers to both giant and bull kelp unless stated otherwise. Each of the administrative kelp beds fall within one of the following management categories: open (open to harvest by all commercial kelp harvesters), closed (commercial harvest of kelp is prohibited), leasable (available to harvest by commercial kelp harvesters, until an exclusive lease is granted by the California Fish and Game Commission [Commission] then only available to the lessee), and lease only (commercial harvest of kelp is prohibited unless an exclusive lease is granted by the Commission). Currently, of the 87 administrative kelp beds, 33 are open, 28 are available for lease, five are leased, three are lease-only beds, and 18 are closed to commercial harvest. Commercial harvesters of marine algae must abide by commercial algae harvest regulations (California Code of Regulations [CCR], Title 14, §165 and 165.5). Kelp harvesters may not cut attached kelp at a depth greater than four feet below the surface of the water at the time of harvest.

Commercial giant kelp harvesting offshore of California began in the early 1900s. By World War One, giant kelp was mostly harvested to extract potash and ace-

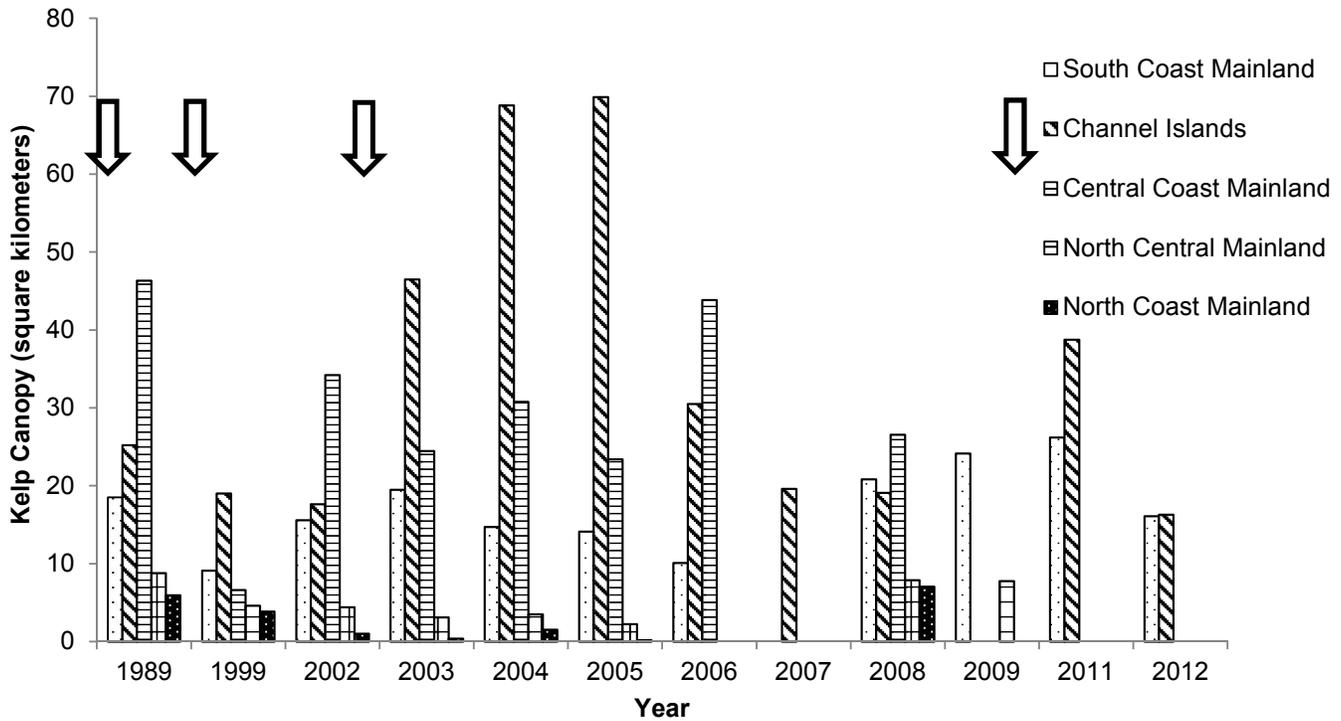


Figure 34. California Department of Fish and Wildlife aerial kelp surveys, 1989–2012 (surveys were not conducted during all years or in all regions). Regions: South coast mainland – Point Conception to the California/Mexico border; Central coast mainland – Pigeon Point to Point Conception; North central mainland – Alder Creek near Point Arena to Pigeon Point; and North coast –California/Oregon border to Alder Creek near Point Arena. Arrows represent strong (1987–88 and 1997–98) and moderate (2002–03 and 2009–10) El Niño events.

tone, which were used to manufacture explosives. After the war, giant kelp was commercially harvested for use in manufactured livestock and poultry food and as feed for aquacultured abalone. However, the majority of giant kelp harvested from 1929 to 2005 was used to extract algin. Algin is an effective thickening, stabilizing, suspending, and gelling agent and has been utilized in food products, the medical field, as well as industrial and cosmetic industries. Large-scale commercial harvesting of giant kelp in California last occurred in 2005, before ISP Alginates moved their operations overseas, with a harvest of 65,867 wet t (harvest includes other industries). From 2006 to 2013, the reported commercial harvest of giant kelp has remained relatively consistent, averaging 3,510 wet t per year. Reported landings include a nominal amount of bull kelp. Giant kelp harvested during the January 1–December 31, 2013 harvest season was 3,305 t (fig. 33). During this time the majority of giant kelp was harvested from boats using small mechanized harvesters or by hand to provide food for aquacultured abalone. Most of the current commercial giant kelp harvesting ranges from Santa Barbara County to Monterey County. Currently, there is no commercial giant or bull kelp harvest in northern California. Increased harvesting of giant kelp in California is speculated over the next few years due to a renewed interest in commercially harvesting giant kelp for a variety of uses including nutra-

ceutical and cosmeceutical products, as functional food ingredients, and as a biofuel.

The California Department of Fish and Wildlife (Department) has conducted coast-wide (including the offshore Channel Islands) aerial surveys of giant and bull kelp. Aerial surveys were conducted in 1989 and 1999, no surveys occurred in 2000 and 2001. Annual surveys began in 2002, although some years and regions the surveys were not completed due to budget constraints. Geographic Information Systems (GIS) shapefiles of the aerial kelp surveys can be found on the Department webpage (<http://www.dfg.ca.gov/marine/kelp.asp>). Results of the aerial surveys are depicted in Figure 34.

Commercial edible algae harvesting includes a variety of marine algae. Eelgrass (*Zostera*) and surfgrass (*Phyllospadix*) are prohibited from commercial harvest. Edible algae harvest data from logbooks are available from 1997 to 2013; however, specific species and location information did not become available until 2000. In 2013, the total reported commercial harvest of edible algae was 17 t, up slightly from the annual average of 14 t reported from 1997 to 2013 (fig. 35). The commercial harvest of edible algae is regional, with 90% of the harvest occurring along the north coast (Alder Creek in Mendocino County to the California/Oregon border) during 2000–13.

Recreational harvest of giant and bull kelp and other

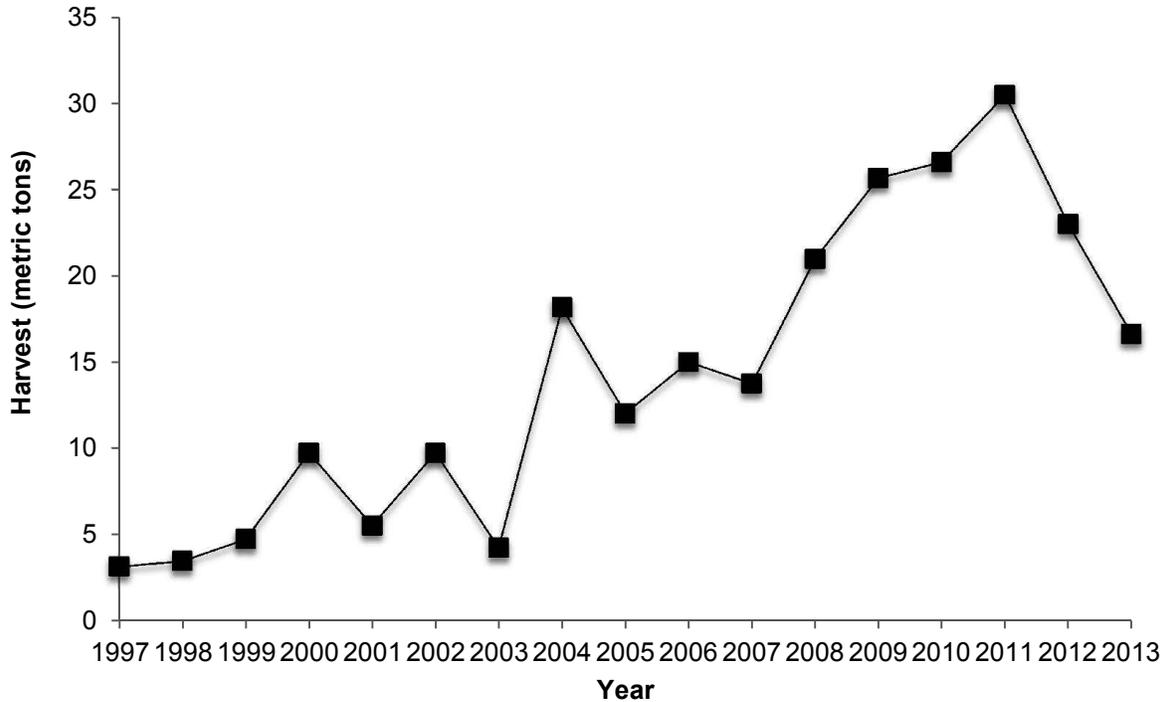


Figure 35. Commercial edible algae harvest logbook data, 1997–2013.

edible algae for personal use is permitted. Those harvesting for personal use must abide by regulations governing the recreational harvest. The daily bag limit for recreational harvesters of marine algae is 4.5 kg wet weight in the aggregate. Recreational harvesters are prohibited from harvesting eelgrass (*Zostera*), surfgrass (*Phyllospadix*), and sea palm (*Postelsia*).

Amendments to the regulations governing the commercial harvest of giant and bull kelp were implemented in 2013. The regulations can be found in CCR, Title 14, §165 and 165.5. These amendments: (a) clarify existing regulations; (b) update administrative kelp bed boundaries to reference coordinates of latitude and longitude; (c) eliminate the development plan requirement for lease holders; (d) require a Commission-approved kelp harvest plan for lease holders and for the mechanical harvest of kelp in all locations where harvest is allowed; (e) require current lease holders to provide additional information to meet the kelp harvest plan requirement; and (f) specify the information required in the kelp harvest plan. The regulation amendments were Phase One of a three phase process. Phase Two will address commercial marine algae license fees and royalty rates. Phase Three will follow with a focus on marine algae management policies including marine algae harvest methods.

### Marine Aquaculture

The California Fish and Game Commission (Commission) have been given the authority to regulate cer-

tain aspects of commercial marine aquaculture on state lands or in state waters, specifically through the Fish and Game Code and Title 14 of the California Code of Regulations. The California Department of Fish and Wildlife (Department) has management responsibility over these aspects of the industry. A major feature of the Fish and Game Code is its provision for the allotment of State tidelands through the Commission. In California, the Department manages 21 state water bottom leases for marine aquaculture, totaling 1,952 acres. Additional marine aquaculture operations occur on granted or privately owned tidelands, adding an addition 3,948 acres for a statewide total of 5,900 acres of water bottoms utilized for marine aquaculture. There are also marine aquaculture facilities established on privately owned uplands along the California coastline. The Department’s management authority also includes the registration of aquaculture facilities and species cultured within the state; the detection, control, and eradication of disease in aquaculture facilities, and the permitting and licensing of aquaculture-related activities, such as stocking, broodstock collection, and importation.

California’s commercial marine aquaculture industry consists of the production of five oyster species, clams, mussels, and abalone. The Pacific oyster (*Crassostrea gigas*), originally from Japan, is the principal species cultured on the West Coast. The Kumamoto oyster (*Crassostrea sikamea*), also from Japan, is the second most popular species grown in California estuaries. The eastern oyster

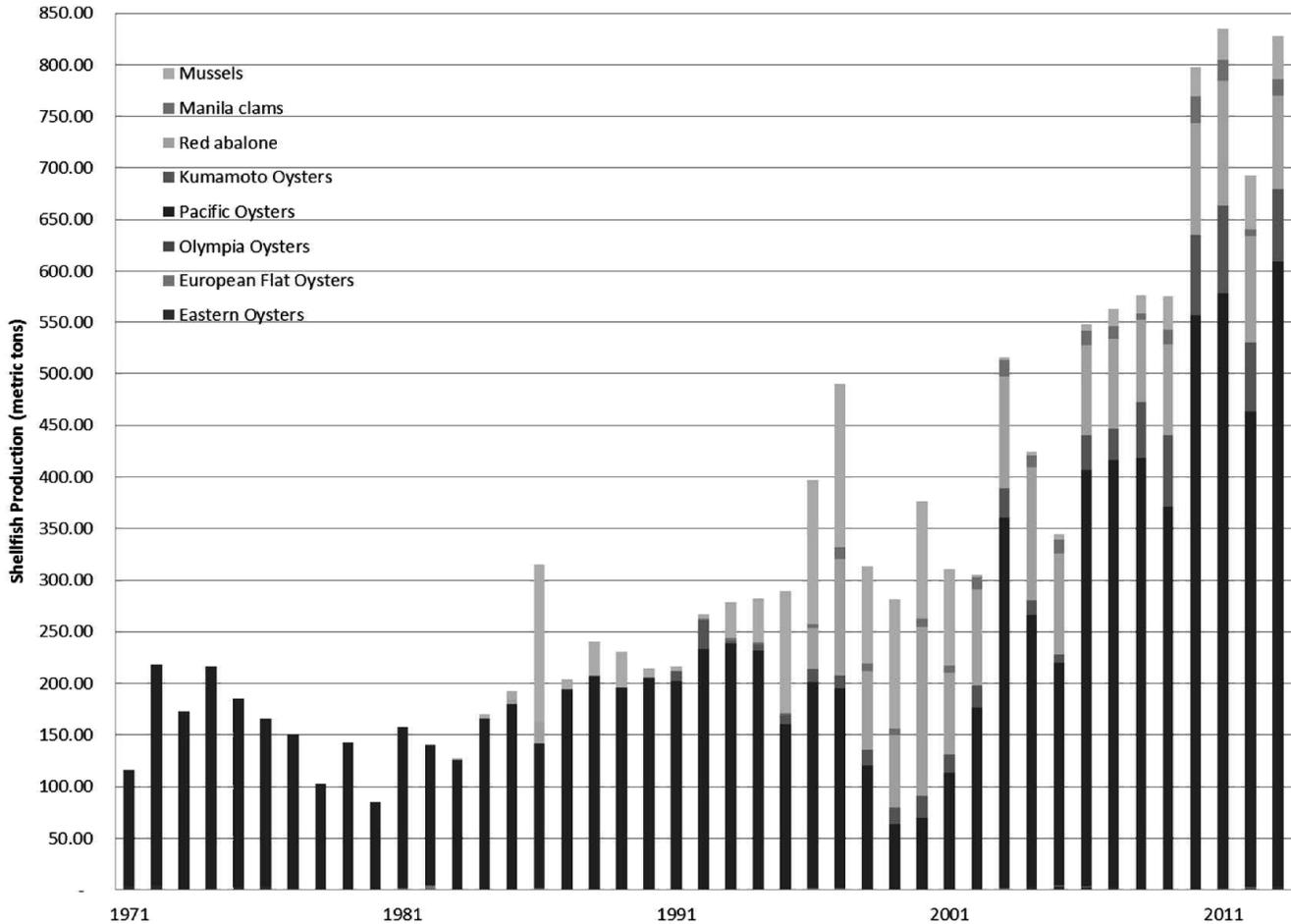


Figure 36. California commercial production of mussels (*Mytilus* spp.), Manila clams (*Venerupis philippinarum*), red abalone (*Haliotis rufescens*), kumamoto oysters (*Crassostrea sikamea*), Pacific oysters (*C. gigas*), Olympia oysters (*Ostrea lurida*), European flat oysters (*O. edulis*), Eastern oysters (*C. virginica*), 1971–2013.

(*Crassostrea virginica*), grown on the Atlantic and Gulf coasts of North America, accounts for most US oyster landings, but is just a small percentage of the oyster production in California. Two species of the genus *Ostrea* are cultivated to a lesser extent. The European flat oyster (*Ostrea edulis*) leads in production for this genus, while the Olympia oyster (*Ostrea lurida*), indigenous to the Pacific coast, has been the least important. Currently, the Manila clam (*Venerupis philippinarum*) is the only clam species grown commercially in California. Most mussel production in California comes from naturally set Mediterranean mussel or bay mussel seed (*Mytilus galloprovincialis* and *M. trossulus*, respectively). However, some growers acquire Mediterranean mussel seed from West Coast hatcheries, the same species that is cultured in Spain and most of Europe. Red abalone (*Haliotis rufescens*) is the mainstay of the commercial abalone industry, grown in either land-based tanks or in cages suspended in the water column.

Shellfish aquaculture is currently centered in nine areas along the coastline; Humboldt Bay, Tomales Bay, Drakes Estero, Santa Cruz, Monterey Bay, San Luis

Obispo, Morro Bay, Santa Barbara, and Agua Hedionda Lagoon. Total shellfish production in 2013 (January through December) had the second highest recorded harvest in the 42 year history of landings, reaching a total of 828.24 t all species combined (fig. 36, table 7). This resulted in a value of \$24.2 million. Compared to 2012, there was a 19% increase in production in 2013, all species combined. The culture of Pacific oysters represented the largest production for the industry, resulting in 73% of the total production, and 70% of the total value in 2013.

**Oysters.** The first commercial oyster beds were established in San Francisco Bay about 1851 when mature native (Olympia) oysters were shipped from Shoalwater Bay, Washington (Willapa Bay), and later from other bays in the Pacific Northwest and Mexico. Market demand for a larger half-shell product stimulated experiments in transporting the Eastern oyster from the Atlantic states to the West Coast. Cool summer water temperatures, however, prevented successful natural reproduction of the Eastern oyster. Soon after comple-

TABLE 7  
 Commercial shellfish production in California (metric tons).

Year	Eastern Oysters	European Flat Oysters	Olympia Oysters	Pacific Oysters	Kumamoto Oysters	Abalone	Clams	Mussels	Total Shellfish
1971	3.11	—	—	112.94	—	—	—	—	116.05
1972	4.01	—	—	214.58	—	—	—	—	218.59
1973	0.64	—	—	172.57	—	—	—	—	173.21
1974	1.22	—	—	215.46	—	—	—	—	216.69
1975	2.19	—	—	182.75	—	—	—	—	184.94
1976	3.36	—	—	162.87	—	—	—	—	166.23
1977	1.49	—	—	149.37	—	—	—	—	150.86
1978	0.23	0.09	—	102.32	—	—	—	—	102.65
1979	0.04	0.21	—	142.80	—	—	—	—	143.05
1980	0.05	0.18	—	84.51	—	—	—	—	84.74
1981	—	1.59	—	156.59	—	—	—	—	158.18
1982	—	4.03	—	136.41	—	—	—	0.02	140.46
1983	—	0.16	—	125.29	—	—	—	1.84	127.29
1984	—	—	—	165.68	—	—	—	4.80	170.48
1985	—	0.09	—	180.28	—	4.54	—	7.49	192.40
1986	—	1.15	—	140.65	0.03	20.10	—	153.01	314.94
1987	—	0.10	—	193.92	0.04	—	—	10.35	204.41
1988	—	0.02	—	207.09	0.10	0.30	—	33.38	240.89
1989	—	0.08	—	195.69	—	0.23	—	34.65	230.65
1990	—	0.48	0	204.82	0.08	—	—	9.75	215.13
1991	0.02	0.61	0.01	202.03	9.31	—	0.04	4.27	216.29
1992	0.05	0.30	0	232.61	28.18	—	1.22	5.14	267.49
1993	0.01	0.86	—	237.53	3.01	0.36	2.04	34.68	278.49
1994	0.32	0.48	—	230.63	6.17	0.60	1.69	42.75	282.64
1995	0.45	0.40	—	159.88	8.32	—	2.54	117.46	289.05
1996	0.61	0.45	—	200.21	12.78	39.62	3.78	139.82	397.28
1997	0.76	0.44	—	193.68	12.87	113.07	11.52	157.53	489.86
1998	0.67	0.08	—	120.01	15.01	76.60	7.08	94.30	313.75
1999	0.36	0.23	—	62.73	16.17	70.76	6.16	125.26	281.68
2000	0.07	—	—	69.57	21.81	163.29	7.72	113.55	376.01
2001	0.08	0.09	—	113.09	17.97	79.12	7.16	93.45	310.95
2002	1.20	0.64	—	174.98	20.57	93.65	11.53	2.93	305.50
2003	0.71	0.87	—	358.61	28.55	108.31	15.89	2.86	515.80
2004	2.00	0.32	—	263.94	14.02	128.98	11.35	3.93	424.54
2005	3.23	0.74	—	216.22	7.54	98.06	13.25	5.20	344.24
2006	2.69	0.15	—	403.95	33.79	87.15	13.60	6.52	547.86
2007	1.96	—	—	414.37	29.91	87.20	12.47	16.84	562.75
2008	0.65	0.04	—	417.24	54.32	80.22	6.07	17.75	576.29
2009	0.84	—	0.03	370.07	69.22	88.05	14.70	32.23	575.14
2010	0.27	—	0.05	556.78	77.96	108.83	25.09	28.40	797.37
2011	0.94	—	0.11	576.77	85.68	120.96	20.16	30.62	835.25
2012	1.86	0.58	—	461.48	66.11	103.86	6.78	52.46	693.13
2013	3.08	0.03	—	606.44	70.28	90.71	15.88	41.82	828.24

tion of the transcontinental railroad in 1869, shipments of Eastern oyster seed were made and transplanted in San Francisco Bay for further growth, marking the beginning of actual oyster raising in California. However, with California's population and industrial growth came a degradation of water quality in San Francisco Bay and by 1939 the last of the San Francisco Bay oysters were commercially harvested.

The commercial oyster industry and California Department of Fish and Game began conducting earlier experimental plantings using the Pacific oyster in Tomales Bay, Elkhorn Slough, Drakes Estero, Bodega Lagoon, and Morro, Newport, and San Francisco bays throughout the 1930s. Several Pacific oyster plantings proved successful, demonstrating that imported Pacific

oyster seed could be grown commercially in California. Oyster culture is now centered on five major growing areas: Humboldt Bay, Tomales Bay, Drakes Estero, Morro Bay, and Agua Hedionda Lagoon.

In 2013 there was the largest production of oysters, 679.83 t worth \$20.6 million. This was a 28% increase in production compared to 2012 (530.03 t). Commercial harvest of oysters averaged 481.57 t over the ten-year period from 2004–13 (fig. 37). In 2013, Humboldt Bay was the leading producer of oysters in California, representing 46% of the total oyster production, all species combined. Humboldt Bay produced 239.50 t of Pacific oysters, the highest production on record for this area since 1971, with a value of \$6.7 million. In addition, 69.96 t of Kumamoto oysters were produced, a slight

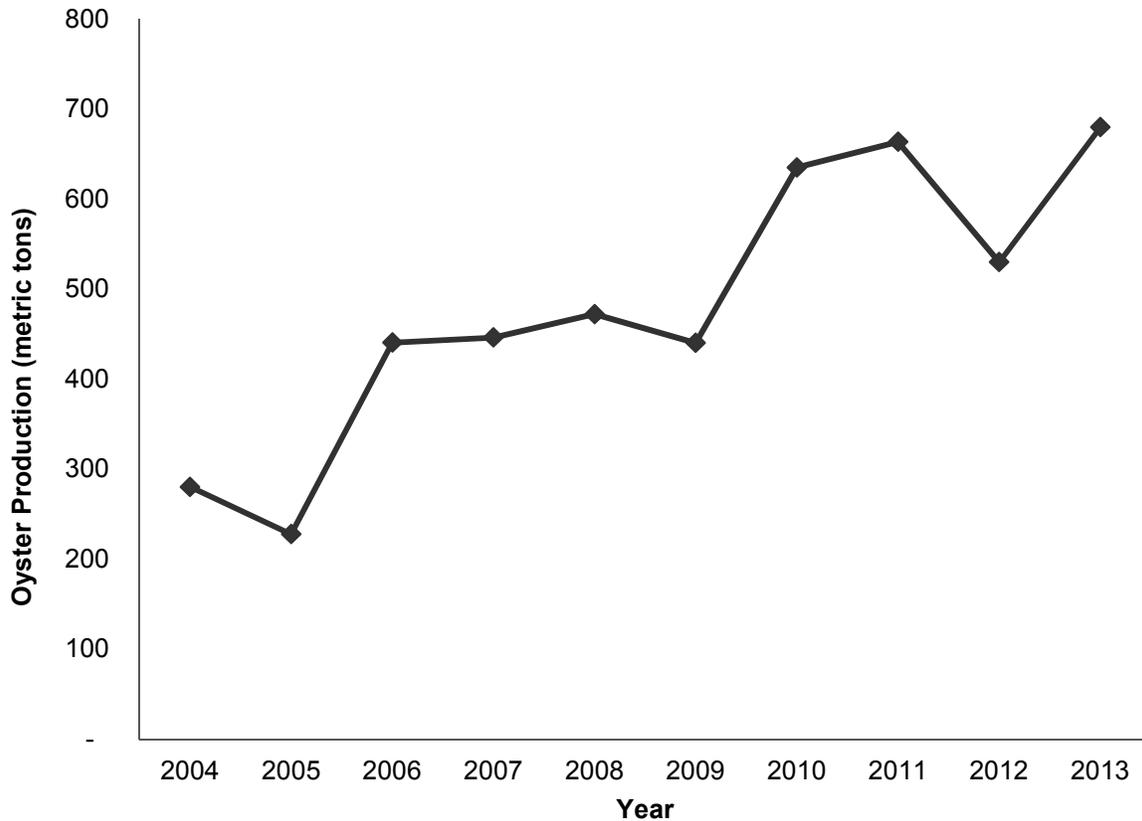


Figure 37. Commercial production of oysters in California, 2004–13.

decrease from a recent peak in 2011, totaling \$3.5 million in value. Pacific oyster production in Tomales Bay reached 158.97 t, \$4.4 million, a 1% decrease from last year's peak. Kumamoto oyster production in Tomales Bay decreased significantly to 0.32 t, a 95% decrease from the high in 2009, representing \$16,400 in value. In addition, Tomales Bay harvested small amounts of Eastern and European flat oysters, 3.08 and 0.03 t, respectively, totaling \$156,000 combined. Pacific oyster production in Drakes Estero reached 188.86 t, the highest production for this area. Value totaled \$5.3 million, a 29% increase compared to the previous year for the estero. Pacific oysters are currently the only species of shellfish grown in Morro Bay and totaled 18.72 t, \$520,800 in 2013, a decline of 24% from a recent peak in 2012 (table 8). Agua Hedionda Lagoon also cultivates Pacific oysters; however, data was unavailable in time for preparation of this report.

**Clams.** The Manila clam was unintentionally introduced to the West Coast with import of Pacific oyster seed in the 1930s, and has since become an important species to the aquaculture industry in California. The culture of clams in California began in 1981, but production levels were relatively low until the mid-1990s. While British Columbia and Washington are the larg-

est commercial producers of adult Manila clams, Humboldt Bay, California, is the leading supplier of clam seed worldwide. Tomales Bay is the only growing area in California to produce adult Manila clams with 15.88 t and \$175,100 in value for 2013.

**Mussels.** Experiments in culturing wild mussel seed stock and in developing hatchery and growout methods in the 1980s have greatly increased the importance of commercial mussel production, particularly the Mediterranean mussel, which occurs primarily in southern and south-central California. A related species, the bay mussel, occurs in northern California and hybrids of the two species are commonly found between Cape Mendocino and Monterey Bay. Tomales Bay, Santa Barbara, and Agua Hedionda Lagoon are the primary growing areas of mussels in California. Santa Barbara produced 32.58 t, \$215,500, and Tomales Bay produced 9.24 t, \$61,100 in 2013. This was a 20% decrease in statewide production of mussels compared to the peak 2012 (52.46 t). Data for mussel production in Agua Hedionda Lagoon was not available in time for preparation of this report.

**Abalone.** Pioneering efforts to mass cultivate abalone in California began about 45 years ago, with a peak in abalone production in 1997. Participation in

**TABLE 8**  
**Production (metric tons) and value of Eastern, European Flat, Pacific, and Kumamoto oysters in California shellfish growing areas for 2013.**

Area	Eastern Oysters			European Flat Oysters			Pacific Oysters			Kumamoto Oysters			Totals		
	Production	Value	% Total	Production	Value	% Total	Production	Value	% Total	Production	Value	% Total	Production	Value	% Total
Drakes Estero	0	\$0.00	0%	0	\$0.00	0%	188.86	\$5,253,466	27.78%	0	\$0.00	0%	188.86	\$5,253,466	27.78%
Humboldt Bay	0	\$0.00	0%	0	\$0.00	0%	239.50	\$6,662,282	35.23%	69.96	\$3,538,210	10.29%	309.46	\$10,200,492	45.52%
Morro Bay	0	\$0.00	0%	0	\$0.00	0%	18.72	\$520,825	2.75%	0	\$0.00	0%	18.72	\$520,825	2.75%
Santa Barbara	0	\$0.00	0%	0	\$0.00	0%	0.39	\$10,859	0.06%	0	\$0.00	0%	0.39	\$10,859	0.06%
Tomales Bay	3.08	\$155,610	0.45%	0.03	\$650	0.00%	158.97	\$4,422,029	23.38%	0.32	\$16,380	0.05%	162.40	\$4,594,669	23.89%
Total	3.08	\$155,610	0.45%	0.03	\$650	0.00%	606.44	\$16,869,461	89.21%	70.28	\$3,554,590	10.34%	679.83	\$20,580,311	100.00%

the industry has declined since that time, which was due in part to disease impacts. However, interest in abalone aquaculture remains high, prompted in part by the closure of the commercial abalone fishery in 1997. Presently, the commercial culture of red abalone occurs in three main coastal areas: Santa Cruz area, Monterey Bay, and San Luis Obispo area. There is a high market demand and price for growing the farmed product and production had been steadily increasing since the decline with a recent peak in 2011 (120.96 t). However, more recent production has experienced a 25% decrease the past couple years, reaching 90.71 t in 2013, totaling \$3.2 million for the industry.

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### ABSTRACT

In 2013, the California current was dominated by strong coastal upwelling and high productivity. Indices of total cumulative upwelling for particular coastal locations reached some of the highest values on record. Chlorophyll *a* levels were high throughout spring and summer. Catches of upwelling-related fish species were also high. After a moderate drop in upwelling during fall 2013, the California current system underwent a major change in phase. Three major basin-scale indicators, the PDO, the NPGO, and the ENSO-MEI, all changed

phase at some point during the winter of 2013/14. The PDO changed to positive values, indicative of warmer waters in the North Pacific; the NPGO to negative values, indicative of lower productivity along the coast; and the MEI to positive values, indicative of an oncoming El Niño. Whereas the majority of the California Current system appears to have transitioned to an El Niño state by August 2014, based on decreases in upwelling and chlorophyll *a* concentration, and increases in SST, there still remained pockets of moderate upwelling, cold water, and high chlorophyll *a* biomass at various

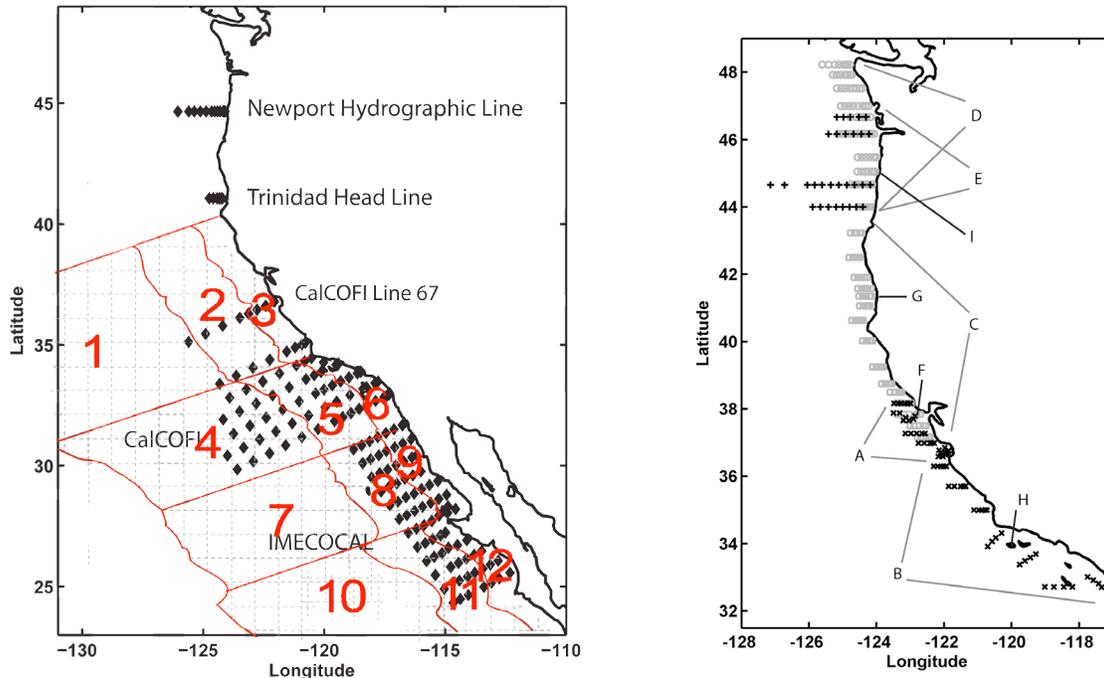


Figure 1. Left: Station maps for surveys that were conducted multiple times per year during different seasons to provide year-round observations in the California Current system. The CalCOFI survey (including CalCOFI Line 67) was occupied quarterly; the spring CalCOFI survey grid extends just north of San Francisco. The IMECOCAL survey is conducted quarterly or semiannually, however, there was no sampling during 2013 due to a changeover in vessels during that year. The Newport Hydrographic Line was occupied biweekly. The Trinidad Head Line was occupied at biweekly to monthly intervals. Right: Location of annual or seasonal surveys, including locations of studies on higher trophic levels, from which data was included in this report. Different symbols are used to help differentiate the extent of overlapping surveys. Red overlay and numbers denotes areas for SST and chlorophyll *a* analysis. A. SWFSC Fisheries Ecology Division (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. NOAA/BPA pelagic rope trawl survey (May through September). F. Southeast Farallon Island. G. Castle Rock. H. San Miguel Island. I. Yaquina Head Outstanding Natural Area.

central coast locations, unlike patterns seen during the more major El Niños (e.g., the 97–98 event). Catches of rockfish, market squid, euphausiids, and juvenile sanddab remained high along the central coast, whereas catches of sardine and anchovy were low throughout the CCS. 2014 appears to be heading towards a moderate El Niño state, with some remaining patchy regions of upwelling-driven productivity along the coast. Superimposed on this pattern, three major regions have experienced possibly non-El Niño-related warming since winter: the Bering Sea, the Gulf of Alaska, and offshore of southern California. It is unclear how this warming may interact with the predicted El Niño, but the result will likely be reduced growth or reproduction for many key fisheries species.

## INTRODUCTION

This report reviews the oceanographic and ecosystem responses of the California Current system (CCS) between spring 2013 and spring of 2014. Biological and hydrographic data from a number of academic, private, and government institutions have been consolidated and described in the context of historical data (fig. 1). The various institutions have provided data and explanation of the data after an open solicitation for contributions;

these contributions are acknowledged in the author list. These data are synthesized here, in the spirit of providing a broader description of the present condition of the CCS. All data are distilled from complex sampling programs covering multiple spatial and temporal scales into simple figures that may not convey the full complexity of the region being studied. As a consequence, we focus on the findings of the data and limit our descriptions of the methodology to only that which is required for interpretation. More complete descriptions of the data and methodologies can be found through links to the individual survey programs. The survey designs that we examine are dissimilar and each has unique limitations restricting a common interpretation within the California Current Large Marine Ecosystem (CCLME). Therefore, this report should be considered a first examination for instigating more focused exploration of potential drivers of the ecosystem dynamics.

This report will focus on data highlighting the conditions during 2013–spring 2014, with a particular emphasis on the evidence that the CCS may be transitioning to El Niño conditions during 2014. New for the report this year, we have moved some of the physical supporting data from this document to an online supplement (<http://www.calcofi.org/ccpublications/ccreports/state->

TABLE 1  
List of CCS indices, their current status, and link to live supplement (e.g., S1 = supplement Figure 1).

Index	Current State	Trend	Implication	Link
PDO	Positive	Increasing	Warming	S1
NPGO	Negative	Decreasing	Low Productivity	S1
ENSO (MEI)	Positive	Increasing	El Niño	S1
Upwelling Anomaly	Negative	Neutral	Warm, low productivity	Fig. 2, S2
Cumulative Upwelling	Neutral	Neutral	Average yearly upwelling	Fig. 3, S3
SST Anomaly	Positive	Increasing	Warm surface waters	Fig. 4, 7, S4, S5
Wind Anomaly	Cyclonic	Anti- to Cyclonic	Warm surface waters	Fig. 4, S5
Temperature-Salinity, CalCOFI	Warmer and Saltier at N Coastal, Surface	NA	Change in transport	S6
Mixed-Layer Salinity, CalCOFI	Positive Anomaly	Decreasing	NA	S7
Mixed-Layer NO <sub>3</sub> , CalCOFI	Negative Anomaly	Neutral	Decreased Productivity	S7
Nitricline Depth, CalCOFI	Negative Anomaly	Decreasing	Decreased productivity	S7
Integrated chlorophyll <i>a</i> , CalCOFI	Neutral	Neutral	Similar to long-term mean	S8
Integrated PP, CalCOFI	Positive Anomaly	Increasing	Possibly higher productivity	S8
Zooplankton Volume, CalCOFI	Positive Anomaly	Increasing	Increased secondary production	S8
Chlorophyll <i>a</i> Profiles, CalCOFI	High in Coastal North	NA	Increased productivity	S9
Chlorophyll <i>a</i>	Negative	Decreasing	Low productivity	S10

of-the-current.html). The goal is to create a “live” State of the California Current (SOTCC) web page resource, where information can be rapidly obtained as to the most recent, up-to-date state of the CCS. As a result, several long-term time series of physical climate that have traditionally been found within this document have been replaced by a table stating only their current state, along with a link to the appropriate web page. As in past reports, we begin with an analysis of large-scale climate modes and upwelling conditions in the California Current. Following, the various observational data sampling programs are reviewed to highlight the links between ecosystem structure, processes, and climate. Lastly, a short synthesis/discussion of the most recent conditions within the CCS and the potential implications of the looming El Niño are presented.

### NORTH PACIFIC CLIMATE INDICES

The winter of 2013–14 marked a transition of a cool phase in the North Pacific as indicated by the Pacific Decadal Oscillation index (table 1, PDO; Mantua and Hare 2002) and strong California Current strength with associated high nutrient levels as indicated by the North Pacific Gyre Oscillation (table 1, NPGO; Di Lorenzo et al. 2008) index. The PDO switched to positive values in January 2014 after four years of continuous negative values, while the NPGO switched to negative values in October 2013 after seven years of continuous positive values (online supplement, fig. S1). These transitions are likely due to variations in the strength of the Aleutian Low pressure system in the winter, which is highly influenced by the onset of El Niño events (Bjerknes 1966; Trenberth and Hurrell 1994). The multivariate El Niño Southern Oscillation (ENSO) index (MEI; Wolter and Timlin 1998) transitioned from neutral La Niña conditions in 2013 to positive values in April 2014. The April

value (0.93) of the MEI was slightly less than the maximum value experienced in the short-lived El Niño event in the winter of 2010 (MEI value of 1.5 for February 2010) (fig. 2). The NINO3.4 index (which is the SST anomalies averaged over 5°S–5°N and 120°W–170°W; <http://www.cpc.ncep.noaa.gov/data/indices/wksst8110>. for) indicated El Niño conditions, as values greater than 0.5°C were reached during May 2014 with an anomaly of 0.6°C. The September NINO3.4 values were just at the threshold indicating an El Niño event and were much lower than the anomalies at the height of the 1997–98 El Niño event, which had anomalies over 2.5°C. However, short-term forecasts suggest that a weak El Niño event may be imminent ([http://www.cpc.ncep.noaa.gov/products/analysis\\_monitoring/enso\\_advisory/ensodisc.html](http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/enso_advisory/ensodisc.html)).

### Upwelling in the California Current

Monthly means of daily upwelling index (Bakun 1973; Schwing et al. 1996) indicated downwelling conditions from October to December of 2012 for areas north of 33°N. The downwelling quickly switched to strong upwelling (values >50 m<sup>3</sup> s<sup>-1</sup> per 100 m) in January 2013 (fig. 2). The anomalies of the upwelling index showed strong upwelling relative to long-term means (anomaly values >50 m<sup>3</sup> s<sup>-1</sup> per 100 m) during 2013 especially in January, April, July and December for latitudes between 36° and 48°N. The positive upwelling anomalies (calculated from monthly means for 1967–2013) continued into January 2014, but since February 2014 upwelling has been near the climatological mean. The cumulative upwelling index (CUI) provides an estimate of the net influence of upwelling on ecosystem structure and productivity over the course of the year (Bograd et al. 2009). For all latitudes the CUI for 2013 was one of the highest over the past 40 years and was

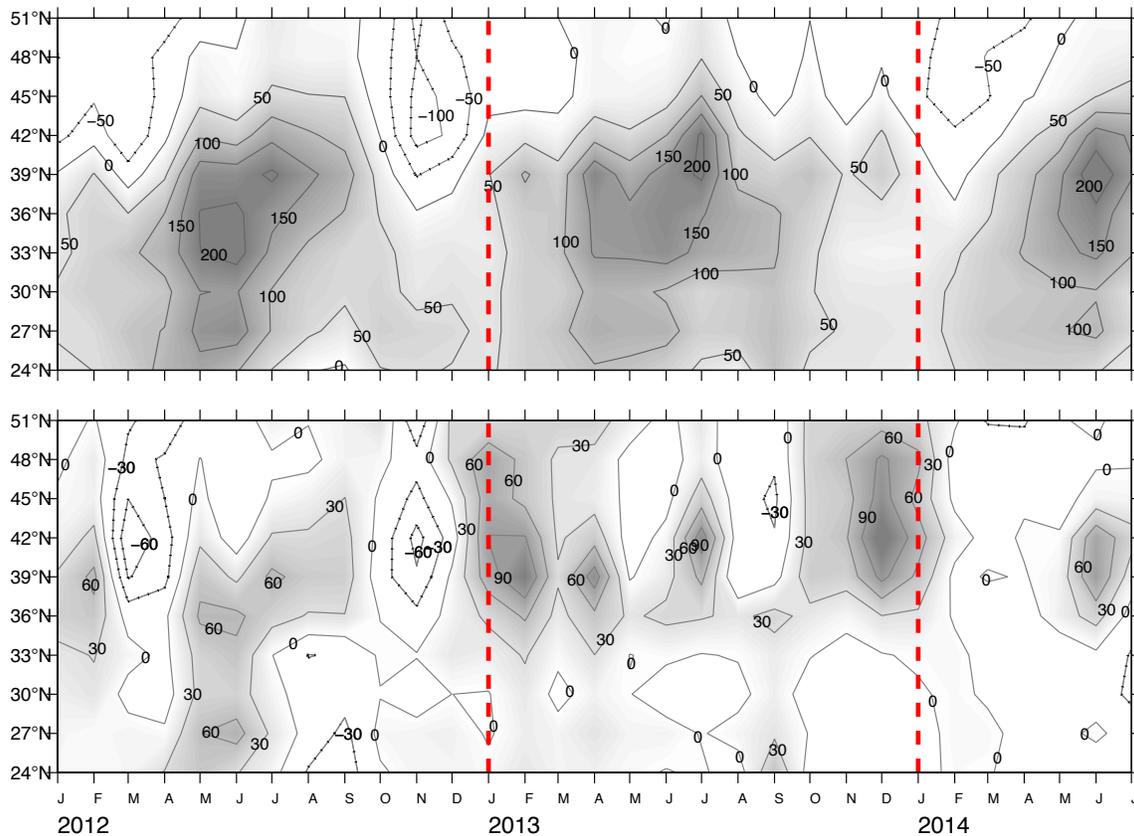


Figure 2. Monthly means of daily Bakun Upwelling Index (top) and anomalies (bottom) for January 2012–July 2014. Shaded areas denote positive (upwelling-favorable) values in upper panel, and positive anomalies (generally greater than normal upwelling) in lower panel. Anomalies are relative to 1967–2013 monthly means. Units are in  $\text{m}^3 \text{s}^{-1}$  per 100 m of coastline. Daily upwelling index data obtained from <http://pfeq.noaa.gov/products/PFELData/upwell/daily>.

the highest on record for latitudes  $39^{\circ}$ – $48^{\circ}$ N (fig. 3). In 2014 the CUI was high during mid to late January, especially for the northernmost latitudes, but soon dropped towards the long-term mean by the end of May.

### North Pacific Climate Patterns

A basin-scale examination of SST allows for the interpretation of the spatial evolution of climate patterns and wind forcing over the North Pacific related to trends in the basin-scale and upwelling indices (figs. 2, 3). In the summer of 2013, predominantly positive SST anomalies (calculated from a climatology based on 1950–79) less than  $0.5^{\circ}\text{C}$  extended over most of the North Pacific, with the highest anomalies of  $1^{\circ}\text{C}$  occurring in the Northeast Pacific (fig. 4). These high temperatures were concurrent with anticyclonic wind anomalies which result in increased alongshore upwelling producing winds and negative SST anomalies along the Oregon and Washington coast. The same pattern extended into December 2013 with increased SST ( $> +2.0^{\circ}\text{C}$ ) anomalies in the Northeast Pacific with increased anticyclonic wind anomalies, resulting in strong upwelling along the US West Coast and negative SST ( $-1.0^{\circ}\text{C}$ ) anomalies. In

February 2014, these high SST anomalies persisted while the area of highest anticyclonic wind anomalies dropped from  $\sim 40^{\circ}$ N in July and December of 2013 to  $\sim 30^{\circ}$ N. The wind anomalies for February 2014 (calculated from a climatology based on 1968–96) also show a cyclonic pattern in the northeast Pacific due to a deepening of the Aleutian Low pressure system. In May 2014, positive SST anomalies ( $> 1.0^{\circ}\text{C}$ ) extended across the Equatorial Pacific and along the West Coast of North America from Alaska to Mexico, with the exception of a narrow band of coastal waters (within 60 miles offshore) off of central and northern California, where strong upwelling winds kept the ocean cool and productive through May and June of 2014 (not shown in fig. 4).

### Coastal Sea Surface Temperature

In 2013, the daily January through April SST, as measured by National Data Buoy Center (NDBC) buoys, were lower than the climatological mean (based on the total time series for each individual buoy; see: <http://www.ndbc.noaa.gov> for specific details) for all buoys along the West Coast from Oregon (northernmost location 46050:  $44.639^{\circ}$  N  $124.534^{\circ}$  W) to south-

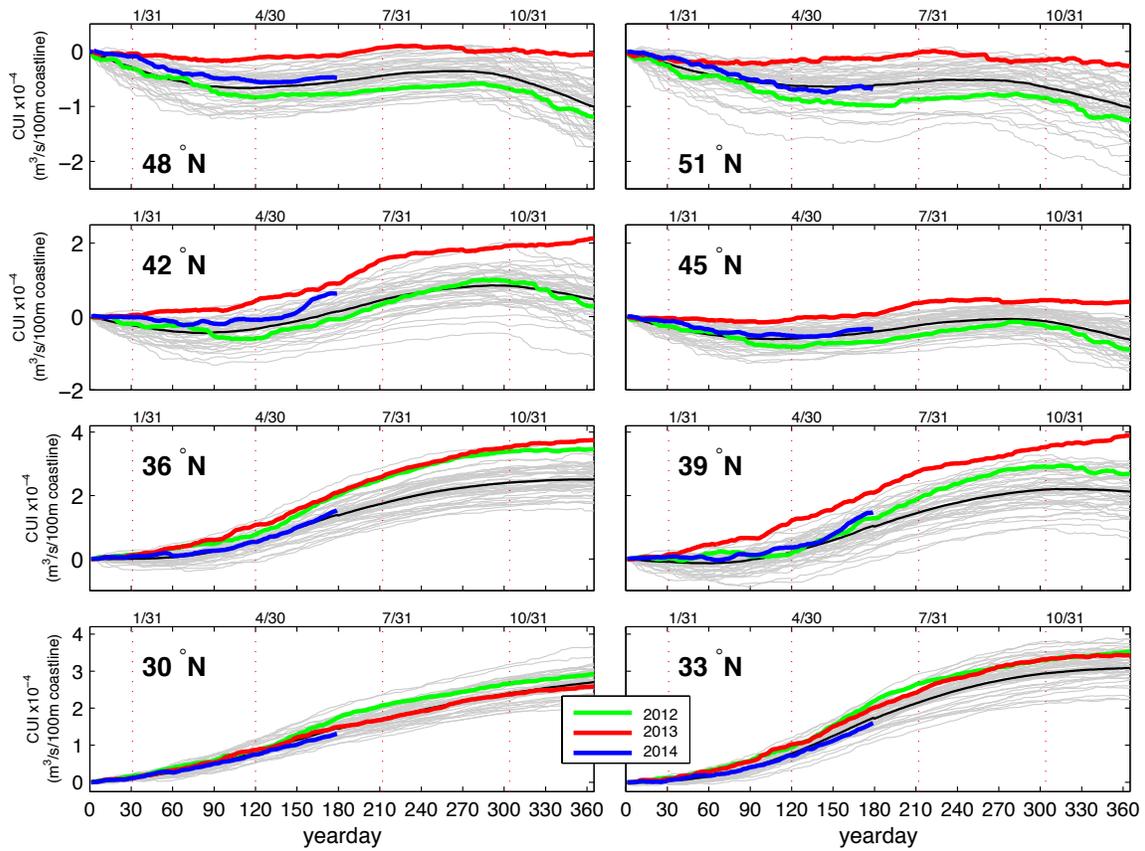


Figure 3. Cumulative upwelling index (CUI) from January 1 calculated from the daily Bakun Upwelling Index at locations along the West Coast of North America for 1967–2013 (grey lines), the mean value for the period 1967–2011 (black line), 2012 (green line), 2013 (red line), and 2014 (blue line). The red dashed vertical lines mark the end of January, April, July and October.

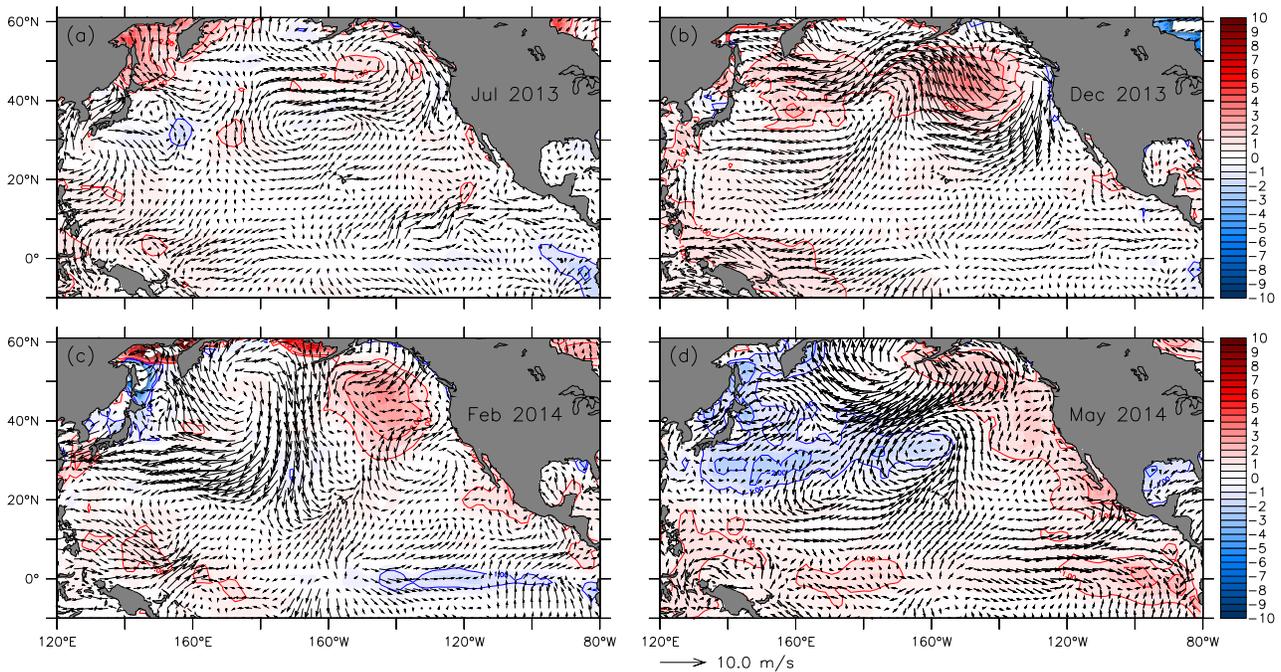


Figure 4. Anomalies of surface wind velocity and sea surface temperature (SST) in the North Pacific Ocean, July 2013, December 2013, February 2014, and May 2014. Arrows denote magnitude and direction of wind anomaly (scale arrow at bottom). Contours demote SST anomaly. Shading interval is 0.5°C and contour intervals of  $\pm 1$  and 2°C are shown. Negative (cool) SST anomalies are shaded blue. Wind climatology period is 1968–96. SST climatology period is 1950–79. Both SST and wind data are from NCEP/NCAR Reanalysis and were obtained from <http://www.esrl.noaa.gov>.

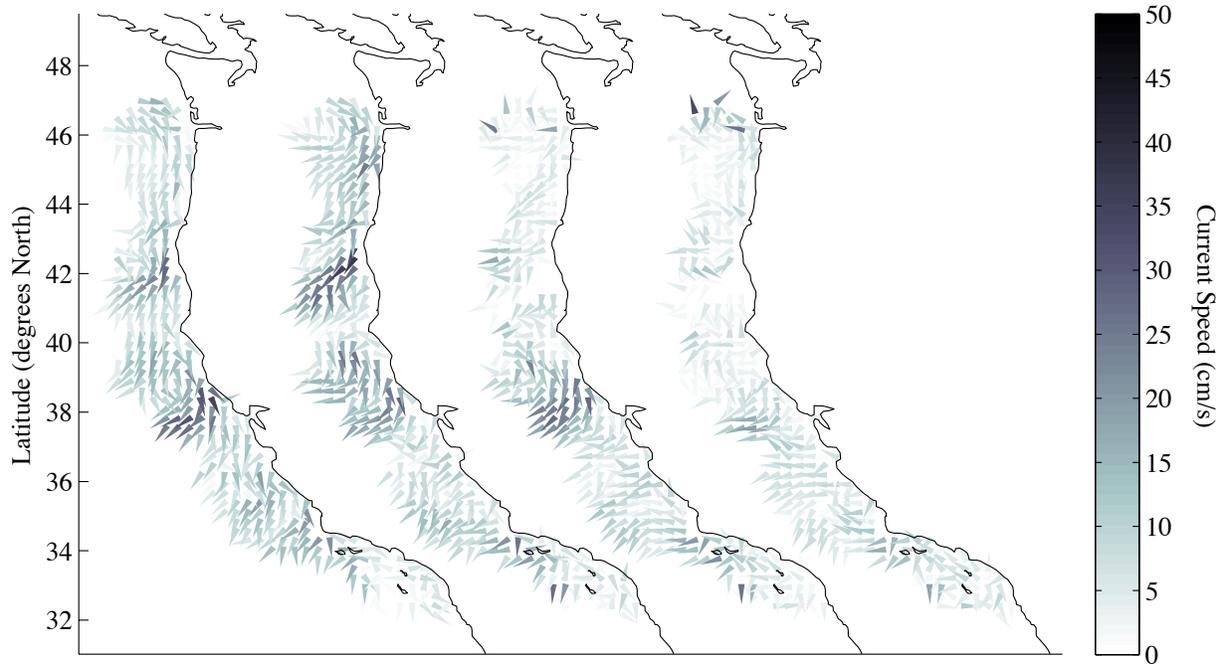


Figure 5. Mean maps of HF-radar surface currents observed quarterly throughout the CCS. From left to right, the panels present data for spring (March–May), summer (June–August), fall (September–November), and winter (December–February). Current speed is indicated by shading and direction given by orientation of arrow extending from observation location. For clarity, currents are displayed with spatial resolution of 30 km.

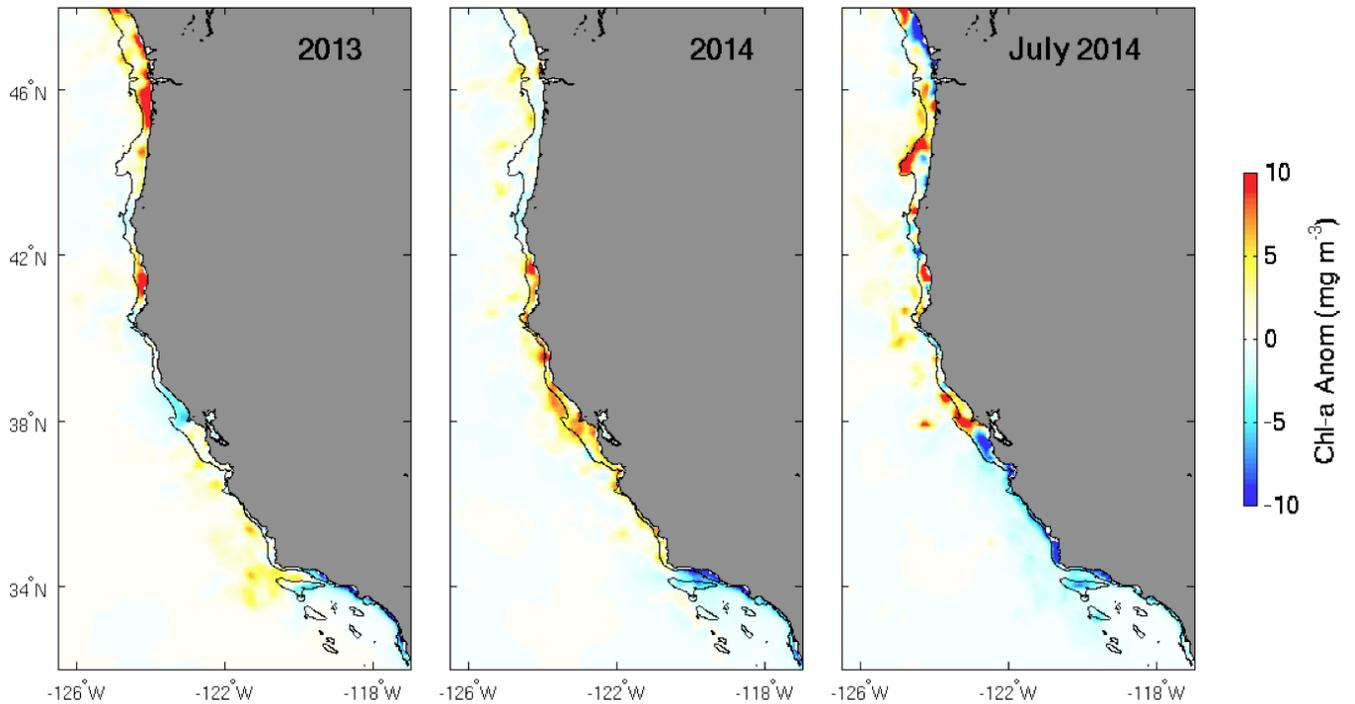


Figure 6. Chlorophyll a anomaly from Aqua MODIS, monthly composite (0.1 deg x 0.1 deg grid). Monthly climatology based on 2002–July 2014. 2013 March–May average anomaly (left panel), March–May 2014 average (center), and Jul 2014 only average (right panel).

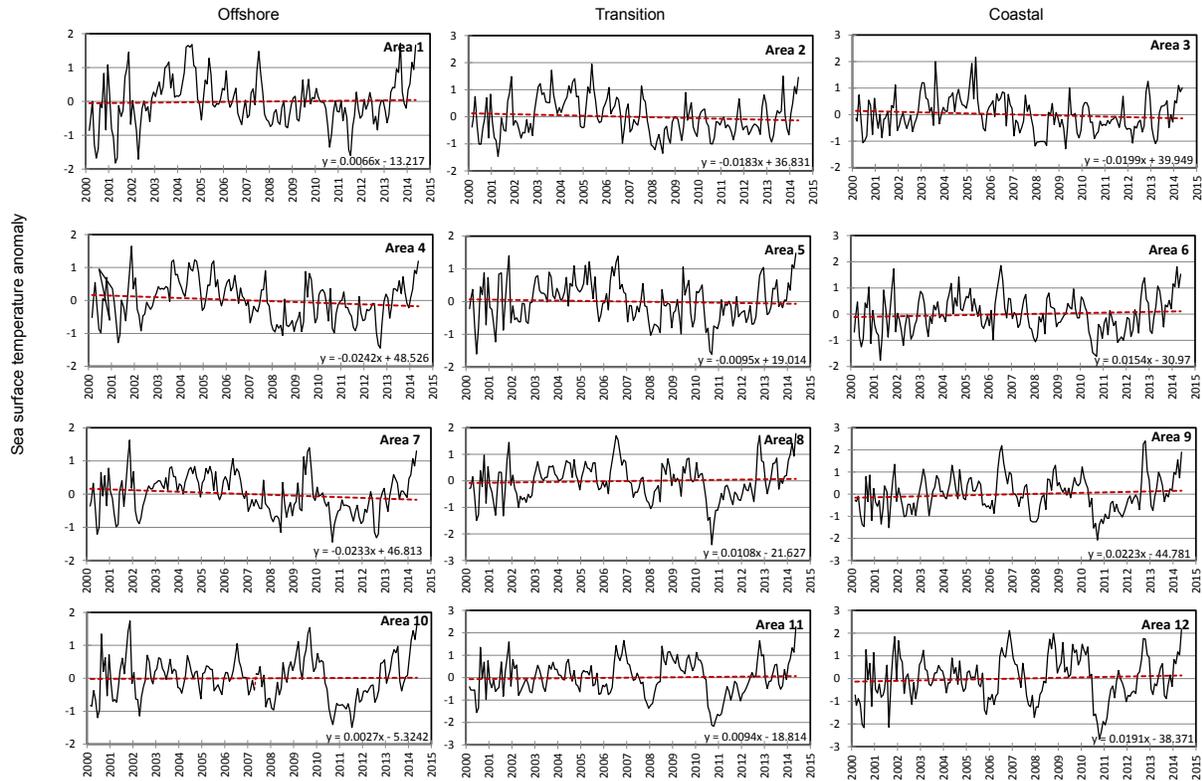


Figure 7. Time series of monthly mean SST anomaly ( $^{\circ}\text{C}$ ; black line) on the grid of  $3 \times 4$  regions (fig. 1a red numbered grid). Monthly anomalies relative to the monthly means were calculated as the difference from the monthly mean. Red dashed line indicates long-term trend (mean and slope given in lower right hand corner of each panel).

ern California (southernmost location 46025: 33.749 N 119.053 W; supplement fig. S4). The cool SST in these months was associated with periods of strong southward winds driving upwelling (winds were typically at or very near 1 Standard Error level of the biharmonic annual climatic cycle; fig. S4). Warm SST were observed in June and August–September in locations north of San Francisco due to a reversal in the southward winds. By November 2013, winds were once again stronger southward than the climatological mean and SST in the north were low. In early 2014, SST were average to warmer than the climatological mean for all regions and all months except for the two most northern buoys (46050: 44.639 N 124.534 W, and 46027: 41.850 N 124.381 W), which experienced low SST in January and February due to the slackening of the northward winds in this region.

### HF Radar Surface Current Observations

During 2013–14, surface currents observed were predominantly southward through spring, summer, and fall, with weak northward flows during winter in the southern and northern parts of the domain (fig. 5). While anomalous southward flows were persistent off Oregon during fall in 2013 (Sep–Nov), an equally anomalous northward flow was observed during the fall just north

of Point Conception. The strong offshore flows ( $>30 \text{ cm s}^{-1}$ ) that are typically associated with headlands are most marked immediately off Point Arena ( $37^{\circ}$ – $39^{\circ}\text{N}$ ), and unusually, persisted through the 2013–14 winter. Also, south of Cape Blanco ( $41^{\circ}$ – $43^{\circ}\text{N}$ ), the offshore jet that typically develops during the upwelling season was stronger and more persistent than in other years (Wells et al. 2013; Bjorkstedt et al. 2012). Further south in the winter, a broad offshore flow was observed between Point Conception and Monterey Bay ( $34^{\circ}$ – $37^{\circ}\text{N}$ ), associated with convergence between southward flows to the north and northward flows to the south.

### Satellite-Derived Surface Chlorophyll *a* and Temperature

Springtime 2013 anomalies (based on a monthly climatology measured by the Aqua MODIS satellite from 2002–May 2014) of chlorophyll *a* (March–May average) were high for most of the nearshore region, except for northern California (fig. 6). In contrast to 2013, the chlorophyll *a* anomalies during springtime 2014 were high for central California, but low in southern California and Oregon/Washington coast (fig. 6). By July 2014, this pattern had changed, with anomalously high values found in small patches from San Francisco Bay to Vancouver, with some low regions in between. The entire

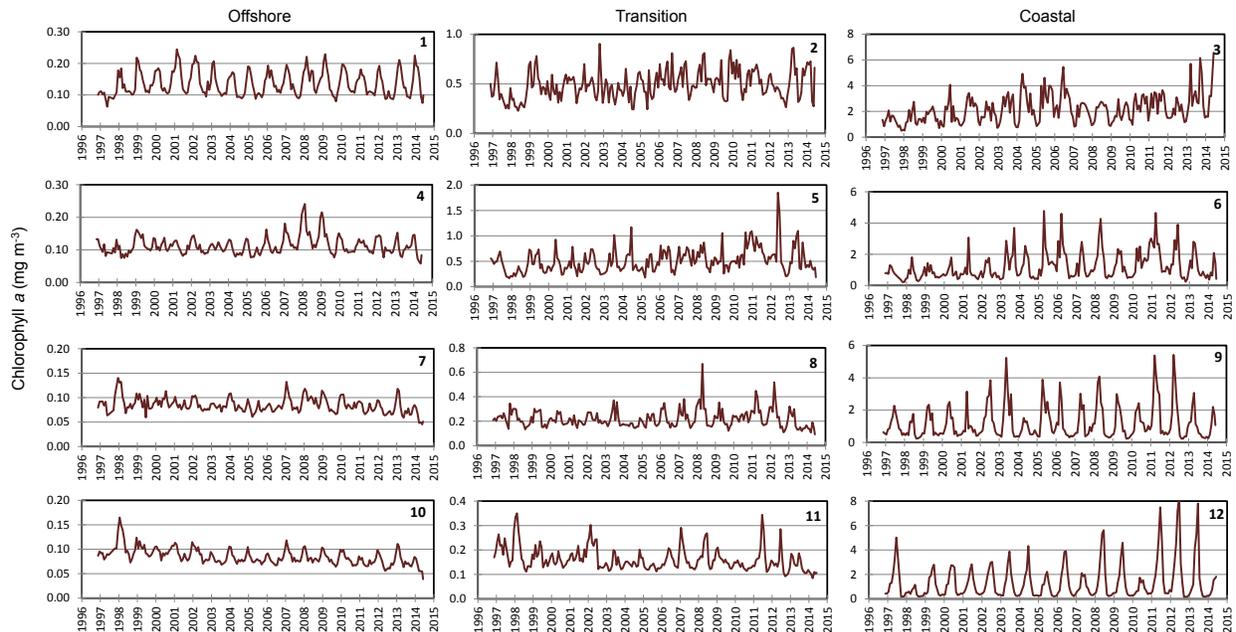


Figure 8. Time series of the monthly mean chlorophyll *a* merged from multiple satellite sensors (OCTS, SeaWiFS, MERIS, MODISA) on the grid of 3 x 4 regions (fig. 1a red grid).

southern portion of the nearshore region had anomalously low chlorophyll *a* levels (fig. 6).

Previous analysis of satellite-detected time series of surface chlorophyll *a* concentration (chlorophyll *a*, mg m<sup>-3</sup>) in the California Current region from late 1996 to the end of 2011 (Kahru et al. 2012) showed a statistically significant increasing trend of chlorophyll *a* in the coastal upwelling region of central California and significant decreasing trends of chlorophyll *a* in the central North Pacific gyre and off southern Baja California.

SST and satellite-detected surface chlorophyll *a* concentration (mg m<sup>-3</sup>) was estimated from multiple ocean color sensors (OCTS, SeaWiFS, MERIS, MODIS-aqua) using empirical algorithms tuned to in situ measurements from the California Current (primarily CalCOFI and CCE-LTER; Kahru et al. 2012)<sup>1</sup>. Monthly anomalies relative to the monthly means were calculated as the ratio to the monthly mean for chlorophyll *a* or as the difference from the monthly mean for SST. The ratio anomaly was expressed as percentage anomaly with 100\*(Anomaly - 1).

Warming was evident from the beginning of 2014 with SST anomalies up to +2°C at the beginning of

June 2014 (fig. 7). SST anomalies were the weakest (+1°C) in the coastal region of central California (area 3, fig. 1 left panel). The approximately 18-year time series of surface chlorophyll *a* (fig. 8) shows spatially different trends. Correlated with the recent warming, chlorophyll *a* anomalies (fig. 9) turned negative approximately from the middle of 2013 in all areas except the coastal upwelling region of central California where they stayed positive. As a result, in the beginning of June of 2014, eleven regions had negative chlorophyll *a* anomalies and only one had a positive chlorophyll *a* anomaly.

## REGIONAL ECOSYSTEM INDICATORS

### Northern California Current: Oregon (Newport Hydrographic Line<sup>1</sup>)

The winter of Dec 2012–Mar 2013 was quite mild with no large southwesterly storms, resulting in bottom waters on the midshelf that were colder and saltier than normal (saltiest and second coldest since 1997; not shown) at the baseline station (NH-5) off Oregon (45°N). These conditions continued during the spring (April–June) of 2013 when the second coldest temperature and third highest salinity values were observed since 1997 (fig. 10). The other “cold and salty” years were 2007 and 2008.

The day of spring transition in 2013 (based on the Cumulative Upwelling Index–CUI, fig. 3 45°N panel) was on 7 April, which was six days earlier than average (40-year climatology). Despite the near-average date of transition, upwelling continued to be weak through most

<sup>1</sup>After the end of data transmission from MERIS in April 2012, estimates of chlorophyll *a* are based solely on MODIS-aqua (MODISA) data. SST data were merged from MODISA and MODIS-Terra sensors from 2000 to end of May, 2014. Time series of monthly mean chlorophyll *a* were created on a grid of 3 by 4 areas (fig. 1, red grid) from offshore (~ distance from coast 300–1000 km) through transition zone (100–300 km from coast) to coastal zone (0–100 km from coast), and from north to south as central California (areas 1–3), southern California (areas 4–6), northern Baja California (areas 7–9) and southern Baja California (areas 9–12), following Kahru and Mitchell (2001) and Lynn and Simpson (1987).

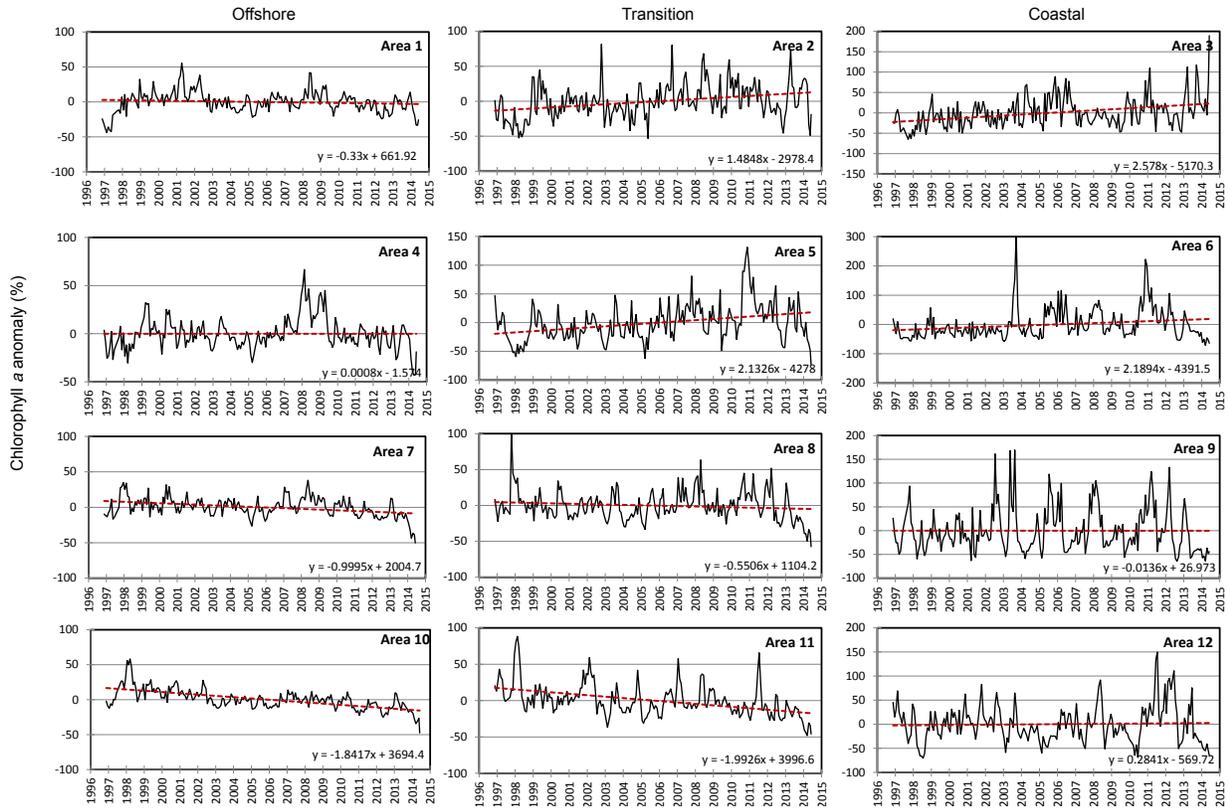


Figure 9. Time series of monthly chlorophyll a anomaly (%) on the grid of 3 x 4 regions (fig. 1a red numbered grid). Monthly anomalies relative to the monthly means were calculated as the ratio to the monthly mean. The ratio anomaly was expressed as percentage anomaly with  $100(\text{Anomaly} - 1)$ . Red dashed line indicates long-term trend (mean and slope given in lower right hand corner of each panel).

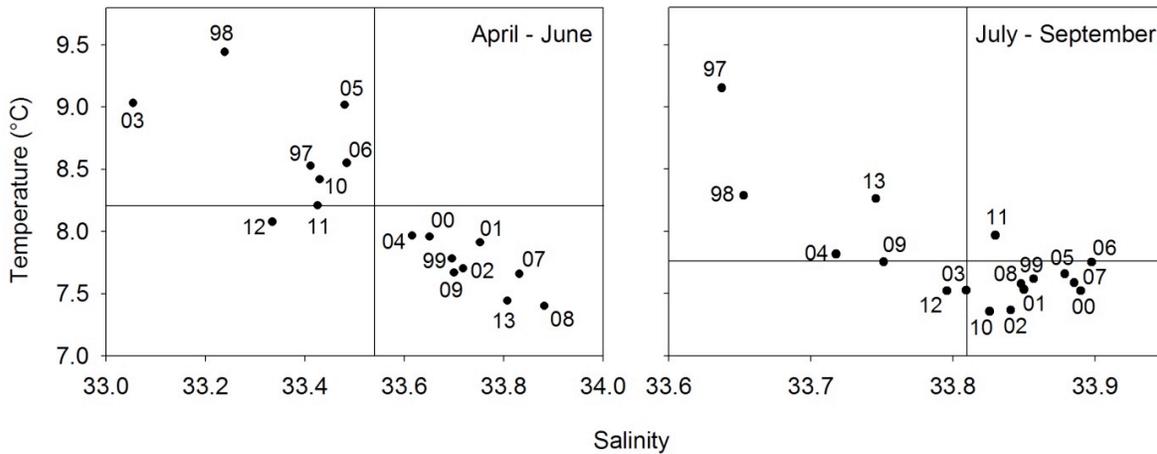


Figure 10. Seasonal mean temperature and salinity at 50 m depth at station NH-5 (Latitude: 44.6517 N Longitude: 124.1770 W) along the Newport Hydrographic Line for spring (left panel) and summer (right panel). Note changes in scale on both temperature and salinity axes. Numbers next to points indicate year of observations.

of May and June 2013, including a two-week period in mid-June of northeastward winds which resulted in warmer than average temperatures in July (fig. 11). Although the total upwelling from May–Sept was nearly the same as the 16-year average, most of the upwelling occurred during July through mid-August. Upwelling effectively ended in mid-September, three weeks earlier

than climatology. The average temperature and salinity during the summer (July–Sept) were warm and fresh, respectively, compared to the typical values for this season, ranking the third and fourth warmest and freshest water observed during the upwelling season since 1997 (fig. 10). In fact, deep waters in summer 2013 were very similar to the 1998 El Niño event.

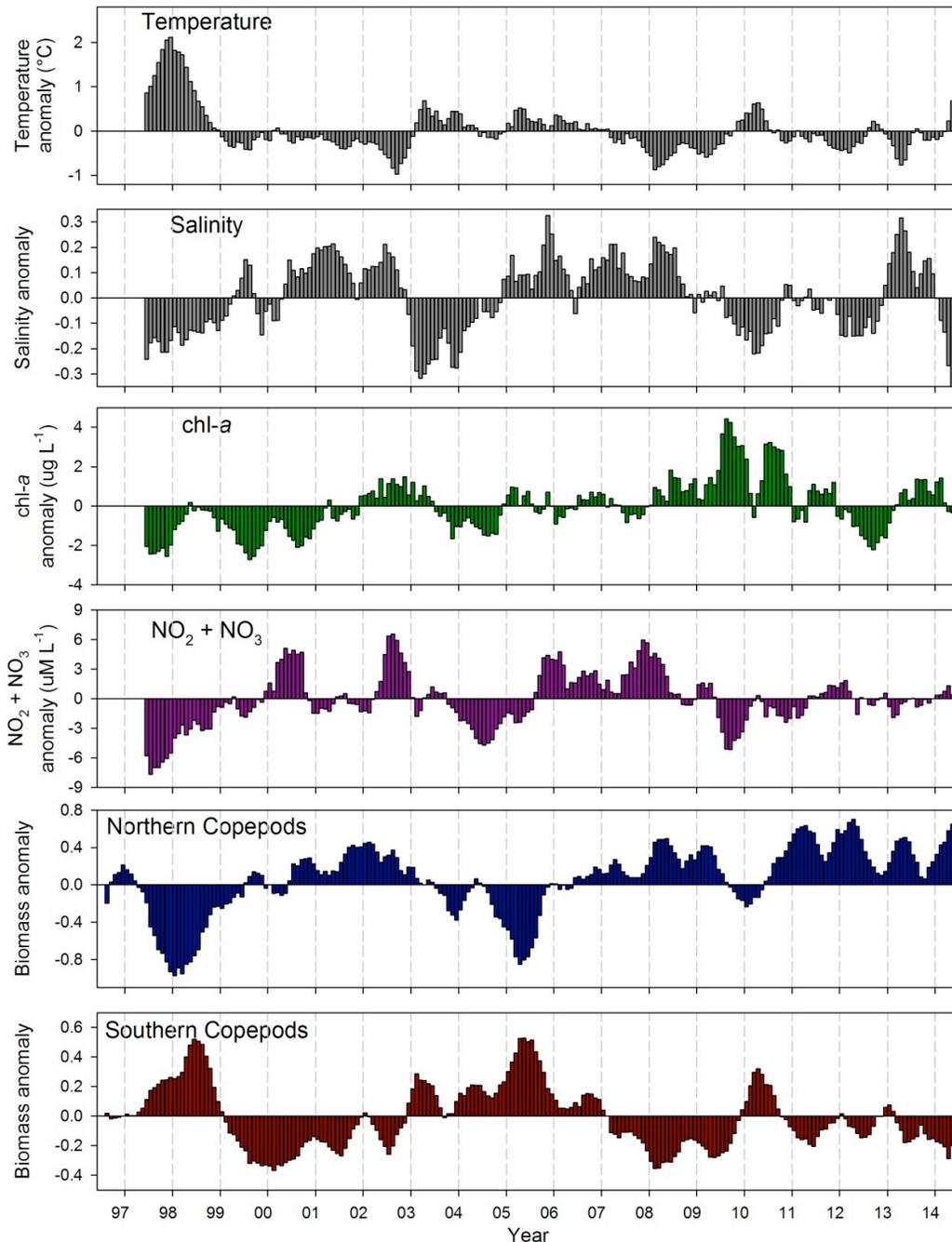


Figure 11. Time series plots of local physical and biological anomalies (monthly climatology removed) from 1997–present at NH-5 (Latitude: 44.6517 N Longitude: 124.1770 W) along the Newport Hydrographic Line. Temperature and salinity from 50 m, chlorophyll a and NO<sub>2</sub> + NO<sub>3</sub> from the surface and copepod biomass anomalies are integrated over the upper 60 m. All data were smoothed with a 7-month running mean to remove high frequency variability.

As for the copepods, during winter (Nov 2012–March 2013), the biomass of southern (“warm water”) copepods was moderately high (fig. 11) compared to values from 2011–mid 2014, in correspondence with positive values of the Oceanic Niño Index during autumn 2012–winter 2013. In the spring (April–June) of 2013, the biomass of southern copepods was less than average and the biomass of northern (“cold water”) copepods

increased dramatically and remained high throughout the summer upwelling period (fig. 11). This increase in northern copepods was consistent with observations of high biomass of these boreal species since 2011 throughout the year, and generally followed strongly negative values of the PDO. However, the PDO during 2013 was only moderately negative yet northern copepod biomass was high.

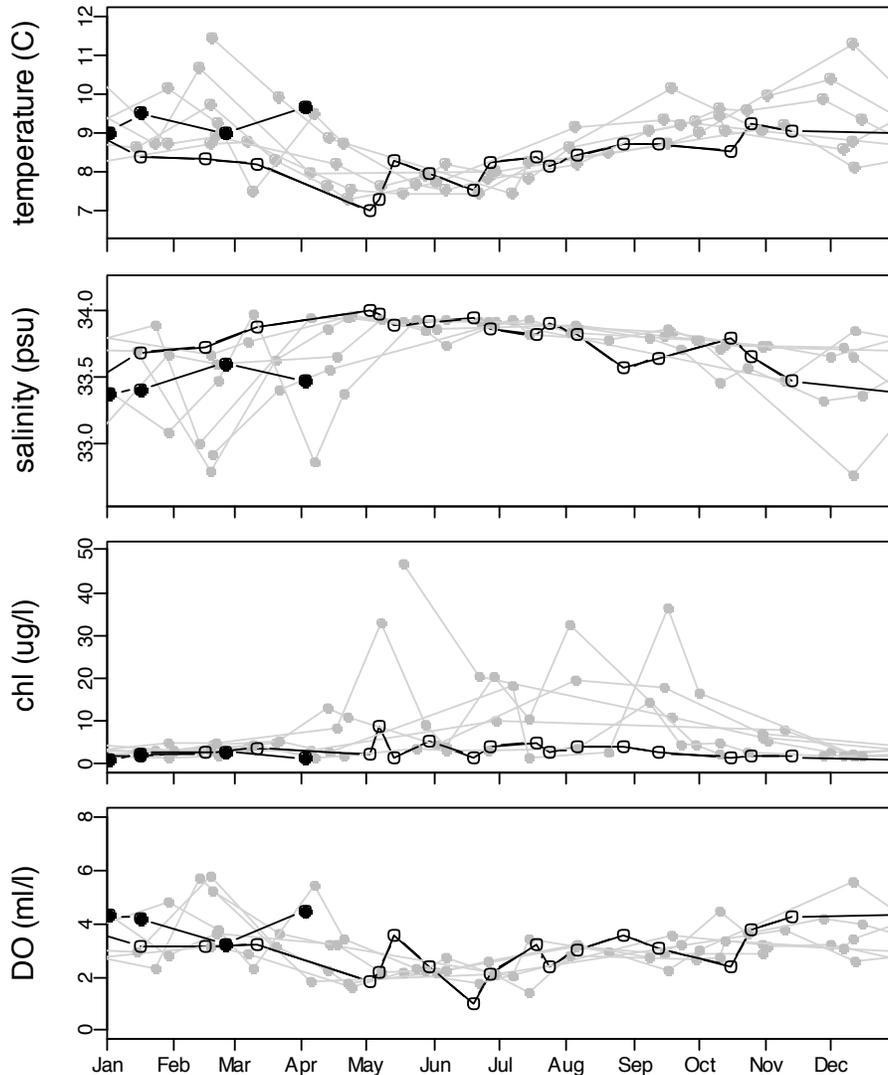


Figure 12. Hydrographic and ecosystem indicators at midshelf along the Trinidad Head Line (station TH02; 41°03.5' N, 124°16' W, 75m depth). Panels from top to bottom show near-bottom (60 m) temperature, near-bottom (60 m) salinity, mean chlorophyll *a* concentration over the upper 30 meters of the water column, and near bottom (60 m) dissolved oxygen concentrations. Grey symbols indicate historical observations (2006–12), unfilled circles indicate observations during 2013, and filled symbols indicate observations in 2014.

As we entered 2014, storms (which likely are reflected in the higher than average CUI values) were more frequent in winter compared to 2013, but similar to climatology. Average T-S values of deep shelf water at NH05 for the Jan–Mar 2014 period were near the long-term mean values (9.34°C and 32.8). Other aspects of ocean conditions in 2013 along with our forecasts of salmon returns can be seen at <http://www.nwfsc.noaa.gov> by selecting “Salmon Forecasts.”<sup>2</sup>

Copepod data were based on samples collected with a 0.5 m diameter ring net of 202 µm mesh, hauled from

<sup>2</sup>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/fe/estuarine/oeip/ka-hydrography-zoo-ichthyoplankton.cfm>.

near the bottom to the sea surface. A TSK flowmeter was used to estimate distance towed.

### Trinidad Head Line, Northern California

Temperature and salinity near the seafloor at midshelf were generally consistent with strong upwelling throughout much of the spring and early summer in 2013, and especially with consistent, strong southward winds that persisted throughout much of April and into June 2013 (fig. 12). Despite this strong upwelling, chlorophyll *a* concentrations remained relatively low over the shelf, possibly due to offshore advection or intense grazing. Dissolved oxygen reached the lowest levels observed in the 9-year time series in mid-June.

Observations of low dissolved oxygen (DO) over

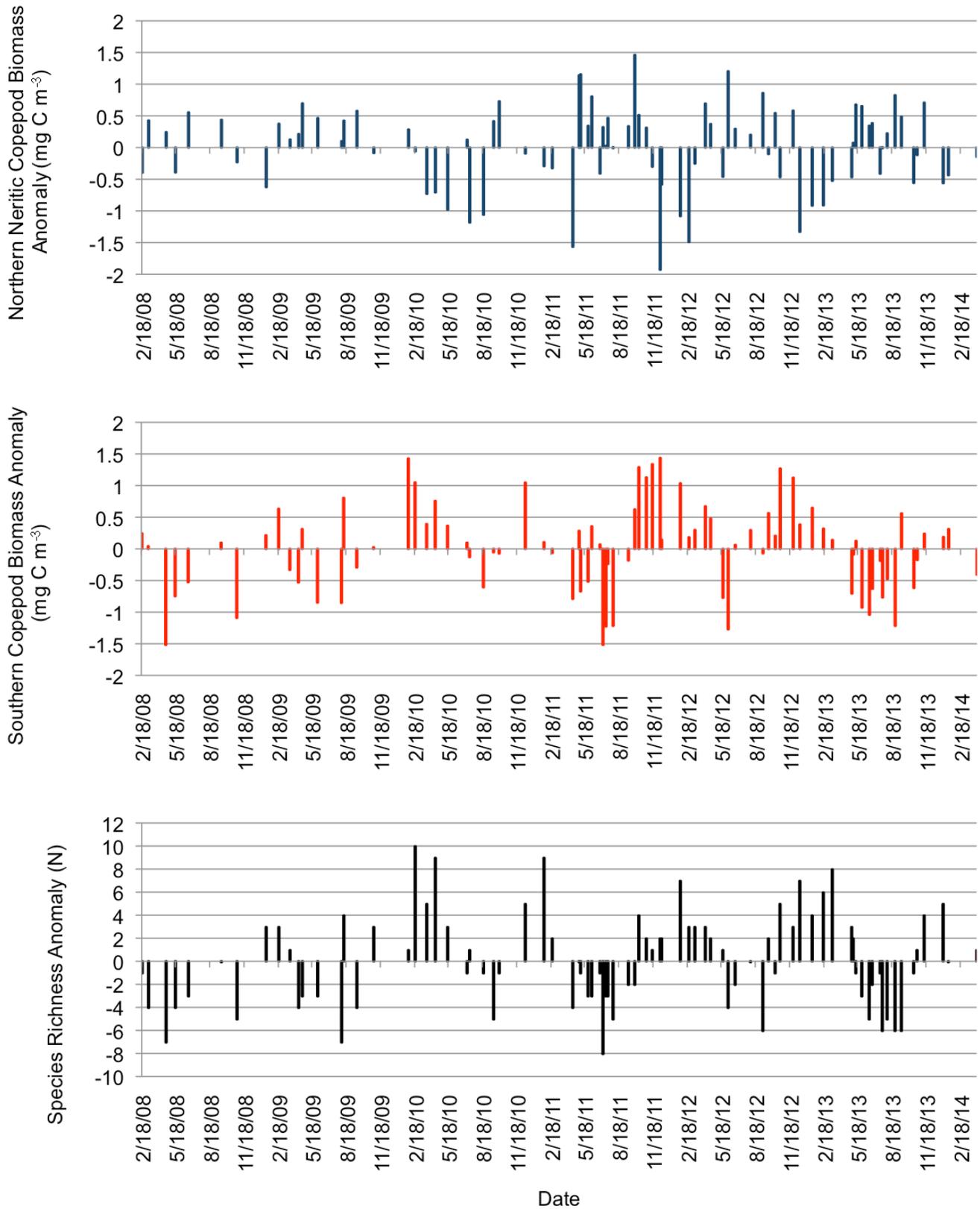


Figure 13. Anomalies (from the 2008–14 mean) in biomass and species richness of the copepod assemblage at midshelf on the Trinidad Head Line (station TH02; 41°03.5' N, 124°16' W, 75m depth). Upper panel: biomass anomaly of dominant northern neritic copepods (dominated by *Pseudocalanus mimus*, *Calanus marshallae*, and *Acartia longiremis*). Middle panel: biomass anomaly of southern copepods (neritic and oceanic taxa combined; dominated by *Acartia tonsa*, *Acartia danae*, *Calanus pacificus*, *Ctenocalanus vanus*, *Paracalanus parvus*, *Clausocalanus* spp., and *Calocalanus* spp.). Lower panel: species richness anomaly (N species).

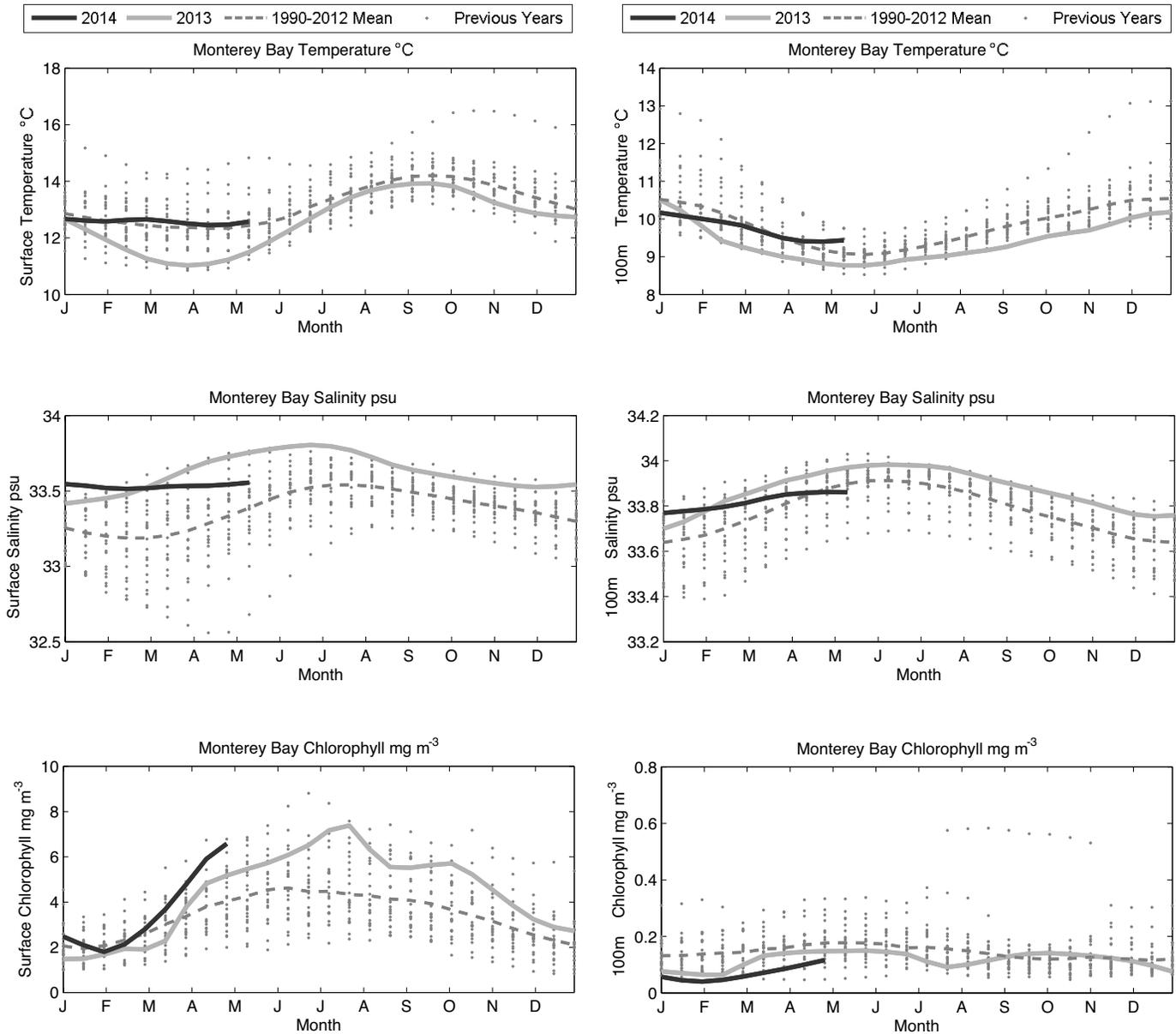


Figure 14. Temperature (top panels), salinity (middle panels) and chlorophyll *a* concentration (bottom panels) at the surface (left hand column) and at 100 m (right hand column) observed at the M1 mooring in Monterey Bay, CA.

the shelf in mid-June coincided with low DO/low pH detected at Trinidad Wharf (Frank Shaughnessy, pers. comm.; CeNCOOS data) during the intense upwelling in late May and early June. This event appears to have triggered an extensive stranding of krill (mostly *Thysanoessa spinifera*) in mid-June along beaches in northern California and southern Oregon following an unusual reversal to strong northward winds (see <http://caseagrantnews.org/2013/07/01/sea-grant-studying-krill-die-off>).

In contrast to early 2013, conditions in early 2014 have been consistent with very mild southward winds and greatly reduced storm activity along the north coast. More recently, southward winds have been consistently

intense throughout May and into early June, and have triggered a substantial phytoplankton bloom over the shelf (data not shown).

During the spring and summer of 2013, the copepod assemblage at station TH02 showed a shift to northern neritic species, a clear decline of southern species, and concurrent decline in species richness than had been observed in 2012 (fig. 13). Although biomass of northern neritic species declined during the winter of 2014, the biomass of southern species did not reach levels observed during most past winters, again perhaps a consequence of limited northward winds and winter storms during the 2013–14 winter.

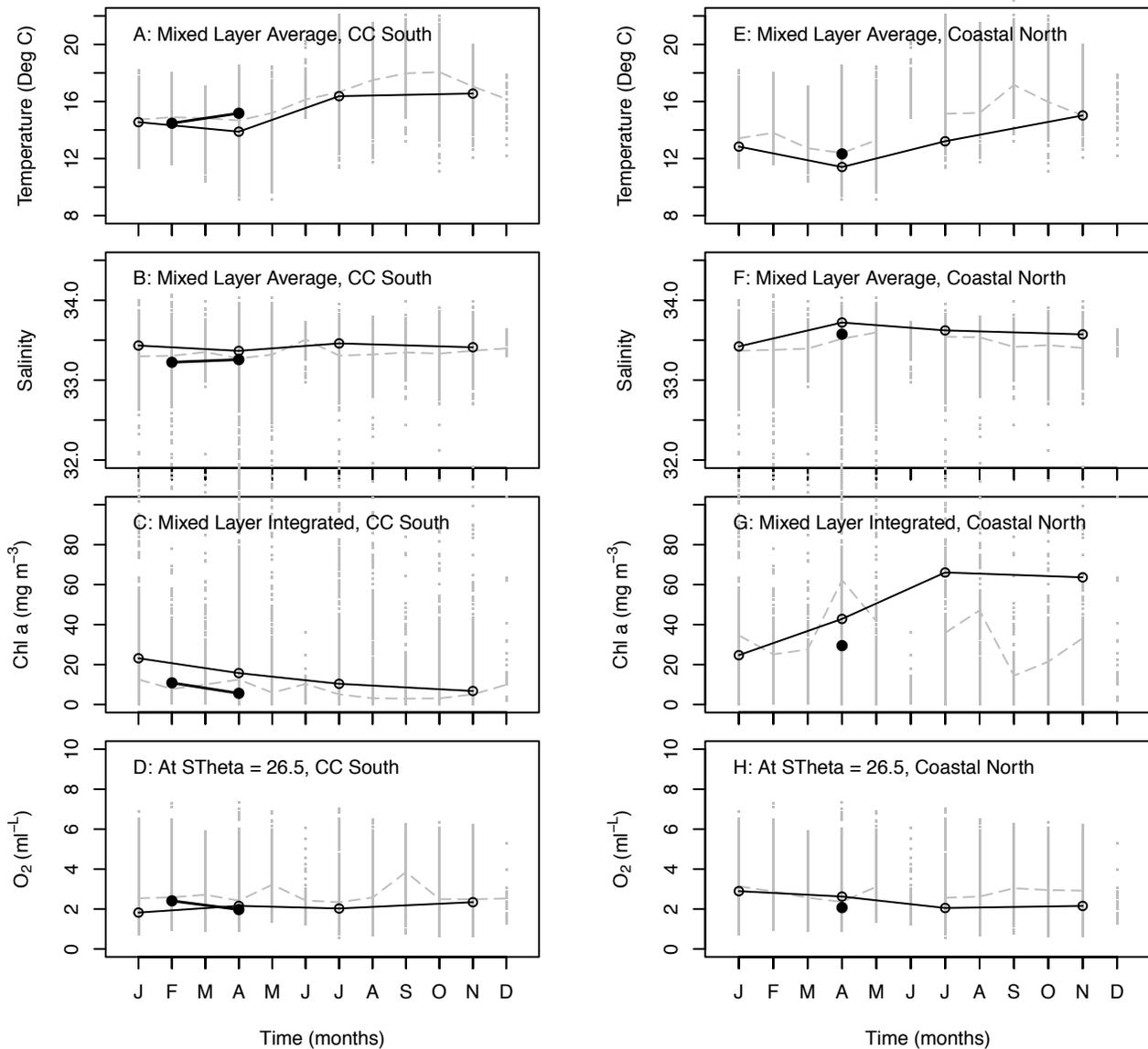


Figure 15. Average mixed-layer temperature (A+E), average mixed layer salinity (B+F), integrated mixed-layer chlorophyll *a* (C+G), and average O<sub>2</sub> concentration at the  $\sigma_{\theta}$  26.5 kg m<sup>-3</sup> isopycnal, from the southern coastal region of the CalCOFI grid (CC South, left-hand column) and the north coastal region of the CalCOFI grid (Coastal north, right-hand column). Grey dots show averages for individual cruises from 1984–2012, dashed line shows climatological monthly average (1984–2012), line with open symbols shows 2013, and line with closed symbols is 2014. Note, the Feb 2014 cruise was cancelled partway through the cruise due to engine failure, thus there were no samples from the coastal north region.

### MBARI, M1 Mooring, Central California

Temperatures in Monterey Bay were cooler than the 1990–2012 climatological mean during most of 2013 particularly at the surface during the spring (fig. 14), likely indicative of high upwelling (fig. 3). Salinities were also higher during 2013 than the climatological mean. Chlorophyll *a* was high at the surface during 2013, especially during the summer months. 2014 saw a shift to temperatures similar to the climatological mean through May, however salinity in the winter of 2013–14 remained high, with values decreasing towards the climatological mean by May. Chlorophyll *a* was relatively high at the surface in April and May 2014. Temperature and salin-

ity followed a similar pattern at 100 m as at the surface, whereas chlorophyll *a* was lower than the mean for 2013–14 (fig. 14, right-hand panels).

### CalCOFI Surveys, Southern California

Because the CalCOFI program samples an area large enough that it encompasses at least three somewhat distinct oceanographic zones, we have divided the area into three subregions for analysis, following Wells et al. (2013). The first subregion, “CC South,” denotes the area landward of the main core of the California Current, south of Pt. Conception; essentially the Southern California Bight (CalCOFI lines 93–87, and stations 60–90). The

second region, “Coastal North,” denotes the nearshore, upwelling-dominated region from Pt. Conception north to Pt. San Luis (lines 80–77, and stations <60). The third region, “Edge of North Pacific Gyre,” is to the south and offshore, influenced by the subtropical gyre (defined by lines 90–93, and stations 100–120). Within each of these regions, we compared cruise-averaged mixed-layer temperature, salinity, integrated chlorophyll *a*, and oxygen at the  $\sigma_{\theta}$  26.5 kg m<sup>-3</sup> isopycnal versus their respective climatological monthly means (based on 1984–2012).

In 2013, within CC South, average mixed-layer temperatures and salinity were similar to the climatological monthly means (figs. 15A, B, S6). Integrated chlorophyll *a* was higher (22, 18, and 15 mg m<sup>-2</sup>) than the mean (14, 15, and 8 mg m<sup>-2</sup>) during winter, spring, and summer cruises, respectively (fig. 15C, S9). In contrast, oxygen at the  $\sigma_{\theta}$  26.5 kg m<sup>-3</sup> isopycnal was similar to the mean (fig. 15D). During spring 2014, temperatures were only slightly higher than average, whereas salinities and oxygen at the  $\sigma_{\theta}$  26.5 kg m<sup>-3</sup> isopycnal were similar to the mean. Chlorophyll *a*, however, was lower (8 mg m<sup>-2</sup>) than the spring mean (15 mg m<sup>-2</sup>; fig. 15C).

In 2013, within the Coastal North subregion, temperatures were anomalously low (typically 1–2 degrees cooler) and salinities at the surface were high (typically 0.1 higher) as compared to the monthly means for the entire year (fig. 15E, S6), consistent with strong upwelling during this period (fig. 2). Oxygen was similar to the mean (fig. 15F, H), but chlorophyll *a* was much higher than the mean in summer and fall (>60 mg m<sup>-2</sup> versus the mean of <40 mg m<sup>-2</sup>; fig. 15G), again consistent with high upwelling during this period in this location. Profiles of chlorophyll *a* for this region showed a marked increase within the mixed layer compared to previous years and the long-term climatology (fig. S9c). The 2014 winter cruise was terminated before reaching region 2 (due to engine problems). 2014 spring temperature, salinity, and mid-depth oxygen were similar to the climatological mean, whereas chlorophyll *a* was anomalously low (28 mg m<sup>-2</sup> compared to the mean of ~60 mg m<sup>-2</sup>).

Averaging over the entire CalCOFI grid, mixed-layer temperatures were lower than the long-term mean (calculated from 1984–2014) by ~0.5°C in 2013, but above the mean by ~0.5°C in February and April 2014 (fig. S7a). Mixed-layer salinity, nitrate, and integrated primary production anomalies were also greater in 2013 compared to the long term mean (anomalies of 0.18 psu, 1 µg NO<sub>3</sub> L<sup>-1</sup>, and 200 mg m<sup>-2</sup> d<sup>-1</sup>, respectively), but decreased during early 2014 (figs. S7, S8). The nitricline depth was deeper than the mean for all of 2013–14 (anomaly = -12 m), but shoaled somewhat from 2013 to 2014 (anomaly = -1 m; fig. S7d). Total zooplank-

ton displacement volume was high in both 2013 and 2014 (average anomaly of +0.57 ln displacement volume; fig. S8).

## REGIONAL PATTERNS IN FISH SPECIES

### Northern California Current, Newport Line

Ichthyoplankton samples were collected from three stations representing coastal (<100 m in depth), shelf (100–1000 m), and offshore (>1000 m) regions along both the Newport Hydrographic (NH; 44.65°N, 124.35–125.12°W) and Columbia River (CR; 46.16°N, 124.22–125.18°W) lines off the coast of Oregon between June 15 and July 20 in 2007–13. In addition, ichthyoplankton samples were collected from five coastal-shelf stations along the NH line (44.65°N, 124.18–124.65°W) in winter (January–March) of 1998–2014. For the complete June–July and winter larval fish sampling methods, see Auth (2011) and Daly et al. (2013), respectively.

The ichthyoplankton community along the central-northern coast of Oregon in June–July 2013 was similar to the average community structures found in the same area and season during the previous six years both in terms of mean concentrations and relative concentrations of the dominant taxa, except compared to the anomalously high concentrations of northern anchovy found in 2011 (fig. 16). However, larval rockfish were found in the highest concentration in June–July 2013 of the seven-year time series, while larval northern anchovy were found in the lowest concentration since 2008.

The biomass of ichthyoplankton that were likely salmon prey in 2014 from winter collections along the NH line were low (total mean biomass = 2.7 mg C 10<sup>-3</sup> m<sup>-3</sup>) and ranked 16th in the 17-yr time-series (1998–2014), predicting low food conditions for juvenile salmon during the 2014 out-migration. The total biomass of all fish larvae was also low (mean = 12.5 mg C 10<sup>-3</sup> m<sup>-3</sup>, not just salmon prey; fig. 17). Also low was the proportion of the total larvae that have been identified as common salmon prey. Ocean conditions in late fall were predictive of winter larval fish biomass in January–March based upon the PDO, and 2013 October–December PDO would predict average winter larval biomass, but early 2014 NPGO values are negative suggesting poorer ocean conditions for juvenile salmon as they out-migrate. Additionally, the proportion of the total larvae considered important salmon prey was below average (ranked 13th out of 17 years at 21.6%; data range from a low of 7.4% in 2011, and a high of 95% in 2000). The community of winter ichthyoplankton in 2014 is grouped with 1998: an El Niño year. Current predictions suggest that 2014 has a very good chance of having El Niño ocean conditions, and we have found that El Niño ocean conditions can add uncertainty to our

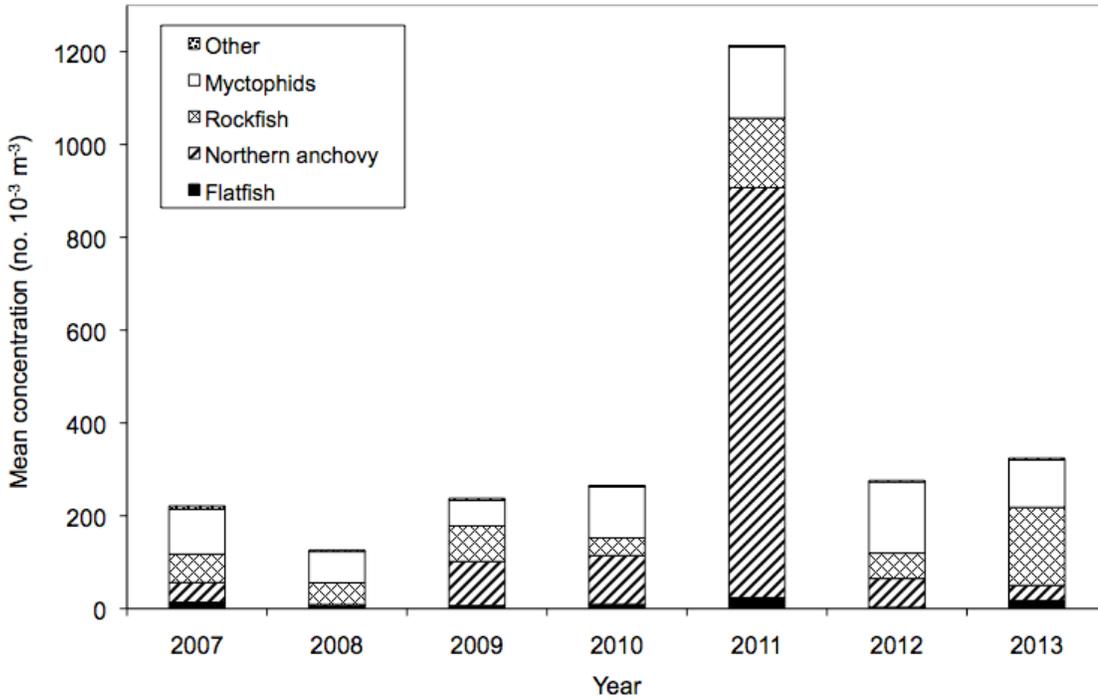


Figure 16. Mean concentrations (no.  $10^{-3} \text{ m}^{-3}$ ) of the dominant larval fish taxa collected during June–July in 2007–13 along the Newport Hydrographic (NH; 44.65°N, 124.35–125.12°W) and Columbia River (CR; 46.16°N, 124.22–125.18°W) lines off the coast of Oregon.

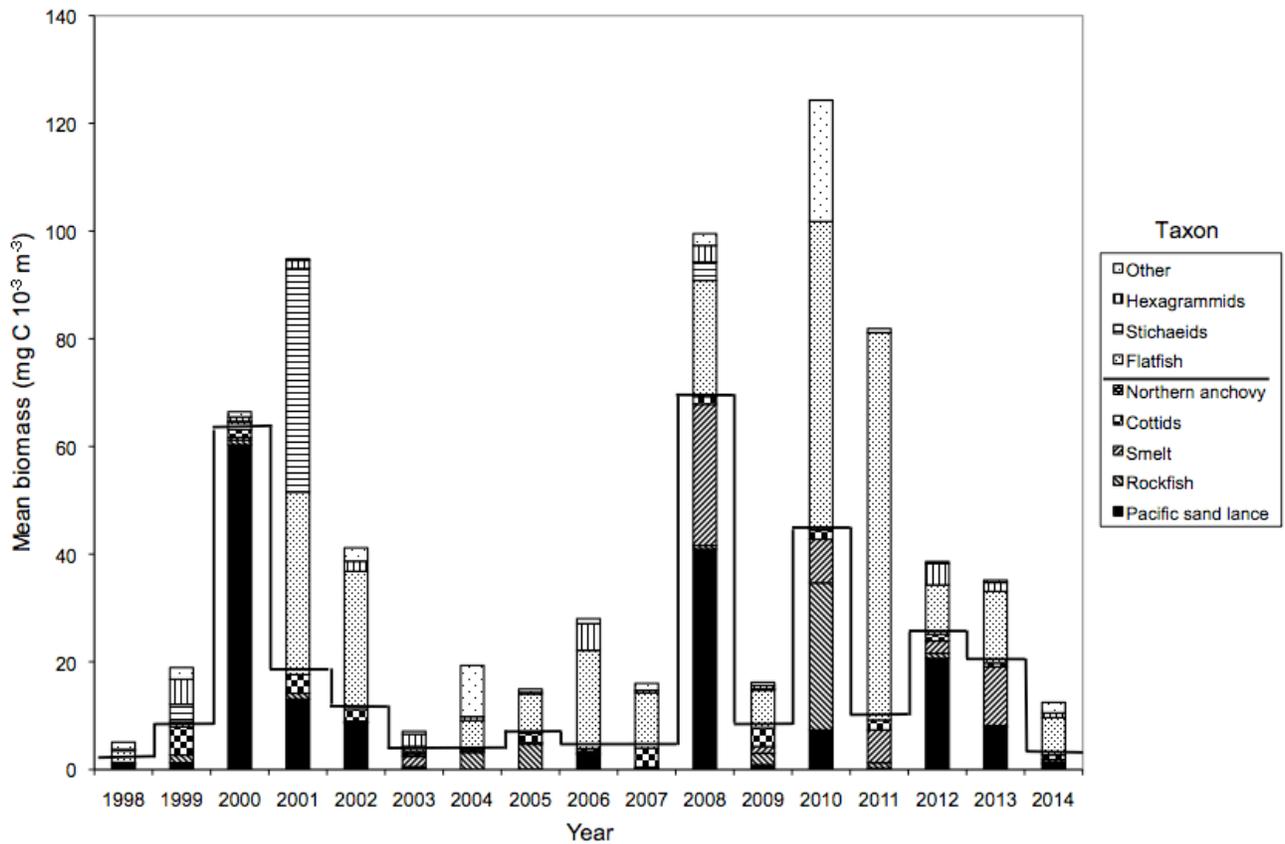


Figure 17. Annual mean biomass (mg C  $10^{-3} \text{ m}^{-3}$ ) of the five important salmon prey taxa (below solid line) and four other dominant larval fish taxa (above solid line) collected during winter (January–March) in 1998–2014 along the Newport Hydrographic (NH) line off the coast of Oregon (44.65°N, 124.18–124.65°W). Figure expanded from one presented in Daly et al. (2013).

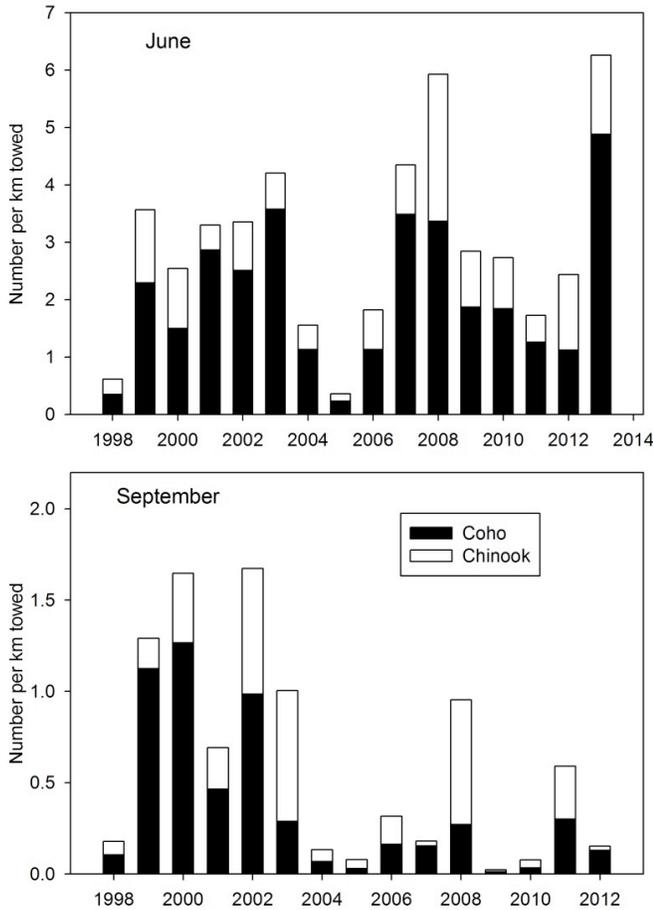


Figure 18. Catches of juvenile coho (black bars) and chinook (white bars) salmon off the coast of Oregon and Washington in June and September from 1998-present. Surveys were not conducted September 2013.

ability to accurately predict adult salmon returns. Overall, winter larval biomass and community structure would predict poor food conditions for juvenile salmon entering the ocean in 2014.

### Northern California Current, Oregon and Washington Coast

Catches of juvenile coho salmon (*Oncorhynchus kisutch*) in pelagic rope trawl surveys off Oregon and Washington<sup>19</sup> were the highest in June 2013 since 1998 (fig. 18). Catches of juvenile (primarily sub-yearling) chinook salmon (*O. tshawytscha*) in June 2013 were about average. Due to funding constraints, there was no survey in September 2013.<sup>3</sup>

Pelagic fish catch data were collected by the NWFSC-NOAA Bonneville Power Administration survey surface trawls on standard stations along transects between La Push, WA and Newport, OR in June from 1999 to 2013. All tows were made during the day at predetermined

locations along transects extending off the coast to the shelf break (Brodeur et al. 2005). We restricted the dataset to stations that were sampled consistently and >10 y over the sampling time period. Numbers of individuals were recorded for each species caught in each haul and were standardized by the horizontal distance sampled by the towed net as CPUE (#/km<sup>2</sup> towed). Yearly abundance data were obtained by averaging the standardized CPUE data across stations for each species sampled during the June survey. We restricted the species data to the top 15 abundant species captured in this dataset over the 14 years sampled years. We applied a Hellinger transformation (square root transformation of standardized row abundance values [Thompson et al. 2014]) to the species × year data set (15 species × 15 years), on which we ran a principal components analysis (PCA) ordination to describe the similarity of each year's community in species space (fig. 19). Additionally, we ran a two-way hierarchical cluster analysis on the yearly species community data with the Hellinger transformation. All community analyses were conducted in PC-ORD v.6.2 (McCune & Mefford 2011).

The resulting PCA ordination was 3 dimensional, explaining 94% of the total variance, with PCs 1, 2, and 3 (not shown) explaining 60.13%, 24.97%, 8.89% of the variability, respectively. Additionally, the loadings of the most abundant species in each PC were generated and are presented in Figure 20. Northern anchovy was strongly positively loaded onto PC 1 (0.74) whereas Pacific herring was strongly negatively loaded onto the same PC (0.65). Pacific sardine was strongly positively loaded onto PC 2. Salmonids (chinook, chum, and coho) were the species most loaded (negatively) onto PC 3 (0.58, 0.44, 0.53, respectively). 1999, 2001, and 2002 were anomalous years in terms of community structure during the surveyed time period relative to other years. A clear separation of these years from the rest is evident along PC 1 (fig. 19) and in the two-way cluster analysis (fig. 20). The separation of these years from the rest is due to the low abundance of anchovy and the relatively high abundance of herring during these years. There was also a dramatic shift in community composition between 1999 and 2000 and between 2000 and 2001. Some years showed remarkable similarities to other years. For example, based on the branch lengths of the cluster analysis, 2000 was very similar to 2005, 2007 and 2010, while 2003, 2004, 2009 and 2011 were very similar (fig. 21).

### Ecosystem Indicators for the Central California Coast, May–June 2014

The Fisheries Ecology Division of the SWFSC has conducted an annual midwater trawl survey for juvenile rockfish (*Sebastes* spp.) and other pelagic micronekton along the central California coast in late spring (May–

<sup>3</sup> <sup>19</sup>Survey protocols are available at <http://www.nwfsc.noaa.gov/research/divisions/fed/oeip/kb-juvenile-salmon-sampling.cfm>.

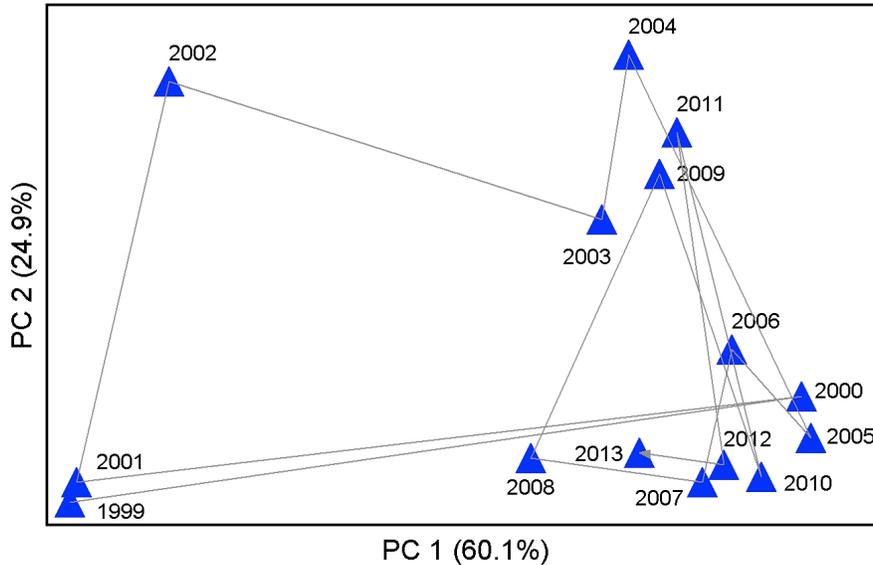


Figure 19. PCA of the yearly NCC pelagic fish community sampled between 1999 and 2013 in June off the Oregon and Washington coasts. The percentage variance explained by PCA1 and PCA2 are shown in parentheses on each axis.

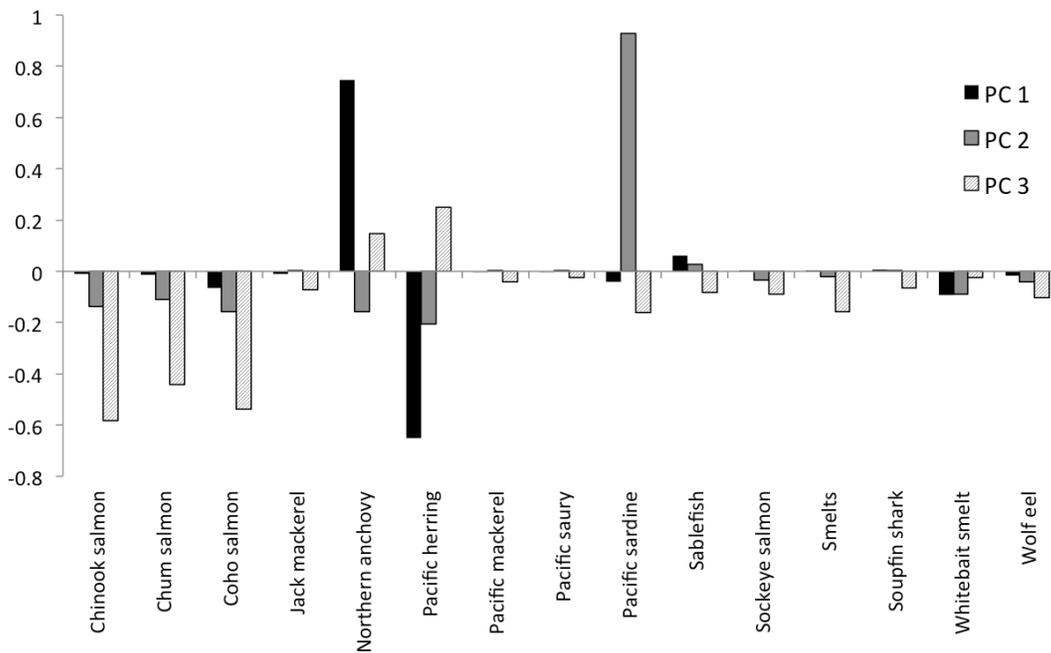


Figure 20. Top 15 abundant species loadings onto PCs 1, 2 and 3 of the 3-dimensional principal component analysis of the 15-year time series of surveyed pelagic fish in the northern California Current.

June) since 1983. Along with oceanographic information, the survey targets pelagic juvenile (young-of-the-year, YOY) rockfish and the micronekton forage assemblage (including other juvenile fishes, krill, coastal pelagic species, and mesopelagic species) for fisheries oceanography studies and stock assessments. The results here update a principal component analysis (PCA) of the pelagic micronekton community in the core area developed by Ralston et al. (2014). The data for the 2014 survey are

preliminary. Trends from the southern (Southern California Bight) and northern (north of Point Reyes to Cape Mendocino) areas, which have been sampled only since 2004, were highly consistent with these “core area” trends for central California for most species. However, catches for juvenile groundfish and some other groups appeared to be below longer-term averages in much of the area north of Mendocino in 2014 (R. Brodeur, unpublished data). Differences in catch rates of YOY

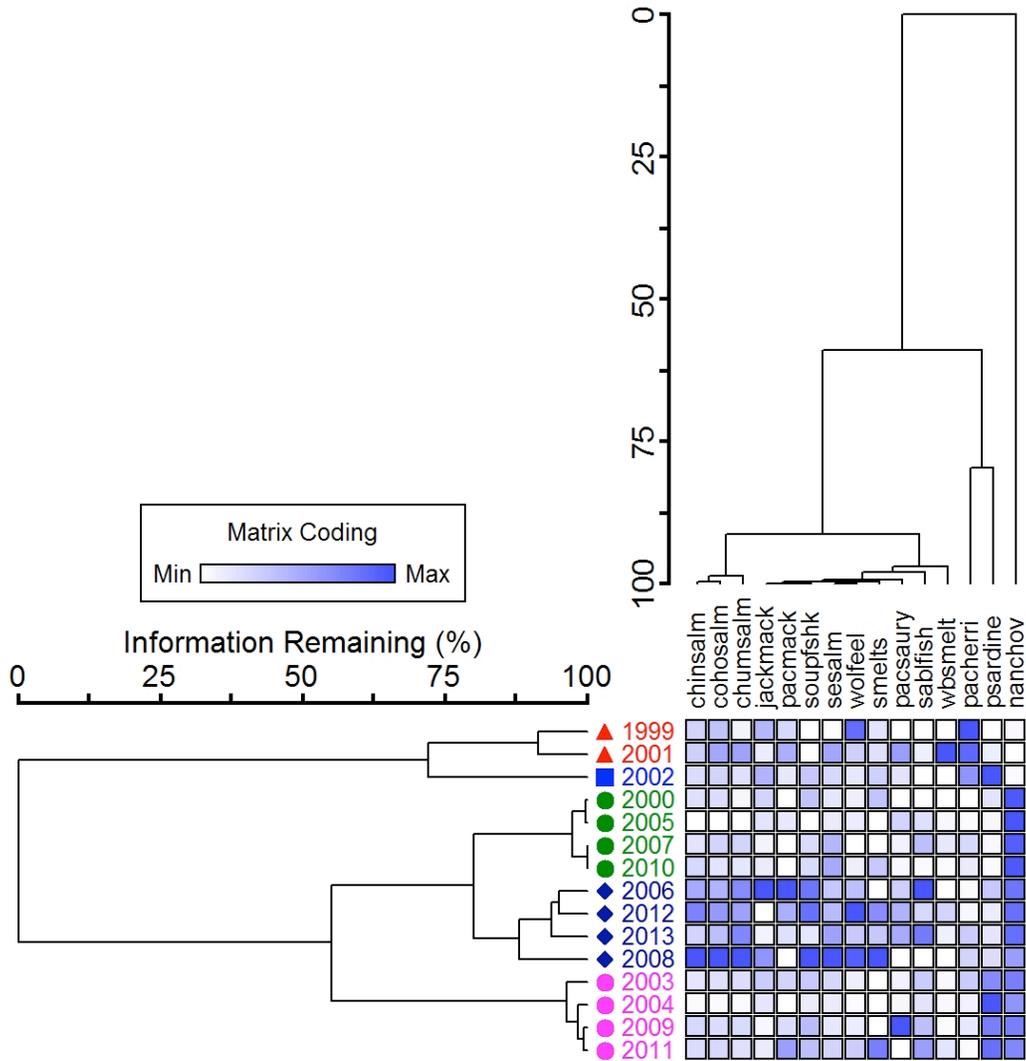


Figure 21. Two-way cluster dendrogram of yearly community composition. Matrix color-coding reflects the species average Hellinger transformed abundance in a given year. Yearly clusters defined at the 95% information remaining level.

rockfish have previously been described for these broad regions of the California Current (Ralston and Stewart 2013).

The standardized anomalies (based on 1990–2014 for central California and 2004–14 for the southern and northern regions, excluding 2012 for northern area) from the mean of the log (x+1) catch rates are shown by year for six key YOY groundfish and forage groups (fig. 22), including all YOY rockfish, market squid (*Doryteuthis opalescens*), krill (primarily *Euphausia pacifica* and *Thysanoessa spinifera*), YOY Pacific sanddab (*Citharichthys sordidus*), Pacific sardine (*Sardinops sagax*) and northern anchovy (*Engraulis mordax*). Notably, 2013 and 2014 had among the highest ever observed catches of juvenile rockfish, sanddab, and market squid in the core, southern and northern areas, following an unusually stable trend of high krill abundance and very low abundance

of Pacific sardine and northern anchovy in preceding years. The longer time series for juvenile rockfish suggests that 1984 and 1985 were years of comparable high abundance for juvenile rockfish (Ralston et al. 2013). In both 2013 and 2014, these observations were consistent with high reported catches of YOY rockfish and other groundfish in power plant impingement surveys, scuba surveys, commercial and recreational fishermen, and from food habits studies of seabirds and other predators in this region.

An additional 14 species and groups were included in the analysis of the forage assemblage developed by Ralston et al. (2014), and are included in the PCA (fig. 23). The additional YOY groundfish groups include Pacific hake (*Merluccius productus*), speckled sanddab (*C. stigmaeus*), rex sole (*Glyptocephalus zachirus*), and lingcod (*Ophiodon elongates*). The remaining spe-

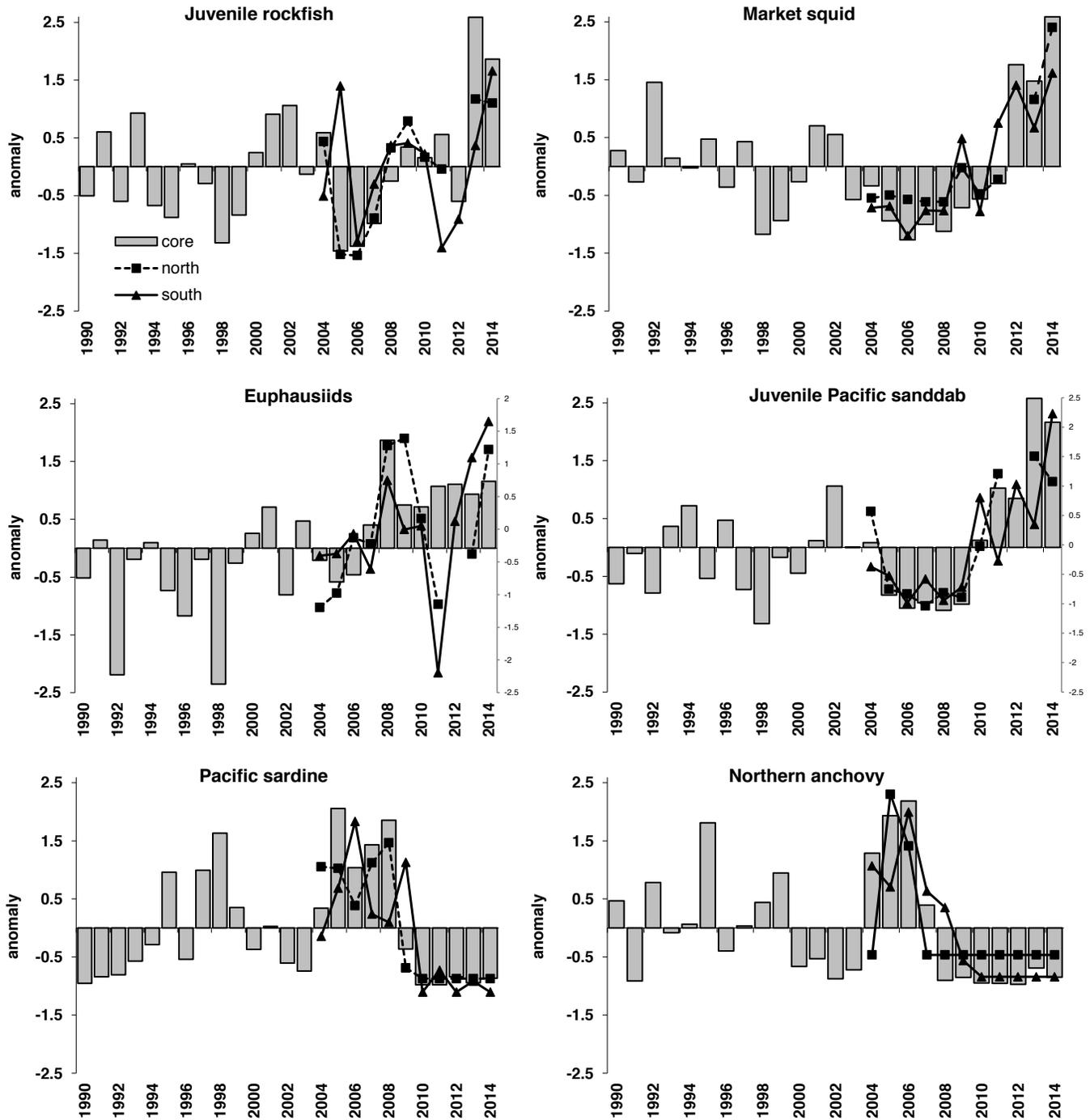


Figure 22. Long-term standardized anomalies of several of the most frequently encountered pelagic forage species from rockfish recruitment survey in the core (central California) region (1990–2014) and the southern and northern California survey areas (2004–14, excluding 2012 for the northern area).

cies and groups in the assemblage include adult Pacific hake, pelagic octopus, sergestid shrimp, gobies (family Gobiidae), plainfin midshipman (*Porichthys notatus*), and a variety of mesopelagic species. YOY groundfish, market squid, krill and several other taxa had strong positive loadings on PC 1 (which explained about 30% of the total variance, the first three PCs explained a

total of 61% of the variance), with northern anchovy, Pacific sardine, and most mesopelagic species loading strongly negative on PC 1. This PC was not significantly related to basin-scale environmental indicators, such as the PDO, MEI, and the NPGO, but strongly related to both localized physical conditions (salinity, density and depth of the  $\sigma_{\theta}$  26.0 isopycnal) and indica-

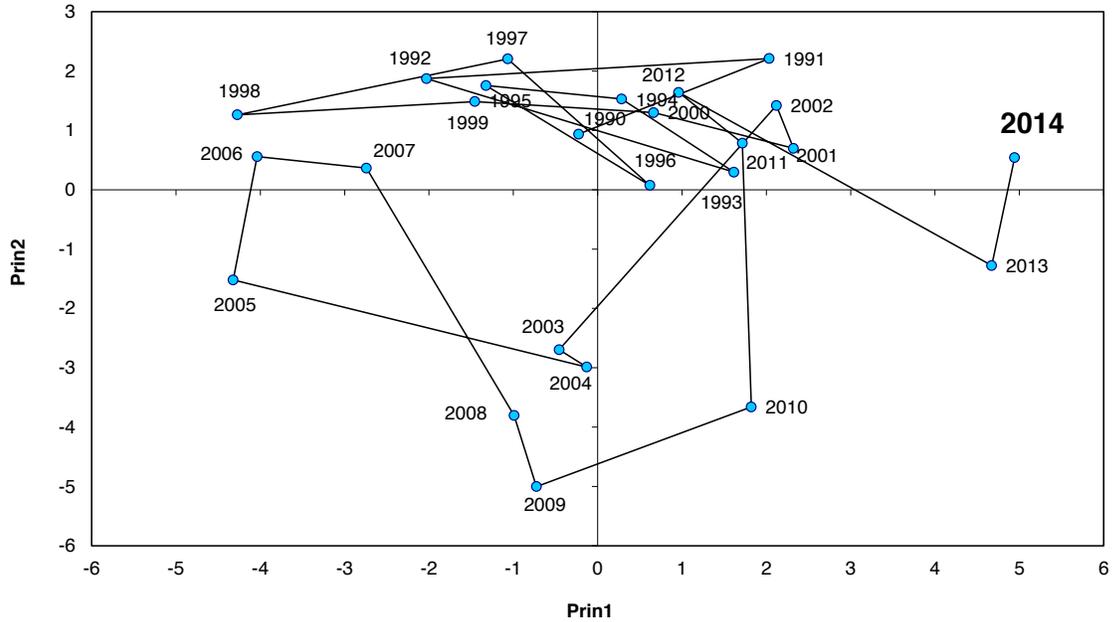


Figure 23. Principal component scores plotted in a phase graph for the twenty most frequently encountered species groups sampled in the central California core area in the 1990–2014 period.

tors of large-scale transport (AVISO sea surface height anomalies), such that the YOY rockfish, squid, and krill groups were more abundant during cool, high transport conditions. The second PC tended to load more strongly on the mesopelagic community, but relate poorly to environmental indicators, while PC 3 had strong loadings on a suite of taxa and was highly correlated to basin-scale climate indicators (see Ralston et al. 2014 for details).

The two leading PCs for the assemblage are shown in Figure 23, and the dramatic separation of 2013 and 2014, as being extremely orthogonal to the low productivity years of 1998, 2005, and 2006, is an indicator of the very high productivity of the cool-water, high transport assemblage in the last two years. Such shifts have important implications for higher trophic level species (such as seabirds, marine mammals, salmon, and adult groundfish) that forage primarily or exclusively on this assemblage. The observed dynamics of the YOY groundfish and high turnover invertebrates is thought to largely represent shifts in productivity associated with higher survival of early life-history stages for these species, while the trends observed for coastal pelagic and mesopelagic species (which load negatively on PC 1 and positively on PC 2) are thought to be more likely related to shifts in their distribution and consequent availability to the midwater trawl (e.g., Song et al. 2012; Wells et al. 2013). Although abundance of salps in the 2013–14 period did not reach the peak observed levels of 2012, the abundance of pyrosomes was the highest recorded in this survey (fig. 24).

### Ecosystem Indicators for the Southern California, CalCOFI Region

The spring CalCOFI and Coastal Pelagic Species (CPS) surveys of 2014 yielded very few sardine eggs or larvae from either the continuous underway fish egg sampler (CUFES, fig. 25) or the vertical PairoVet net tows (see McClatchie 2014 and references therein for methods, survey domain, and descriptions of equipment). Spatial coverage by the two surveys was comparable to earlier years (fig. 26), but the only sardine ichthyoplankton encountered were in very low numbers and very nearshore in the Southern California Bight. 2014 is a low point in the time series since the sardine began to increase in the late 1980s (fig. 26; note the different scales for figs. 25 and 26). Only 17 adult sardine were captured by trawls during the 2014 spring CPS survey, and there were insufficient fish or eggs to permit the calculation of a reliable biomass estimate from either the daily egg production method (DEPM) or acoustics. We speculate that at such low abundance, the sardine distribution was very patchy, and sparse patches were not efficiently sampled by the survey design. The sardine fishing industry (Diane Plescher, California Wetfish Producers Association, personal communication) reported significant catches of sardine off central California early in the season, after which the fish disappeared. Although the survey took place from 28 March to 6 May, a large portion of the central coast was not surveyed until the latter half of April. It is unknown whether the fish spawned earlier than this, whether they began their seasonal northward migration early, or whether they were distributed fur-

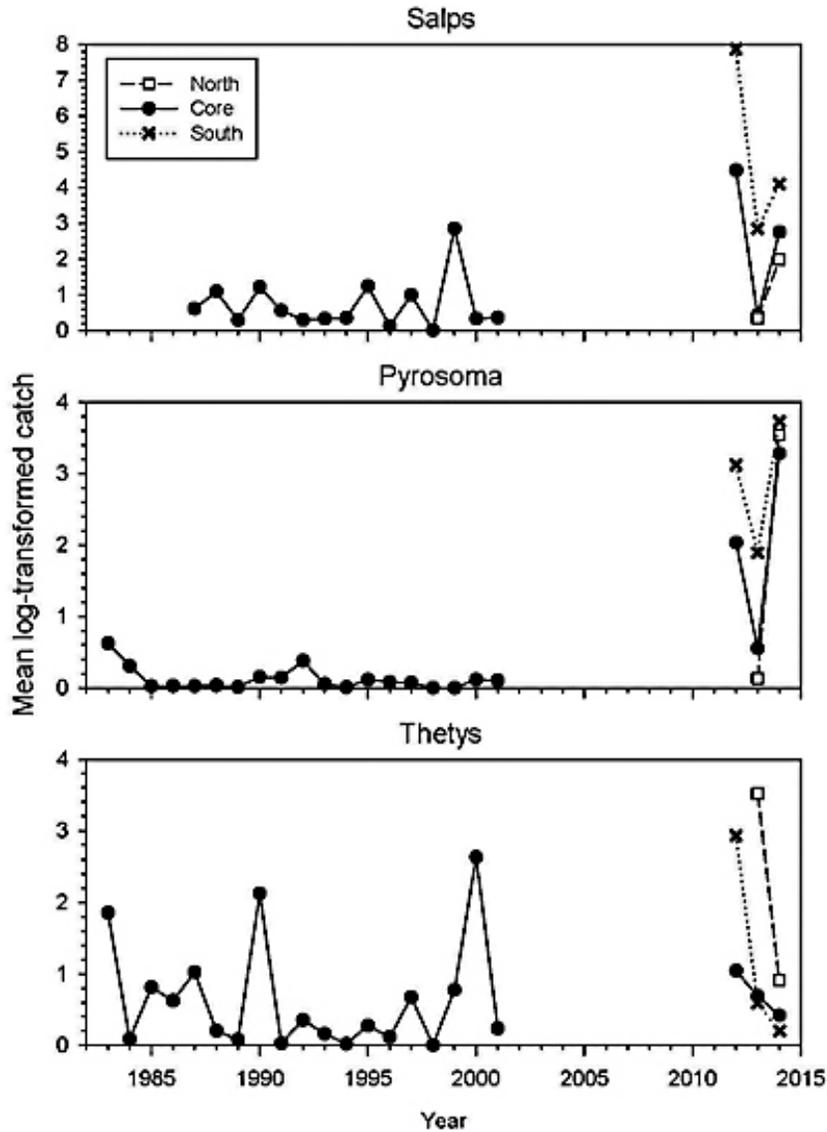


Figure 24. Geometric mean of catches per unit volume of gelatinous zooplankton from the rockfish recruitment survey.

ther offshore than the survey domain. Anchovy numbers also remained low and were distributed close to shore in the Southern California Bight (fig. 25). This was consistent with observations of low abundance of anchovy ichthyoplankton in recent years (Wells et al. 2013). Jack mackerel were the most abundant CPS ichthyoplankton in spring 2014 (fig. 25). Jack mackerel eggs were more abundant off southern California than off the central coast, and eggs were relatively close to shore in the southern region. In summary, the numbers of CPS ichthyoplankton were low in spring 2014, raising some unanswered questions regarding changes in distribution and timing of spawning. The very low sardine egg abundance and scarcity of sardine adults will make it difficult to accurately estimate population biomass for the sardine stock assessment.

## REGIONAL PATTERNS IN BIRDS AND MARINE MAMMALS

### Common Murres at Yaquina Head, Oregon

Median hatch date for common murres at Yaquina Head in 2013 was 4 July, similar to some previous years but a week later than we observed in 2012. Only 41% of the eggs laid hatched a chick (hatching success) and 24% of the eggs laid produced chicks that fledged (reproductive success; chicks  $\geq 15$  days were considered fledged). Reproductive success in 2013 was similar to 2011 and 2012, but less than half of the previous 4 years (2007–10, fig. 27) and the third lowest recorded for this colony. Only the reproductive success in 2010 and during the 1998 El Niño were slightly lower (Gladics et al. in review).

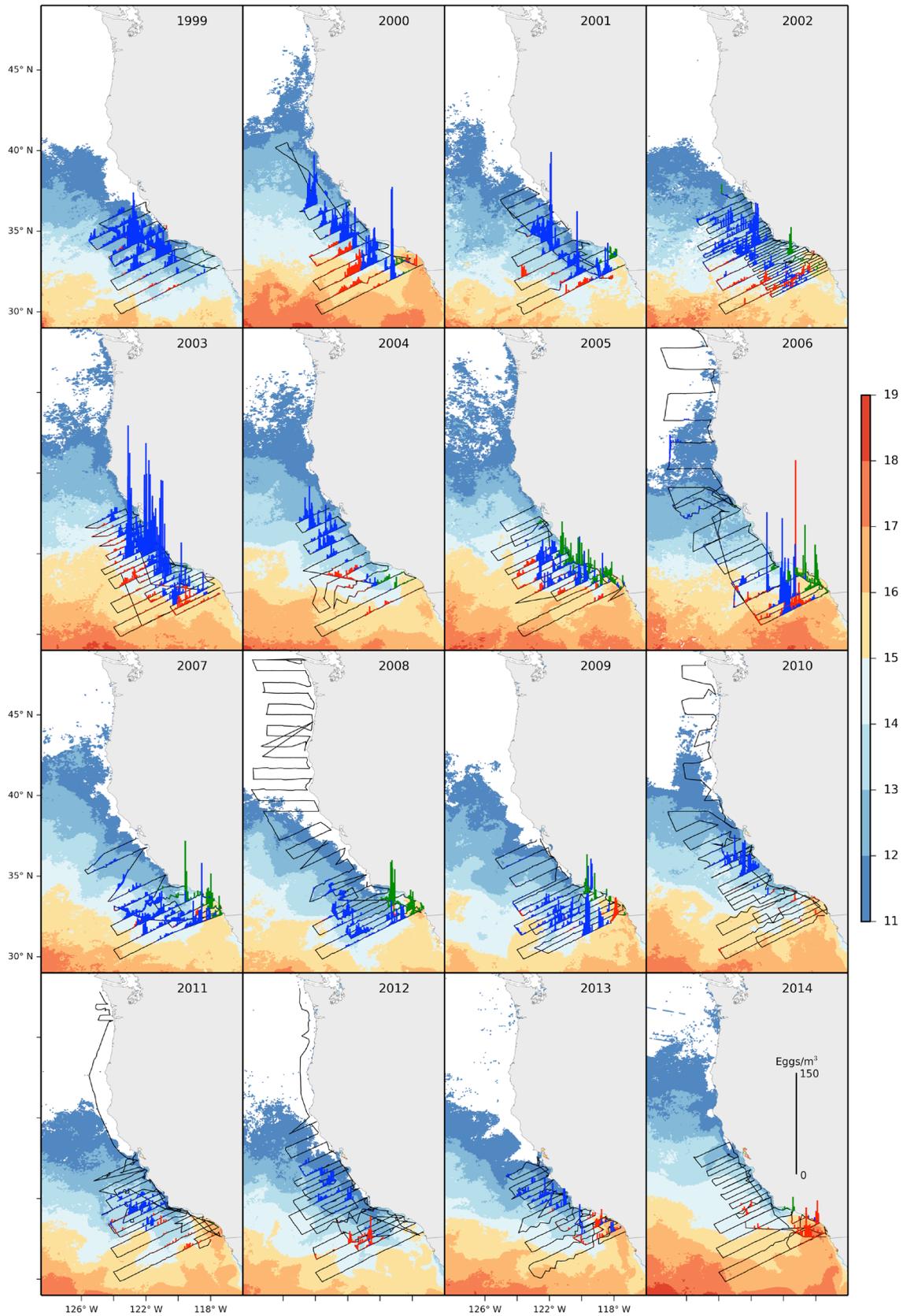


Figure 25: Density of eggs of sardine (blue), anchovy (green), and jack mackerel (red) collected with the continuous underway fish egg sampler (CUFES) overlaid on satellite sea surface temperatures ( $^{\circ}\text{C}$ ) derived from a monthly composite of April AVHRR Pathfinder imagery (1999–2008) and a blended SST product (2009–14). Ship track is shown by the black line. Colorbar indicates SST ( $^{\circ}\text{C}$ ).

**FSV Bell M. Shimada and RV Ocean Starr  
 28 March to 06 May 2014**

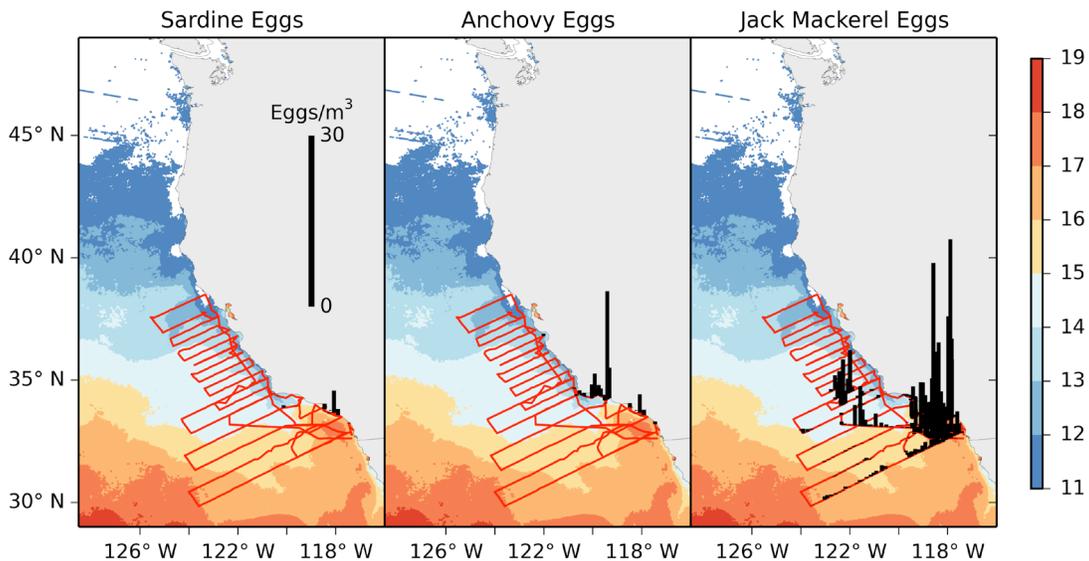


Figure 26: Density of eggs of sardine, anchovy, and jack mackerel collected with the continuous underway fish egg sampler (CUFES) during the spring 2014 CalCOFI and coastal pelagic fish cruises overlaid on satellite sea surface temperatures (°C).

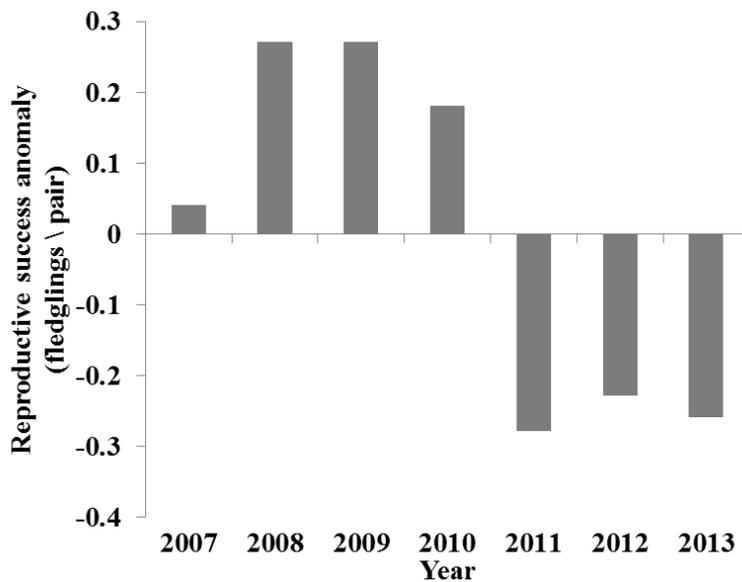


Figure 27. Anomalies of reproductive success for common murre nesting at Yaquina Head, Oregon, 2007–13.

Like the previous two seasons, much of the reproductive loss in 2013 was due to egg and chick predators. The total number of disturbances and the rate of murre egg and adult loss in 2013 were lower than the previous two years but higher than 2007–10. Disturbance rates first began to increase in 2010, and then greatly escalated in 2011, 2012, and 2013 (Horton 2014). The rate of adults killed per hour of observation was similar to those observed in both 2011 and 2012. Bald eagles (*Haliaeetus leucocephalus*) were again the dominant dis-

turbance source (93%, 75 of 80 disturbances), unlike in 2012 when bald eagles caused only half of the disturbances (47%, 104 of 220 disturbances). Also unlike in 2012 when juvenile brown pelicans (*Pelecanus occidentalis*) resorted to eating fish regurgitated by murre chicks or eating murre chicks directly (Horton and Suryan 2012), there were no dramatic disturbances caused by pelicans in 2013, and pelicans were not observed landing on the colonies until the majority of murre had fledged. As of June 2014, we are seeing an early arrival of pelicans,

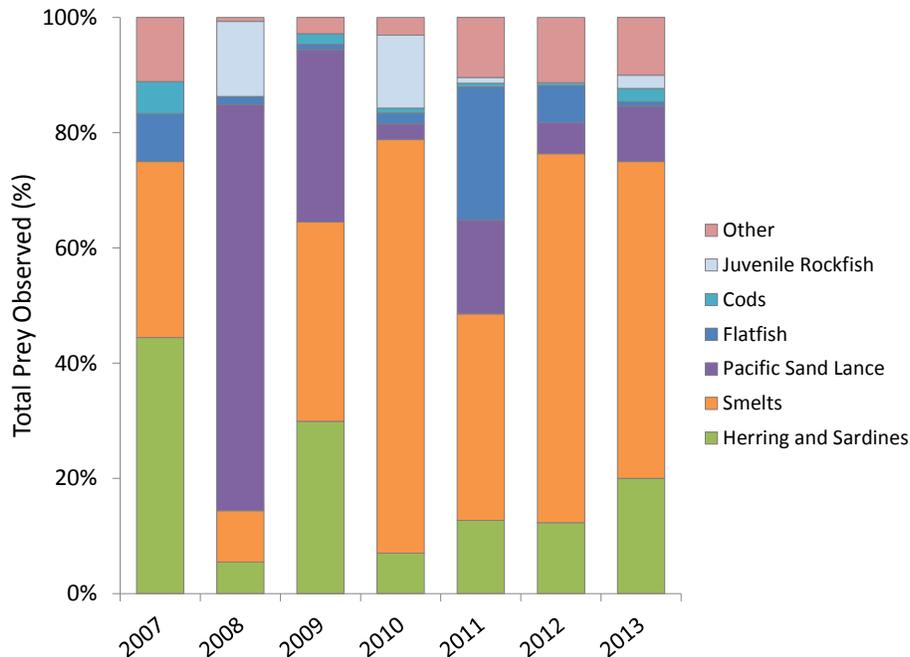


Figure 28. Prey fed to common murre chicks (% occurrence) at Yaquina Head Oregon, 2007–13.

likely resulting from their failed breeding attempts in the southern CCS and early northward departure from the breeding grounds.

Murre diets at Yaquina Head have varied annually. Forage fish species consumed in 2013 included primarily smelt (*Osmeridae*) and secondarily Pacific herring or sardine (*Clupeidae*) and Pacific sand lance (*Ammodytes hexapterus*) (fig. 28). A notable difference in diets among the past six years was the dominance of sand lance (associated with cooler waters) in 2008, and the dominance of smelt in 2010, and the increased consumption of flatfishes in 2011. Results show 2013 as intermediate with less smelt than 2010, but more than other years, somewhat similar to 2012. Clupeids (primarily Pacific herring, *Clupea pallasii*), which are generally associated with warmer water and positive PDO (Gladics et al. in review), increased slightly, but overall has remained low in the diets since 2009.

### Summary of Common Murre Reproductive Success, Phenology, and Diet at Castle Rock National Wildlife Refuge: 2007–13

Castle Rock National Wildlife Refuge (hereafter Castle Rock) is a large common murre breeding colony in northern California near Crescent City, just south of Point St. George. The reproductive success, nesting phenology, and chick diet have been studied since 2007 using a remotely controlled camera monitoring system that was installed at the colony in 2006. The percentage of nests that successfully fledged young in 2013 was

based on 75 nests that were monitored every other day. During 2013, 79% of nests fledged young, which was 6% greater than the long-term average for this colony (fig. 29). Nesting commenced on 22 April, 1 day later than the year with the earliest nest initiation (2009) and 22 days earlier than year with the latest nest initiation (2012; fig. 30). Diet observations occurred for an average of 80 hours each year while common murre chicks were present. In 2013, a total of 13 prey types were identified and prey composition was generally similar to other years, with smelt (*Osmeridae*) being the predominant prey fed to chicks and juvenile rockfish being the second most common prey fed to chicks (fig. 31).

### Breeding Success of Seabirds at Southeast Farallon Island

The 2013 seabird breeding season at Southeast Farallon Island, California, was a very productive year for all species with Brandt's cormorants (*Phalacrocorax penicillatus*), pelagic cormorants (*Phalacrocorax pelagicus*), and Cassin's auklets (*Ptychoramphus aleuticus*) exhibiting exceptionally high breeding success. Piscivorous common murre (*Uria aalge*), rhinoceros auklets (*Cerorhinca monocerata*), and pigeon guillemots (*Cepphus columba*), also had productive years with higher productivity than last season and also above the long-term mean (fig. 32). Western gulls (*Larus occidentalis*) rebounded from four straight years of very poor breeding success and fledged chicks at a rate equivalent to the long-term mean. Cassin's auklets, though declining slightly from 2012, con-

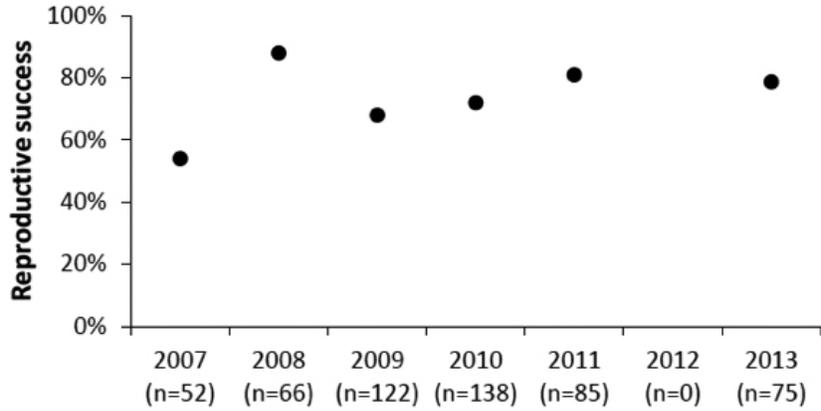


Figure 29. Percentage of common murre (*Uria aalge*) nests that successfully fledged young between 2007 and 2013 at Castle Rock National Wildlife Refuge, Del Norte County, California. The sample size (n) represents the total number of nests observed per year. This figure does not include the success of second clutches. Reproductive success could not be determined in 2012 due to early failure of the video monitoring system.

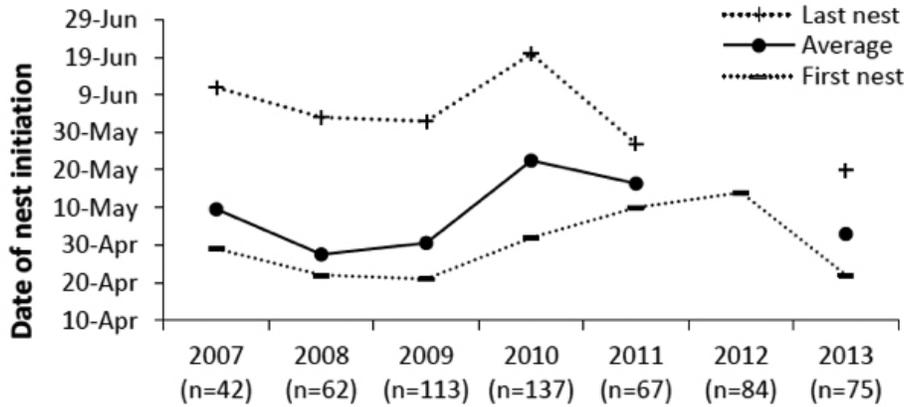


Figure 30. First, average, and last dates for nests initiated by common murres between 2007 and 2013 at Castle Rock National Wildlife Refuge, Del Norte County, CA. The date of nest initiation was defined as the day that an egg was laid at a nest-site. The sample size (n) represents the total number of nests observed each year where nest initiation dates were accurate to  $\pm 3.5$  days. The average and last date of nest initiation could not be determined in 2012 due to early failure of the video monitoring system.

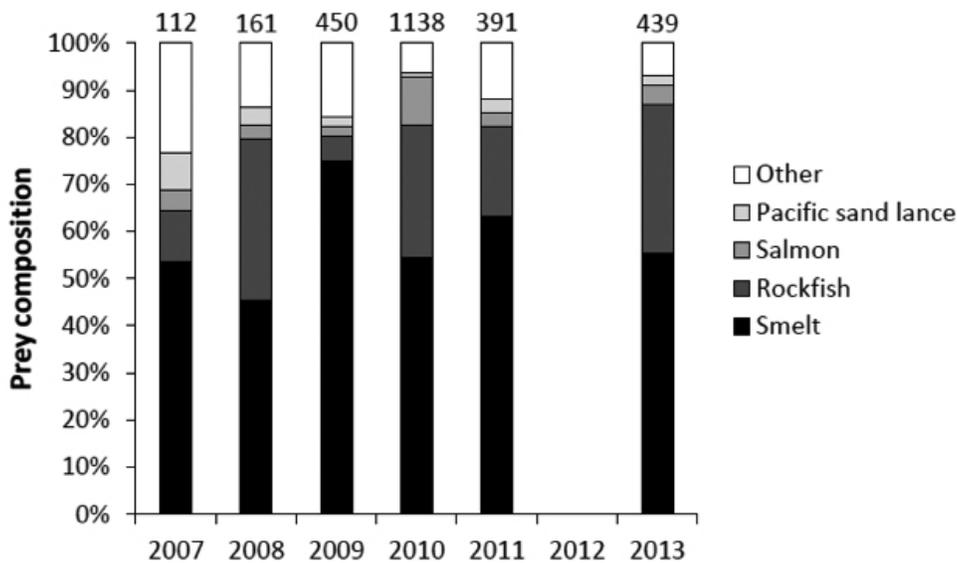


Figure 31. Composition of prey delivered to chicks by common murre between 2007 and 2013 at Castle Rock National Wildlife Refuge, Del Norte County, California. Numbers above each bar indicate the total number of prey identified each year. Prey composition could not be determined in 2012 due to early failure of the video monitoring system.

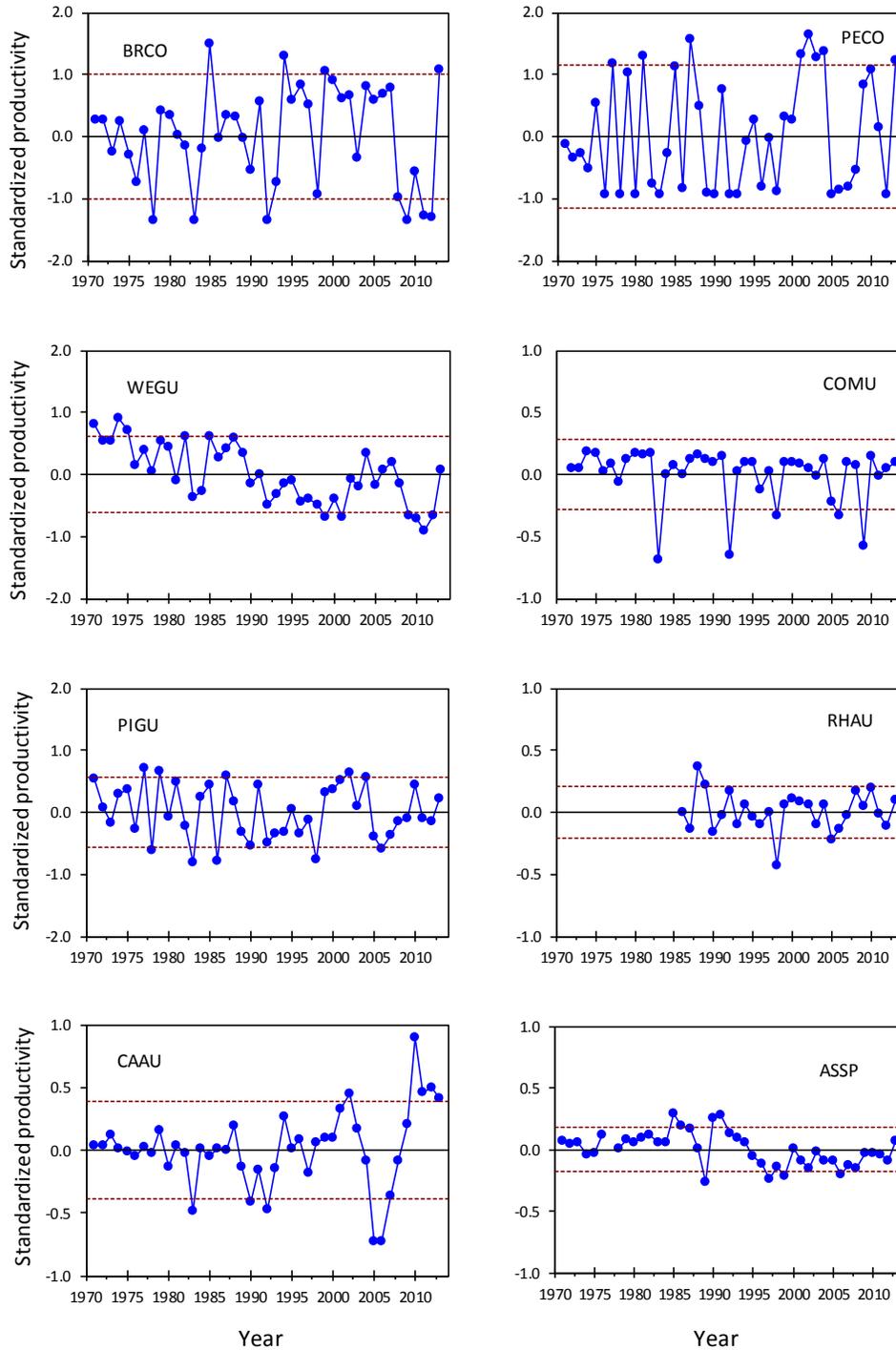


Figure 32. Standardized productivity anomalies (annual productivity–long term mean) for 8 species of seabirds on SEFI, 1971–2013. The dashed lines represent the 80% confidence interval for the long-term mean.

tinued to exhibit exceptionally high productivity with the 2013 productivity value within the top five years since studies began in 1972. This marks the fourth consecutive year of exceptional reproductive performance for Cassin’s auklets. Auklet success was once again driven by abundant prey resources (primarily euphausiids) and a high rate of successful double brooding. Reproductive

success of common murres was also higher than 2012 as well as being above the long-term mean for this species. Murres seemed to thrive once again on a high abundance of juvenile rockfish in the chick diet. Feeding rates were high, chicks grew quickly and fledging success was high. It appears that cormorants benefited from heavy foraging on juvenile rockfish as well.

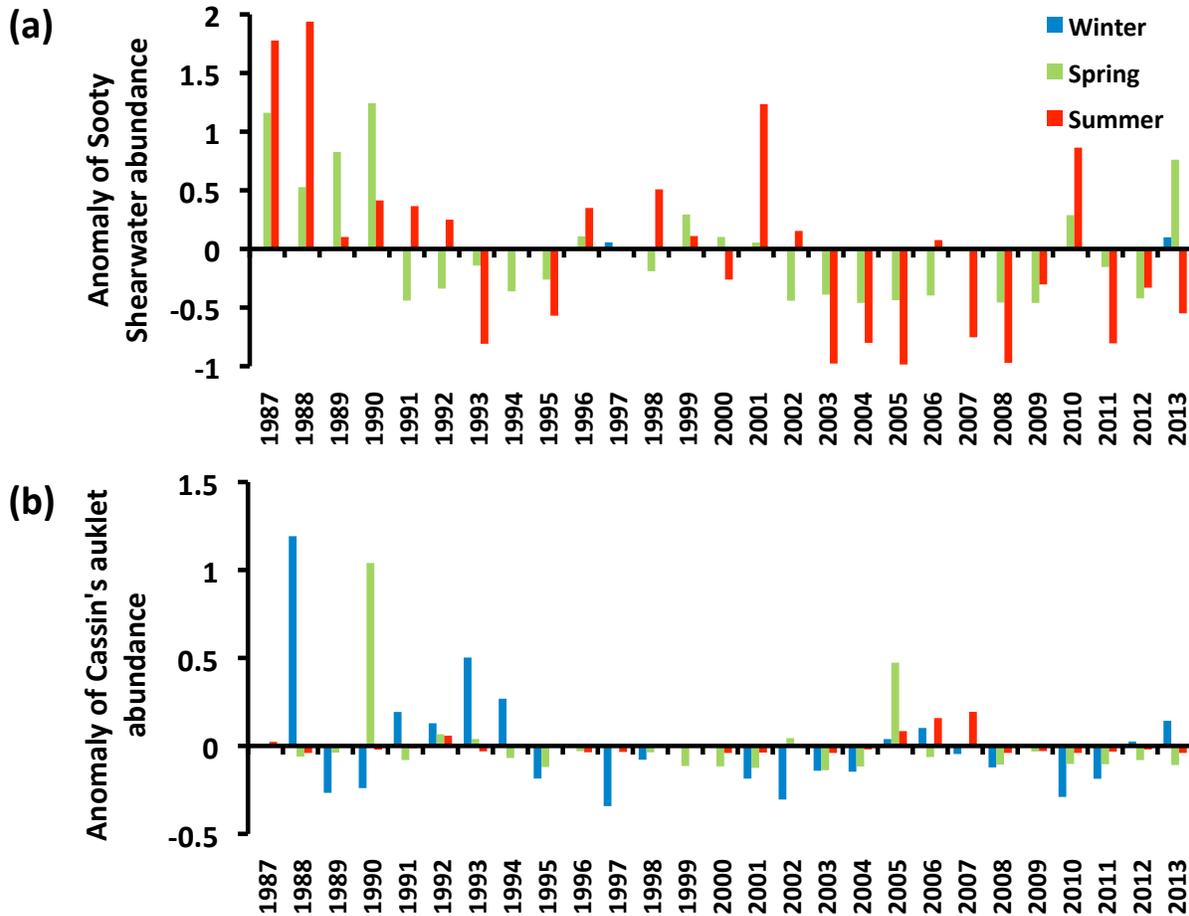


Figure 33. Patterns of change in the abundance (expressed as anomaly of density; long-term mean subtracted) of (a) sooty shearwater (*Puffinus griseus*) and (b) Cassin's auklet (*Ptychoramphus aleuticus*) over three seasons: winter, spring, and summer.

Seabirds integrate marine resources over local to large spatiotemporal scales (e.g., upwelling cells to ocean basins and synoptic to decadal time) such that their distribution and abundance at sea are excellent indicators of coupled climate-marine ecosystem variability. As part of the CalCOFI program, now supplemented by the CCE-LTER and SCCOOS programs, data on seasonal seabird distribution and abundance has been collected since spring 1987. Overall, total seabird abundance in the CalCOFI region has continued to display frequent negative seasonal and annual anomalies with only infrequent positive anomalies occurring once or twice a decade. Recently, Sydeman et al. (2014) attributed the 25-year decline in overall seabird abundance to declines in the availability of nearshore forage fish (primarily northern anchovy) and interannual variability in krill resources. Moreover, seabird species richness (total number of species recorded per survey) has also declined significantly (Sydeman et al. 2009). Together these frequent negative anomalies and the decline of total seabird abundance and species richness warrant further research to quantify the interactive effects of hydrographic and biological condi-

tions on the viability of the seabird community within the CalCOFI region.

As examples of long-term variability of seabird abundance (indexed by density and expressed as numbers  $\text{km}^{-2}$ ), we present data on two species, the sooty shearwater (*Puffinus griseus*; fig. 33a) and Cassin's auklet (*Ptychoramphus aleuticus*; fig. 33b). Sooty shearwaters are southern hemisphere migrants and are most abundant in the California Current during the spring and summer. Auklets are resident in the California Current year-round, but are most abundant in the CalCOFI region in winter. Shearwater density during spring has declined since surveys began in the late 1980s, with each successive peak in abundance (i.e., 1990, 2001, and 2010) lower than the preceding one. Shearwater abundance was lowest during the period 1993–95 and 2003–08. However, shearwaters exhibited a strong positive anomaly during spring 2013, which was similar in magnitude to the peaks recorded earlier in the history of this survey. The abundance of auklets also fluctuates, with no overall change registered since 1998–99. Recent peaks in auklet abundance were due to unusual increases in density

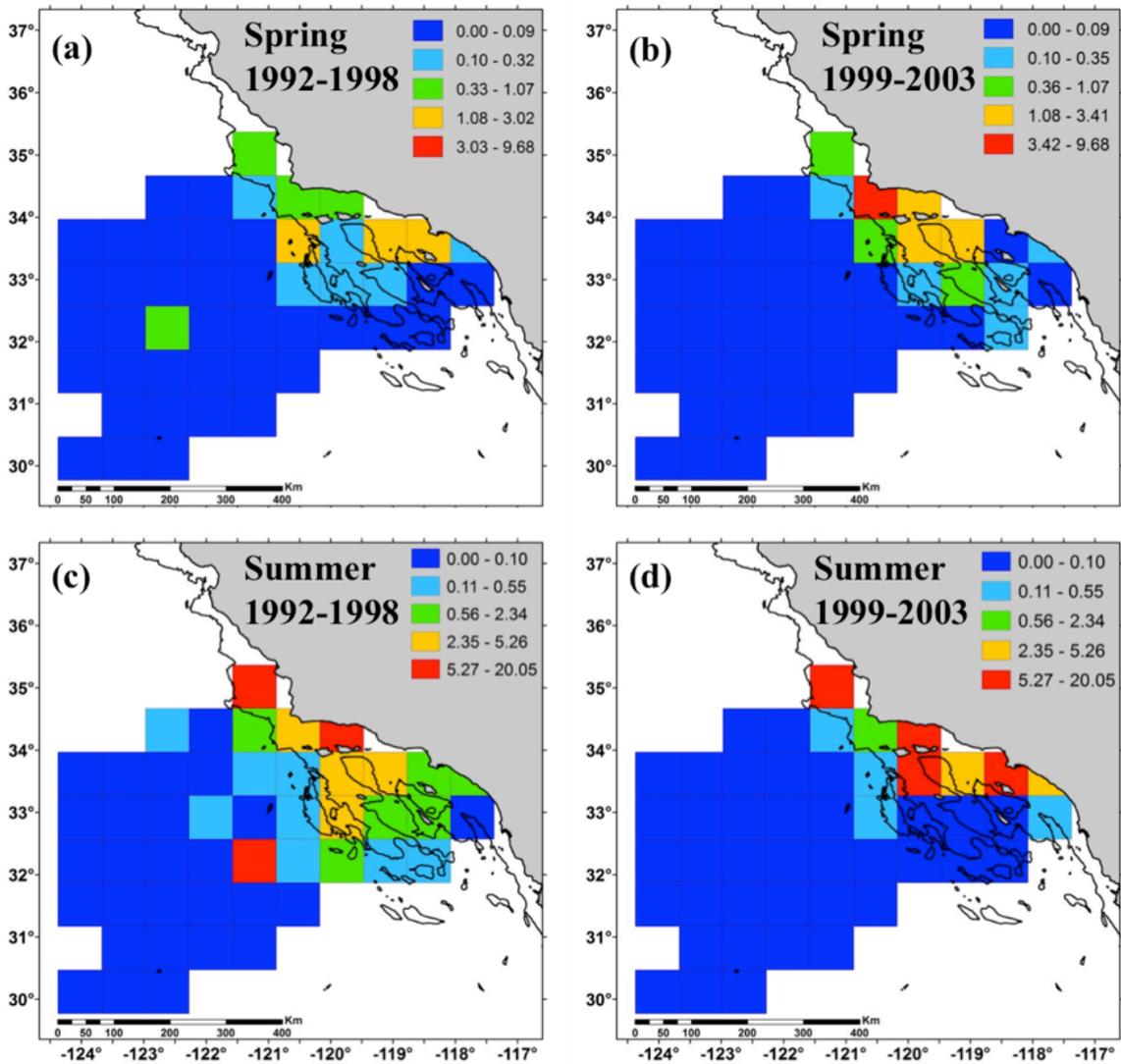


Figure 34. Spatial mean abundance of sooty shearwater from spring and summer CalCOFI surveys during two contrasting periods of El Niño and La Niña: 1992–98 and 1999–2003.

in spring 2005 and summer 2005–07 (related to colony abandonment from the Farallon Islands; Sydeman et al. 2006). However, auklets exhibited a positive anomaly during winter 2013 (largest positive anomaly since 2006) that is similar in magnitude to their anomalies recorded during winter 1991 and 1992.

Mapping seabird distributions in the CalCOFI region reveals that seabird community structure varies annually according to warm and a cool ocean temperatures, with more subtropical species recorded during anomalously warm years (Hyrenbach and Veit 2003) and “hotspots” of abundance associated with Point Conception (Yen et al. 2006). For example, species such as Cook’s petrel (*Pterodroma cookii*), black storm petrel (*Oceanodroma melania*) and black-vented shearwater (*Puffinus opisthomelas*) are relatively more abundant during El Niño years. Moreover, Hyrenbach and Veit (2003) found that some species

with a warm-water affinity increased before the event, while those with a cold-water affinity decreased, suggesting leading indicators of impending El Niño conditions. As examples of these temporal changes in seabird distribution, spatial climatologies of sooty shearwater abundance during two different periods are provided: 1992–98, a prolonged warm-water period associated with the strong El Niño events of 1992–93 (Trenberth and Hoar 1996) and 1997–98; and 1999–2003, a period dominated by La Niña cold-water conditions (Bograd and Lynn 2001; Yen et al. 2006). The spatial mean abundance of shearwaters during spring and summer from these two periods indicate that shearwaters are more abundant and clustered in the coastal domain of the Santa Barbara Basin during the cool period (1999–2003) in comparison to the warm period (1992–98) when they are generally less abundant and more dispersed (fig. 34).

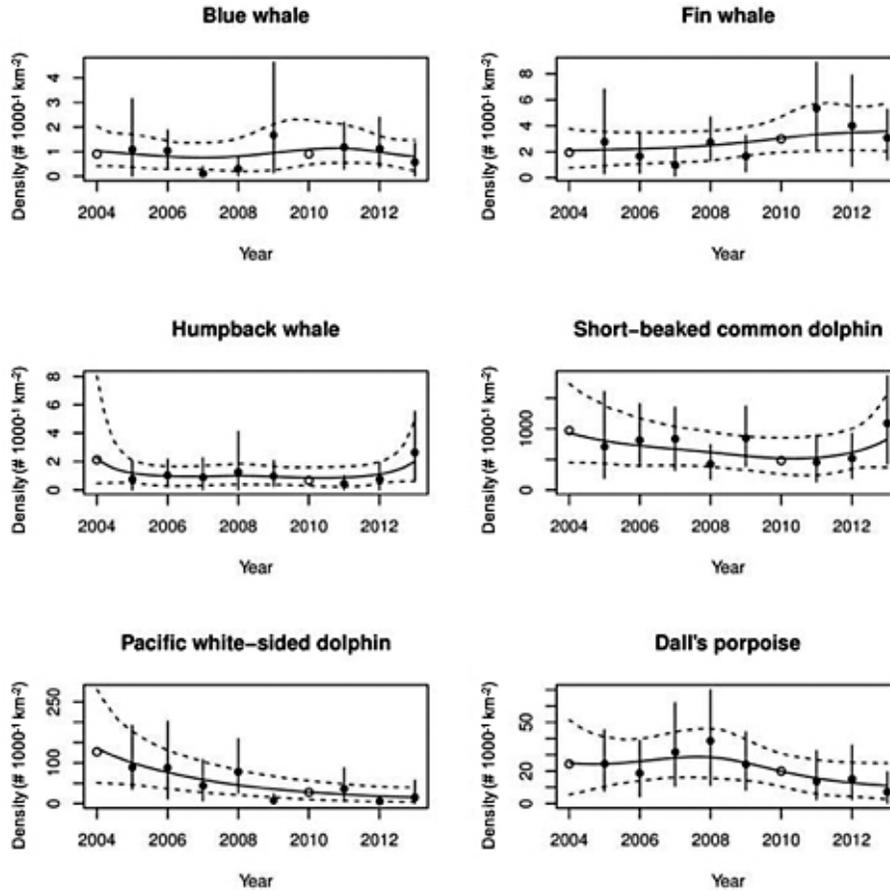


Figure 35. Annual and long-term trend in density by cetacean species. Dots are the mean over seasons of the annual density estimates by year and vertical lines show 95% bootstrap confidence intervals, except for 2004 and 2010 where the dots are the mean of the seasonal estimates where available and the predicted values from the GAM in seasons where no survey was performed. Solid line represents the predicted long-term trend from the GAM and dashed lines represent lower and upper 95% confidence intervals.

If indeed a strong El Niño does impact the California Current during 2014–15, we can expect lower seabird abundance and biomass, as well as an influx of the usual El Niño visitor species. In addition, we also predict that the number and intensity of seabird-forage hotspots would be far less and clustered in coastal upwelling habitats during the El Niño event. In summary, we expect seabird abundance and species occurrence patterns to provide early-warning indications of ecosystem variability resulting from the impending El Niño event.

### Cetacean Density on the Southern CalCOFI Lines from 2004–13

Density estimates for the six most common cetacean species off southern California in 2013 were compared to long-term averages from 2004–12.<sup>4</sup> Despite higher point estimates for five of the six species in 2013, z-tests

indicated these differences were not significantly different from the estimates reported for the pooled 2004–12 surveys (fig. 35). The relatively small sample sizes and associated large variances from a single year preclude a more informative statistical comparison. Overall annual trend analysis indicated that there were no significant changes in blue whale, fin whale, humpback whale, short-beaked common dolphin, or Dall's porpoise densities across the ten-year study period; however, Pacific white-sided dolphins exhibited a significant decrease in density with a mean annual population decrease of 22.5% (95% CI = -34.52% - -9.43%) (fig. 35).

### California Sea Lions at San Miguel Island, California

California sea lions (*Zalophus californianus*) are permanent residents of the CCS, breeding in the California Channel Islands and feeding throughout the CCS in coastal and offshore habitats. They are also sensitive to changes in the CCS on different temporal and spatial scales and so provide a good indicator species for the status of the CCS at the upper trophic level (Melin et al.

<sup>4</sup>A detailed description of the field and analytical methods utilized for the analysis presented here can be found in: Campbell, G. S., L. Thomas, K. Whitaker, A. Douglas, J. Calambokidis, and J. A. Hildebrand. In Revision. Interannual and seasonal trends in cetacean distribution, density, and abundance in waters off southern California. DSR II Special CalCOFI Issue.

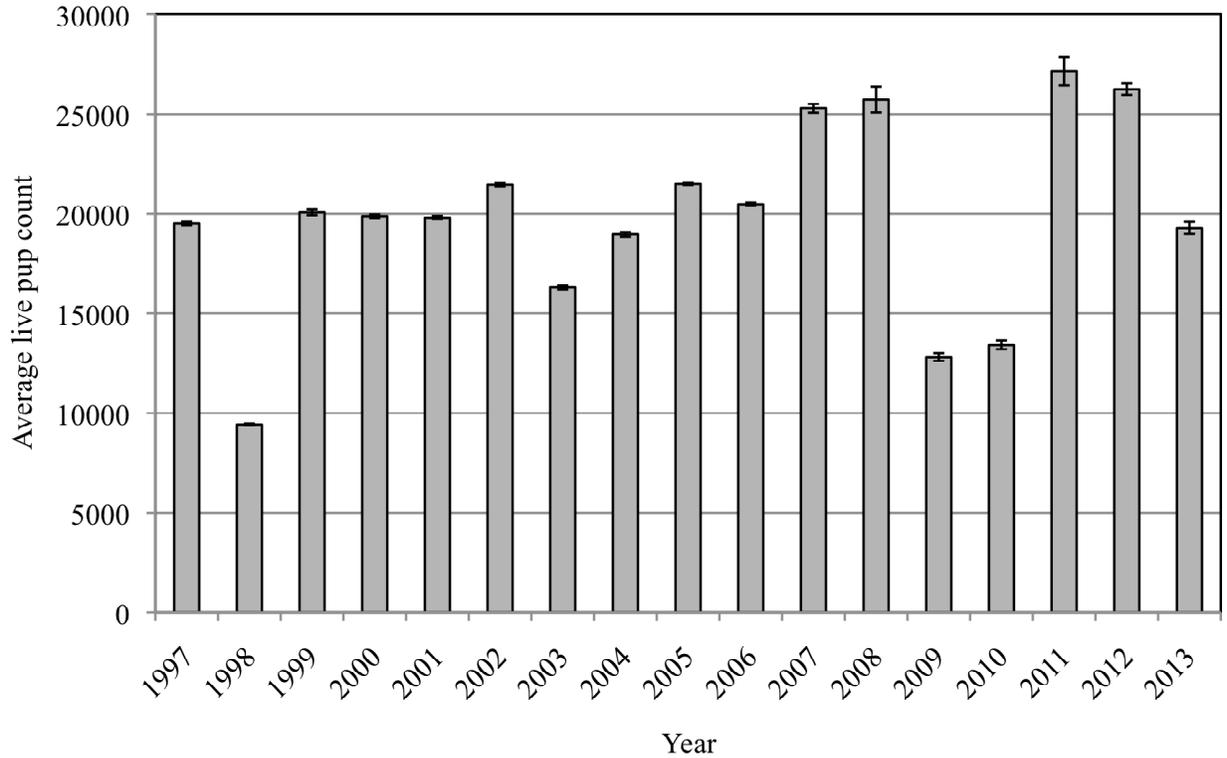


Figure 36. The average number of live California sea lion pups counted at San Miguel Island, California, 1997–2013 in late July when surviving pups were about 6 weeks old. Error bars are  $\pm 1$  standard error.

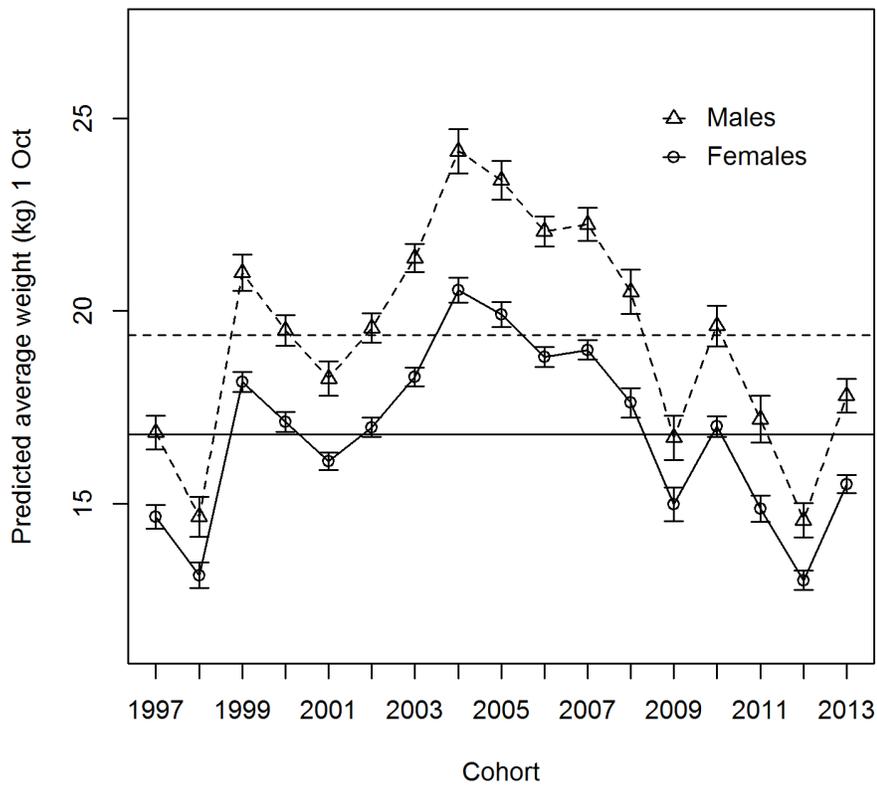


Figure 37. Predicted average weights of 4 month old female (open circle) and male (open triangle) California sea lion pups at San Miguel Island, California, 1997–2013 and long-term average between 1975 and 2013 for females (solid line) and males (dashed line). Error bars are  $\pm 1$  standard error.

2012). 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 US breeding population. As such, it is a useful colony to measure trends and population responses to changes in the marine environment. We used the number of pups alive at the time of the live pup census conducted in late July and the average weights of pups at 4 months and 7 months of age between 1997 and 2013 as indices of the population response to annual conditions in the CCS. The number of live pups in late July represents the number of pups that survived from birth to about 6 weeks of age. Live pups were counted after all pups were born (between 20–30 July) each year. A mean of the number of live pups was calculated from the total number of live pups counted by each observer. Each year, between 200 and 500 pups were weighed when about 4 months old. Pups were sexed, weighed, tagged, branded, and released. Up to 60 pups were captured in February and weighed and measured at 7 months of age. Of the 60 pups captured in February, up to 30 pups were branded and provided a longitudinal data set for estimating a daily growth rate between 4 months and 7 months old. We used a linear mixed-effects model fit by REML in R to predict average weights on 1 October and 1 February in each year because the weighing dates were not the same among years. The model contained random effects with a sex and days interaction (days = the number of days between weighing and 1 October or 1 February) that allowed the growth rate to vary by sex and year, and a full interaction fixed effects of sex and days. The average weights between 1997 and 2013 were compared to the long-term average for the average pup weights between 1975 and 2013.

In March 2013, an Unusual Mortality Event (UME) was declared for California sea lions in southern California (<http://www.nmfs.noaa.gov/pr/health/mmume/californiasealions2013.htm>) in response to unprecedented numbers of young pups from the 2012 cohort stranding along the coast between January and March and poor condition of pups at San Miguel Island and other rookeries during the winter (Wells et al. 2013). By the onset of the California sea lion reproductive season in June 2013, most of the population indices for California sea lions at San Miguel Island showed signs of improvement. Although the average number of live pups counted at San Miguel Island in July 2013 declined 27% from 2012 (fig. 36), the pup growth indices indicated that the condition of dependent pups from the 2013 cohort had improved considerably from 2012. However, pup weights at 4 months of age (fig. 37), 7 months of age (fig. 38) and growth rates to 7 months of age (fig. 39) still remained below the long-term average.

The decline in pup production reflects the inability of

adult females to support pregnancies during the winter and spring of 2013 and coincides with a reduced availability of Pacific sardine and northern anchovy in the spring of 2013 as indicated by surveys in central California in spring 2013 (Wells et al. 2013). The improved condition of pups in 2013 suggests that foraging conditions improved for lactating females during the period of pup dependence.

## DISCUSSION

During 2013, upwelling started early and was relatively strong during the entire summer, leading to one of the highest cumulative upwelling indices on record for much of the coastal CCS (fig. 3). The enhanced upwelling was most evident from central to mid-California, with decreased enhancement in northern California and Oregon. As a result, surface temperatures in most areas during spring and early summer were low and chlorophyll *a* was high, although not as high as expected in northern California and Oregon. Both northern California and Oregon observed high numbers of “northern copepods”—an indicator of good feeding conditions for higher trophic levels, particularly fish, since this copepod species assemblage typically has high levels of lipids (Peterson and Keister 2003; Hoof and Peterson 2006; Peterson 2009).

Based on the strong upwelling, 2013 was expected to be a highly productive year, particularly for coastal species. The strong upwelling in the winter of 2013 was due to a strong north Pacific high (Schroeder et al. 2013), which results in high production, especially in central California (Black et al. 2010; Black et al. 2011; Garcia et al. 2014). Off Oregon, larval rockfish were found in higher than average numbers during the summer, whereas larval northern anchovy were found at low concentrations; within the central CCS, strong upwelling may reduce anchovy density (Santora et al. 2014). Also, juvenile coho salmon were found at high numbers during summer 2013. A PCA of pelagic fish species found that off Oregon, 2013 was similar to 2006, 2008, and 2012. On the central California coast, juvenile rockfish were found at very high abundances, along with market squid and krill, and a moderately high abundance of Pacific hake. These findings are consistent with 2013 being a year that favored species that respond to high transport and coastal upwelling conditions in the winter and spring (Black et al. 2011; Santora et al. 2014).

In general, the response of seabirds within the CCS to this heightened coastal productivity was also positive. Murres in northern California fledged an above average number of young in 2013. Breeding at Southeast Farallon Island was also high for all species examined there, with Cassin’s auklets having an exceptional year. The bird species examined all tend to feed on prey that responds

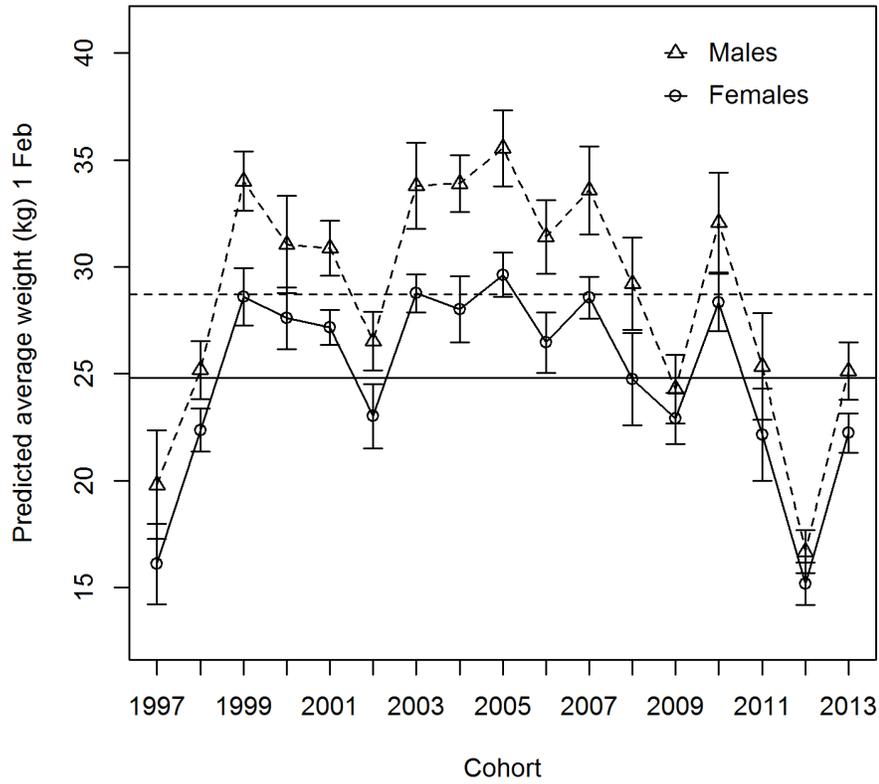


Figure 38. Predicted average weights of 7 month old female (open circle) and male (open triangle) California sea lion pups at San Miguel Island, California, 1997–2013 and long-term average between 1975 and 2013 for females (solid line) and males (dashed line). Error bars are  $\pm 1$  standard error.

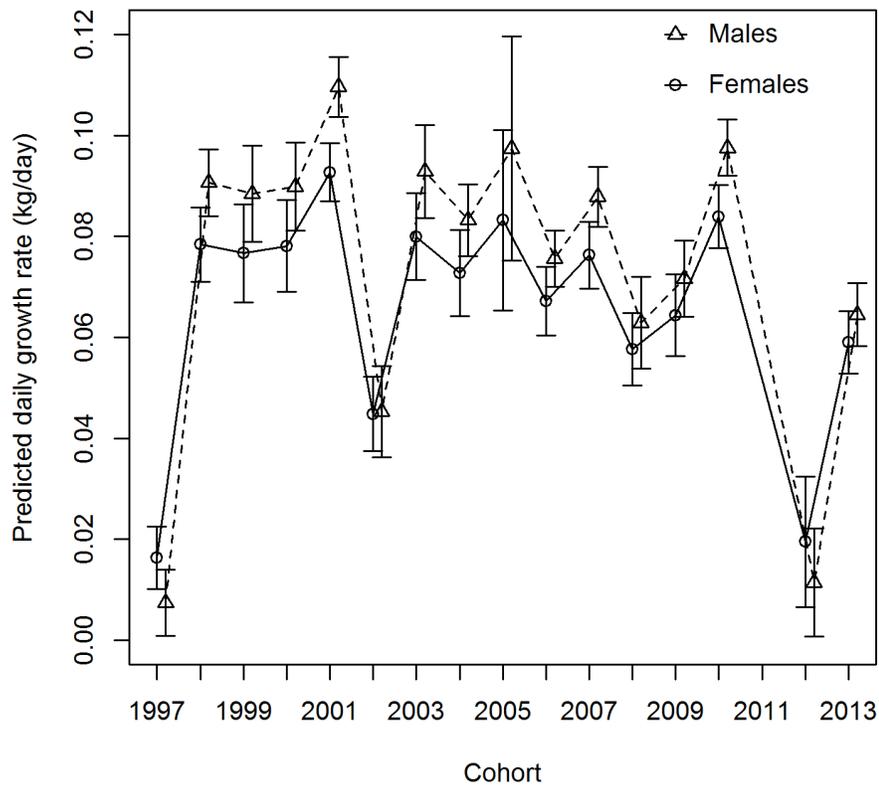


Figure 39. Predicted average daily growth rate of female (open circle) and male (open triangle) California sea lion pups between 4 and 7 months old at San Miguel Island, California, 1997–2013. Error bars are  $\pm 1$  standard error.

well to upwelling; in these cases, the high numbers of juvenile rockfish and euphausiids that responded to the increased upwelling during 2013 (Ainley et al. 1995; Wells et al. 2013; Santora et al. 2014). Farther north, in Oregon, the murrelets at Yaquina head did not show a positive response in 2013, however, this was likely due to increased predation on the chicks and eggs. Within the CalCOFI region, sooty shearwater abundance was high in spring, but was low during summer 2013; the majority of the CalCOFI region was not as heavily influenced by the strong 2013 upwelling that occurred primarily along central California.

The previous year's SOTCC annual report (Wells et al. 2013) speculated on the potential effects of the strong winds that occurred early in 2013 on the overall productivity and structure of the ecosystem. Specifically, such anomalously strong winds could lead to increased diffusion of nutrients and phytoplankton away from the coast, and concomitant changes in the upwelling reliant species. Within the CalCOFI region, where there were subsurface measurements of nutrients, this was clearly not the case; 2013 saw high levels of nitrate, particularly during the spring (April) cruise (fig. S7). Primary production and chlorophyll *a* were also generally high throughout the CalCOFI region for most of 2013 (fig. S8). Chlorophyll *a* levels were also high along coastal central California, as evidenced by the observations from Monterey Bay (fig. 14). In a detailed spatial analysis of chlorophyll *a* long-term trends, 2013 also showed relatively high levels of chlorophyll *a* compared to the long-term mean for most regions examined (fig. 9). Chlorophyll *a* levels sampled off of Oregon were also high throughout 2013 (fig. 11). The Trinidad Head line was the one exception to this, with relatively low chlorophyll *a* throughout 2013, as compared to previous years (fig. 12). Thus productivity, at least as evidenced by chlorophyll *a* biomass, does not seem to have been negatively impacted by "too much upwelling," except perhaps at a few limited locations. This is in contrast to another recent high upwelling year, 1999, in which chlorophyll *a* concentrations were observed to be high nearly 50 km offshore rather than next to the coast, consistent with the offshore position of the upwelling front (Schwing et al. 2000). However, as correctly predicted, the strong upwelling and resulting high coastal productivity did favor species which rely on this type of structure; northern copepod species saw increased abundances to the north, and within the south, total zooplankton volumes were high. Species such as juvenile rockfish (*Sebastes* spp.) and market squid thrived, whereas sardine and anchovy abundances were very low.

In the spring and early summer of 2014 the CCS transitioned away from the cool, strong upwelling con-

ditions of 2013, marking a significant change in the state of the California Current from the past few years. As of August 2014, most basin-scale indices suggest that 2014 is transitioning to a moderate El Niño state. The ENSO-MEI, PDO, and NPGO all changed sign during the winter of 2013–14 (table 1, fig. S1). SST was anomalously high throughout most of the CCS during spring and summer 2014, with springtime chlorophyll *a* levels anomalously low in nearly all locations, except a few spots along the central coast. Surface temperatures measured from coastal buoys were also high during the spring of 2014, except for the northernmost stations. Unlike SST and chlorophyll *a*, several indices remain more near a "neutral state" similar to the long-term monthly or seasonal climatological means. Upwelling anomaly was neutral or only slightly negative throughout most of the coastal region during the spring and early summer (fig. 2). The cumulative upwelling index was also near long-term seasonal averages for most locations (fig. 3). Biomass of northern copepods off Oregon remained relatively high through early summer of 2014 (fig. 11), which is counter-indicative of an El Niño state (Peterson et al. 2002; Hoof and Peterson 2006). Within the CalCOFI region, spring 2014 yielded very few sardine eggs or larvae, and also very low numbers of adults, although the distribution of adults was likely very patchy, confounding an interpretation of abundance (fig. 26). Sardine and anchovy abundance was also low along the central coast (fig. 22), similar to conditions found during past El Niños (McClatchie 2014). Conditions in the Equatorial Pacific signify a developing El Niño but its current impact on environmental conditions in the CCS due to atmospheric teleconnections is not so pronounced (Schwing et al. 2002a; Schwing et al. 2002b; Schwing et al. 2005). So far, the effects seem to be more to the very north and south ends of the CCS, with a much more minor impact to the central coast area. Upwelling and chlorophyll *a* levels are still near the climatological means for the mid to central California coast. Catches of rockfish, market squid, pacific sanddab, and euphausiids were also high along the central and southern California coast during summer 2014 (fig. 22). The effects of the looming El Niño also seem to have impacted a larger total area of the CCS during the winter of 2013–14, as compared to the late spring of 2014, which saw a moderate amount of upwelling in certain locations. The winter of 2013–14 saw some of the larger anomalous El Niño-type values throughout the region, which corresponded to warm SST in the central equatorial region and led to the prediction of an El Niño event occurring in 2014 (Ludescher et al. 2014).

Comparing the conditions leading up to this point within the CCS with previous time periods leading up

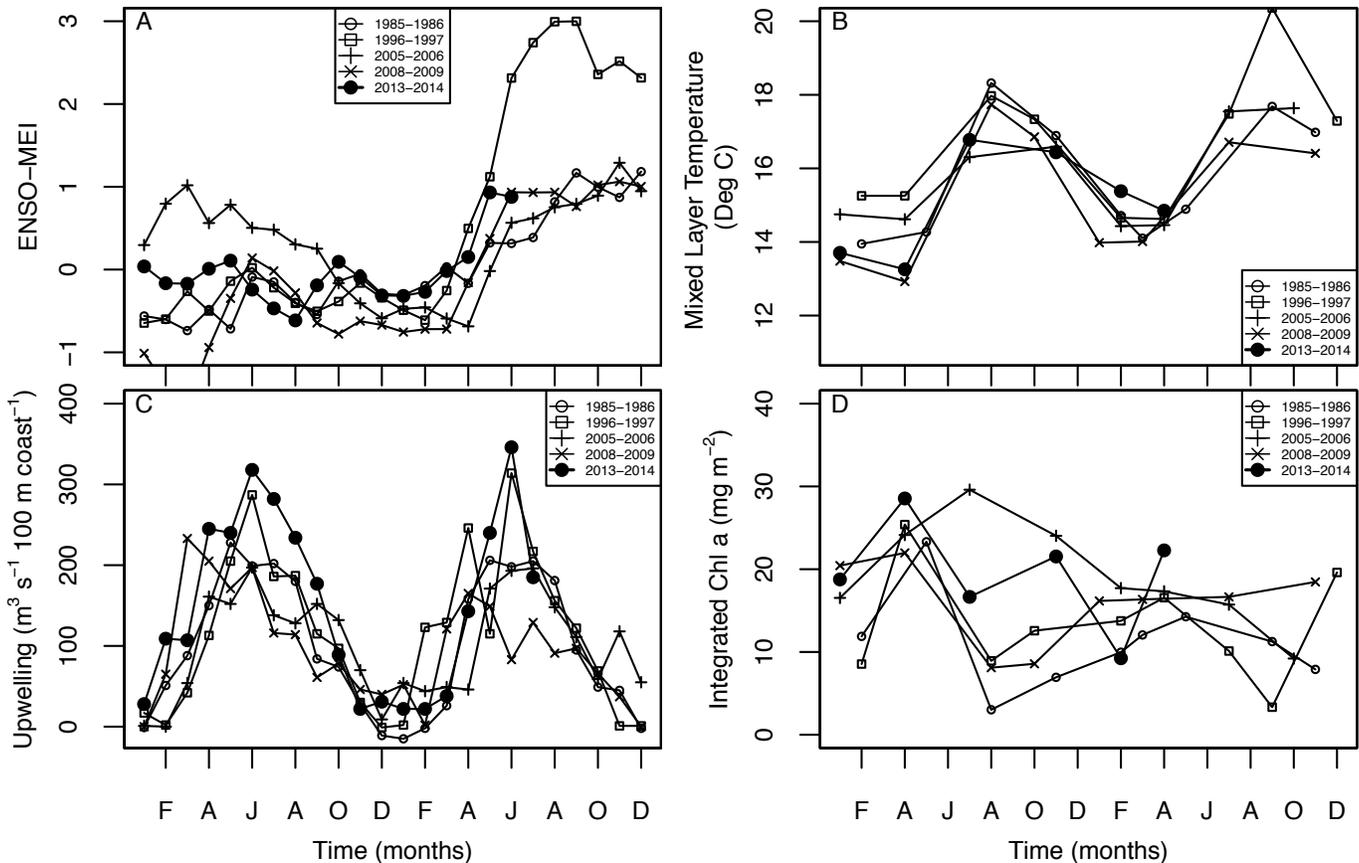


Figure 40. Selected indicators for Jan 2013 to July 2014 by month versus similar time periods leading up to several past El Niño events; a) MEI- ENSO index, b) Average mixed-layer temperature within the CalCOFI grid, c) Average upwelling index from 36N, 122W, and d) Chlorophyll *a* integrated within the mixed layer from the CalCOFI grid.

to other El Niños suggests this will be only a moderate event (fig. 40), if it does occur (as of Oct 2014, NOAA’s National Weather Service predicts a weak El Niño to begin in Nov–Dec and last until spring 2015; <http://www.elnino.noaa.gov>). The ENSO-MEI index for Jan 2013–July 2014 was similar to the more moderate El Niños, with a notable drop off for June, and unlike the strong 1996–98 El Niño (fig. 40a). Average mixed-layer temperature throughout the CalCOFI region was also most similar to the more moderate El Niño of 2005–06 during this lead-in period than the other El Niños compared (fig. 40b). Upwelling during this lead-in period was also similar to previous El Niños, although higher for certain months than several other comparable El Niños (fig. 40c). Chlorophyll *a* also appears to have been higher during this lead-in period than the other El Niños (except the 05–06 time period, and February 2014; this latter cruise only covered the southern portion of the grid, thus this average is artificially low for that month). Unlike these past El Niños, we know that the lead-in year, 2013, was a year of generally strong upwelling, with generally enhanced biological response. What is unclear is how much this longer-term El Niño

“preconditioning” could be affecting the evolution of the impacts of the predicted, apparently mild, El Niño on the CCS.

Already it is clear that as of the end of August 2014, at least some portions of the central, coastal CCS are not as impacted—upwelling remains near climatological levels and chlorophyll *a* remains high. However, the more detailed spatially explicit analysis of temperature and chlorophyll *a* suggests that the majority of the CCS is both warm and low in chlorophyll *a* (figs. 7–9). If this spatial trend continues—mild El Niño conditions for the northern, most southern, and offshore portions of the CCS, with moderate upwelling along the central coast—then it may be that 2014 will be a year with a very patchy distribution in production, and fairly different overall from 2013. Indeed, the most recent view of chlorophyll *a* anomaly for July 2014 shows a very patchy distribution of both low and high chlorophyll *a* regions spread throughout the nearshore region, with a pattern markedly different from only a few months ago (fig. 6). How this spatial and temporal patchiness in upwelling, chlorophyll *a*, and presumably productivity will affect the evolution of the ecosystem during

2014 remains to be seen, but may result in an interesting mix of El Niño responsive species in the most southern, northern, and offshore regions, with nearshore patches of upwelling-dominant species. Superimposed on these conditions, recent analysis of satellite SST and wind data shows that there has been extensive, possibly non-El Niño-related warming to three major areas within the Northeast Pacific: the Bering Sea; the Gulf of Alaska; and most recently, offshore of southern California (Milstein et al. NOAA-Technical Report, 2014, [http://www.nwfsc.noaa.gov/news/features/food\\_chain/index.cfm](http://www.nwfsc.noaa.gov/news/features/food_chain/index.cfm)). Although it is unclear exactly how the looming El Niño will interact with these warm pools, the likely result will be even more warming and stronger El Niño-like conditions than expected from a moderate El Niño alone; such conditions are generally unfavorable to many key fisheries species.

## ACKNOWLEDGEMENTS

Andrew W. Leising was partially funded through NOAA's Fisheries and the Environment (FATE) program. Ichthyoplankton collections off the Oregon coast were supported in part by NOAA's Stock Assessment Improvement Plan (SAIP) and Fisheries and the Environment (FATE) programs, as well as from a grant through the Bonneville Power Administration (BPA). Financial support was provided by the NASA Ocean Biology and Biogeochemistry Program Grants NNX-09AT01G (M. K.), National Science Foundation (Grant OCE-1026607 to the CCE LTER Program). Satellite data were provided by the NASA Ocean Color Processing Group and ESA MERIS team. We thank the CalCOFI and CCE-LTER programs, NOAA SWFSC survey, Monterey Bay Aquarium Research Institute and Pacific Coastal Ocean Observing System for in situ data. R. DeLong, J. Harris, J. Laake, A. Orr and many field assistants participated in the data collection and summaries. Funding was provided by the National Marine Fisheries Service. Research was conducted under NMFS Permit 16087 issued to the National Marine Mammal Laboratory.

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Part II

**SYMPOSIUM OF  
THE CALCOFI CONFERENCE  
2013**



## DIET OF A PISCIVOROUS SEABIRD REVEALS SPATIOTEMPORAL VARIATION IN ABUNDANCE OF FORAGE FISHES IN THE MONTEREY BAY REGION

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### EXTENDED ABSTRACT ARTICLE

#### EXTENDED ABSTRACT

Seabirds have increasingly been studied as indicators of the marine ecosystem (Piatt et al. 2007). As a piscivorous generalist (Ainley et al. 1981) the Brandt's Cormorant (*Phalacrocorax penicillatus*) is a good indicator species in the California Current System (CCS). Their distribution includes the full latitudinal extent of the CCS (Wallace and Wallace 1998), thereby providing insight into the spatial aspects of prey fluctuations. Northern anchovy (*Engraulis mordax*), rockfishes (*Sebastes* spp.), and market squid (*Doryteuthis opalescens*) that are common in Brandt's Cormorant diet are important to many other predators in the CCS (Morejohn et al. 1978; Ainley et al. 1990).

The Brandt's Cormorant is the most abundant locally nesting seabird in the Monterey Bay region of central California. From 1989 to the mid-2000s many new colonies formed, some with rapid growth, including the first report of nesting within Monterey Bay (Carter et al. 1992; Bechaver et al. 2013; Capitolo et al. 2014). The species occupies a middle-to-upper trophic position in the nearshore marine food web (Ainley et al. 1995), consuming young-of-the-year, juvenile, and small adult fishes and, to a lesser extent, squid (Sydeman et al. 2001; Webb 2013). Given their reliance on the inner continental shelf habitat, year-round occurrence (Briggs et al. 1987; Wallace and Wallace 1998), and consumption of approximately 20% of their body mass per day (Ancel et al. 1997), Brandt's Cormorants can potentially extract large numbers of prey from the Monterey Bay region.

Two previous Brandt's Cormorant diet studies in Monterey Bay were conducted during the 1970s and sampled the nonbreeding season, September to March (Baltz and Morejohn 1977; Talent 1984). Rockfishes and Pacific sanddab (*Citharichthys sordidus*) were the two main prey during the 1970–71 and 1974–75 nonbreeding seasons; however, northern anchovy and market squid also were important in 1974–75. Since then, overfishing and an unfavorable warm water period caused a substan-

tial decrease in abundance of juvenile rockfishes during the 1990s in the central California Current with only partial recovery as of the early 2000s (Mills et al. 2007). Commercial market squid landings in Monterey Bay decreased substantially beginning in 2005 (CDFG 2009) indicating decreased abundance. Our goal was to determine present diet composition of Brandt's Cormorants to further our understanding of how a major avian predator responds to a decrease of multiple important prey resources, thereby providing important information about central California food web dynamics. El Niño and La Niña conditions during the study (CalCOFI 2008) provided a unique opportunity to examine predator response to changes in oceanographic conditions (Webb 2013; Webb and Harvey 2014).

Brandt's Cormorant diet composition in the Monterey Bay region was investigated using regurgitated pellets ( $n = 285$ ) collected on 19 sampling days at 3 roosting locations: Año Nuevo Island, Moss Landing Harbor, and Monterey Harbor, during the 2006–07 and 2007–08 nonbreeding seasons. Each cormorant casts one regurgitated pellet per day at roosting locations containing prey remains from the prior 24 h. Most fish otoliths, cephalopod beaks, and other prey hard parts contained in cormorant pellets have enough structure to determine species ingested; therefore, pellets are useful for answering broad spatial and temporal questions such as comparing diet among seasons or years (Ainley et al. 1981; Duffy and Laurenson 1983). Pellets can be collected with minimal disturbance, especially during the nonbreeding season, but this source of diet information has been underutilized. Sampling design, sample size, pellet processing method, prey size, and fine-scale spatiotemporal variability in the diet also were assessed (Webb 2013; Webb and Harvey 2014).

Although 29 prey species were consumed during the 2006–07 and 2007–08 nonbreeding seasons, northern anchovy dominated and speckled sanddab (*Citharichthys stigmaeus*) also was important in the diet. Few rock-

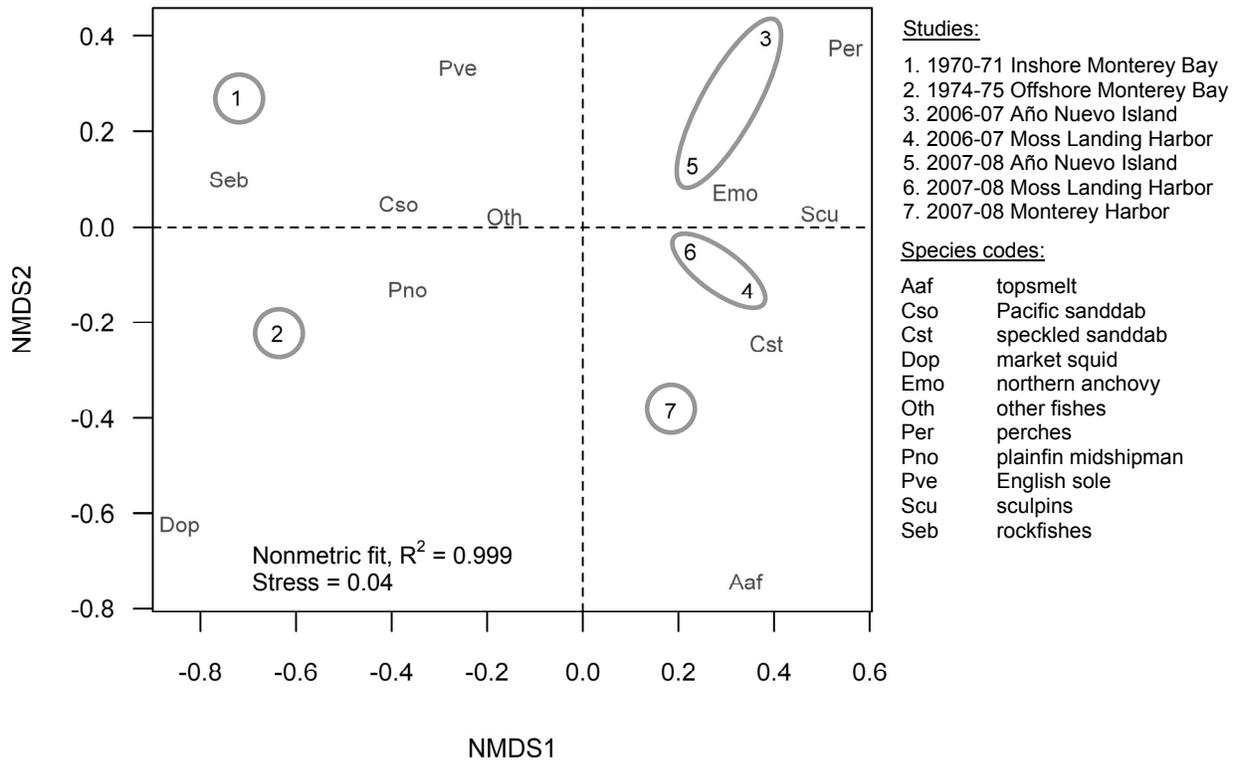


Figure 1. Nonmetric multidimensional scaling ordination comparing overall Brandt's Cormorant diet composition by percent number (%N) among studies in the Monterey Bay region. Each study is represented by a number and studies with the same location are circled. Prey species comprising less than 5% of the diet were combined into category "other fishes". Proximity to three letter prey species codes indicates importance in the diet. Historic data are from 1) Talent 1984 and 2) Baltz and Morejohn 1977 while the remaining data are from this study.

fishes and market squid were consumed compared with great prevalence in previous studies in the Monterey Bay region during the 1970s.

Overall multivariate diet composition data (percent number, %N) for the two historical nonbreeding season diet data sets in Monterey Bay during the early 1970s (Baltz and Morejohn 1977; Talent 1984) and the five location and nonbreeding season combinations sampled in this study were compared using nonmetric multidimensional scaling (NMDS; fig. 1). The first NMDS axis separates the historic data from this study by differences in dominant prey: rockfishes were prevalent in the historical data compared with northern anchovy in this study. The second NMDS axis further separates the diet by prey consumed in particular nonbreeding seasons and locations. Pacific sanddab was consumed during both studies in the 1970s whereas market squid was only in the diet of birds collected offshore in Monterey Bay during the 1974–75 nonbreeding season. During this study, perches (Embiotocidae) occurred in the diet at Año Nuevo Island, speckled sanddab was prevalent in the diet at both locations inside Monterey Bay, whereas topsmelt (*Atherinops affinis*) was mainly observed in the diet at Monterey Harbor.

There was a clear shift in the diet of Brandt's Cormorants from rockfishes in the 1970s to northern anchovy

in the mid-2000s in Monterey Bay. There is some evidence that another major fluctuation in the dominant prey of Brandt's Cormorants began at the end of this study. The dominance of northern anchovy waned during the 2007–08 nonbreeding season. Brandt's Cormorant breeding population size in the Monterey Bay region peaked during our study, declined in 2008 and 2009, and then began rebounding in 2010 (Bechaver et al. 2013; Capitolo et al. 2014). Abundance of northern anchovy in central California has been suggested as a contributing factor to the breeding population increase and the subsequent decline of northern anchovy as the potential cause of the 2009 central coast die-off of Brandt's Cormorants (Gibble et al. 2010; Bechaver et al. 2013; Capitolo et al. 2014). This study demonstrated the importance of periodic sampling to detect spatiotemporal variability in the diet of opportunistic generalists.

#### ACKNOWLEDGMENTS

Point Blue Conservation Science provided access to Año Nuevo Island and the U.S. Coast Guard granted access to the Monterey Harbor breakwater. Samples were collected under National Marine Fisheries Service Permit No. 87-1851-00 and IACUC Protocols 2003-E, F, & G, and 2007-E, F, & H. Thank you to the many volunteers who assisted with sample collection. Financial

support was provided by H. Thomas Harvey Fellowship, Gerds Fellowship, Signe Lundstrom Memorial Scholarship, Myers Oceanographic and Marine Biology Trust, David and Lucile Packard Research and Travel Award, and a National Science Foundation Grant (No. HRD-0802628) administered by William Head at the California State University Monterey Bay Undergraduate Research Opportunities Center. The assistance of Erin Frolli and Chandra Baughman in processing samples was instrumental to the completion of this project. We thank Gregor Cailliet and Josh Adams for their insightful comments on the draft manuscript.

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## PELAGIC AND DEMERSAL FISH PREDATORS ON JUVENILE AND ADULT FORAGE FISHES IN THE NORTHERN CALIFORNIA CURRENT: SPATIAL AND TEMPORAL VARIATIONS

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### ABSTRACT

A requisite for reliable food web models and ecosystem-based management in regions such as the California Current is the availability of diet information on key predators. In upwelling ecosystems, much of the lower trophic level energy may be transferred through a relatively small set of very abundant pelagic forage fish taxa, such as anchovies, sardines, smelts, and herring. In addition the pelagic juvenile stages of some important midwater and demersal fishes (Pacific hake and rockfishes) may act as forage fishes during a more limited time period each year. In this paper, we review what is known about the utilization of these forage species by larger fish predators and elasmobranchs in the Northern California Current (NCC) from northern Washington to northern California (Cape Mendocino) to examine spatial and temporal variations in the kinds and sizes of forage fishes consumed. We found that predation on forage fishes was highly variable in space and time, and was often dependent on the size of the prey available as well as the predator. Pacific hake and spiny dogfish have the potential to be dominant forage fish predators due to their high biomass but other species such as arrowtooth flounder and Pacific halibut can be important due to their high proportion of forage fish in the diet. We also highlight where diet information is limited or lacking, and areas where regular fish diet monitoring could be useful for ecosystem-based management.

### INTRODUCTION

Variability in the spatial and temporal magnitude of predation has important implications for the population structure of prey species (Livingston 1993; Bakun et al. 2009). As a group, small pelagic fish species (and juvenile stages of larger pelagic and demersal species) often form the bulk of fish predator diets, particularly in highly productive upwelling ecosystems. These prey species, collectively called forage fishes, are generally short-lived but highly abundant, and form dense aggregations or schools as an anti-predator strategy in near-surface waters. Forage fish act as an intermediate trophic level and conduit of energy from a large number of primary consumer species up to highly diverse upper trophic levels, but in upwelling systems are generally limited to a few key spe-

cies, thus giving rise to the term “wasp-waist” ecosystems (Rice 1995; Cury et al. 2000). Although recent studies in the California Current (Ware and Thomson 2005; Miller et al. 2010; Madigan et al. 2012) and other pelagic systems (Hunt and McKinnell 2006; Fréon et al. 2009) suggest this is not always the situation, the importance of these small pelagic fishes is unequivocal for some predators. Recent modeling studies suggest that depleting forage fishes can have detrimental effects on upper trophic levels (Field et al. 2010; Smith et al. 2011; Ruzicka et al. 2012; Kaplan et al. 2013). Having an overabundant species of forage fish can also negatively affect predatory fish populations (Bakun et al. 2009). Direct harvesting of this trophic level has precipitated recommendations to leave aside a specific percentage of the forage fish biomass for higher trophic levels dependent upon them as a precautionary approach (Cury et al. 2011; Pikitch et al. 2012, 2014). Conversely, fisheries on predator species can lead to higher biomasses of forage fishes in an ecosystem (Houle et al. 2013).

Forage fishes occupy a prominent role in the pelagic ecosystem of the Northern California Current (NCC), and often dominate catches during pelagic surveys (Brodeur et al. 2005; Emmett et al. 2005; Litz et al. 2014). Some forage species are NCC residents throughout the year (northern anchovy *Engraulis mordax*; Pacific herring *Clupea pallasii*, several smelt species including whitebait smelt *Allosmerus elongatus*, surf smelt *Hyposmesus pretiosus*, and eulachon *Thaleichthys pacificus*), but others are transients, spawning in other regions and migrating into the NCC seasonally (Pacific sardines *Sardinops sagax*), and a few species are of suitable size to be consumed by fish predators only when they are age-0 or age-1 juveniles (juvenile rockfish *Sebastes* spp., and juvenile Pacific hake *Merluccius productus*). However, this occurs only in certain years when their distributions make them available to NCC predators (Phillips et al. 2007, 2009; Brodeur et al. 2011).

Although a substantial body of literature exists on what individual fish predators and even assemblages of fishes consume in the NCC (Brodeur et al. 1987; Buckley et al. 1999; Miller and Brodeur 2007; Dufault et al. 2009), few studies (see Emmett et al. 2006) have examined this from the perspective of the prey (i.e., what are

the important predators on a particular prey species?). In this paper, we review what is known about the utilization of these forage species by larger fish predators and elasmobranchs in the Northern California Current from northern Washington to northern California (Cape Mendocino) to examine spatial and temporal variations in the kinds and sizes of forage fishes consumed. As many fish predator diets change as they increase in size, we attempt to examine ontogenetic or size-based changes as well. We also discuss factors (seasonal occurrence, aggregation patterns, energetic quality) that make these forage fishes attractive prey for these nektonic predators. We also highlight where diet information is limited or lacking and areas where regular fish diet monitoring could be useful for ecosystem-based management.

## METHODS

The geographic area considered in this study is primarily the continental shelf waters off the coast of Washington, Oregon, and northern California down to Cape Mendocino (fig. 1), which encompasses the majority of the NCC domain. This domain can extend northward to off the west coast of Canada in many years and some diets studies have been done in the northern region of the NCC for the predators considered in this study (e.g., Tanasichuk et al. 1991; Ware and McFarlane 1995; Tanasichuk 1997), but we chose to narrow our focus to the NCC in US waters where the bulk of the studies have been undertaken.

We conducted a review of primary and unpublished (theses and technical reports) diet studies for all potential fish predators on forage fishes. Although a large number of studies exist on elasmobranch and fish predators from this geographic area (many summarized by Dufault et al. 2009), we restricted our analysis to those species that had at least 25% by weight of their diet made up of forage fish, to focus on the main predators. To make the available data comparative among the different predators, we summarized diet information based on the percent by weight of the total diet made up by the following forage fishes: northern anchovy, Pacific herring, true smelts (Family Osmeridae, several species combined as often not differentiated in the diet studies), Pacific sardine, juvenile rockfish, and juvenile Pacific hake. Other forage fishes were found occasionally (Pacific saury *Cololabis saira*, Pacific sand lance *Ammodytes hexapterus*, juvenile salmon *Oncorhynchus* spp., and American shad *Alosa sapidissima*) but their occurrence was highly sporadic (i.e., often just one predator preyed upon them or they were consumed only in one or two studies), so for the purposes of this study we grouped these into a category called “other fishes”, which may include some prey fishes not listed above (juvenile flatfishes, mesopelagic species, sculpins, etc.). This category also includes all fishes not

identified to family due to poor state of digestion and may in fact include some proportion of our target forage fish taxa but were not identifiable to one of our forage groupings. Other important prey not considered forage fish such as euphausiids, other crustaceans, squids (mostly the market squid *Doryteuthis opalescens*), and jellyfish (gelatinous zooplankton) were included when consumed, but these alternative prey were not emphasized in the diet comparisons. Fish predators were grouped into pelagic fishes and demersal fishes depending on the primary habitat of the adult population. When available, data were summarized from tables provided in the source literature or from unpublished data from the original author(s). The reader is referred to the original publication for detailed information on sampling and stomach analysis methodologies. We could not provide graphs for all the studies examined as in some cases the sample size was insufficient or the data were not provided in a form that we could use (e.g., diets given in percent by number or frequency of occurrence), but in these cases we refer to these studies in the text.

We also incorporated some unpublished data for certain predators or time periods where a sufficient body of literature was unavailable. The main source for this additional diet data is a food habits database from West Coast groundfish surveys undertaken within the past decade (Keller et al. 2012). Yellowtail *Sebastes flavidus*, yelloweye *Sebastes ruberrimus*, rougheye *Sebastes aleutianus*, and bocaccio rockfish *Sebastes paucispinis* stomachs were collected from May through September of 2005–13 as part of an ongoing diet study conducted during the annual Northwest Fisheries Science Center (NWFS) West Coast Groundfish Bottom Trawl (WCGBT) surveys. Sablefish *Anoplopoma fimbria* stomachs were collected as well in 2005 and 2008 on this survey. The WCGBT survey uses an Aberdeen 85–104 bottom trawl, and the fishing stations are selected by stratified random sampling design. This survey operates annually from May–October from the Mexico/US border (32.5°N) to Cape Flattery, WA. (48.2°N) but we used only samples obtained from the area north of Cape Mendocino, CA (fig. 1) (40.26°N) for this study. WCGBT sampling is conducted during daylight hours and target depths from 55 to 1280 m. Stomachs are randomly selected from each haul, but any sampled fish with signs of regurgitation or extruding stomach are excluded from collection. Samples are preserved in individual bags and length, weight, and sex of each fish are recorded at sea, along with trawl station information, including location and depth. In the laboratory, stomach contents are identified under a dissecting microscope down to species when possible and weighed. Several items in the stomach were subsequently discarded as they were likely offal from bait fisheries.

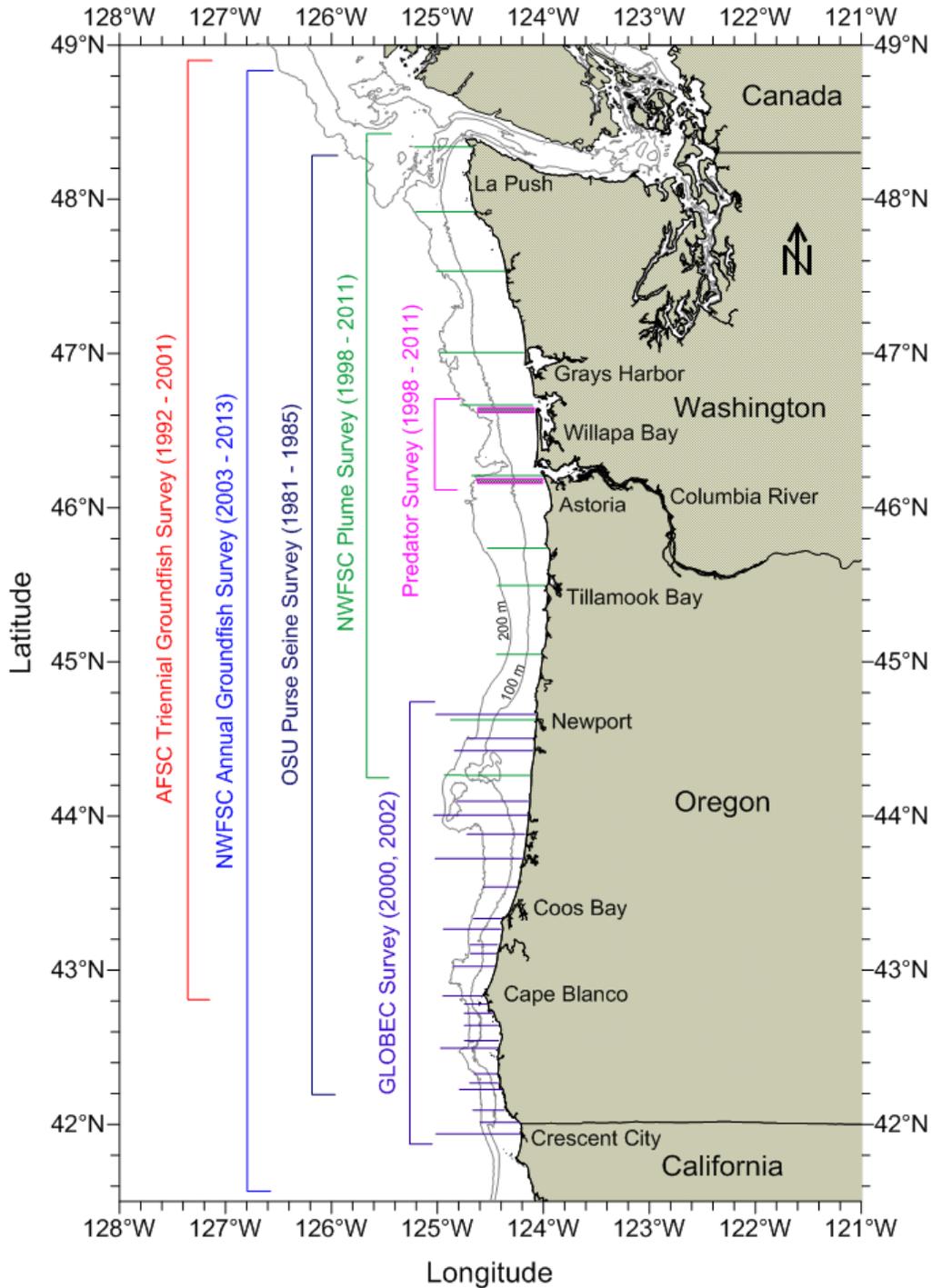


Figure 1. Location of major sampling programs off the coasts of Washington, Oregon and Northern California. Transect lines regularly sampled during NWFS Plume surveys, predator surveys, and GLOBEC survey are indicated and the other surveys occupied a more irregular sampling pattern.

We also examined the prey size composition of two predators (Pacific hake and adult Chinook salmon *Oncorhynchus tshawytscha*) for which we had substantial prey length information (Emmett and Krutzikowsky 2008; Daly et al. 2009) and compared these to what were available from pelagic trawl surveys done at

night in the same region (Emmett et al. 2005; Litz et al. 2014).

To estimate the relative impact of the various forage fish predators in the NCC, we derived estimates of the summer biomass along the shelf and slope waters off Washington, Oregon, and Northern California based

TABLE 1  
 List of Northern California Current fishes that have the potential to have forage fish in their diets and that were included in this study.

Scientific Name	Common Name	Included	Diet Information
<i>Lamna ditropis</i>	Salmon shark		Not available for N. California Current
<i>Alopias vulpinus</i>	Thresher shark		Not available for N. California Current
<i>Galeorhinus zyopterus</i>	Soupin shark	x	
<i>Prionace glauca</i>	Blue shark	x	
<i>Squalus suckleyi</i>	Spiny dogfish	x	
Torpedinidae	Electric (torpedo) rays		Not available for N. California Current
<i>Oncorhynchus kisutch</i>	Coho salmon	x	
<i>Oncorhynchus tshawytscha</i>	Chinook Salmon	x	
<i>Oncorhynchus clarki</i>	Cutthroat trout		Limited information
<i>Oncorhynchus mykiss</i>	Steelhead		Limited information
<i>Gadus macrocephalus</i>	Pacific cod		Not available for N. California Current
<i>Merluccius productus</i>	Pacific hake	x	
<i>Sebastes</i> spp.	Rockfishes	x	
<i>Ophiodon elongatus</i>	Lingcod	x	
<i>Anoplopoma fimbria</i>	Sablefish	x	
<i>Scopaeinichthys marmoratus</i>	Cabezon		Limited information
<i>Trachurus symmetricus</i>	Jack mackerel	x	
<i>Thunnus alalunga</i>	Albacore	x	
<i>Trichodon trichodon</i>	Pacific sandfish		Not available for N. California Current
<i>Anarrhichthys ocellatus</i>	Wolf-eel		Not available for N. California Current
<i>Hippoglossus stenolepis</i>	Pacific halibut	x	
<i>Atheresthes stomias</i>	Arrowtooth flounder	x	

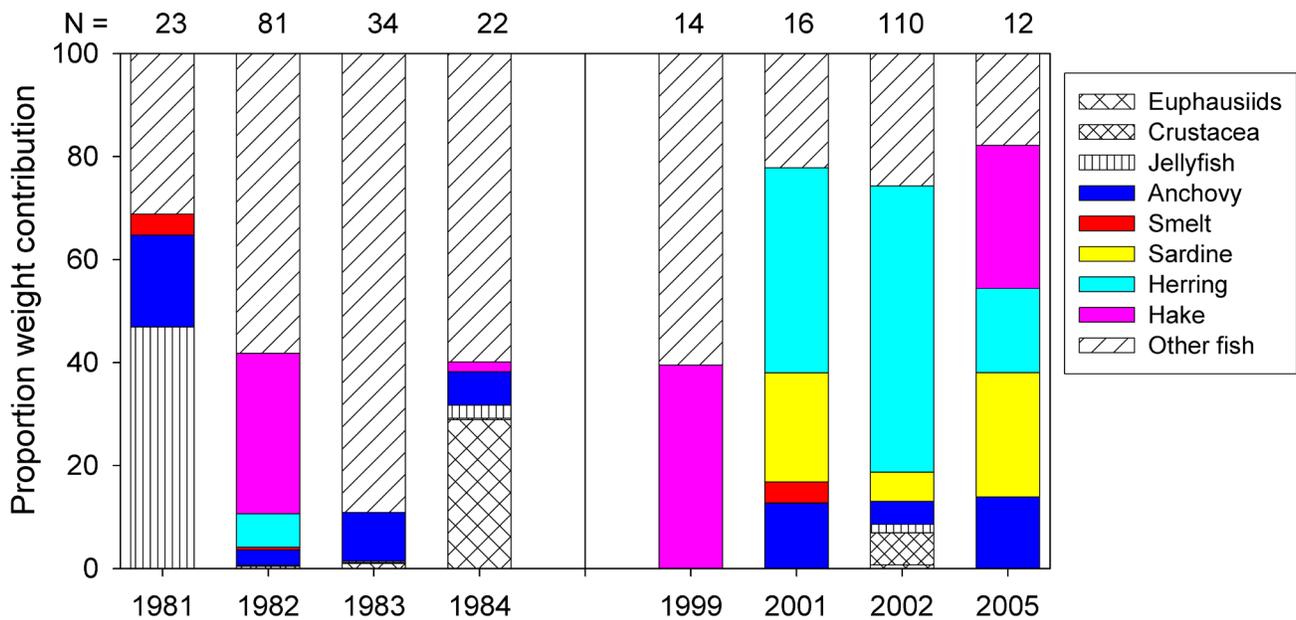


Figure 2. Diet composition of spiny dogfish (*Squalus suckleyi*) collected off Oregon and Washington during the OSU Purse Seine Survey (left panel) and the NWFSC Plume Survey (right panel) from May through September during different years. Number of stomachs with food is indicated at the top of each bar.

on stock assessments available from the Pacific Fisheries Management Council or the International Pacific Halibut Commission. For unassessed species we used biomass estimates from the WCGBT surveys for demersal species (see Keller et al. 2012 for sampling details) and from scaled biomass estimates derived for ecosystem modeling (Ruzicka et al. 2012) for pelagic species. As the population size and age structure changes through

time, we attempted to confine our biomass estimates to the decade of 2000–09 where possible, although in some cases only a limited number of years were available.

RESULTS AND DISCUSSION

Overall, the number of fishes or elasmobranchs that have large proportions of their diet composed of forage fish is relatively small (table 1). Unfortunately there are

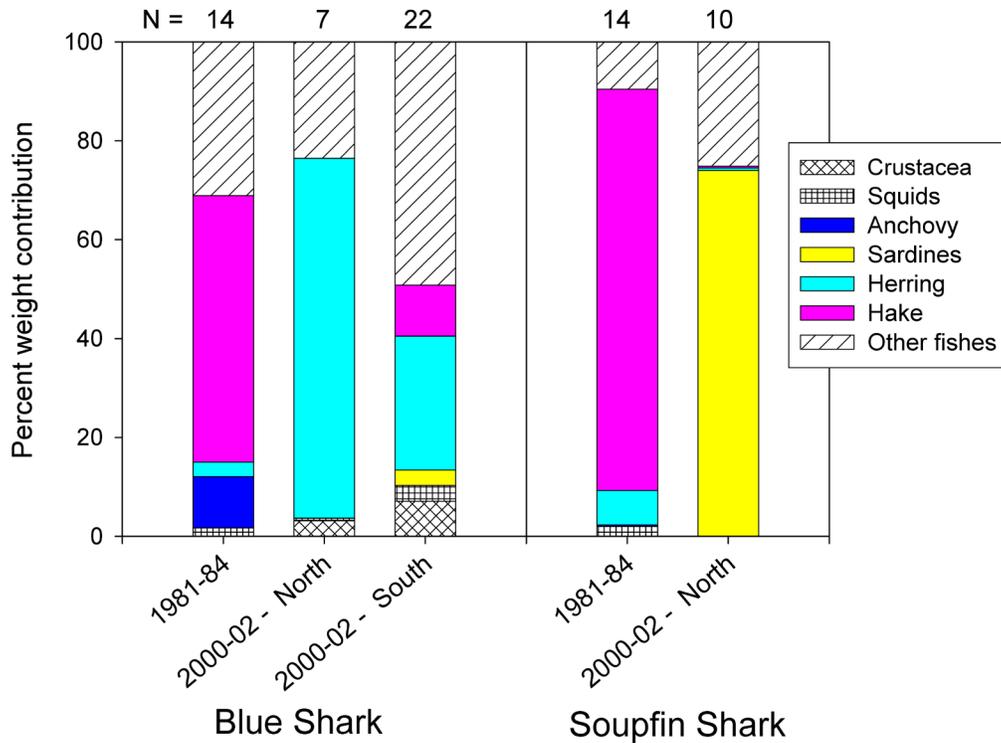


Figure 3. Diet composition of blue sharks (*Prionace glauca*, left) and soupfin sharks (*Galeorhinus zyopterus*, right) collected off Oregon and Washington during different time periods and regions. Number of stomachs with food is indicated at the top of each bar. Data from the 1980s were presented in Brodeur et al. 1987. North and South designate shelf areas north (Brodeur unpub. data) and south (Miller and Brodeur 2007) of Newport, OR (44° 40').

gaps in our knowledge regarding the diets of some large sharks (e.g., Preti et al. 2012) and other elasmobranch such as skates (Bizzaro et al. 2007) in the NCC. However, given the relatively small biomass of these species (Keller et al. 2012), they probably have relatively small effects on forage fish populations. Many rockfish species inhabit the Northern California Current but most tend to consume primarily crustaceans, gelatinous zooplankton, or other small fishes (Brodeur and Pearcy 1984; York 2005; Lee and Sampson 2009) and only a few rockfishes included here can be considered major consumers of forage fishes. Similarly, there are several flatfishes that are very important in terms of NCC biomass, but other than Pacific halibut (*Hippoglossus stenolepis*) and arrowtooth flounder (*Atheresthes stomius*), these species feed mainly on crustaceans and other benthic animals (Percy and Hancock 1978; Wakefield 1984).

**Spiny Dogfish.** The spiny dogfish (*Squalus suckleyi*) is a relative small shark species that is widely distributed in the Northern California Current. It is commonly caught in both pelagic and demersal trawl surveys on the shelf extending offshore (Brodeur et al. 2009). Dominant forage fishes consumed in the 1980s from purse seine caught dogfish (length from 320–1190 mm) included juvenile Pacific hake, northern anchovy, and Pacific herring, although flatfish juveniles were most important in the “other fish” category (Brodeur et al. 1987; fig. 2). In

more recent trawl sampling, these same three forage taxa contributed to the diet with the addition of Pacific sardine and smelt in some years (Brodeur et al. 2009; fig. 2). Studies off British Columbia north of our study area documented Pacific herring and Pacific hake as important prey as well (Jones and Geen 1977; Tanisichuk et al. 1991). Dogfish have been shown to transition from a mostly invertebrate diet (euphausiids and gelatinous zooplankton) to a predominantly fish diet as they increase in size (Tanisichuk et al. 1991; Brodeur et al. 2009).

**Blue Shark.** The diet composition (fig. 3) of blue sharks (*Prionace glauca*) consists primarily of fishes, including Pacific hake and northern anchovy in the 1980s (Brodeur et al. 1987) but also Pacific hake and small proportions of Pacific sardine and Pacific herring in more recent periods (Miller and Brodeur 2007). Studies of this species in Monterey Bay, California, indicated that it consumes large amounts of pelagic nekton (northern anchovy, spiny dogfish, and Pacific hake) by percent volume, although euphausiids can also be important (Harvey 1989). Studies off Baja California, Mexico and elsewhere indicate that cephalopods are often dominant prey in the diets of these sharks (Markaida and Sosa-Nishizaki 2010).

**Soupfin Shark.** Soupfin sharks (*Galeorhinus zyopterus*) in the NCC fed primarily on Pacific hake in the 1980s (Brodeur et al. 1987; fig. 3), however, the majority (74%

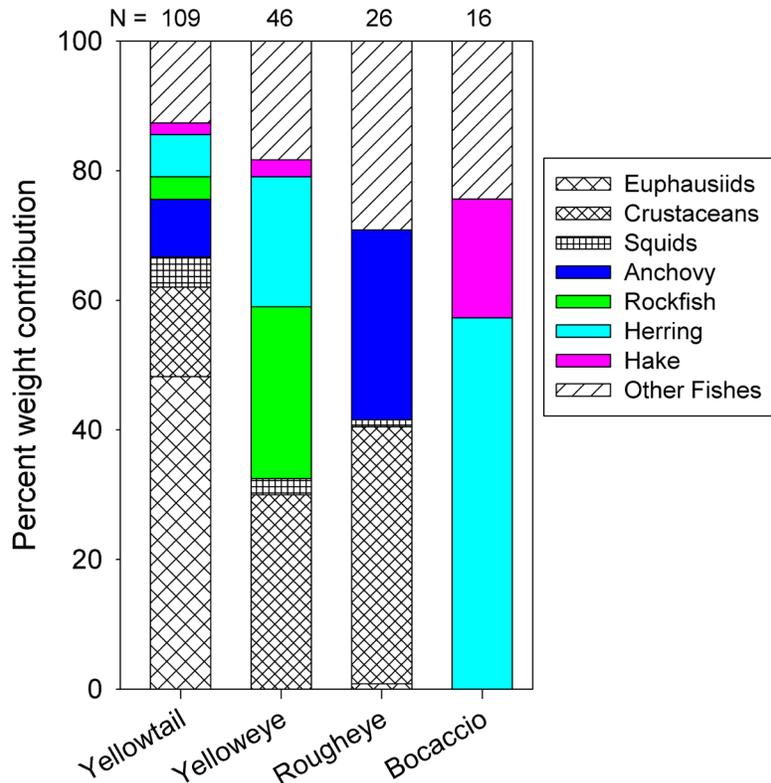


Figure 4. Diets of four species of adult rockfishes (*Sebastes* spp.) collected from Northwest Fisheries Science Center Groundfish Surveys off Washington, Oregon and Northern California from May–September, from 2005–13 (Buchanan, unpub.). Number of stomachs with food is indicated at the top of each bar.

by weight) of the prey in the early 2000s were Pacific sardine (Brodeur, unpub. data), but it is noteworthy that other fish prey consumed included unidentified juvenile salmon (*Oncorhynchus* sp.) and hagfish (*Eptatretus* sp.; fig. 3).

**Yellowtail Rockfish.** Forage fish made up 28.5% of the overall diet weight in yellowtail rockfish (*Sebastes flavidus*) stomachs collected during the 2006 and 2008 WCGBT surveys (fig. 4). Pacific hake, Pacific herring, northern anchovy, Pacific viperfish (*Chauliodus macouini*), as well as lanternfish, rockfish, and flatfish species, were also found. The remainder of prey were euphausiids (*E. pacifica* and *T. spinifera*), shrimp (species of *Pandalus*, *Sergestes*, and *Crangon*), and squids. Fish came in second to euphausiids in yellowtail rockfish diets. Although fish were found in the stomachs of small individuals ranging from 20–55 cm, the majority of fish prey was consumed by larger yellowtail rockfish (>40 cm fork length (FL)). The fish prey taxa were primarily adult northern anchovy (14 cm FL), juvenile Pacific herring (8–10 cm FL), adult and juvenile Pacific hake and juvenile rockfishes. Euphausiids dominated the juvenile (<30 cm) size-classes food composition by weight, whereas fishes and squids became increasingly important prey as rockfish grew in size. Fishes (mostly age-0 Pacific hake) were the dominant prey of yellowtail rockfish during

the summer of 1998, although quarterly samples during other times of the year showed that salps and euphausiids were equally important by weight proportions (Lee and Sampson 2009).

**Yelloweye Rockfish.** Yelloweye rockfish (*Sebastes ruberrimus*) stomachs were collected in 2008 to 2013 on WCGBT surveys. Stomachs were obtained from fish ranging from 18–68 cm FL, however, few <40 cm FL fish were obtained. Fish made up 68.2% of the overall weight in yelloweye rockfish diets (fig. 4). Pacific herring (20–25 cm), Pacific hake, and juvenile and smaller adult rockfishes (5–25 cm) were the primary forage fish consumed; but rex sole (*Glyptocephalus zachirus*), slender sole (*Lyopsetta exilis*), and arrowtooth flounder were found in the stomachs in lesser proportions. The remaining prey types consisted of shrimp (*Pandalus jordani* and *Pandalus platyceros*), crab (Galatheidae and *Lopholithodes*), and cephalopod species (fig. 4). York (2005) found Pacific herring made up over half of the diet of yelloweye rockfish (n = 9) collected in the NCC in summer and fall of 2003 and 2004.

**Rougheye Rockfish.** Rougheye rockfish (*Sebastes aleutianus*) stomachs were collected in 2008 and 2013 during the NWFSC WCGBT survey. Stomachs were obtained from fish ranging from 11–55 cm FL, however,

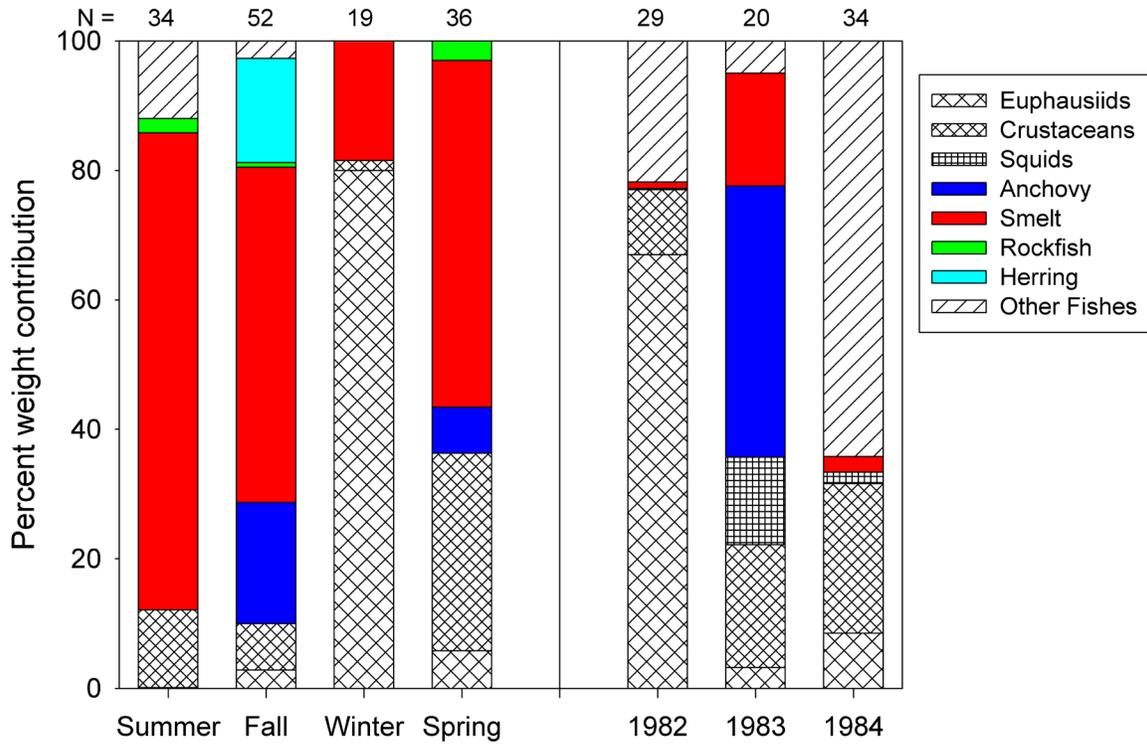


Figure 5. Diet composition of black rockfish (*Sebastes melanops*) collected seasonally from sport fishing vessels off central Oregon from 1976–77 (left, Steiner 1979) and collected during the summers of 1982–84 from OSU purse seine surveys off Oregon and Washington (right, Brodeur et al. 1987). Number of stomachs with food is indicated at the top of each bar.

few juveniles or large adults were collected. Fish made up 57.1% of the overall weight in the rougheye rockfish diet (fig. 4), with most of the weight coming from one sample containing northern anchovy. The remaining prey types were shrimp (species of *Pasiphaea*, *Pandalus* and *Crangon*), amphipods, and euphausiids.

**Bocaccio.** Bocaccio rockfish (*Sebastes paucispinis*) stomachs were collected from 2005–12 on the NWFSC WCGBT surveys. Sampled fishes ranged from 13–82 cm FL, but most were taken from 50+ cm FL fish. Fish made up 100% of the diet in the NCC samples (fig. 4). Age-1 and -2 Pacific hake and adult Pacific herring were the dominant fish prey. Other bocaccio samples taken from off southern California during the same survey revealed the addition of market squid as a prey item, as well northern anchovy, and Pacific sardine (J. Buchanan, unpub. data).

**Black Rockfish.** Black rockfish (*Sebastes melanops*) is one of the dominant coastal reef fishes in the NCC although they can often be caught close to the surface. Seasonal sampling from charter fishing boats on a reef just north of Newport, Oregon, showed that the diet was dominated by smelt all year, but northern anchovy and Pacific herring were also seasonally important (Steiner 1979; fig. 5). The proportion of fish eaten declined to less than 20% of the prey total in winter due to a high consumption of gelatinous zooplankton. Stomach data from

pelagic purse seine catches showed that black rockfish diets were very variable. In 1982, diet consisted mainly of crustaceans, whereas forage fishes (northern anchovy and Pacific herring) were dominant in the El Niño year of 1983 (Brodeur et al. 1987; fig. 5). A recent study of sport-caught black rockfish caught off Newport, OR from May to August of 2010 and 2011 showed a lower percent of fish biomass consumed compared to crustaceans, with smelt being the dominant forage species consumed (Gladics et al. 2014).

**Lingcod.** Lingcod (*Ophiodon elongatus*) are an important nearshore demersal predator known to consume a variety of fishes. Seasonal studies off central Oregon (Steiner 1979), revealed that Pacific hake were a dominant prey in all but winter when hake Pacific hake have largely migrated to the Southern California Current, and were replaced by smelt and rockfishes (fig. 6). Other fishes such as flatfishes and sculpins were the most important prey, but less so in the summer. In a study of sport-caught lingcod at two sites off central Oregon from May through October of 2003–05 (Tinus 2012) found that Pacific herring was the most important forage fish consumed, with juvenile rockfishes of secondary importance (fig. 6).

**Sablefish.** Sablefish (*Anoplopoma fimbria*), also known as black cod, is one of the dominant groundfish species in outer shelf and slope waters in the NCC. Early stud-

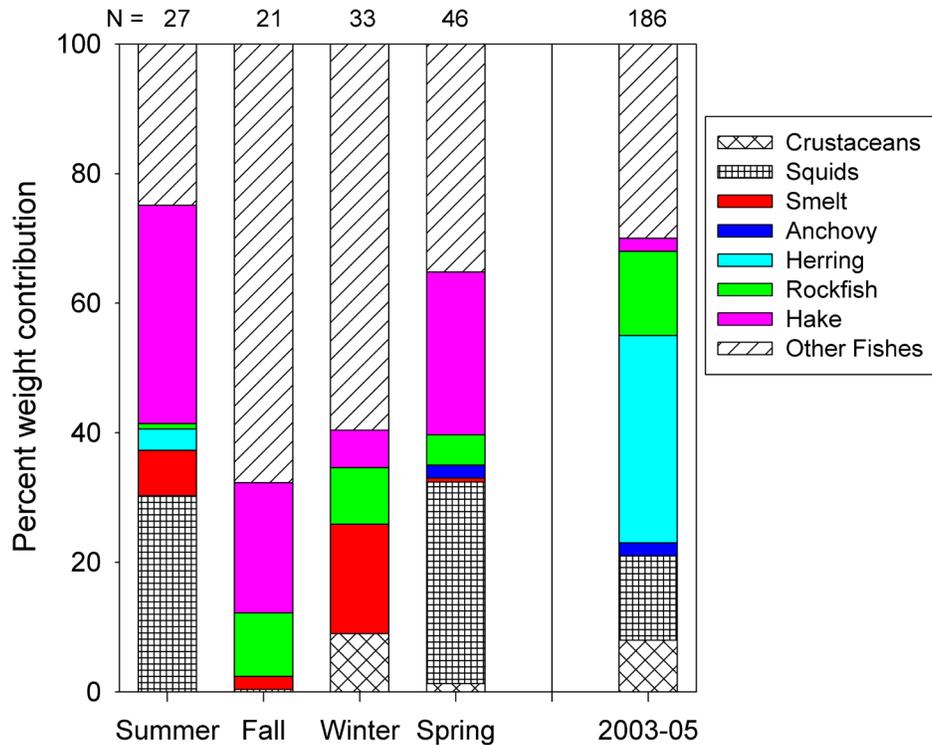


Figure 6. Diet composition of lingcod (*Ophiodon elongatus*) collected seasonally from sport fishing vessels off central Oregon from 1976 to 1977 (left, Steiner 1979) and collected over a three year period from surveys off central and southern Oregon (right, Tinus 2012). Number of stomachs with food is indicated at the top of each bar.

ies conducted during the West Coast Alaska Fisheries Science Center (AFSC) Triennial Groundfish surveys and Upper Continental Slope surveys (fig. 1) indicated substantial diet variability, with Pacific herring being the dominant forage fish in summer 1989, and rockfish and Pacific hake important in autumn 1992 (fig. 7). More recently, sablefish stomachs were collected during the 2005 and 2008 summer–fall WCGBT surveys from depths ranging from 62–1242 m. Diet results from these two years were remarkably similar, with fish making up 83.1% (2005) and 81.1% (2008) of the overall diet by weight in these samples. Pacific herring and northern anchovy were found in both years. Other fish prey identified were Pacific hake, longspine thornyhead (*Sebastolobus altivelis*), Dover sole (*Microsotmus pacificus*), slender sole (*L. exilis*), Pacific viperfish (*C. macouni*), and miscellaneous lanternfish, rockfish, and flatfish species. The remaining important prey types encountered were euphausiids (*E. pacifica* and *T. spinifera*) and several squid species. In contrast to the NCC fish, sablefish stomachs collected from off of California during the 2005 and 2008 WCGBT surveys showed decreased consumption of euphausiids, but increased crab predation, and the addition of Pacific sardines to the diet. The species composition of sablefish diet from these two years was analogous except for the absence of rockfish as a prey item in 2008. A breakdown of diet composition into

size classes for both years showed that the euphausiid diet of smaller sablefish (<50 cm FL) was replaced by increased consumption of fish and cephalopods as the sablefish grew. In the region just north of our study area (southwest Vancouver Island), Tanasichuk (1997) found euphausiids to be the main prey of sablefish but Pacific herring were the most important fish prey consumed. In the most complete analysis of sablefish diets to date, Laidig et al. (1997) examined 1868 stomachs from NCC (Oregon and California north of Cape Mendocino) and southern California Current (south of San Francisco Bay to Point Conception) and found that fishes represented >76% of the diet by volume, with rockfishes comprising 35% and Pacific hake 11% of the total diet. These authors also found the volume of fish consumed increased as the sablefish size increased.

**Jack Mackerel.** Adult jack mackerel (*Trachurus symmetricus*) migrate up from California spawning grounds during the summer and are important predators in the NCC (Emmett and Krutzikowsky 2008). Based on jack mackerel caught during summer in purse seine in the 1980s, Brodeur et al. (1987) found that mackerel diets varied interannually, from a high reliance on northern anchovy during the strong upwelling year of 1982, to a diet dominated by crustaceans the following two years (fig. 8). Euphausiids were the dominant prey consumed during two of the three years examined. In

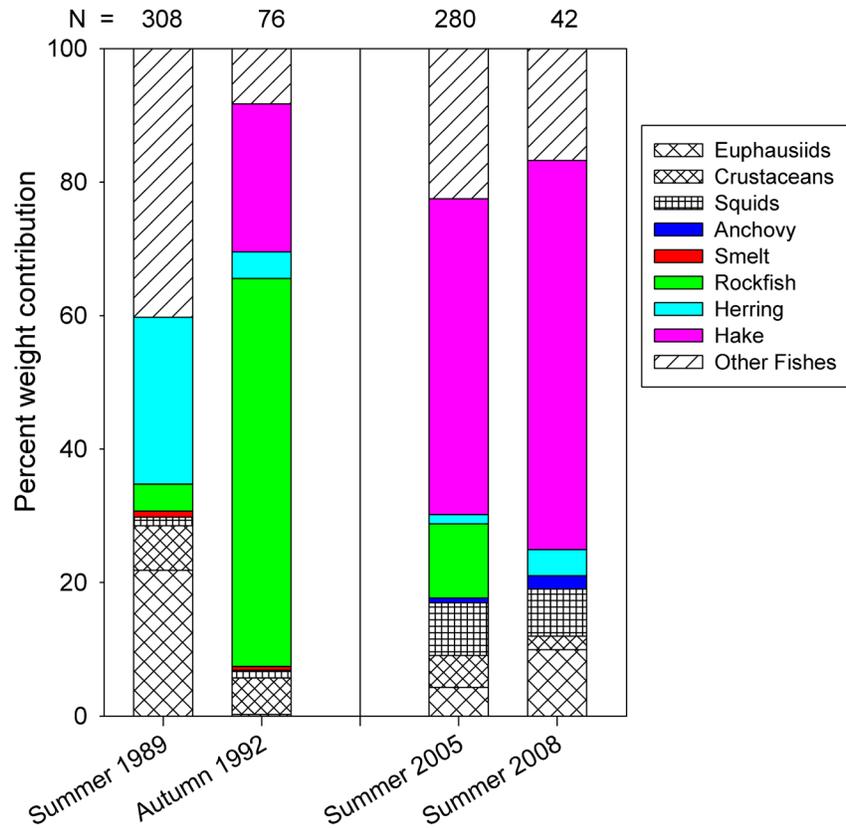


Figure 7. Diet composition of sablefish (*Anoplopoma fimbria*) collected from West Coast trawl surveys conducted by the Alaska Fisheries Science Center in 1989 and 1992 (left, Buckley et al. 1999) and more recent NWFSC (2005 and 2008) annual surveys off Washington to northern California (right, Buchanan unpub.). Number of stomachs with food is indicated at the top of each bar.

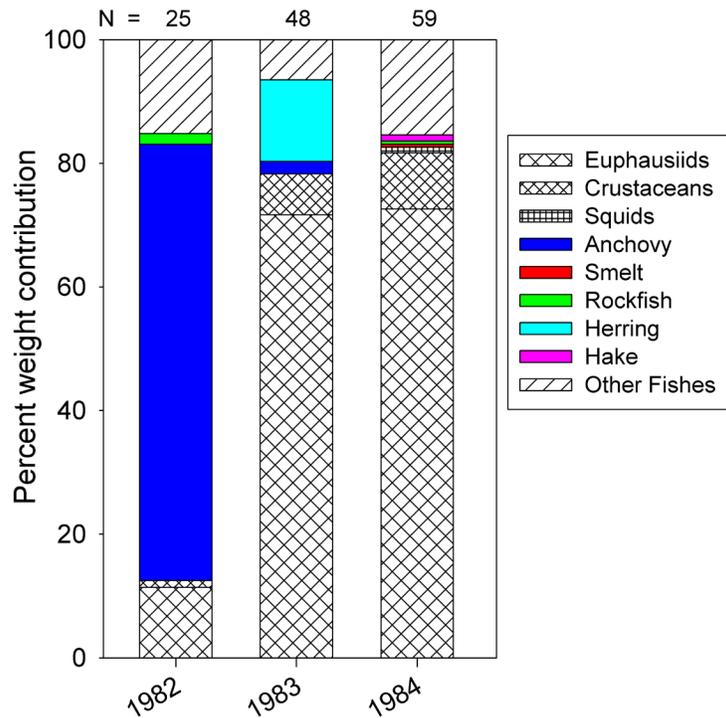


Figure 8. Diet composition of jack mackerel (*Trachurus symmetricus*) collected annually (1982–84) from purse seine surveys off Oregon and Washington (Brodeur et al. 1987). Number of stomachs with food is indicated at the top of each bar.

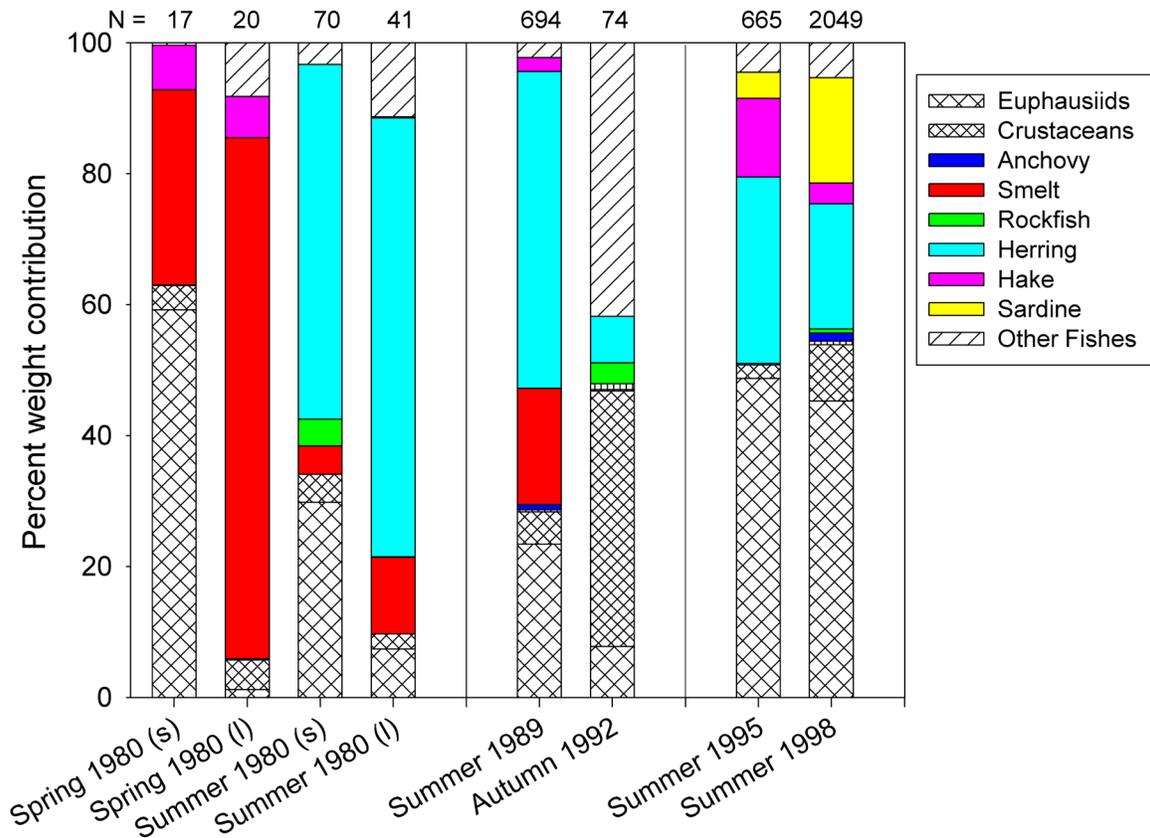


Figure 9. Diet composition of Pacific hake (*Merluccius productus*) collected from West Coast trawl surveys conducted by the Alaska Fisheries Science Center in spring and summer of 1980 for two size classes (s = 450–549 mm and l = >550 mm) (left, Livingston 1983), in summer of 1989 and autumn of 1992 (center, Buckley et al. 1999) and in 1995 and 1998 at onshore (< 200 m depth) locations (right, Nelson 2004). Number of stomachs with food is indicated at the top of each bar.

more recent studies, Miller and Brodeur (2007) found that jack mackerel predominantly fed on euphausiids in most years, with relatively small (<5% by weight) contributions by forage fish. In a seven year (1998–2004) study off the mouth of the Columbia River, Emmett and Krutzikowsky (2008) found forage fishes to occur frequently (no weight data available) in the diet in some years and not others. They found that northern anchovy, and to a lesser extent Pacific herring and whitebait smelt, were consumed by jack mackerel in higher proportions than their abundance would indicate from trawl catches (Emmett and Krutzikowsky 2008).

**Pacific Hake.** Pacific hake (*Merluccius productus*), play a major trophic role in the NCC ecosystem due to their high biomass. They migrate into the NCC in summer and back to California waters in the fall and winter (Ressler et al. 2007). Numerous studies have examined the diets of Pacific hake in different months, years, and geographic areas (Livingston and Bailey 1985; Ressler et al. 2007) and we summarize only a few representative studies here. Livingston (1983) examined dietary variability in Pacific hake caught in the NCC during spring and summer of 1980. This study showed that Pacific

hake exhibited substantial changes in diet between the seasons, shifting from mostly smelt (primarily eulachon, *Thaleichthys pacificus*) in spring, to mainly Pacific herring in the summer. This was especially true for larger Pacific hake (fig. 9). However, neither smelt nor Pacific herring were common in the diet of Pacific hake in the summer of 1967 (Livingston 1983). Buckley et al. (1999) examined hake diets from the summer of 1989 and found a high proportion of fish (primarily northern anchovy and smelt) but a relatively small proportion in autumn (fig. 9). Nelson (2004) examined Pacific hake diet from the same area in 1995 (non-El Niño year) and 1998 (El Niño year) collected on and off the shelf. He found Pacific herring to be the dominant forage fish consumed in 1995 but were largely supplemented by Pacific sardine in 1998. The differences by year and location were relative minor, with more forage fishes consumed in 1995 (fig 9).

The ontogenetic shift in diet to more piscivory can be clearly seen in Figure 10, with smaller size classes of Pacific hake consuming mostly euphausiids, whereas the larger size classes (>45 cm FL) consuming mostly fish (Rexstad and Pikitch 1986). The largest size class consumed almost entirely smaller Pacific hake (fig. 10).

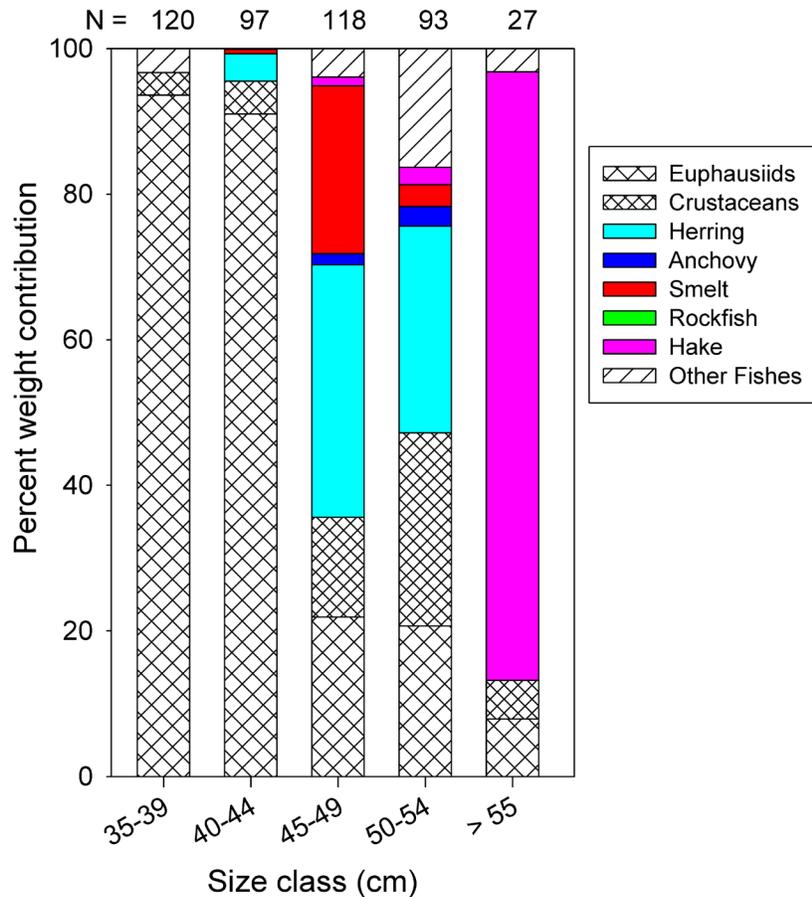


Figure 10. Diet composition of Pacific hake (*Merluccius productus*) collected from the 1983 West Coast trawl surveys conducted by the Alaska Fisheries Science Center off Washington and Oregon for five size classes (in cm) from Rexstad and Pikitch 1986. Number of stomachs with food is indicated at the top of each bar.

This cannibalistic behavior (primarily on age-0 and age-1 individuals) has been noted in other studies on this species (e.g., Buckley and Livingston 1997), and is an important aspect of their population biology.

**Coho Salmon.** Coho salmon (*Oncorhynchus kisutch*) are anadromous and spend their juvenile and adult lives in coastal or offshore waters before returning to freshwater to spawn. Juveniles consume a mixed diet of crustaceans and fishes when they first enter the ocean but soon become mostly piscivorous, although they are able to consume only larval and juvenile fishes until they become adults (Daly et al. 2009). Therefore, we restrict our analysis to adults in coastal waters prior to return to freshwater. Despite their importance as a commercial and recreational species, there have been relatively few studies directed at their feeding ecology as adults. The diet of coho salmon adults collected from 1948 to 1950 in the commercial fisheries off Oregon showed that they were feeding mostly on fish, mainly northern anchovy in the early summer, and then switched to eating more Pacific herring in late summer, and a combination of Pacific herring and Pacific hake in the fall (Heg and van Hyn-

ing 1951; fig. 11a). Coho salmon adults caught in purse seines from 1981 through 1984 showed a remarkable consistency in the diet from year to year, with Pacific herring and northern anchovy being the primary forage prey overall (fig. 11b). Juvenile rockfishes were also eaten during all years including 1979 and 1980, years that showed higher predation on smelt (Brodeur et al. 1987). Silliman (1941) also found Pacific sardine to be an important food of adult coho salmon caught off Washington in 1938. Recent studies have confirmed that adult coho salmon have fed on Pacific sardine since the resurgence of this important resource in the NCC in the late 1990s (Emmett et al. 2006).

**Chinook Salmon.** Similar to coho salmon, adult Chinook salmon (*Oncorhynchus tshawytscha*) are large-bodied piscivores known to feed on forage fishes during their marine life (Daly et al. 2009). Numerous studies have examined juvenile Chinook salmon diets in the NCC (e.g., Brodeur and Pearcy 1992; Daly et al. 2009) but there have been relatively few which have examined adult stomachs prior to their entry into fresh water. Although northern anchovy were the dominant

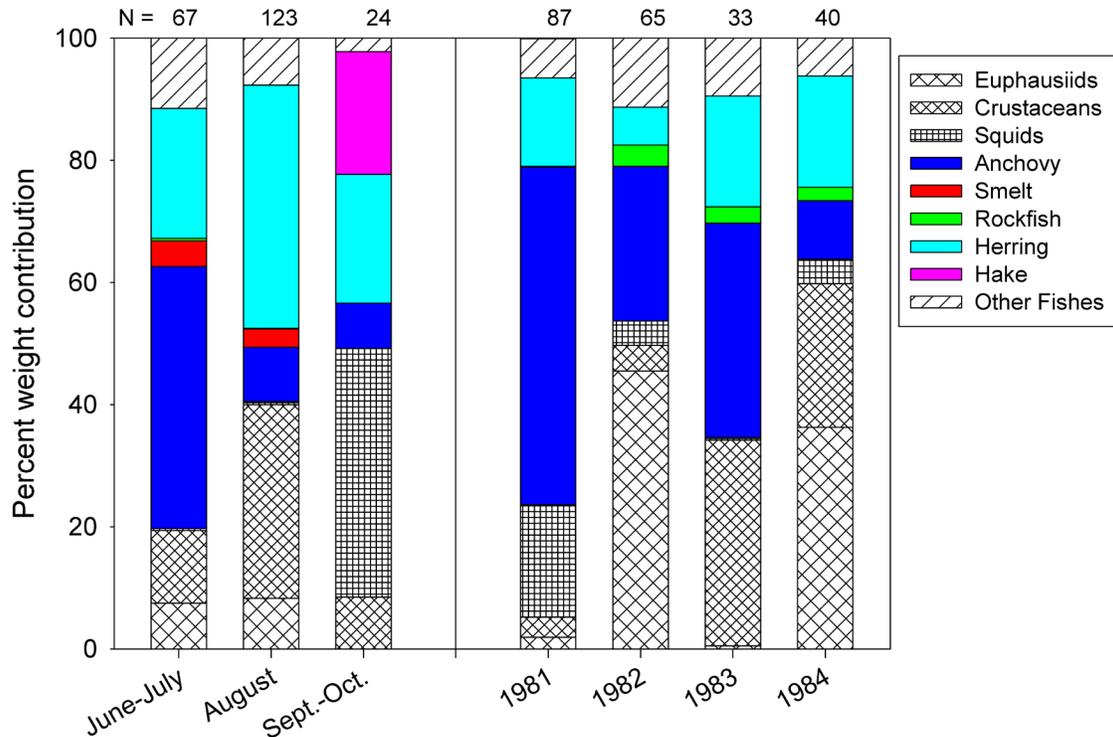


Figure 11. Diet composition of adult coho salmon (*Oncorhynchus kisutch*) collected from 1948–50 commercial fisheries off Oregon from Heg and van Hyning 1951 (left) and from purse seine surveys from 1981–84 from Brodeur et al. 1987 (right). Number of stomachs with food is indicated at the top of each bar.

forage prey of Chinook salmon in four years of summer sampling off Washington and Oregon in the early 1980s (Brodeur et al. 1987), other prey such as Pacific hake, Pacific herring, and rockfish were important in some years (fig. 12). Chinook salmon adult diets tend to be more piscivorous in recent (since 1999) summer trawl sampling with Pacific herring and smelt supplanting northern anchovy as important prey during different time periods (fig. 12). In a diet study of multiple predators off southern Oregon and northern California during 2000 and 2002, Miller and Brodeur (2007) found that Pacific herring and Pacific sardine were important prey of adult Chinook salmon, especially in late summer. In a study of sport caught adult Chinook salmon along the California coast north of Cape Mendocino, Hunt et al. (1999) found in the summers of 1994 and 1995 that Pacific herring and various smelt species were the dominant forage fish prey consumed during one summer, whereas northern anchovy, Pacific herring, and Pacific saury were important in the following year. Thayer et al. (2014) found that central California coast Chinook salmon diets declined in diversity since 1955, with recent diets dominated by northern anchovy, euphausiids, and Pacific sardine. This study showed substantial seasonality in Chinook salmon diets with juvenile rockfish important mainly in the summer, northern anchovy in the summer and fall, and Pacific herring only in the winter months (Thayer et al. 2014).

All these studies taken collectively suggest substantial plasticity in the forage fish feeding of adult Chinook salmon in the ocean.

**Albacore.** In the eastern North Pacific, albacore (*Thunnus alalunga*) are the dominant non-tropical tuna species that migrate into the offshore waters of the California Current to feed as juveniles during the summer and fall, before undergoing transoceanic migrations to their spawning grounds in the Western North Pacific. Albacore collected from commercial fisheries in 1968 (July–November) and 1969 (July–August) (Pinkas et al. 1971) north of Cape Blanco fed predominantly (>50% by weight) on northern anchovy. In contrast, more recent work done in 2005–06, they consumed a high proportion of northern anchovy, but juvenile Pacific hake rockfishes and Pacific sardine were also represented in the diets (Glaser 2010; Glaser et al. 2014; fig. 13). Earlier work by Percy (1973) found that fish (primarily Pacific saury and rockfishes) were the dominant prey of albacore caught in the Columbia River plume off Oregon, but their diet was dominated by squid and crustaceans offshore in more oceanic waters.

**Pacific Halibut.** Pacific halibut (*Hippoglossus stenolepis*) are known to be important piscivores throughout their distribution and capable of eating fairly large fish (see review by Best and St. Pierre, 1986). Surprisingly little diet information is available on Pacific halibut caught in the NCC. Pacific halibut collected in recreational fish-

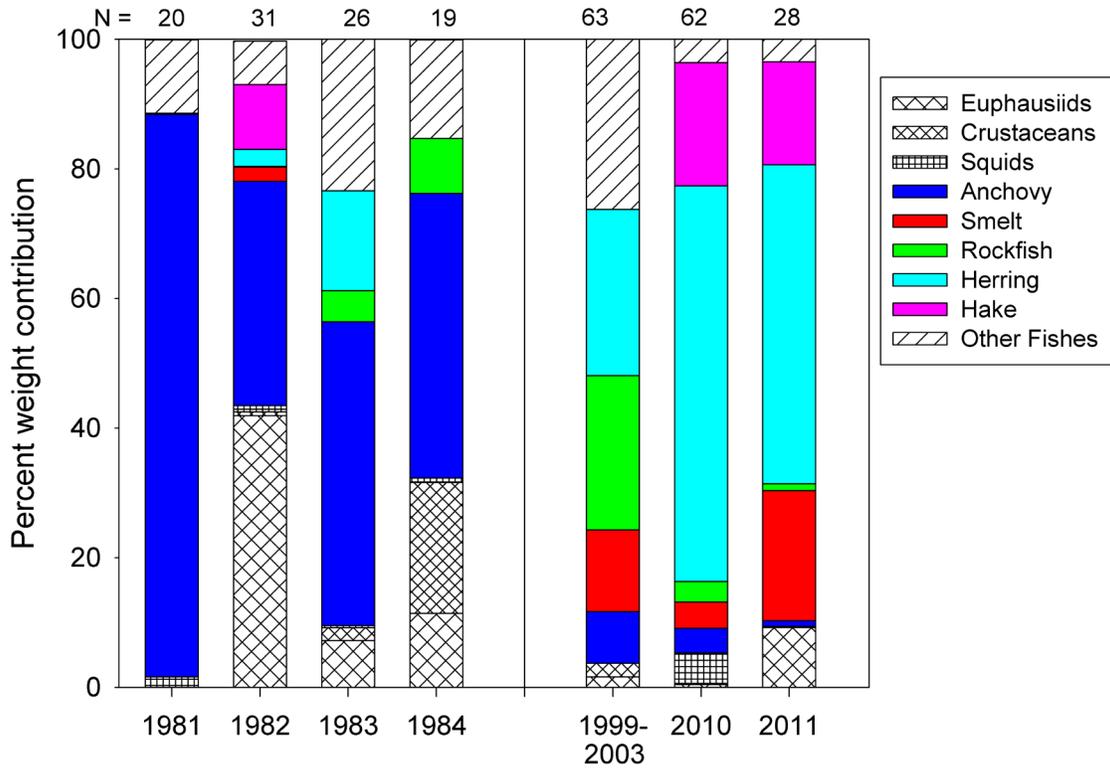


Figure 12. Diet composition of adult Chinook salmon (*Oncorhynchus tshawytscha*) collected from summer purse seine surveys from 1981–84 (Brodeur et al. 1987, left) and from summer surface trawl collections from 1999–2011 (Daly and Brodeur, unpub., right). Number of stomachs with food is indicated at the top of each bar.

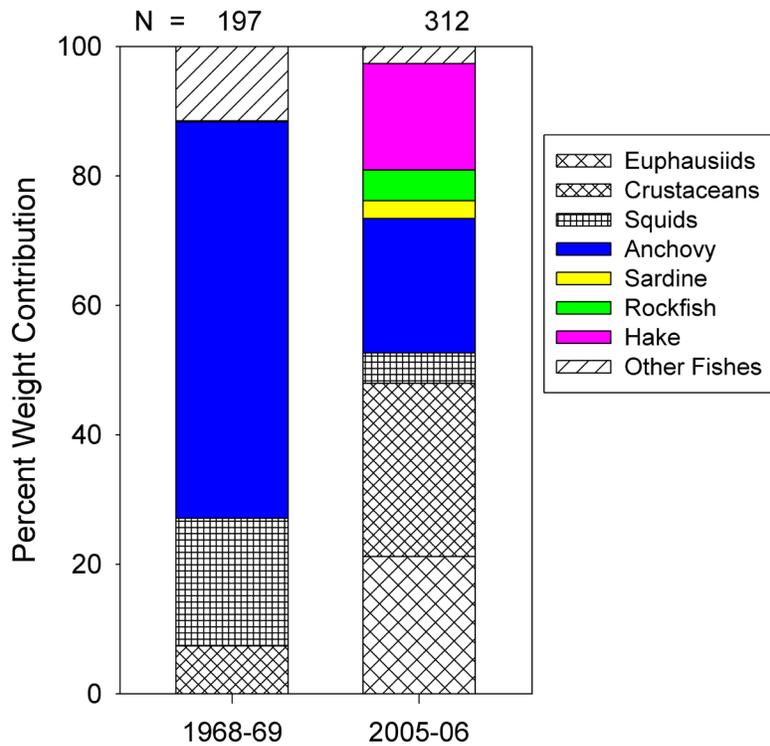


Figure 13. Diet composition of albacore (*Thunnus alalunga*) collected from commercial fisheries from 1968–69 (Pinkas et al. 1971) and from 2005–06 (Glaser 2010) north of Cape Blanco, Oregon. Data were originally presented as percent energetic values by Glaser 2010 but are given here as percent by weight based on unpublished data (Glaser unpub.). Number of stomachs with food is indicated at the top of each bar.

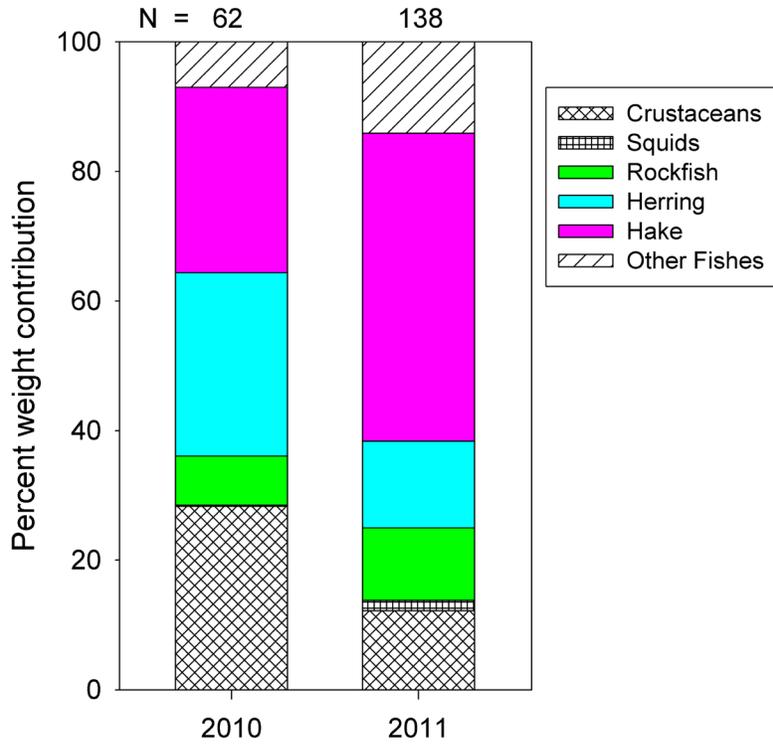


Figure 14. Diet composition of Pacific halibut (*Hippoglossus stenolepis*) collected in May–August from recreational fisheries from 2010–11 off central Oregon (Gladics et al. 2014). Number of stomachs with food is indicated at the top of each bar.

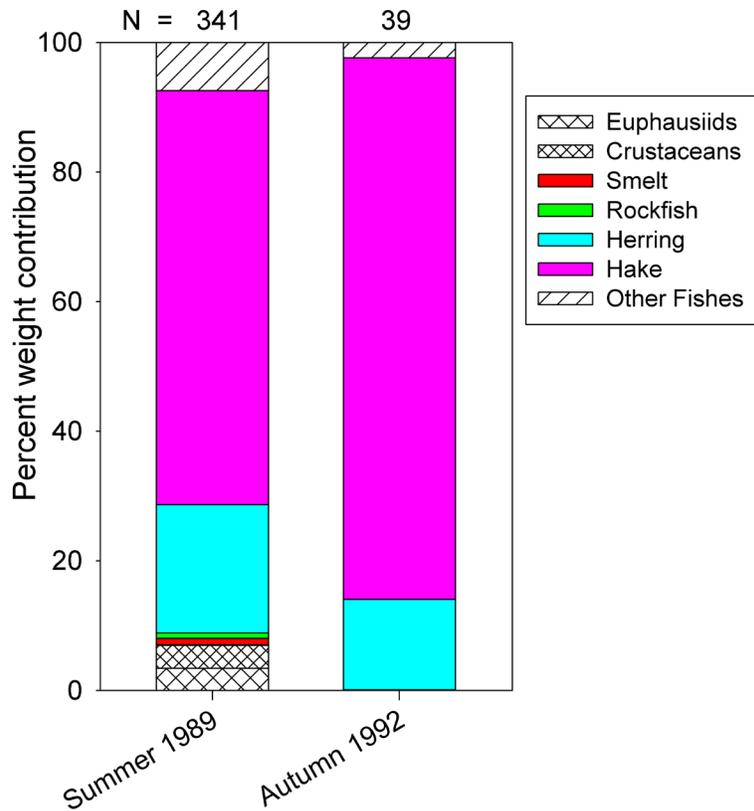


Figure 15. Diet composition of arrowtooth flounder (*Atheresthes stomius*) collected from West Coast trawl surveys conducted by the Alaska Fisheries Science Center in 1989 and 1992 (Buckley et al. 1999). Number of stomachs with food is indicated at the top of each bar.

eries from May through August of 2010–11 off central Oregon (Gladics et al. 2014) found Pacific hake, Pacific herring, and juvenile rockfishes to be the dominant prey in these two contrasting years in terms of oceanography (fig. 14).

**Arrowtooth Flounder.** Arrowtooth flounder (*Atheresthes stomus*) are a large-bodied, semipelagic flatfish known to be an important fish predator throughout their range, which is mainly north of our study area. Fish were the dominant prey in arrowtooth flounder collected from the AFSC West Coast trawl surveys conducted in the summer of 1989 and autumn of 1992 (Buckley et al. 1999; fig. 15). The majority of the fish diet was Pacific hake, with herring also being of secondary importance (Buckley et al. 1999). Gotshall (1969) found fish to be of less importance than shrimp in terms of volume for arrowtooth flounder collected off northern California.

### Size Composition of Prey and Available Prey

The size and availability of various forage fish species plays an important role in the determining the diets of forage fish predators. Predators are generally limited as to the largest prey they can consume because of their mouth size and their swimming speeds (Juanes et al. 2002). For example, adult Pacific sardine averaged about 200 mm FL (fig. 16a) off Oregon from 1998–2011 and therefore only large predators such as sharks, adult Chinook salmon, and large Pacific hake are able to feed on fish of this size. While capturing a large forage fish (i.e., Pacific sardine) provides a large amount of calories, it requires the expenditure of time and energy that would not be necessary if other smaller prey are available, particularly if the latter are very abundant. Predators commonly switch to eating prey that is highly abundant even if this prey is on the lower range of their size spectrum (Murdock et al. 1975; Rindorf et al. 2006).

Small forage fish such as smelt and northern anchovy mature at relatively small sizes and are thus available as prey for many predator species (fig. 16a). Pacific herring, in contrast, can reach relatively large size as they mature, but their juvenile stages (0 and 1-age) are often abundant in the NCC and thus a primary food for predators during some years (Tanasichuk et al. 1991).

Annual and decadal oceanographic conditions directly affect forage fish abundance (Chavez et al. 2001; Emmett et al. 2006; Litz et al. 2008, 2014). Off Oregon, large annual fluctuations in the abundance of forage fish can alter the size structure of available fish prey community (fig. 16b) and thus directly affect the diets of predators. For example, during 1998 and 1999 the forage prey size spectrum was weighted heavily towards large prey (i.e., older Pacific herring and Pacific sardine) and not towards smaller forage fishes such as northern anchovy (fig. 16a). In 2003, Pacific herring had two abundant year

classes (one small and one large) (fig. 16a) and thus were available as prey for many different sizes of predators. Other years (2010, 2011) had predominantly northern anchovy and whitebait smelt, the smaller forage fishes generally available (fig. 16a). As such, the suite of forage fish species/sizes that is available any given year varies significantly (fig. 16b), which may impact the relative foraging success of piscivores.

Most fish predators have a preferred prey size range (Juanes et al. 2002). Pacific hake (size range 338–731 mm,  $n = 581$ ) off Oregon for example, appear to eat fish prey of a mean size of 120 mm (fig. 17), which would substantiate why we found that northern anchovy, smelt, and Pacific herring are their most common fish prey. Adult Chinook salmon (252–506 mm,  $n = 114$ ), in contrast, do not appear to have a preferred prey size (fig. 17), but appear instead to eat a wide size range of prey. Chinook salmon can grow relatively large, enabling them to eat the larger forage fish prey. Chinook salmon are very active and mobile predators that can quickly switch to the most abundant forage fish prey available.

### Ranking of Important Fish Predators on Forage Fishes

The overall ecological effect of any fish predator on an ecosystem and forage fish population can be estimated by considering the biomass of the predator and the percent of forage fish in its diet (fig. 18). From this analysis it is evident that Pacific hake has a very large effect on the forage fish community, primarily because of its very large population biomass. Other predators that have a large effect on forage fish include spiny dogfish, albacore tuna, and jack mackerel. Albacore may have a disproportionately large overall effect on forage fish because their substantial biomass in the NCC in summer coupled with a high metabolic rate (Sharp and Dizon 1979), which allows them to digest prey relatively quickly. Glaser (2010) calculated that albacore can have substantial impacts on northern anchovy populations in the California Current, but these consumption estimates are sensitive to predator abundance estimates.

Many predators appear to have similar predation effects on forage fish populations. This is because they have similar population biomass (approximately 1,000 mt) and composition of forage fish in their diet, 40–60% (fig. 18). Two large shark predators, blue shark and soupfin shark, probably do not have a large effect on forage fish abundance because their population biomasses are relatively small. Our estimates of the relative importance of the forage fish predators are only meant to be approximate and are based on the limited diet studies reported here and estimates of biomass from various methodologies, each of which has considerable variability on both a seasonal and interannual basis.

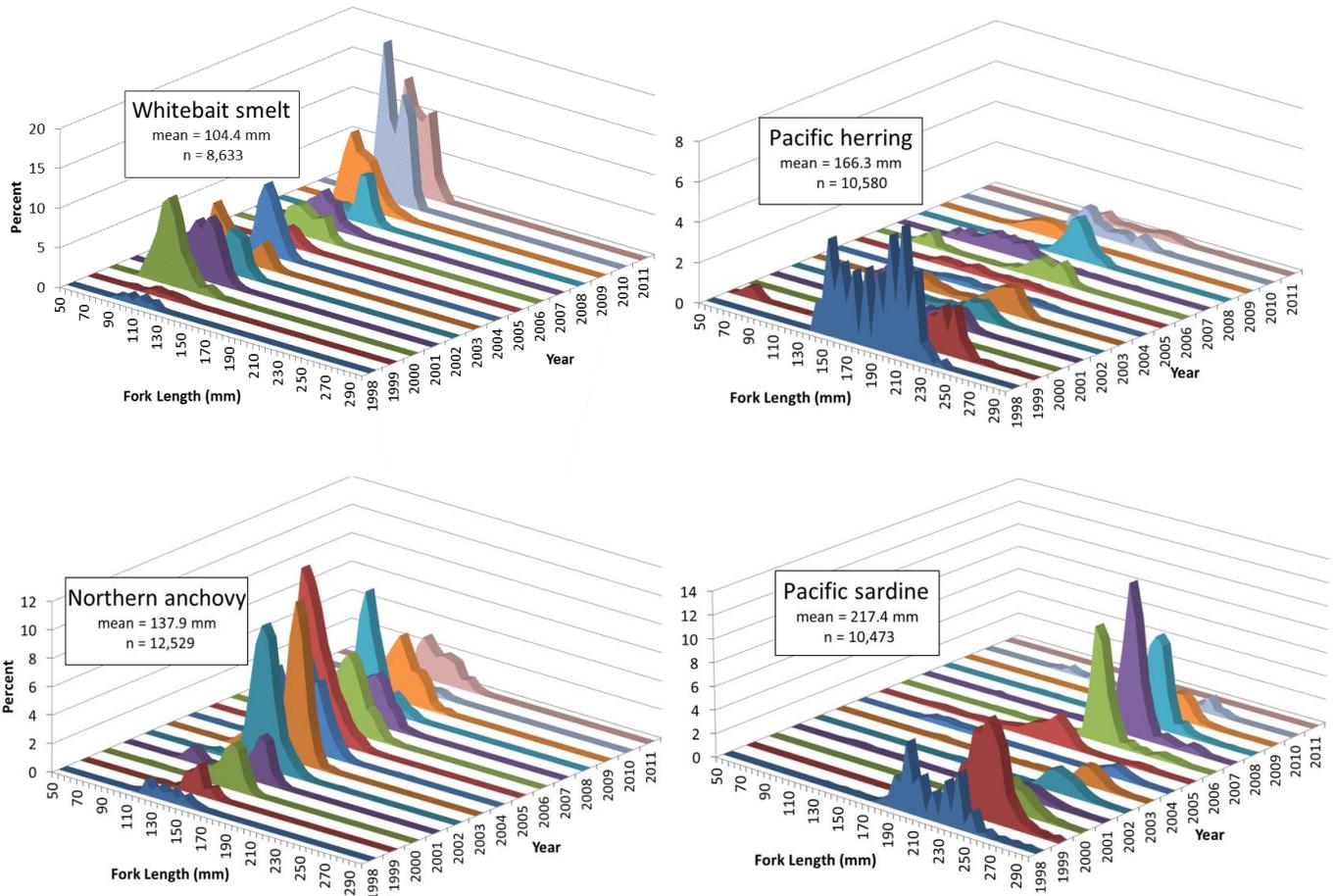


Figure 16a. Available forage fish fork length distributions from spring–summer trawl surveys off the mouth of the Columbia River from 1998–2011 (Emmett unpub. data). These four species represent greater than 90% of all forage fish collected in these pelagic trawl surveys done at night. Data are represented as a percent of the catch made up of that length (mm) within a given year.

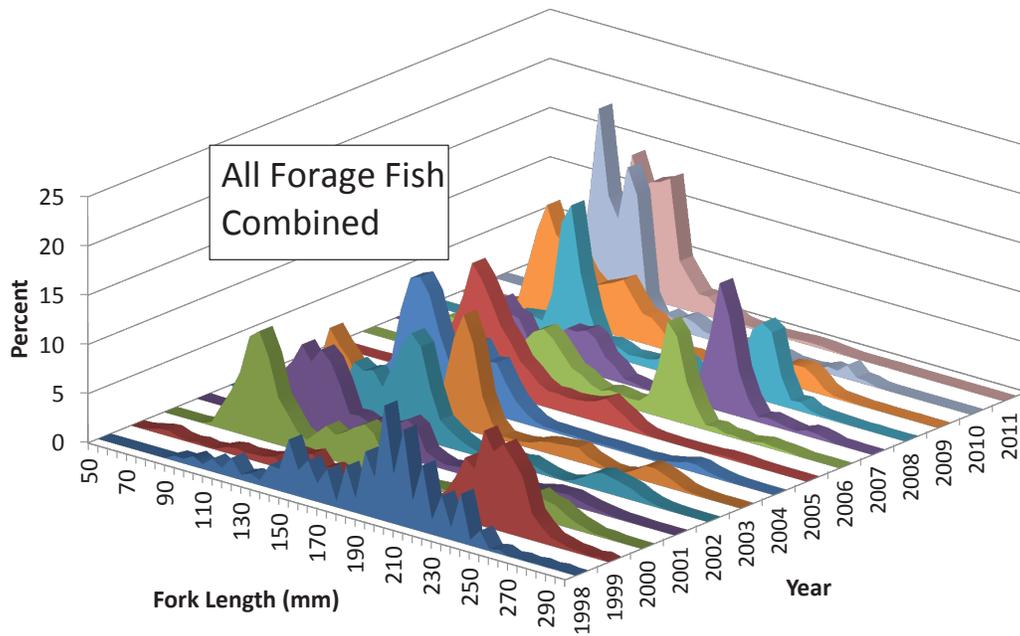


Figure 16b. Summed availability of the four forage fish fork length distributions from spring–summer trawl surveys off the mouth of the Columbia River from 1998–2011 by year (Emmett unpub. data). Data are represented as a percent of the catch made up of that length (mm) within a given year.

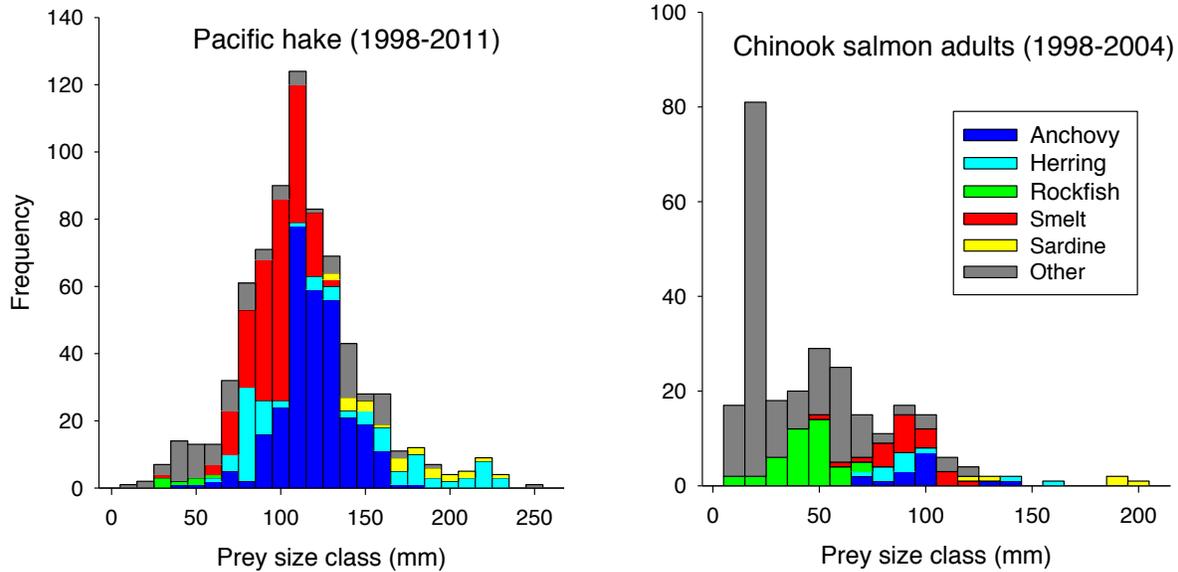


Figure 17. Size (total length) frequencies of the dominant forage fishes found in Pacific hake (left) and Chinook salmon adult (right) stomachs collected in summer (May through August) of the years indicated on each graph.

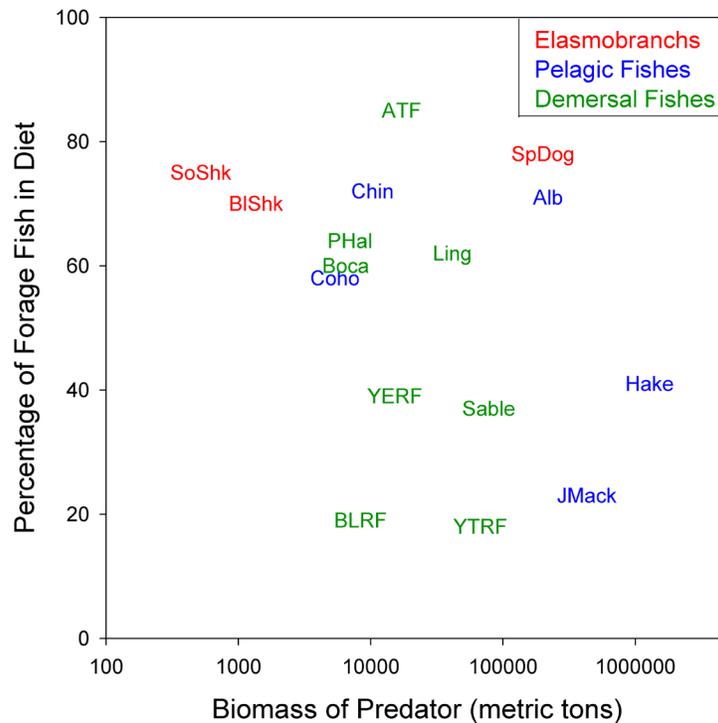


Figure 18. Comparison of usage of forage fish by the dominant predators examined in this study, based on the estimated predator biomass from 2000–09 (x axis) and the percentage of forage fish in the diets (y axis). The predators are color coded by type (red = elasmobranchs, blue = pelagic fishes, green = demersal fishes). ATF = arrowtooth flounder, SpDog = spiny dogfish, PHal = Pacific halibut, Alb = albacore, BLRF = black rockfish, BShk = blue shark, Boca = bocaccio, Sable = sablefish, Chin = Chinook salmon, Coho = coho salmon, SoShk = soupfin shark, YERF = yelloweye rockfish, Hake = Pacific hake, Ling = lingcod, JMack = jack mackerel, YTRF = yellowtail rockfish.

### Spatial and Temporal Variability

The coastal waters of the NCC are affected by several large-scale and local environmental variables with seasonal, annual, and even decadal variability (Checkley and Barth 2009). These variations may have been enhanced by climate changes over the past several decades

(Sydeman et al. 2013). Primary drivers of these changes at the large scale include the Pacific Decadal Oscillation (PDO, Mantua et al. 1997) and El Niño/Southern Oscillation (ENSO) cycles (Chavez 1992) while at a more regional scale, upwelling and riverine plumes may have more spatially-localized effects. The PDO is likely

to affect the spatial distribution and recruitment of the forage fishes and their predators (Chavez et al. 2001), whereas ENSO may have direct effects on the food web leading up to the top predators (Brodeur and Pearcy 1992; Francis et al. 2012).

Changes in ocean conditions can affect the spatial distribution of the predators and prey, creating novel forage communities and predator ensembles during some years. Examples of this are the northward shift of Pacific hake spawning in some warm years which results in age-0 and age-1 fish occurring in the NCC (Phillips et al. 2007), where they may be preyed upon by piscivores. On longer time scales, increases in abundance of forage species such as Pacific sardine along with changes in ocean conditions allowed this species to spread to the NCC in recent years where they were absent for decades (Emmett et al. 2006). Thus, Pacific sardine was evident in the diet of several species (spiny dogfish, sharks, Pacific hake, albacore) in recent sampling but not in the 1970s and 1980s, when it rarely occurred north of Southern California. Changing ocean conditions may also allow for the invasion of new predators into the region, which can directly affect the biomass of forage fish and their predators. The recent influx of the voracious cephalopod predator, Humboldt squid (*Dosidicus gigas*) into the NCC from southern latitudes (Field et al. 2007; Litz et al. 2011) is a striking example of this.

Changes in the food web structure associated with El Niño conditions can have major impacts on higher trophic level predators in the NCC (Brodeur et al. 1987; Brodeur and Pearcy 1992; Nelson 2004; Lee and Sampson 2009). However, not all El Niños are alike and during a particular El Niño, not all predators are similarly affected (Gladics et al. 2014). Other years, such as 2005, which was not an El Niño year, had extremely delayed spring upwelling resulting in El Niño-like conditions in the NCC (Brodeur et al. 2006). In addition to changing the availability of these forage species, changes in the base of the food web in these years of poor ocean conditions in the NCC can lead to differences in the quality (lipid content, fatty acid composition) of the forage fish prey (Daly et al. 2010; Litz et al. 2010), further diminishing their utility as prey to top predators.

The relative consumption calculations of the various predators on forage fishes are only meant to be first-order approximations for comparative purposes and encompass many assumptions and unknowns. Our abundance estimates used in were derived mainly for the summer months (May–October; Keller et al. 2012) when the most predator sampling and diet information are available. Although some migratory species that exhibit high biomass (Pacific hake, jack mackerel, and albacore) are only present in the NCC during the productive sum-

mer months, a number of lower biomass but resident species (rockfishes, lingcod, sablefish) may have potentially greater cumulative impacts throughout the year that were not accounted for in our analysis. Our biomass estimates include all age/length categories of the predators and does not account for ontogenetic changes in diet composition (Rexstad and Pikitch 1986; Daly et al. 2009). We have considered that consumption rates per capita are equal for all the fish and years we examined and this assumption is not likely as temperature and hence metabolism levels are likely to differ particularly between highly-migratory pelagic species (albacore, jack mackerel) and more sedentary demersal species (rockfish, sablefish).

Finally, the NCC is not homogeneous in terms of its productivity or standing stocks of fish prey (Checkley and Barth 2009). Areas such as the Columbia River Plume may act as important hotspots of forage fish biomass and predator abundance (Emmett et al. 2006; Litz et al. 2014). Cross-shelf differences tend to be more pronounced than along shelf differences and certain predators may be found mainly inshore (e.g., black rockfish) whereas others are restricted to more offshore waters (e.g., albacore, blue sharks), thus limiting the suite of forage fish prey available to them. Spatially explicit mapping of where predation is occurring on the important forage species (e.g., Buckley et al. 1999; Glaser 2009) should be considered in future studies and would be critical to differentiating where the important predation hotspots are located. More spatial information of this kind is needed to assess the predator-prey interactions which may happen on localized scales that may not be detected in large-scale surveys.

## CONCLUSIONS

Forage fish species, size, and availability vary substantially in the NCC on seasonal, annual, and decadal scales (Brodeur et al. 2003; Emmett et al. 2006; Litz et al. 2014). These fluctuations affect the feeding, growth, migration, and movements of predatory fishes such as Pacific hake, tuna, sharks, and adult salmon. As Field et al. (2006) found, Pacific hake/forage fish interactions have a very large influence in the fish trophic community in the California Current. When analyzed by specific forage fish taxa, Pacific hake may significantly influence populations of northern anchovy, Pacific sardine, Pacific herring, smelt, and its own population abundance (cannibalism) (Buckley and Livingston 1997). Unfortunately there is limited information indicating whether predation by Pacific hake or other predators is directly influencing forage fish abundance (i.e., top-down) or if bottom-up processes are determining forage fish populations abundance. Bottom-up processes appear to be have important effects on Pacific sardine and northern

anchovy populations (Rykaczewski and Checkley 2008), and perhaps most forage fish populations in the NCC (Ware and Thompson 2005; Hill et al. 2014). Top-down processes may be most important for Pacific herring (Ware and McFarlane 1995) and northern anchovy during some years (Glaser 2011; Glaser et al. 2014).

The abundance and size of available forage fish influences the diets of predators. The typical length of adult northern anchovy is a suitable prey size for a large number of predators and thus of primary importance to many predatory fishes in the California Current (Glaser 2011). Young Pacific herring and Pacific sardine may also fulfill the same role, although the size of these forage fish can often exceed the gape limitations of many of the smaller fish piscivores. Rockfish and Pacific hake populations make up a large biomass within the northern California Current system and these species serve as predators upon juvenile and adult forage fish as well as being prey during their juvenile pelagic stage for other midwater and demersal elasmobranchs and fishes. Analysis of stomachs of apex predators indicated that they feed on a wide range of prey and have the capacity to exploit what is readily available (Brodeur and Percy 1984, 1992; Emmett and Krutzikowsky 2008), making them an important nexus in shelf food webs (Field et al. 2006; Ruzicka et al. 2012).

Despite the abundance of information on some key predators species such as Pacific hake and adult salmon, there is a paucity of information on some key species which are important in terms of biomass (albacore, jack mackerel, sablefish) or consumption of forage fishes (elasmobranchs, Pacific halibut, arrowtooth flounder). Monitoring the diets of these and other top predators can provide valuable information on the recruitment success and abundance of forage species (Anderson et al. 1980; Mills et al. 2007; Thayer et al. 2008; Brodeur et al. 2011; Gladics et al. 2014). Although new information is provided in our study, many of the studies of demersal species in this region were conducted during past decades when environmental and biological conditions were vastly different. Therefore a critical need exists to continue and expand the sampling to include all potential forage fish predators. Much of the information presented herein is based upon collections made primarily in late spring through early fall, when most surveys of fish abundance (and diet studies) are routinely conducted, and a critical data gap exists on what predators are important during other times of the year (e.g., Thayer et al. 2014). Fisheries for many of the forage fish examined here are under federal (hake, rockfish, sardine, and anchovy) or state (herring) management at the present time and the role these fishes play in the ecosystem is being considered. However, other taxa not directly fished (e.g., smelts, lanternfishes) presently lack protection although measures are under consideration would include the trophic

importance of these species in the food web of the West Coast (<http://www.pccouncil.org/ecosystem-based-management/protection-for-unfished-forage-fish-initiative/>). Consumption by fish and elasmobranch predators may be substantial but in estimating impact on the forage fishes themselves, the competing needs of other predators not examined here (seabirds, marine mammals, large squid, and humans) need to be evaluated (e.g., Cury et al. 2011; Kaplan et al. 2013; Ainley et al. 2014; Pikitch et al. 2014). Examining the spatial and temporal complexities of predator-prey relationships involving forage fishes is essential when moving towards Ecosystem Based Fisheries Management in the California Current in the future (Field and Francis 2006; Pacific Fishery Management Council 2013; Ainley et al. 2014).

## ACKNOWLEDGEMENTS

We thank the many dedicated scientists who have collected and analyzed the diets of these predators over the many years covered in this study. We appreciate the contribution of unpublished diet information by Todd Miller, Sarah Glaser, Craig Tinus, and Elizabeth Daly. Pete Lawson, Jim Ruzicka, and Ian Stewart provided biomass estimates of predators. We thank the anonymous journal reviewers for helpful comments on the manuscript. David Ainley and Sam McClatchie provided the initial invitation to present this work that led to the writing of this paper. Funding was provided by the Northwest Fisheries Science Center, NOAA Fisheries.

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Part III

## **SCIENTIFIC CONTRIBUTIONS**



## LONG-TERM TRENDS OF SOUTHERN CALIFORNIA'S KELP AND BARRED SAND BASS POPULATIONS: A FISHERY-INDEPENDENT ASSESSMENT

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### ABSTRACT

Power plant entrapment monitoring data provided insights on conditions leading up to and contributing to previously documented collapses of the southern California kelp bass (*Paralabrax clathratus*) and barred sand bass (*P. nebulifer*) fisheries. Individuals from all size classes from both species were taken over time at three sites spanning nearly 100 km along the southern California coast. Size class abundance peaked in the 200 to 250 mm SL size classes, or near the minimum size limit for the two southern California fisheries (250 mm SL). Annual modal lengths remained relatively static in *P. clathratus*, but significantly declined in *P. nebulifer* with a strong downsizing after 1993. Abundance indices for each species significantly declined over nearly four decades of monitoring: 97% in *P. clathratus* and 86% in *P. nebulifer*. Evidence suggests sporadic larval settlement by each species led to occasionally abundant year classes, such as 1982 (*P. clathratus*) and 1994 (*P. nebulifer*), interspersed with several consecutive years of comparably minimal settlement. No significant correlations with common climate indices including the Multivariate ENSO Index, Pacific Decadal Oscillation, and North Pacific Gyre Oscillation were detected for either species' year-class abundance index. The *P. nebulifer* year-class abundance index did significantly correlate, albeit weakly, with annual mean sea surface temperature. These results signify that, at this time, no environmental proxy for either species larval settlement exists.

### INTRODUCTION

Marine fish population dynamics are both variable and complicated as the suite of harvest pressures, management responses (Worm et al. 2009), and stress from sources other than harvesting (pollution, habitat loss/alteration, environmental change, etc.) grows increasingly complex and intertwined. Furthermore, growing evidence indicates fishing decreases resiliency to environmental change, especially for rigorously targeted species (Anderson et al. 2008; Hsieh et al. 2010). Long thought benign, mounting evidence indicates recreational fisheries are capable of exerting pressures on scales equivalent to commercial fisheries (Schroeder and Love 2002;

Coleman et al. 2004; Cooke and Cowx 2004; Post 2012) including some southern California examples (Schroeder and Love 2002; Coleman et al. 2004; Erisman et al. 2011). Unfortunately, little effort has been applied to understanding recreationally fished species' response to environmental change in comparison to commercially important species, regardless of their overfished status, social importance, or economic importance.

The kelp bass (*Paralabrax clathratus*) and barred sand bass (*P. nebulifer*) fisheries represent two cases of recreationally depleted fisheries (Hill and Schneider 1999; Erisman et al. 2011). Both species, individually or combined, were the subject of numerous papers as they represent the most important summertime marine recreational fisheries in southern California for the last three decades (Love et al. 1996; Allen and Hovey 2001a,b; Dotson and Charter 2003; Jarvis et al. 2010; Mason and Lowe 2010; Erisman et al. 2011). Between 1959 and 2012, regulations for both fisheries included a 305 mm (total length) minimum size limit that targeted mature individuals (Love et al. 1996), and a ten-fish total bag limit (Bedford and Ryan 2002; California Fish and Game Commission 2012). Despite their importance to local fisheries, little information exists on their population dynamics including larval settlement, fishery recruitment, and general population trends. Genetic analyses suggested kelp bass year-class strength was influenced by dominant local current strength rather than commonly used climate indices (Selkoe et al. 2006; Selkoe et al. 2007). Beyond this, little information exists on kelp bass population interannual abundance variability while nothing similar has been completed for barred sand bass. This leaves the two bass species in a precarious position. Lacking understanding of factors regulating population abundance hinders adaptive fishery management, ultimately complicating the evaluation of the efficacy of newly enacted fishing regulations.

Building upon the well-documented trends in the fisheries catch records, this analysis focused on temporal trends in abundance, size structure, and larval settlement of kelp bass and barred sand bass in southern California. We derived these trends using fishery-independent data sets that recorded the abundance and size of fish

entrapped in the intake systems of coastal power plants as described by Miller and McGowan 2013. These analyses attempted to identify presently available information that can be used to describe factors underlying the recent decline and provide insight on the future status of the fisheries. This concept was ultimately tested by examining the relationship between indices derived from power plant monitoring and fishery landings.

## MATERIALS AND METHODS

### Data Sources

Fishery landings data consisted of total catch reported by the commercial passenger fishing vessel fleet in southern California. Daily catch reports submitted to the California Department of Fish and Wildlife included, at a minimum, catch by species, number of anglers, and primary location targeted using a grid of 10-minute latitude  $\times$  10-minute longitude numbered blocks designated by the Department. An annual catch per unit effort (CPUE) representing the catch/angler was derived from these data for each species, 1980–2010. Data used in our analyses do not include fishes caught and released or landings from private vessels.

Fishery-independent abundance indices were taken from coastal power plant cooling water intake monitoring (1972–2010) as described by Miller et al. 2011 and hereafter referred to as entrapment data. Fish lengths (mm SL) were recorded during most years (1979–2010). All fishes were exposed to lethal temperatures during routine “heat treatment” procedures conducted at three coastal power plants in southern California ranging from San Clemente to El Segundo, California. Additional surveys, termed a “fish chase,” unique to the San Onofre Nuclear Generating Station (SONGS) Units Two and Three were conducted before each heat treatment since 1989. Both heat treatments and fish chases were scheduled at a frequency of every 6–12 weeks, on average. Power plant-specific cooling water intake conduits extended 500–900 m offshore to a vertical intake riser situated along the 8–15 m isobaths and rising 4 m above the seafloor. The conduits terminated inland at a large basin or forebay where water velocities slowed before passing through 1 cm square mesh traveling screens. In the forebay, fishes took up residence until the next heat treatment. During heat treatments, all fishes were exposed to temperatures exceeding 38°C and were subsequently impinged on the traveling screens and conveyed out of the forebay to a collection basket. All fishes were counted and measured after each heat treatment. Fish chase surveys included estimating the abundance by species while the fishes were raised and held in a steel tray. The steel tray was emptied into a dedicated return conduit once the estimate was complete. All data

were standardized to the volume of cooling water circulated since the last heat treatment (described below). Data from each fish chase and the following heat treatment were combined before standardization to cooling water flow volumes. This sampling program provided abundance indices comparable to traditional offshore net sampling programs (Miller et al. 2011).

A total of 1107 surveys across all three sites were completed. The total sample size included 297 events at El Segundo Generating Station (ESGS, 1972–2010), 213 events at Huntington Beach Generating Station (HBGS, 1972–98; 2001–10), and 597 events at San Onofre Nuclear Generating Station (SONGS, 1972–74; 1976–79; 1981–2010). Cooling water circulated between heat treatments averaged  $1.84 \times 10^8$  ( $\pm 3.69 \times 10^7$ , standard error)  $m^3$ , or  $5.52 \times 10^7$  ( $\pm 3.21 \times 10^6$ ) at ESGS to  $2.94 \times 10^8$  ( $\pm 6.82 \times 10^7$ ) at SONGS.

### Data Analysis

Lengths recorded during heat treatments were compiled into 25 mm bins by rounding each SL up to the next 25 mm increment. This avoided the creation of a 0 mm SL size class. The annual modal length for each species was examined for changes in the size structure of individuals recorded during entrapment surveys. An abundance index (entrapment rate or ER) was computed by standardizing survey-specific abundance to the total volume of seawater ( $\text{count}/10^6 m^3$ ) circulated since the last heat treatment (survey). This accounted for operational seawater demand differences between the sites and between years at each site. The annual means across all sites and surveys were derived from these data. Significance (meaningfulness) of the abundance and modal length trends was determined using the Microsoft Excel add-in developed by Bryhn and Dimberg 2011. After deriving the five-year running mean for each species, the maximum and minimal periods in each abundance index were compared. The five-year mean was used rather than individual years to avoid comparing maximum and minimum values in each time series that may result from an anomalously abundant (depauperate) year and thereby overestimate (underestimate) the change in abundance. Each five-year period was also ranked in descending order.

Cross-correlation analysis was used to determine at what temporal lag (years) the ER and CPUE trends were most similar. The lag with the lowest p-value was chosen in each case. After adjusting the two series in relation to each other per the cross-correlation results, a Spearman rank correlation was used to quantify the similarity between the two temporally adjusted series. An entrapment rate estimating next year's fishery (NYFI) was derived using the abundance of individuals in the 200 to 250 mm SL size classes, assuming these indi-

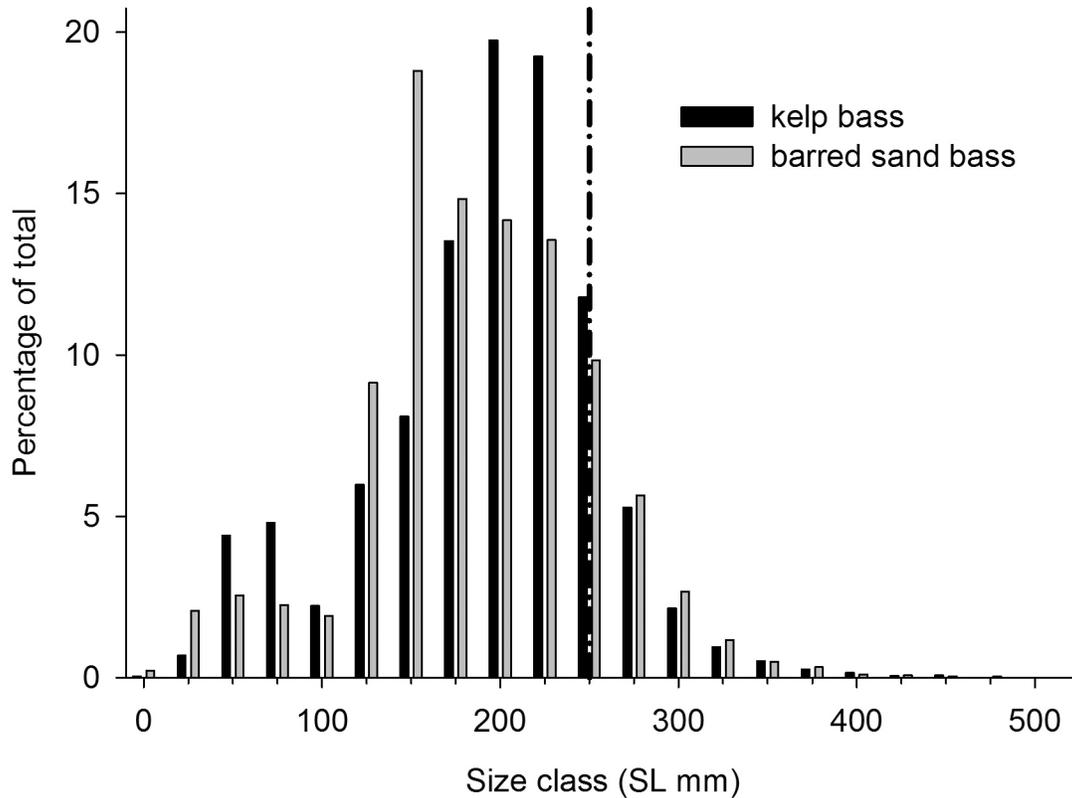


Figure 1. Length frequency distribution (percent of total sample) for kelp bass ( $n = 17,033$ ) and barred sand bass ( $n = 13,371$ ) measured during power plant entrapment monitoring, 1979–2010. The dashed lines represent the fisheries' minimum size limit.

viduals were one-year's growth from recruiting to the fishery. The long-term trend was also tested for significance consistent with the methods described for the ER. The NYFI's relationship to the corresponding species' CPUE was derived using the same methods described for the ER.

Assuming individuals measuring  $<150$  mm SL were young-of-the-year (Love et al. 1996), an abundance index (YOYI) was generated from lengths recorded during power plant surveys. This index served as a proxy for year-class abundance. The number of individuals, by species, was standardized consistent with the entrapment rate (ER) described above. This YOYI ( $\text{count}/10^8 \text{ m}^3$ ) was used in all later analyses after assigning values to the appropriate year-classes based on known spawning seasons for each species. Results of surveys conducted in July–December were assigned to the year of capture while those taken in January–June were assigned to the year preceding the year of capture. The YOYI's relationship to the corresponding species' CPUE using the same methods described for the ER.

Oceanographic data included observed daily sea surface temperature (SST) recorded at the Scripps Institution of Oceanography Pier in La Jolla, California (Scripps Institution of Oceanography 2012). Climate

indices included: North Pacific Gyre Oscillation (NPGO) (Di Lorenzo et al. 2008), Pacific Decadal Oscillation (PDO) (Mantua et al. 1997), and the Multivariate ENSO Index (MEI) (Wolter and Timlin 1998). Spearman rank correlation was used to compare the YOYI to each environmental index using after testing for autocorrelation using a Durbin–Watson test. Spearman rank correlation results were adjusted using the modified Chelton method (Pyper and Peterman 1998) when temporal autocorrelation was detected. All statistic analyses, with the exceptions of trend significance testing, were completed in R using Rcmdr (Fox 2005).

## RESULTS

### Kelp Bass

Entrapment surveys recorded 38,875 kelp bass during the 39 years examined in sizes ranging from 21–505 mm SL. Approximately 40% of all kelp bass were represented in the 200 and 225 mm SL size classes, or near the minimum fishery size limit of 250 mm SL (fig. 1). Between 1979 and 2010, the kelp bass modal length oscillated between 322 mm SL in 2001 and 126 mm SL in 2002 and 2005 (fig. 2a). Most years, however, the modal length was between 200 and 250 mm SL with no significant

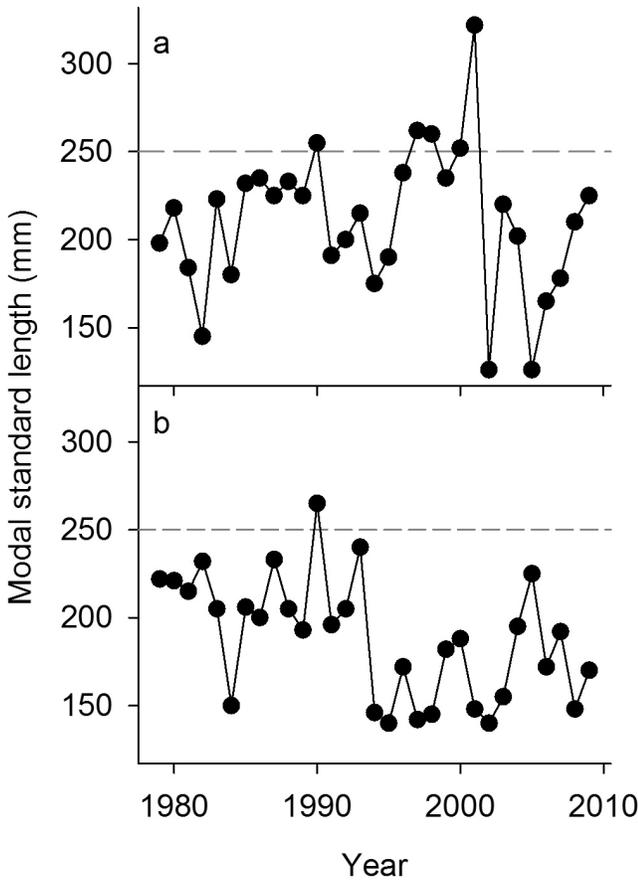


Figure 2. Annual modal length for a) kelp bass and b) barred sand bass measured during power plant entrapment monitoring, 1979–2010. The dashed lines represent the fisheries' minimum size limit.

trend ( $r^2 < 0.01$ ,  $p < 0.91$ ). The annual mean ER oscillated between 0.39–4.11 fish/ $10^6$  m<sup>3</sup> from 1972 and 1983. The most abundant period occurred from 1979–83, with an average of 2.93 fish/ $10^6$  m<sup>3</sup> before declining 97% to the series minimum during the 1998–2002 period at 0.09 / $10^6$  m<sup>3</sup> ( $r^2 = 0.39$ ,  $p < 0.001$ ; fig. 3a). All years after the 1987–91 period ranked >10th (out of 35 five-year running mean periods), and all years during the last decade ranked >24th. The kelp bass ER was significantly correlated with the CPUE ( $r = 0.65$ ,  $p < 0.001$ ) after lagging the data seven years (table 1). During a nearly commensurate time, the annual mean NYFI significantly declined ( $r^2 = 0.45$ ,  $p < 0.001$ ) from its peak in 1979 of 1.8 / $10^6$  m<sup>3</sup> to a low of 0.0 / $10^6$  m<sup>3</sup> in 2002 (fig. 3b). Between 1979 and 1999, the annual mean NYFI was <0.2 nine times, but only the 2000 mean NYFI exceeded this mark during the last 11 years examined. Overall, the NYFI was significantly correlated with the CPUE one year later ( $r = 0.77$ ,  $p < 0.001$ ).

The kelp bass YOYI trend declined, but in a statistically insignificant ( $r^2 = 0.22$ ,  $p = 0.07$ ) pattern (fig. 4). Larval settlement between 1998 and 2003 was especially poor

TABLE 1  
 Spearman rank correlation results after lagging data as indicated by cross-correlation analysis comparing the fishery catch per unit effort and each fishery-independent abundance index. Indices include the entrapment rate (ER), next year's fishery (NYFI), and the young-of-the-year (YOYI). NS denotes not significant.

Index	kelp bass			barred sand bass		
	Lag	<i>r</i>	<i>p</i>	Lag	<i>r</i>	<i>p</i>
ER	7	0.65	< 0.001	7	0.51	0.01
NYFI	1	0.77	< 0.01	1	NS	NS
YOYI	8	0.49	0.02	7	0.71	<0.001

with each year's YOYI < 100/ $10^8$  m<sup>3</sup>. The YOYI peaked during the 1979–83 period at 4341/ $10^8$  m<sup>3</sup>, whereas the lowest values occurred during the 1998–2003 period at 160/ $10^8$  m<sup>3</sup>. None of the oceanographic indices (PDO, NPGO, and MEI) correlated with the YOYI (table 2). Exclusion of the 1983 YOYI value, which was 4.0 standard deviations above the mean, did not improve the relationships. Like the ER and NYFI, the YOYI was also significantly correlated with the CPUE ( $r = 0.49$ ,  $p < 0.02$ ) at a lag of eight years (table 1).

### Barred Sand Bass

Power plant monitoring recorded 33,855 barred sand bass measuring between 6 and 479 mm SL. Nineteen percent of all individuals were represented in the 150–mm SL size class with an additional 43% distributed amongst the 175, 200, and 225 mm SL size classes, combined (fig. 1). Modal lengths during the 1979–93 period averaged 212 mm SL before declining to a bulk mean of 166 mm SL through 2010 (fig. 2b). This trend was a significantly negative trajectory ( $r^2 = 0.25$ ,  $p < 0.01$ ). Entrapment rates peaked during the 1979–83 period at 1.43/ $10^6$  m<sup>3</sup> and reached its lowest point in 2000–04 at 0.2/ $10^6$  m<sup>3</sup>, or an 86% decline (fig. 3c). Of the 35 five-year running means computed, each has ranked >10th since the 1984–88 period, including >20th every year since 1997–2001. The ER significantly correlated ( $r = 0.51$ ,  $p = 0.01$ ) with the CPUE after lagging the data seven years (table 1).

Since 1979, the NYFI also significantly declined ( $r^2 = 0.63$ ,  $p < 0.001$ ) from a peak of 0.6/ $10^6$  m<sup>3</sup> in 1979 to 0.0/ $10^6$  m<sup>3</sup> in 1999 and 2010 (fig. 3d). From 1979 to 1986, the annual mean NYFI was <0.2 once (1984) while every year's mean NYFI since was <0.2. If this arbitrary threshold was lowered to 0.1/ $10^6$  m<sup>3</sup>, then 17 of the last 21 years' mean NYFI was <0.1/ $10^6$  m<sup>3</sup>. Unlike the kelp bass, the barred sand bass NYFI did not significantly correlate with the CPUE (table 1).

The 1994 YOYI (13,834/ $10^8$  m<sup>3</sup>) was nearly four-times larger than the 1997 YOYI (3794/ $10^8$  m<sup>3</sup>), which ranked second (fig. 4). Year-class abundance was high-

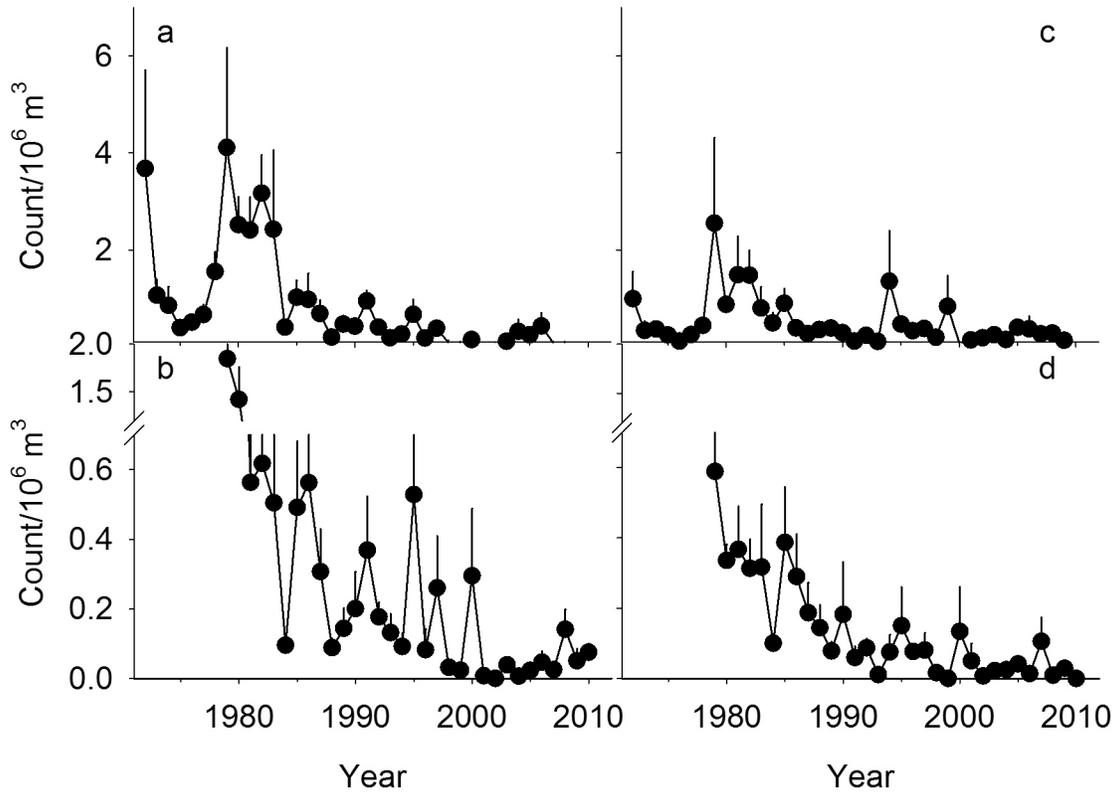


Figure 3. Mean annual entrapment rate (count/10<sup>6</sup> m<sup>3</sup>) with standard error derived from power plant monitoring, 1972–2010, for a) kelp bass and c) barred sand bass. Mean annual next year's fishery index (count/10<sup>6</sup> m<sup>3</sup>), 1979–2010, for b) kelp bass and d) barred sand bass.

est in the mid-1990s with three year classes measuring >3000/10<sup>8</sup> m<sup>3</sup>. The YOYI trend was insignificant ( $r^2 = 0.01$ ,  $p = 0.70$ ) and failed to significantly correlate with the climate indices (PDO, NPGO, and MEI; table 2). It did correlate with SST ( $r = 0.37$ ,  $p = 0.04$ ). These results did not change after excluding 1994, which was 5.0 standard deviations above the mean. The barred sand bass YOYI was highly correlated with the CPUE ( $r = 0.71$ ,  $p < 0.001$ ) at a lag of seven years (table 1).

**DISCUSSION**

Both California sea bass populations studied here showed evidence of depletion that predated fishery declines, but what precipitated this decline? Recent information suggests the coastal southern California fish community ensemble mean abundance declined by 78% utilizing similar data sources (Miller and McGowan 2013). These declines reportedly transcended fishing pressure, although fishing was not absolved of all responsibility. The question remains, was the decline in California sea bass populations an effect of overfishing, environmental variability, or some combination of the two? Fishing was clearly implicated as a contributing factor as prior work concluded the kelp bass and barred sand bass fisheries suffered from hyperstability

**TABLE 2**  
 Durbin-Watson (DW) autocorrelation test results for each oceanographic parameter used in Spearman rank correlation tests with barred sand bass and kelp bass YOYI-indices. Spearman rank correlation results for each comparison are presented. Bold text denotes significant at the  $p < 0.05$  level. Significant correlations between autocorrelation parameters were reexamined after deriving a new  $r_{crit}$  accounting for autocorrelation using the modified Chelton method (Pyper and Peterman 1998).  
 Barred sand bass DW = 1.58,  $p = 0.16$ ;  
 kelp bass DW = 1.38,  $p < 0.05$ . Derived  $r_{crit}$  for kelp bass: NPGO correlation = 0.69, therefore the correlation is not significant.

	DW	p	barred sand bass		kelp bass	
			r	p	r	p
SST	1.56	0.07	<b>0.37</b>	<b>0.04</b>	0.13	0.49
MEI	1.71	0.16	0.13	0.48	0.23	0.20
NPGO	<b>0.60</b>	<b>&lt;0.01</b>	-0.25	0.17	-0.52	<0.01
PDO	<b>1.40</b>	<b>0.03</b>	0.25	0.17	0.22	0.24

(Erisman et al. 2011). Hyperstability occurs when catch rates remain stable or increase while the underlying populations decline, typically by targeting aggregation sites. Hyperstability, however, does not exclude oceanographic effects undermining the populations' resiliency and stability.

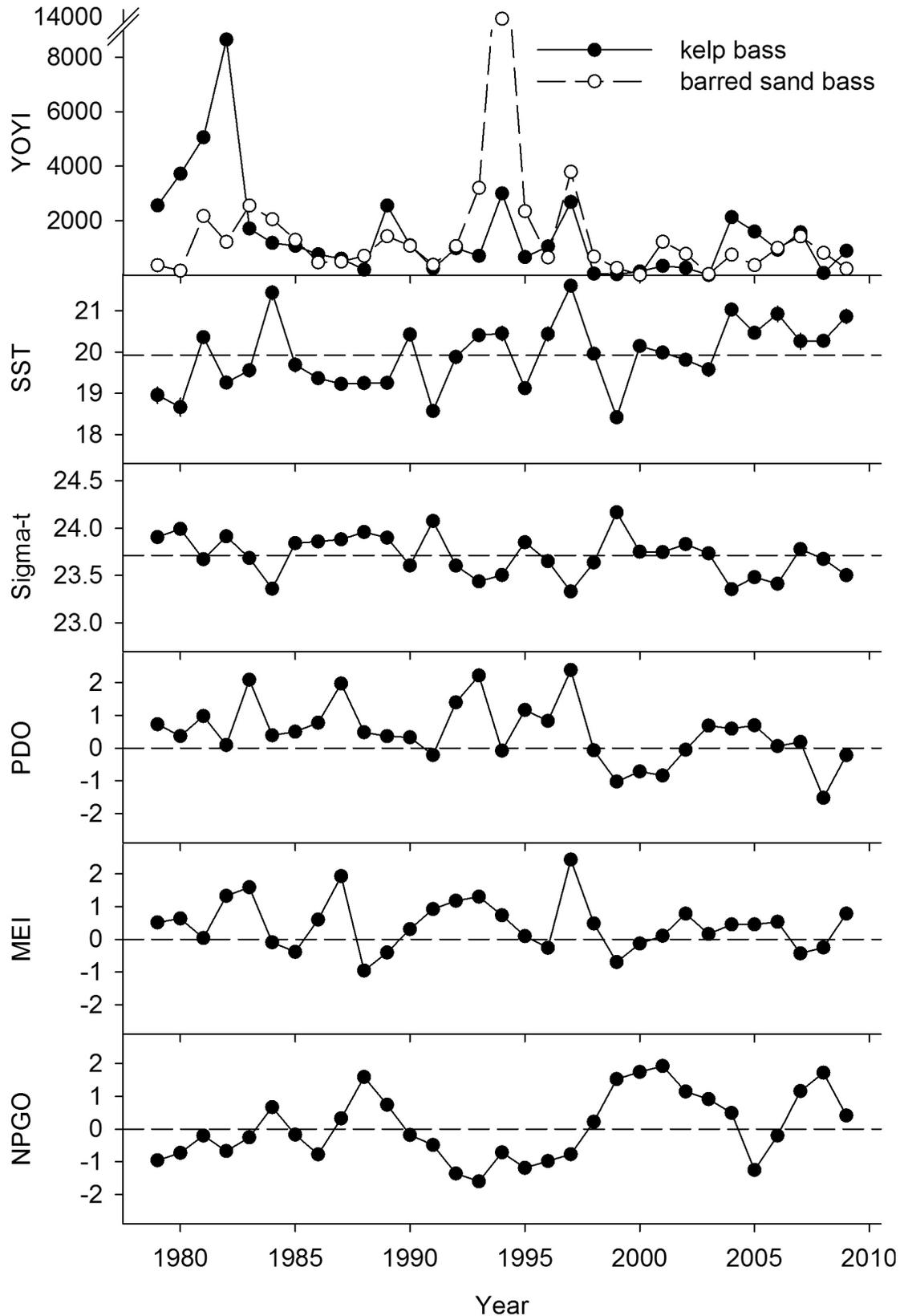


Figure 4. Annual young-of-the-year index (YOYI; count/10<sup>8</sup> m<sup>3</sup>) for kelp bass and barred sand bass derived from lengths recorded during power plant monitoring, 1979–2010. Annual summer (June–September) oceanographic or climate index values, 1979–2010, including: sea surface temperature (°C; SST), seawater density (sigma-t), Pacific Decadal Oscillation (PDO), Multivariate ENSO Index (MEI), and North Pacific Gyre Oscillation (NPGO).

Aggregation fisheries and hyperstability unfortunately often go hand in hand and are rarely sustainable (Sadovy and Domeier 2005). One of the growing concerns related to overfishing is the potential impact to life history parameters especially when the capture of large individuals are preferred by anglers, such as commonly occurs in recreational fisheries (Berkeley et al. 2004; Birkeland and Dayton 2005; McClenachan 2009). Inconclusive, but highly suggestive, evidence of life history impacts were detected in barred sand bass. Kelp bass modal lengths remained relatively unchanged over time, but significant downsizing in barred sand bass was indicated. Lacking more refined data on growth and reproduction parameters, any conclusion would be speculative at this point. The trend in barred sand bass, however, warrants further investigation to discern potential evolutionary effects recent overfishing may have had on the population (Conover and Munch 2002; Heino and Godo 2002; Walsh et al. 2006; Brown et al. 2008; Enberg et al. 2009; Garcia et al. 2012). Fishing-induced evolution has slowed the rebuilding of collapsed fisheries, such as Atlantic cod (Enberg et al. 2009), which would effect future management of the California sea basses.

While evidence of declining populations and apparent changes to the size structure of the populations now exists, the underlying question remains unanswered: What precipitated the decline? A common culprit was variable year-class strength. Abundance indices of younger age classes, ranging from larvae through recruitment into the fishery, commonly received extensive study from fishery scientists as a way to predict future fishery yield (Houde 2008). For example, years with higher abundance of juvenile yellow snapper (*Lutjanus argentiventris*) and leopard grouper (*Mycteroperca rosacea*) translated into greater commercial landings once individuals recruited into their fisheries (Aburto-Oropeza et al. 2010). Fishery science was rich with descriptions of year-class abundance effects on future fishery yields. The “gadoid outburst” in North Atlantic cod (*Gadus morhua*) being among the best known examples (Cushing 1980; Beaugrand et al. 2003). Abundant North Atlantic cod year classes resulted from environmental conditions conducive to their settlement in preferred habitat (Beaugrand et al. 2003; Beaugrand and Kirby 2010a,b; Olsen et al. 2011) regardless of high harvest pressure. Once the environment changed, year-class abundance declined, fishing pressure remained constant, and the stock soon collapsed (Beaugrand et al. 2003; Beaugrand and Kirby 2010a). Parallels between the southern California sea bass trends and those reported in North Atlantic cod existed. Specifically, each supported robust fisheries until fishing outpaced larval settlement leading to a fishery collapse.

In compilation with this and prior studies (Hill and Schneider 1999; Moser et al. 2001; Erisman et al. 2011), a robust case can be made that the environment no longer promoted strong local settlement while fishing continued unabated. Miller and McGowan 2013 identified significant, negative shifts in the southern California coastal fish community culminating in 1984 and 1989, or after a substantial Californian El Niño (Simpson 1984; McGowan 1984) and a documented oceanographic regime shift lacking a thermal signature (Hare and Mantua 2001; Polovina 2005; DiLorenzo et al. 2008). Fishery-independent investigations, especially using larval settlement and subsequent fishery recruitment in the southern California sea bass species, suffer from a lack of relevant data. Ichthyoplankton data extends at variable sampling intervals and spatial resolution to 1960, but samples were identified to genus rather than species (Moser et al. 2001). In southern California, three *Paralabrax* species co-occur (kelp bass, barred sand bass, and spotted sand bass, *P. maculatofasciatus*). Beyond the general decline, the presently available ichthyoplankton data adds little clarity regarding species-specific trends. Similar to our YOYI, diver-recorded densities of kelp bass and barred sand bass young-of-the-year in King Harbor, Redondo Beach, California, declined over time (Love et al. 1996).

The novel power plant sampling program data proved informative through an analysis of pre-recruitment age-class abundances over time. Our examination signaled the fishery demise was unavoidable given the  $\geq 86\%$  declines in southern California sea bass populations indexed by the ER. These results were consistent with more localized studies, including substantial declines in kelp bass abundances surveyed more than 20 years apart in a no-take marine reserve (Parnell et al. 2005). Despite the resolution, the notable ichthyoplankton declines described previously were evident for the genus since 1989 (Moser et al. 2001) thus corroborating our observed declining trends in the power plant abundance indices.

The power plant-derived YOYI for both species declined in species-specific patterns during recent decades. Since 1998, neither species' YOYI reached early-1980s levels with each suffering several periods of near-zero YOYI. No clear environmental relationship could be determined in our evaluation beyond a weak correlation between barred sand bass and SST, consistent with prior work (Selkoe et al. 2006; Selkoe et al. 2007). Anecdotal opinion suggested that populations of both basses benefited (increased growth rates, increased larval settlement, etc.) from warm water periods, such as El Niño conditions in southern California (California Fish and Game Commission 2012). Our results did not support this opinion. The two largest year-to-year declines in each species' YOYI occurred in the second

year of a large El Niño (1983 and 1998) when coastal water temperatures remained above average. Furthermore, recent work signals that abundance patterns in southern California coastal fishes have responded to an oceanographic shift (1989) independent of the typical warm/cool characterizations (Miller and McGowan 2013). Similar work on the 1989 oceanographic shift indicated changes in coastal productivity, current patterns, and other temperature-independent processes (Polovina 2005; Di Lorenzo et al. 2008). The two sea bass species' population abundances over time (Hill and Schneider 1999; Moser et al. 2001) suggest differing conditions (environmental, fishing pressure, etc.) were favored by each species. Additional studies using more robust models coupling biological and physical processes may prove fruitful in identifying the suite of conditions favored by each species (Asch and Checkley Jr. 2013).

Utilizing the power plant abundance indices (ER, NYFI, and YOYI), a declining trend in larval settlement and recruitment were evident in the populations. Cross-correlation analysis indicated the ERs declined approximately seven years before the fishery, or approximately the perceived age of recruitment for both species (Love et al. 1996). The difference in each species' connection between the CPUE and fishery-independent data was indicative of varying levels of hyperstability in the fisheries, with greater effects occurring in the barred sand bass fishery. Such disconnects between population abundance and fishery landings represent an extreme form of hyperstability (Erisman et al. 2011). Therefore, the insignificant correlation between the barred sand bass CPUE and NYFI was not surprising given prior hyperstability evidence reported in the literature.

Unfortunately, these results do not clearly portion responsibility for the declines to either the environment or fishing. They simply, and repeatedly, reaffirm that the significant declines observed in the fishery was a function of depleted populations. Our analyses failed to identify a commonly measured environmental metric or index that could be used as a reasonable proxy for either bass species' year-class strength. These examinations reinforced prior conclusions; abundance of the two dominant southern California sea bass species dramatically declined in recent decades. New management strategies were implemented in hopes of restoring the stocks. Despite these actions, both the current investigation and prior studies documenting hyperstability in the two populations highlights the clear need for a detailed stock assessment. In the absence of such an assessment, adaptive management to restore and maintain healthy stocks in the face of oceanographic change may be out of reach. Given the slow growth realized in both species (Love et al. 1996), effects of the new regulations,

measured as increased CPUE, will not likely materialize for a decade or more. Therefore continued fishery-independent monitoring will be critical to the evaluation of these new regulations.

## ACKNOWLEDGEMENTS

We would like to thank the power plant operators for their long-running support of the entrapment monitoring and the data's use here in this analysis. A debt of gratitude to K. Herbinson for beginning the long-term database used here before transferring it to E. Miller prior to his retirement. This manuscript was significantly improved by the comments of J. Field, J. Froeschke, and three anonymous reviewers.

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## AGE AND GROWTH OF THE GIANT SEA BASS, *STEREOLEPIS GIGAS*

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### ABSTRACT

The giant sea bass, *Stereolepis gigas*, is the largest bony fish that inhabits California shallow rocky reef communities and is listed by IUCN as a critically endangered species, yet little is known about its life history. To address questions of growth and longevity, 64 samples were obtained through collaborative efforts with commercial fish markets and scientific gillnetting. Sagittae (otoliths) were cross-sectioned and analyzed with digital microscopy. Age estimates indicate that *S. gigas* is a long-lived species attaining at least 76 years of age. Over 90% of the variation between age (years) and standard length (mm) was accounted for in the von Bertalanffy growth model ( $R^2 = 0.911$ ). The calculated von Bertalanffy growth function parameters ( $K = 0.044$ ,  $t_0 = -0.339$ ,  $L_\infty = 2026.2$  mm SL) for *S. gigas* were characteristic of a large, slow-growing, apex predator.

### INTRODUCTION

The giant sea bass, *Stereolepis gigas*, is the largest bony fish associated with the California rocky reef communities. The species is a grouper-like member of the wreckfish family, Polyprionidae (Shane et al. 1996). Historically, giant sea bass were distributed from Humboldt Bay to southern Baja California and the Sea of Cortez with populations concentrated south of Point Conception in shallow rocky reefs. Giant sea bass were commercially and recreationally sought after for most of the twentieth century in California waters. Commercial fishing of this species shifted south of the US border as population numbers in the southern California peaked in 1934 and declined after 1935 when this species became relatively rare in catches (Crooke 1992). Commercial fishers originally caught giant sea bass by hand line then switched to gillnetting, significantly decreasing fish numbers off California by 1934. Commercial landings from US waters peaked in 1932 near 90 mt before declining dramatically to under 10 mt by 1935. US landings coming from Mexican waters were generally higher (peaking at over 360 mt in 1932) and did not permanently sink below 90 mt until 1964 and were below 5 mt when US take from Mexican waters was banned in 1982 (Domeier 2001). Commercial and recreational fishing depleted giant sea

bass stocks to the point that a moratorium was declared in 1982. Although this species cannot be targeted, commercial vessels are now allowed to retain and sell one individual per trip as incidental catch. Giant sea bass caught in Mexican waters by recreational anglers are allowed to be landed and sold in California markets; however the limit is two fish per trip per angler. There are no commercial or recreational restrictions on giant sea bass in Mexico today (Baldwin and Keiser 2008).

In 1994, gillnetting was banned within state waters (three miles off mainland) and one mile from the Channel Islands in southern California. Most recently, concerns over sustained population viability led to the International Union for Conservation of Nature (IUCN) red listing the giant sea bass as a "Critically Endangered" species (Musick et al. 2000; Cornish 2004). The measures taken to protect this species appear to have been effective because the number of juvenile giant sea bass reported as caught and released is increasing (Baldwin and Keiser 2008), and it is one of the five species of large nearshore predators reported as returning to the Southern California Bight (SCB) (Pondella and Allen 2008).

The lack of life history information for giant sea bass is likely a result of the practice of dressing-out (beheading and eviscerating) fish prior to landing to conserve space on fishing vessels (Crooke 1992). Unfortunately, this results in the loss of data on actual fish size and of the head and entrails that contain the structures most useful in life history studies (Allen and Andrews 2012). Because of this practice, little data exist on age, growth, and estimated age at maturity in giant sea bass. Early accounts reported that giant sea bass reach 178 mm (7 in) by age 1 year and twice this length at age 2 years (Fitch and Lavenberg 1971). Age estimates reported for small to medium-sized fish are 6 years at 14 kg (30 lb), 10 years at 45 kg (100 lb), and 15 years at 68 kg (150 lb), but details of the age estimation method were not provided (Domeier 2001). Fitch and Lavenberg 1971 reported an estimated age of 11 to 13 years at sexual maturity. California Department of Fish and Game (Baldwin and Keiser 2008) has reported that females mature between 7 and 11 years of age, however that estimate is unverifiable as there have been no studies confirming age at maturity.

The reported age at maturity of 11 years for giant sea bass is in conflict with the observation by Domeier 2001 that “most fish” were mature at 7 to 8 years.

Gaffney et al. 2007 suggested sex ratios of giant sea bass are approximately 1:1, indicating that giant sea bass are not sequential hermaphrodites. A previous study on two other widespread wreckfishes, *Polyprion americanus* and *P. oxygeneios*, confirmed that both species were gonochores, although some studies have suggested otherwise (Roberts 1989).

Age and growth information is essential to the management of recreational and commercial fisheries and must be considered when assessing the status of a fishery (Craig et al. 1999). Prior to the present study, most age and growth information on *Stereolepis gigas* have been poorly documented or unverifiable. Allen and Andrews 2012 were first to validate annual growth rings for one individual and provide a verified maximum age for giant sea bass using bomb radiocarbon dating techniques. Radiocarbon dating of giant sea bass confirmed that a 227 kg specimen was 62 years old, suggesting that previous estimates that this species lives 100 years may be unsubstantiated (Allen and Andrews 2012). In the present study, we seek to provide the first large data set on the age and growth of giant sea bass as it is vital to our understanding of its biology and critical to the effective management of its exploited population. By developing a realistic growth model, we also aim to confirm that this long-lived species has a slow growth rate ( $k$ ), increasing its susceptibility to overfishing.

## MATERIALS & METHODS

Otoliths (sagittae) were extracted from *Stereolepis gigas* heads obtained from the Santa Barbara Fish Market, Santa Barbara, CA between January 2010 and May 2013 ( $n = 43$ ). These fish were all reported as legal and/or incidental catch taken from the waters off southern California and northern Baja California. Head length (mm) was measured from the tip of the premaxillary bone to the tip of the operculum on each specimen. Sagittal otoliths were also obtained from specimens collected between 2006 and 2010 during a juvenile white seabass (*Atractoscion nobilis*) gill net survey conducted by Allen et al. 2007 for the Ocean Resource and Hatchery Enhancement Program ( $n = 21$ ) where standard lengths were recorded. Once extracted, sagittae were cleaned in 100% ethanol, rinsed with deionized water, and stored in padded envelopes. Length, width, and depth of both the left and right sagittae (if whole and available) were then measured and recorded to the nearest 0.01 mm using digital calipers. Otolith length measurements were taken along the longest axis, parallel to the sulcus. Width was measured across the shortest axis perpendicular to the sulcus while depth was the distance across the shortest

axis of the sagitta at the otolith focus. Unbroken otoliths were weighed on an analytical balance to the nearest 0.001 g.

Two methods of otolith sectioning were used in this study. In the first method, otoliths were embedded in an epoxy mold (mixture of 20 grams of 20-3068RCL15 epoxy resin with approximately 4 grams of CAT.190CL13 catalyst). Each otolith was then placed sulcus side up into a preparatory pool and covered in epoxy. The otolith was then removed from the preparatory pool, air pockets were removed, and then placed into the mold sulcus side down and parallel to the length of the mold. The otolith sat in the mold for 24 hours before being removed from the mold tray and 72 hours before sectioning the otolith within the epoxy mold. A small batch ( $n = 18$ ) was sectioned using a Buehler-Isomet double-bladed low speed saw and was visually inspected for any signs of cracking or breakage. Although many otoliths were sectioned successfully, breakage occurred in a high percentage (50%) of the subsample. Therefore, other protocols were explored for mounting the otoliths safely without threat of cracking during the sectioning process.

The second sectioning method followed that of Craig et al. 1999, where a cyanoacrylate adhesive was used to mount otoliths to wood blocks. This method proved to be successful for giant sea bass otoliths and was employed for the remaining otoliths not sectioned in epoxy ( $n = 46$ ). These remaining otoliths were mounted on approximately 5 cm  $\times$  2.5 cm  $\times$  1 cm blocks with a fast-drying gel cyanoacrylate adhesive and allowed to set for 48 hours. A 0.5 mm section through the nucleus of the otolith was cross-sectioned using a Buehler-Isomet double-bladed low speed saw (Allen et al. 1995). Sections were mounted on glass slides with Crystalbond<sup>®</sup> 509 adhesive (SPI supplies, www.2spi.com) and polished by hand with 3M<sup>®</sup> Wet/Dry 500 grit sandpaper followed by 3M<sup>®</sup> Wet/Dry 1000 grit sandpaper.

Slides were placed in a black bottom Petri dish and digitally photographed using Image Pro 6.3 under a Wilde dissecting microscope. Each photograph was calibrated according to the magnification at which it was imaged and annuli were identified and marked with Image Pro 6.3 Editing software. In total, 64 individuals were aged by viewing digital images along an established axis in the dorso-medial sulcus region. All otolith sections and digital images are archived with the Near-shore Marine Fish Research Program, Department of Biology, California State University Northridge. The digital images of otolith sections were selected randomly and annulus counts made visually on the images with annuli being marked individually on two separate occasions. Where individual counts were in disagreement, otolith images were reexamined by both authors

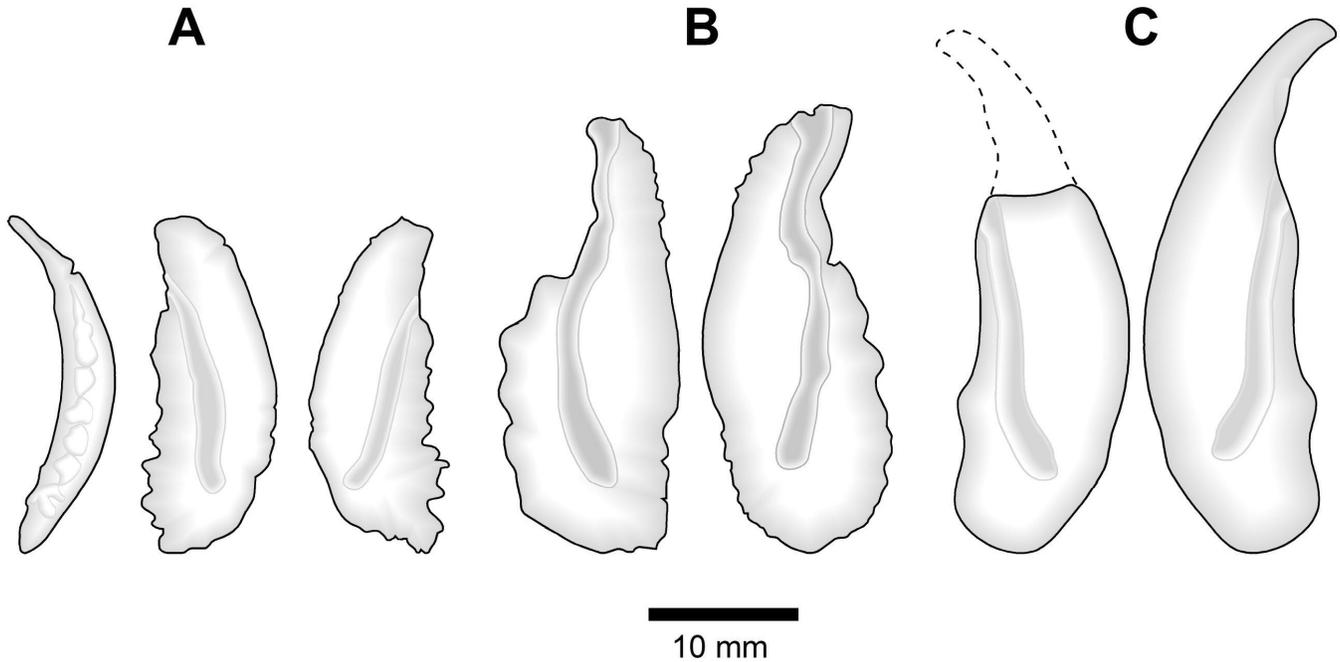


Figure 1. Ontogenetic morphological variation in sagittae of giant sea bass (*Stereolepis gigas*). A) A dorsal view of left and dorso-medial views of left and right sagittae from a 1390 mm SL, specimen and dorso-medial views of left and right sagittae of a B) 1862 mm SL, and a C) 2003 mm SL specimen aged during the present study. © Larry G. Allen.

together, until a consensus age was established by judging the validity of each marked annulus. Head lengths (mm) were converted to standard lengths (mm) for each sample represented only by a head based on the equation:  $SL = (0.282 * HL) + 11.34$  ( $R^2 = 0.998$ ) (L. G. Allen, unpublished data). Lastly, the estimated age of fish obtained from annual increment counts was regressed against whole (unbroken) otolith weight to assess weight as a predictor of age.

As recommended by Cailliet et al. 2006, the relationship between age (yr) and length (mm SL) data was estimated using multiple growth models. In this case, three growth models, the von Bertalanffy, Gompertz, and Logistic models in Growth II (©2006 Pisces Conservation Ltd.) were used where both the Akaike (AIC) and Bayesian Information Criteria (BIC) were calculated to determine the best fit among the models.

## RESULTS

### Otolith Structure

In giant sea bass, the sagittae are elongated, laterally compressed, curved, and very fragile in younger specimens (fig. 1a). In younger specimens the lateral surfaces are irregular, with many mounts and depressions while the medial surface is relatively smooth punctuated by the sulcus acusticus opening anteriorly. The dorsal surface of the sagittae in younger individuals is highly crenellated. The external face of the otolith is concave

(fig. 1a) with grooves and ridges radiating out from the core. With age, the rostrum becomes highly elongated, conspicuous and curved, the sulcus acusticus gets deeper and elongated, while the dorsal surface becomes smooth (figs. 1b and 1c).

Examined with reflected light over a black background, the central area of the sectioned sagitta is white and may show one to seven false (subannular) rings. The central area is surrounded by the first translucent band followed by a clear and distinct opaque band denoting the first annual band (fig. 2). The first band invariably occurs at a sagitta width of approximately 3.0 mm based on the otolith width of a newly age-1 giant sea bass (Allen and Andrews 2012). The subsequent bands could be easily observed in the dorsal (dorso-medial) region of the sulcus (fig. 2).

### Age Determination

The precision of interpreting assumed annual growth bands on digital images was high, with close agreement between the annual counts made by the two readers ( $R^2 = 0.990$ ;  $p < 0.0001$ ;  $n = 64$ ). The number of annuli (age) and otolith weight ( $R^2 = 0.913$ ;  $p < 0.001$ ;  $n = 58$ ; fig. 3), were significantly and positively correlated. This relationship was best explained by the equation:  $Age = 0.029 \times \text{otolith weight (g)} - 0.089$  confirming that the number of annual increments increased linearly as otolith weight increased across the in the range of fish sizes sampled.

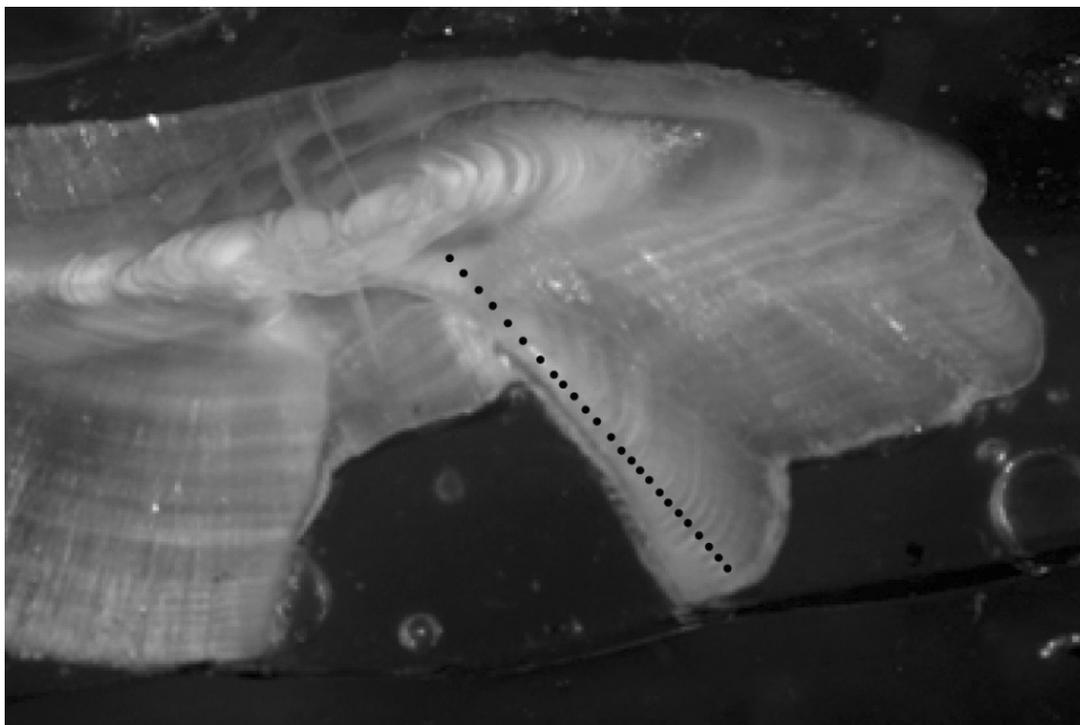


Figure 2. Transverse cross section (25x) of a representative sagitta of 25-year-old, 1572 mm SL *Stereolepis gigas*. Black dots are placed on the image to identify the annuli present.

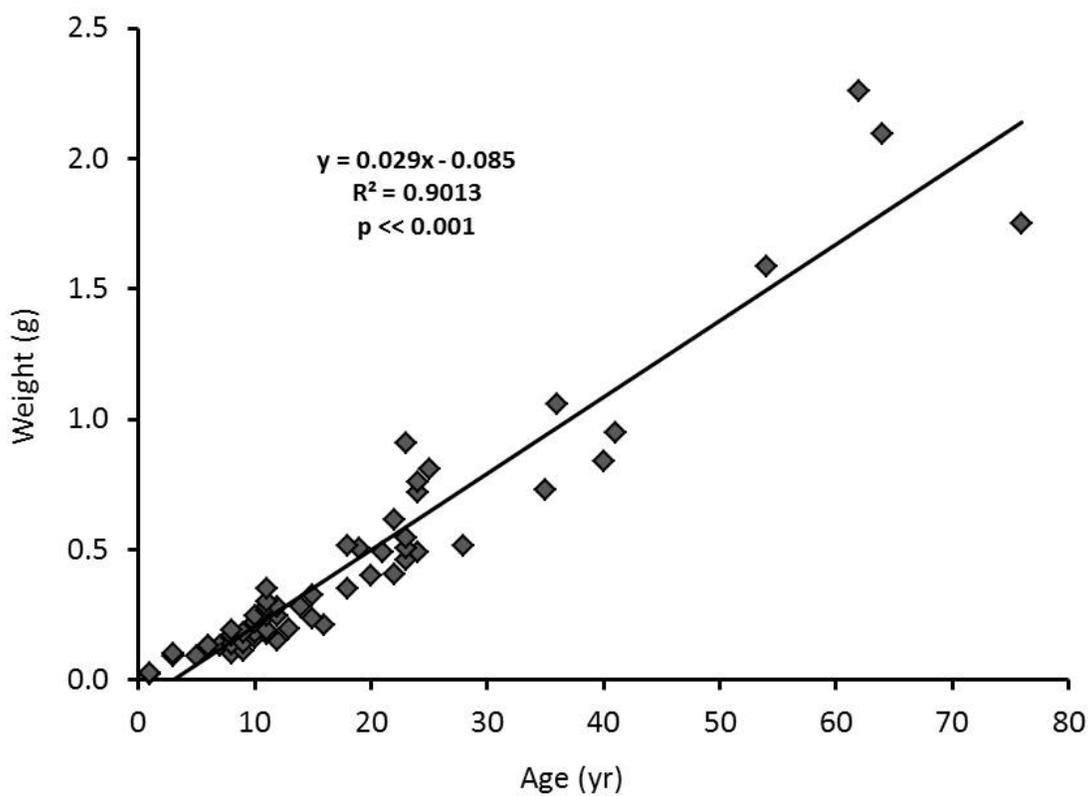


Figure 3. The relationship between otolith weight (g) and estimated age of giant sea bass ( $N = 58$ ).

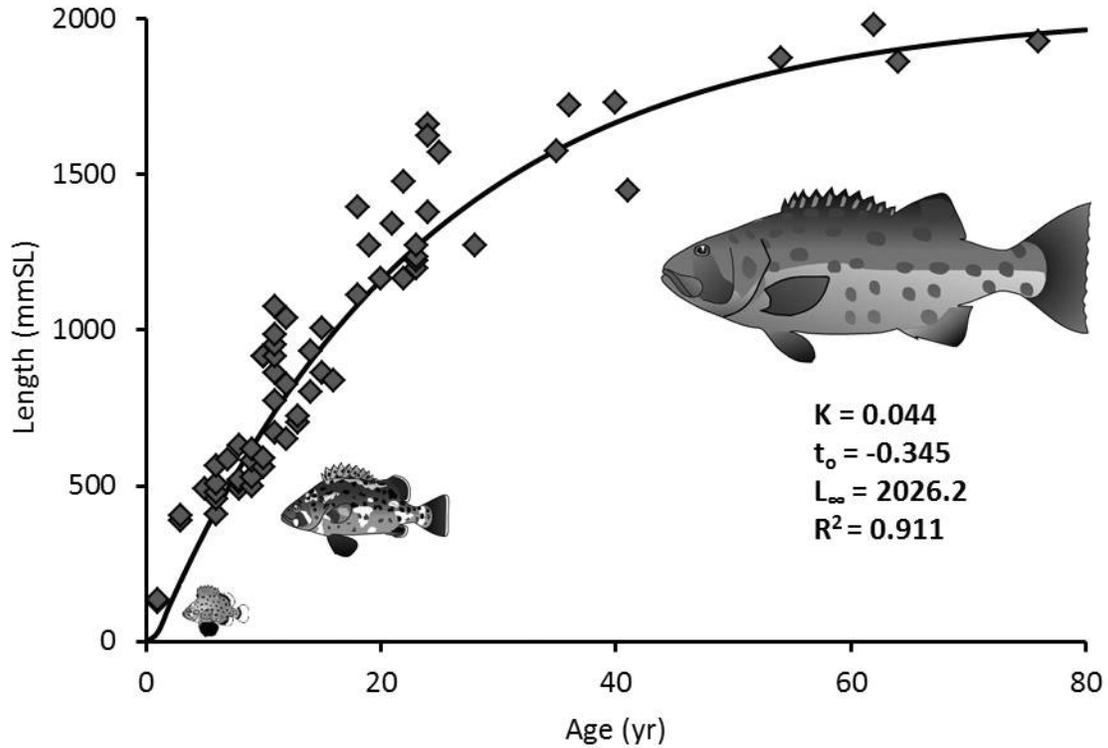


Figure 4. Observed standard length (SL) at age for *Stereolepis gigas* ( $N = 64$ ) taken off California and Mexico. Line is fit to the von Bertalanffy growth curve with parameters given on figure.

TABLE 1  
 Parameters and model diagnostics (Akaike Information Criteria, AIC; Bayesian Information Criterion, BIC; and Inflection point,  $I$ ) for three growth models calculated from size at age data for *Stereolepis gigas* ( $n = 64$ ).

Growth Model	Parameters			Model Diagnostics		
	$L_{\infty}$	K	$t_0$	$I$	AIC	BIC
von Bertalanffy	2026.2	0.044	-0.345	—	908*	914*
Gompertz	1708.2	0.104	—	8.774	914	921
Logistic	1794.9	0.120	—	13.765	914	920

\* — Denotes minimum values indicating best fit.

### Age and Growth

Giant sea bass in this study ranged from 130 mm to 2003 mm SL and from 1 to 76 years old, although only 9.4% of our samples were over age 40 (fig. 4). Of the three growth models tested (table 1), the von Bertalanffy growth function resulted in the best fit with the lowest values calculated for both AIC and BIC diagnostics. Over 90% of the variation between age (years) and standard length (mm) was accounted for in the von Bertalanffy growth model ( $R^2 = 0.911$ ). The growth coefficient ( $K = 0.044$ ) indicate this species has a slow growth rate, however, the negative value for  $t_0$  ( $t_0 = -0.345$ ) is indicative of a species that grows rapidly in the first year and at a decreased growth rate in the years following. A predicted maximum length with indefinite growth ( $L_{\infty} = 2026.2$  mm SL) agreed well with the recorded maximum size of giant sea bass. The theoretical age at length calculations agreed well with observed ages with few

exceptions. The growth equation fit to calculated standard lengths at age was  $l_t = 2026.2 (1 - e^{-0.044(t + 0.345)})$  (von Bertalanffy 1938).

### DISCUSSION

Managing a once heavily fished species such as *Stereolepis gigas* requires robust knowledge of all aspects of the life history of the species. Age validation through otolith analysis allows for a more complete understanding of age, growth, and mortality of *Stereolepis gigas*. Fitch and Lavenberg 1971 published detailed accounts of the natural history of giant sea bass, including reports that a 435 pound specimen was estimated between 72 and 75 years of age. Unfortunately, the methods used to determine its age were not addressed. Otoliths were often read whole at the time (Allen and Andrews 2012), which can lead to a skewed estimation of age. A more recent study using radiocarbon analysis methods validated annular

growth rings in giant sea bass, as well as confirmed the oldest (at the time) known individual to be 62 years of age (Allen and Andrews 2012). There has been much speculation and little information on the longevity of giant sea bass, but here we estimate the age of the oldest known individual at 76 years. There are reports that *S. gigas* reaches 90 to 100 years of age and 600 pounds (Fitch and Lavenberg 1971), yet these reports are unverifiable. In the current study, individuals were collected at the upper size limit of expected growth of giant sea bass and none exceeded 76 years.

Morphology of the sagittae varied as fish increased in size, generally becoming proportionally deeper and heavier with greater anterior extension. However, the greatest morphological variation particularly in otolith weight occurred among the largest and oldest specimens (figs. 1b and 1c). Whether this difference represents sexual dimorphism is impossible to tell, unfortunately, because all of the adult specimens were represented only by heads obtained from market.

*Stereolepis gigas* has only one congener, *Stereolepis doederleini* that occurs in the northwestern Pacific. As with its congener, little life history information is known for *S. doederleini*, but other polyprionids have been the subject of age and growth studies. In a study conducted by Peres and Haimovici 2004 on the Atlantic wreckfish, *Polyprion americanus*, maximum age was estimated at 76 years. Similar to our findings, the von Bertalanffy growth curves for both males and females of *P. americanus* indicated slow growth rates overall, with negative values for  $t_0$ . Unfortunately for the purposes of this study, we were unable to differentiate between males and females as *S. gigas* is not an obviously sexually dimorphic species and gonads were always removed before they were brought to market. Sexual size dimorphism has been suggested for another wreckfish species, the New Zealand hapuku, *Polyprion oxygeneios*, whose females grow larger and faster than males (Francis et al. 1999). It would be beneficial in the future to address possible variances in growth rates among males and females giant sea bass because differences can have implications in sexual selection (Walker and McCormick 2009).

Management and conservation of marine fishes requires the consideration of many factors and consequent comprehensive data collection. Such factors may include, but are not limited to, age and growth data (Cailliet et al. 1996), interspecific interactions (Jackson et al. 2001), and species-specific life history traits (Pinsky et al. 2011). Large, long-lived marine fishes that are particularly susceptible to over-exploitation (Reynolds et al. 2005) and recovery of a population after a decline can take well over a decade to several decades, if at all (Hutchings 2000; Russ and Alcala 2004). The resilience of any fish population and its subsequent recov-

ery depends on a suite of variables, many of which will be species specific such as the longevity and growth rate of individuals, fecundity, larval duration, and age at maturation. Russ and Alcala 2004 suggest that it may take 15 to 40 years for a predatory fish population protected by marine reserves to recover fully.

In support of the recovery of giant sea bass, it may be advantageous if marine protected areas (MPAs) were established where spawning aggregations occur. It is illegal to target giant sea bass, but incidental catch-and-release occurs regularly. One model of five mortality regimes predicting the expected mortality of giant sea bass under varying degrees of catch and release mortality indicated that in an aggregation of 100 giant sea bass with 20% mortality due to catch and release would be driven to local extinction after 16 years (Schroeder and Love 2002). Alternatively, with an estimated natural mortality rate of only 6%, an aggregation of 100 giant sea bass would be reduced to 29 individuals after 25 years (Schroeder and Love 2002). An unrealistic, yet important assumption in the model is that no additional recruits are added to the aggregation over time. However, the model does illustrate the impact that catch-and-release mortality may have on this protected species and supports the proposal that MPAs could be useful in the management and recovery of this species.

Giant sea bass in California are currently protected to some degree, yet those in Mexico continue to be targeted both commercially and recreationally. Unpublished data cited in the 2008 Status of the Fisheries Report for giant sea bass (Baldwin and Keiser 2008) suggested that giant sea bass may in fact migrate long distances, placing even more importance on protecting giant sea bass in California as they remain unprotected and subject to different fishing pressure in Mexico (Gaffney et al. 2007). While fishing mortality can cause an adaptive response in growth rates of a population (Bevacqua et al. 2012), an analysis of covariance indicated there is no difference in growth among Californian and Mexican giant sea bass and that the variation found in length and age of giant sea bass is not due to any variation between individuals sampled in California and Mexico. However, the effects of any possible fishing pressure experienced by Mexican giant sea bass may be offset by genetic exchange (Gaffney et al. 2007) with those protected in California.

## ACKNOWLEDGEMENTS

We thank Brian Colgate of the Santa Barbara Fish Market, Santa Barbara, CA, for making giant sea bass heads available for study. Mark Steele (CSUN) provided the microscope, video camera, and imaging software necessary for the aging work. Greg Cailliet and Milton Love provided insightful and constructive comments on the manuscript. Funds for this work were provided by

the Nearshore Marine Fish Research Program, Department of Biology, California State University Northridge. All specimens collected from the wild were done so under CDFG Scientific Collecting Permit #00032 issued to L.G. Allen.

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## REGIONAL GROWTH PATTERNS OF JUVENILE ALBACORE (*THUNNUS ALALUNGA*) IN THE EASTERN NORTH PACIFIC

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### ABSTRACT

Population structure of North Pacific albacore (*Thunnus alalunga*) may be more complex than the current single-stock hypothesis given the apparent regional differences in size-at-age and movement patterns in the eastern North Pacific. In this study, otolith-based techniques were used to analyze the age structure, daily growth rates and hatch dates of 126 albacore collected from two regions in the eastern North Pacific (northern:  $>40^{\circ}\text{N}$  and southern:  $<40^{\circ}\text{N}$ ) in July through October of 2010 and 2011. Juvenile albacore collected from the southern region had significantly larger size-at-age than those collected from the northern region over a similar age range examined (423–1254 days). No significant regional difference in growth rates of juvenile albacore was detected over the ages examined, suggesting processes occurring in the first year and a half of life may have been driving regional size-at-age differences. Back-calculated hatch dates suggest protracted spawning for fish from both regions ranging from February to September with peak hatch dates between April and July (73% of all fish). Results from this two-year study suggest that juvenile albacore length-at-age estimates in the eastern North Pacific are region-specific and may need to be considered for future life history studies and stock assessments.

### INTRODUCTION

Albacore (*Thunnus alalunga*) are highly migratory predators with a cosmopolitan distribution (Sund et al. 1981). In the Pacific Ocean, albacore are separated into North and South Pacific stocks due to limited mixing across the equator and isolated spawning grounds (Nakamura 1969). In the North Pacific, albacore spawn in the central and western Pacific where many begin transoceanic migrations to utilize the highly productive California Current in the eastern North Pacific (Clemens and Craig 1965; Wetherall et al. 1981). The distribution and relative abundance of albacore in the eastern North Pacific varies latitudinally (Laurs and Lynn 1977; Laurs and Wetherall 1981; Wetherall et al. 1987; Childers et al. 2011) and it has been suggested that there are two subgroups of albacore: a north-

ern group based offshore of the Pacific Northwest of the United States and Canada and a southern group located offshore of southern California and Baja, Mexico (Laurs and Lynn 1977; Laurs and Wetherall 1981; Wetherall et al. 1987; Laurs and Lynn 1991). The dividing line between these two subgroups is considered to be associated with the Mendocino Escarpment located at  $40^{\circ}\text{N}$ . Albacore from the two subgroups have been reported to differ in size composition, growth rates, movement patterns, and peak spawning periods, which has led to the hypothesis that there may be two substocks of albacore in the eastern North Pacific (Laurs and Wetherall 1981; Laurs and Lynn 1991; Barr 2009; Childers et al. 2011).

Stock structure is a key component of management, and current management of North Pacific albacore assumes a single stock in the North Pacific. Growth rates during the juvenile stage can be directly linked to survival and subsequent population dynamics of adult fish populations (Houde 1987). One of the best approaches to retrospectively examine early life history is using otolith-derived age and growth estimates based on the deposition of daily rings. To date, however, few studies have attempted to use daily otolith ageing to examine albacore in the eastern North Pacific (Wetherall et al. 1987) because the technique is technically challenging and labor intensive (Williams et al. 2013). Near-daily deposition of daily growth increments has been validated for North Pacific albacore (Laurs et al. 1985) and allows for relatively high precision in estimates of age, growth rates, and hatch dates.

In this study, otolith microstructure was used to examine regional growth rates and length-at-age estimates of juvenile albacore in the eastern North Pacific. The daily ages of fish were then used to back-calculate fish hatch date to estimate albacore spawning periods, which can be used to address the sub-stock hypothesis. Temporal differences in spawning may support the possibility of two substocks because separate stocks are defined by separation in time and/or space. Ultimately, information on the life history and ecology of albacore in the eastern North Pacific will provide updated biological parameters useful for stock-assessment models.

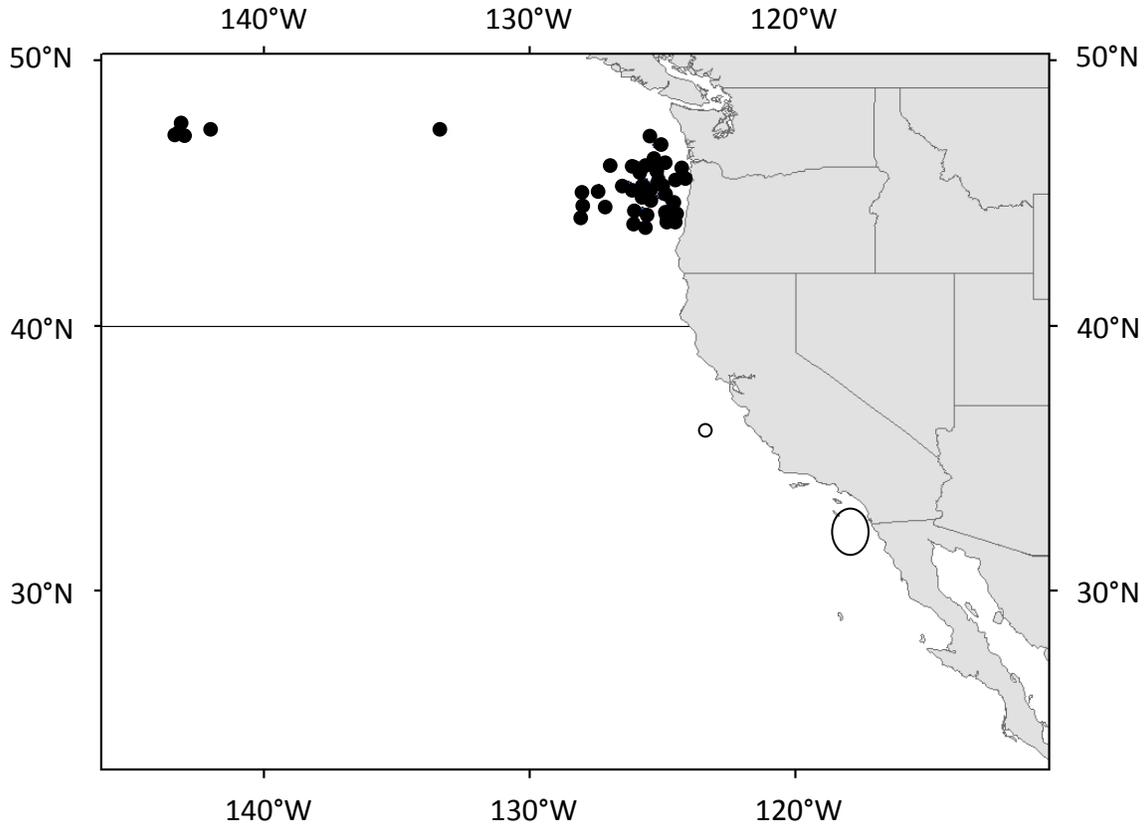


Figure 1. Map of eastern North Pacific where the horizontal line at 40°N latitude represents the boundary between the northern and southern regions. Black solid circles represent location of samples collected from commercial fishing vessels in the northern region while the white ellipse represents location of samples collected from sport fishing vessels in the southern region. The single white circle in the southern region is the collection location of four individuals that were collected during a research-based tagging cruise.

## MATERIALS AND METHODS

### Study Area and Field Collections

The study area is located at the eastern extent of the North Pacific Gyre and is focused on two regions within the California Current during the summer and fall when albacore are targeted by local fisheries (Laurs and Lynn 1977) (fig. 1). The two regions are within the California Current and are exposed to coastal, wind-driven upwelling and are north and south of 40°N at the Mendocino Escarpment, defined as the northern and southern regions.

Albacore samples were collected from the north and south fishing regions from July through October of 2010 and 2011 (table 1). North samples were collected from commercial troll (artificial-jig fishing gears) and pole-and-line (live-bait fishing) surface fisheries targeting albacore. South samples were collected from recreational pole-and-line fishing vessels operating off southern California and Baja California, Mexico. All fish collected were frozen and transported to the NOAA Southwest Fisheries Science Center in La Jolla, California, for later processing.

### Otolith Age and Growth

In the laboratory, albacore were measured to the nearest cm fork length (FL) and sagittal otoliths were removed from each fish, and cleaned following procedures described by Secor et al. 1991. One of the two otoliths was randomly chosen and embedded in low viscosity epoxy resin (fig. 2). After the epoxy resin hardened, the otolith was sectioned transversely using a Buehler isomet low-speed saw equipped with a diamond-wafering blade. Longitudinal sections were also performed on a subset of otoliths ( $n = 20$ ); however, transverse sections produced the best product for counts. The otolith sections were mounted on glass slides with Crystalbond thermoplastic cement and polished with 0.3 $\mu$ m Alumina Alpha polish using 400 and 600 grit

TABLE 1  
 Summary of albacore samples collected and processed for otolith microstructure analysis during 2010 and 2011 from both the northern and southern regions.

Region	2010	2011
North	42	46
South	34	4

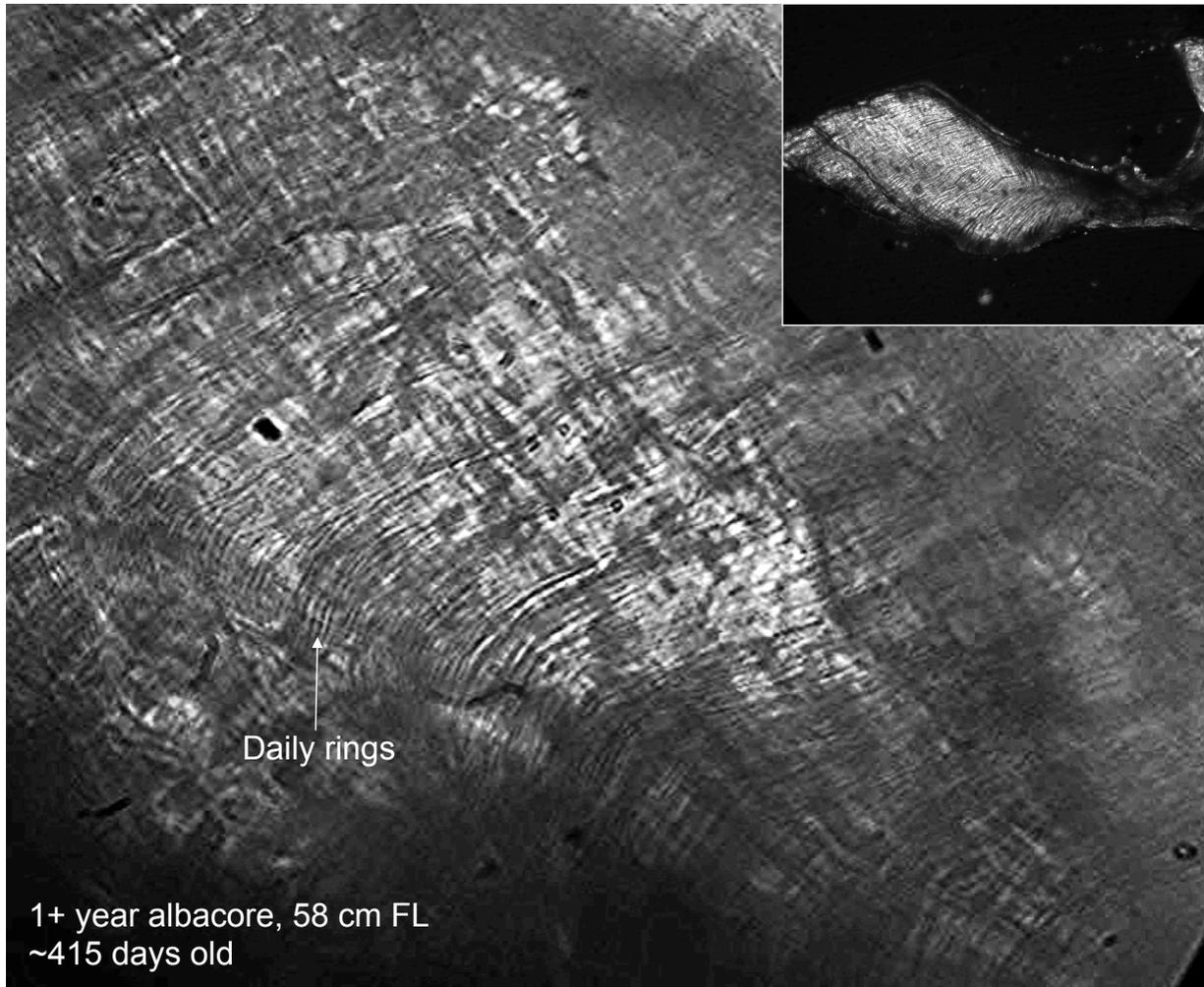


Figure 2. A transverse cross-section of the sagittal otolith from a year-1 albacore viewed at 65x with arrow illustrating a daily growth ring of the otolith microstructure. The image on the top right is a view of the entire otolith at 20x.

sandpaper until the core and daily increments were visible (Secor et al. 1991).

Otoliths were viewed with a Leica light microscope at 65 $\times$  magnification and age was determined by counting daily growth increments from the outer margin to the core. The increments were counted with a Digital Imaging System (DIS). The DIS consisted of a Leica compound microscope, Diagnostic Instruments (2002) SPOT RT digital camera, a desktop computer with two 17-inch LCD monitors, and Image Pro-Plus (IP+) imaging software (Media Cybernetics 2002). The system was calibrated using a stage micrometer within the objective. The SPOT camera has an electronic shutter, which captures live image previews, allowing the user to fine focus and position the section of the otolith that is being imaged. The restricted field of view at this magnification required multiple images to be captured. After each photo, the stage was moved down towards the end of the previous image (i.e., the lead-

ing edge of the previously captured image becomes the trailing edge of the next image). This process was repeated until arrays of images (15–20) were captured. All images were later resized and merged together in Adobe Photoshop CS5 to construct a final image. The “manual tag” tool was used in IP+ to count and label daily growth increments.

In some fish it was difficult to enumerate some of the inner increments near the core. To account for the inner increments that were unclear, a correction factor was applied to 5% of the fish from the northern region and 10% of the fish from the southern region. The correction factor was derived from several clear samples and was based on the relationship between fish age and otolith radius (Wells and Rooker 2004). To determine this relationship the radius was measured and the number of daily increments were counted on seven otoliths from the core to 40 days where inner increments were easily identified producing the following equation:

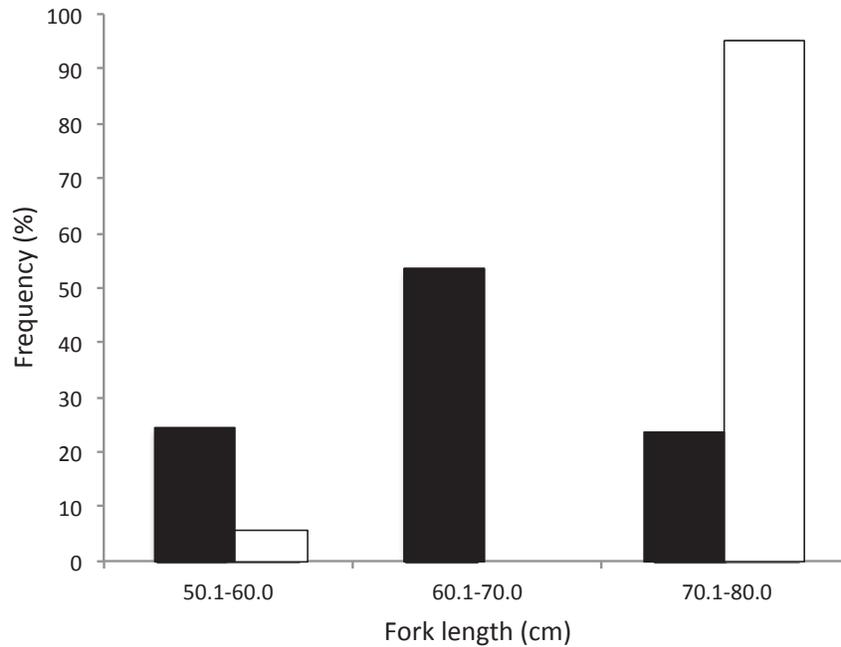


Figure 3. Size distribution of albacore from the northern (black) and southern (white) regions.

$$\text{Age}_p \text{ (days)} = \text{Age}_c \text{ (days)} + [(\text{otolith radius} / 564.14 \mu\text{m}) \times (40 \text{ days})],$$

where  $\text{Age}_p$  is the predicted (corrected) age,  $\text{Age}_c$  is the increment count from the otolith reading, and  $564.14 \mu\text{m}$  is the average otolith radius at 40 days of age. This correction factor was used to assist with age estimates for otoliths that were unclear and difficult to enumerate around the inner core area. This was accomplished by adding the predicted age from the unclear region (correction factor) to the increment count (number of identifiable increments).

A double-blind method was applied when ageing the otoliths. The otoliths were relabeled after sample preparation and a random number generator was used to select otoliths for ageing. Double-blind procedures prevented the reader from knowing any identifying characteristics of the sample (i.e., size, region, collection date). A single reader independently read each otolith three to four times until all age estimates were within 10%, and the average reading was taken as final. Differences in age estimates among three or more readings was evaluated by the average percent error (APE) (Beamish and Fournier 1981) and coefficient of variation (CV) (Chang 1982) to determine ageing precision in age estimates, CV is expressed as:

$$\text{CV}_j = 100\% \times \frac{\sqrt{\sum_{i=1}^R \frac{(X_{ij} - X_j)^2}{R - 1}}}{X_j}$$

where  $X_{ij}$  is the  $i$ th age determination of the  $j$ th fish.  $X_j$  is the average age calculated for the  $j$ th fish and  $R$  is the number of times each individual is aged (Chang 1982).

Near-daily growth increments has been validated for North Pacific albacore using oxytetracycline mark and recapture, with an average growth rate of 0.954 increments per day (Laurs et al. 1985). To account for this discrepancy, a 4.6% increment adjustment change was applied to the raw data.

### Data Analysis

The estimated age of each fish was subtracted from its date of capture to determine hatch dates and spawning periods for the northern and southern regions. Size-at-age relationships were analyzed using linear models to examine the relationship between fish age and fork length. Analysis of covariance (ANCOVA) was used to analyze regional differences in size-at-age ( $y$ -intercept) and growth rates (slopes) between albacore collected in the northern and southern regions. One model tested for size-at-age and growth differences for all albacore between each region, and an additional model was limited only to albacore of similar ages between the two regions (742–1254 days of age). Linearity was tested for the ANCOVA models; full ANCOVA models were first examined with region (factor), age (covariate), and the interaction term (region \* age). Nonsignificant interaction terms ( $p > 0.05$ ) were then removed from both models and only the reduced model was used for statistical interpretations. A single linear regression model

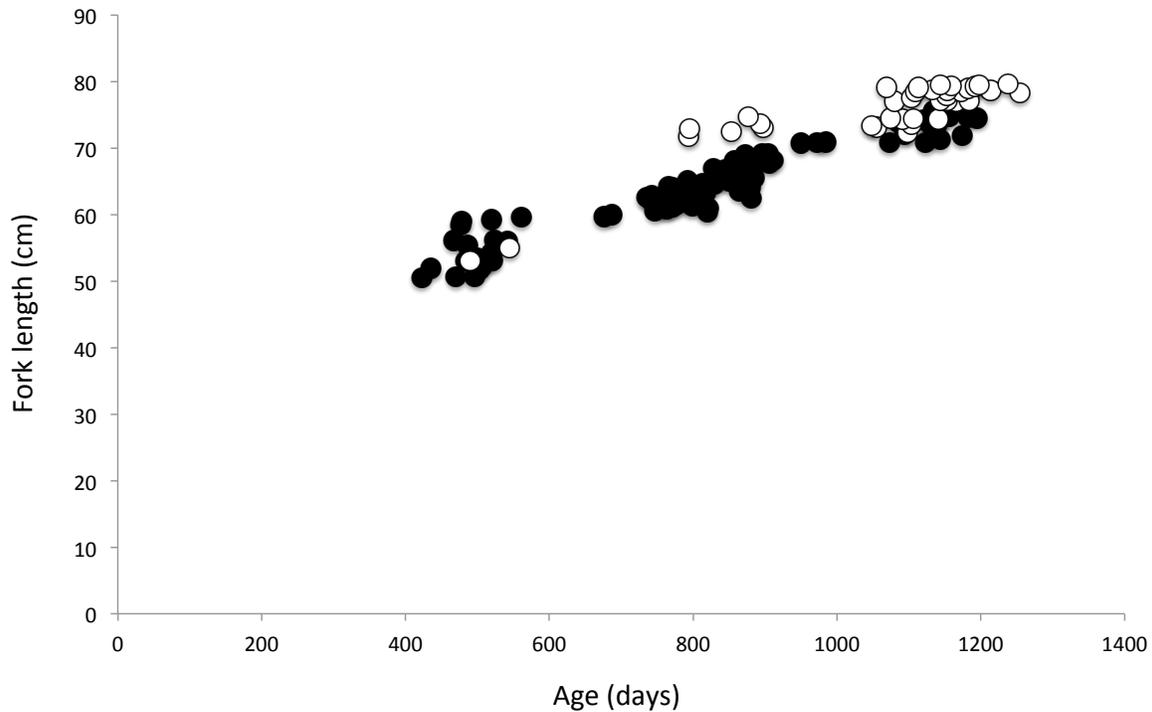


Figure 4. Size-at-age relationship of albacore in the eastern North Pacific by region (northern region=black and southern region=white).

was also performed to provide an overall growth rate estimate for all albacore aged in this study. Analyses were conducted using the statistics software program SAS version 9.2 with  $\alpha = 0.05$ .

## RESULTS

A total of 126 otoliths were collected from albacore in the eastern North Pacific from 2010 to 2011. From the north region, 87 otoliths were aged from fish 50.5 to 78.0 cm FL and from the southern region 36 otoliths were aged from fish ranging in size from 52.9 to 79.6 cm FL (tab. 1, fig. 3). Corresponding ages of all albacore ranged from 423 to 1254 days of age. The northern region was comprised of fish from 423 to 1095 days of age with 50% of the fish between 700 and 900 days of age. In the southern region, fish age ranged from 492 to 1254 days and was primarily dominated (70%) by fish of 1000 to 1200 days of age.

Precision of fish age estimates was assessed. For all age readings the CV for each region ranged from 0 to 6.88% and the APE was 1.07% and 0.34% for the northern and southern region, respectively. A CV value below 10% and an APE value below 5% comprise an acceptable ageing accuracy assessment between ageing estimates for many species and indicate a high level of precision between readings (Campana et al. 1995; Campana 2001).

Size-at-age estimates for albacore collected in the southern region were significantly larger than for fish in the northern region (ANCOVA; y-intercept;  $p < 0.001$ )

(fig. 4). These differences in fish size-at-age can be used as a proxy for regional growth rates, but the lack of a significant slope effect (ANCOVA; interaction term;  $p > 0.05$ ) supports similar growth rates over the ages examined. Similarly, no significant regional growth rate difference (ANCOVA; interaction term;  $p > 0.05$ ) was observed for albacore 742 to 1254 days of age. However, a significant size-at-age difference was found over this age range with larger fish in the south region (ANCOVA; y-intercept;  $p < 0.001$ ) (fig. 4). A combined linear growth model of juvenile albacore resulted in an average growth rate of 0.03 cm per day over the size and age range examined ( $FL = 0.034[\text{age}] + 37.464$ ;  $r^2 = 0.893$ ).

Albacore hatch date distributions were protracted from February to September, with 73% of all fish hatched from April through July (fig. 5). Examination of albacore hatch dates between regions for fish hatched from 2007 through 2010 varied from year to year. In 2007, albacore in the northern region had peak hatching dates from May to August (87.5%) and in the southern region peak hatching dates ranged from April to July (81.4%). A similar range in hatch dates was observed in 2008. For the northern region, 20% of the fish hatched in May and 43.4% hatched in July through August, whereas 50% of the fish hatched from February through March and 37.5% hatched from May through June in the southern region. In 2009 and 2010, the majority of fish in the north region (69.2% and 77.7%) hatched from April to

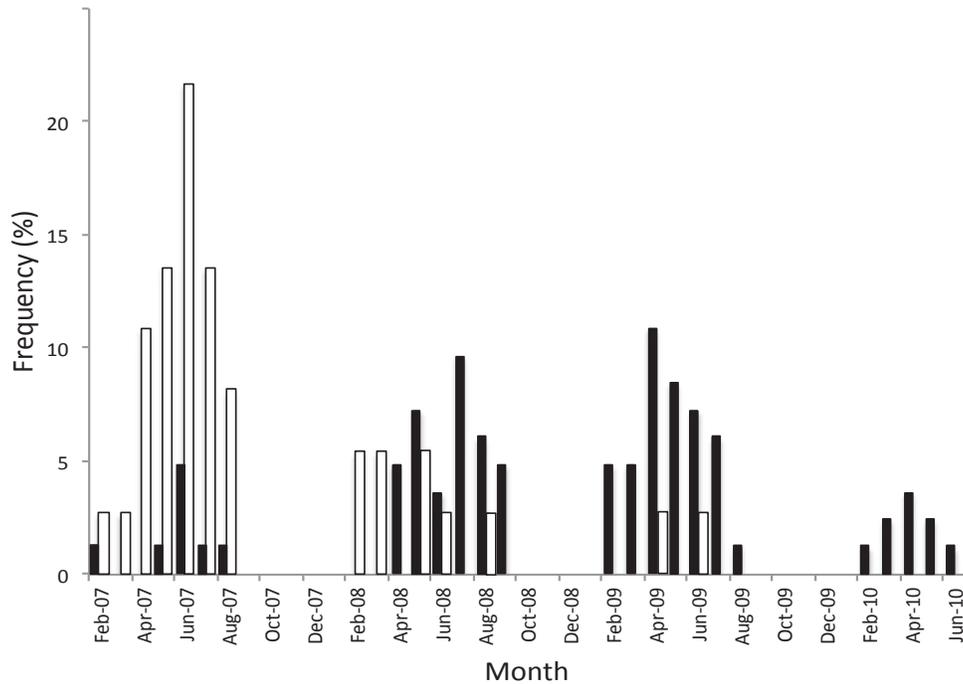


Figure 5. Albacore hatch date distributions in the eastern North Pacific by region (northern region=black and southern region=white).

July and March through May, respectively. Due to small sample sizes for fish in the southern region for 2009 and 2010, no hatching date estimates could be made.

## DISCUSSION

Age estimates of juvenile albacore from the eastern North Pacific reveal a number of differences between fish in the northern and southern regions. Size and age distributions of albacore differed between fishing regions, with smaller and younger individuals (primarily age-2 and age-3) distributed in the northern region, while fish from the southern region were larger and older individuals (primarily age-3 and age-4). Thus, age is one factor accounting for regional size differences between the two regions. Hatch date distributions also reveal different year-class composition between regions sampled; primarily year class 2008 and 2009 for fish from the north and primarily 2007 for fish from the south. Another factor may be differences in growth rates at earlier life stages than examined here, as albacore had similar rates of growth at the ages analyzed in this study. Differences in albacore growth rates between regions have been found in previous studies with faster growth rates for fish in the southern region (Laurs and Wetherall 1981; Wetherall et al. 1987). In addition, South Pacific albacore demonstrate spatial variation in growth that may impact future stock assessment models (Williams et al. 2012).

Regional differences in oceanographic conditions that juvenile albacore are exposed to may affect growth and size. Juvenile albacore utilize the North Pacific Transition Zone (NPTZ) at the convergence between

the subarctic and subtropical fronts to migrate eastward (Laurs and Lynn 1991). The dynamic Transition Zone Chlorophyll Front (TZCF) associated with the NPTZ acts as a migration route for many apex predators and seasonal shifts in these frontal zones have been shown to alter the movement and spatial distribution of tunas in the North Pacific into the highly productive California Current (skipjack, *Katsuwonus pelamis*; bigeye tuna, *Thunnus obesus*; bluefin tuna, *Thunnus orientalis*) (Boustany et al. 2010; Lehodey et al. 2008). At Cape Mendocino (~40°N), oceanic currents converge (Miller et al. 1999) creating conditions that result in alongshore transport influencing species diversity and productivity (Williams and Ralston 2002). Regions north and south of Cape Mendocino differ in sea surface temperature (SST), salinity and dissolved oxygen (NODC 2009). These differences are best observed using electronic tagging data that document the conditions at the location of the fish throughout the year. Tagging data obtained from both regions reveal important differences in both oceanography and migratory patterns for albacore from northern and southern regions (Childers et al. 2011). A focal area in the northern region was characterized by cool SST ( $17.4 \pm 1.3^\circ\text{C}$ ), high Chl-*a* concentrations ( $0.43 \pm 0.44 \text{ mg m}^{-3}$ ), and a shallow mixed layer depth (mld) ( $\leq 25 \text{ m}$ ) in contrast to two focal areas in the southern region characterized by warmer SST ( $18.9 \pm 1.4^\circ\text{C}$ ,  $20.7 \pm 0.6^\circ\text{C}$ ), moderate to lower levels of Chl-*a* concentrations ( $0.32 \pm 0.29 \text{ mg m}^{-3}$ ,  $0.07 \pm 0.02 \text{ mg m}^{-3}$ ), and a shallow to relatively deep mld ( $25.3 \pm 0.9 \text{ m}$ ,  $83.0 \pm 37.0 \text{ m}$ ).

Numerous studies on tuna have indicated the importance of temperature for the early life stages of fish (Sund et al. 1981); however, this study can only infer the impact of environmental characteristics for juvenile albacore between the ages of one to three. A slight increase in SST has been shown to be advantageous to fish by resulting in faster growth rates, reduced mortality and early maturation (Higley et al. 1986; Neuheimer et al. 2011). Fish in the southern region, while residing in the California Current, inhabit an environment with warmer SST and an extended growing season facilitating faster growth rates than in the north (Hickling 1961; Barchard et al. 1972). Similar results have been reported in several studies examining the relationship between SST, food availability, and tuna growth rates (Griffiths et al. 2009; Wexler et al. 2007; Wexler et al. 2011). Growth of juvenile southern bluefin tuna (*Thunnus maccoyi*) in the western Australian fishery is affected by SST, with larger sizes-at-age for fish exposed to the higher water temperatures associated with the Leeuwin Current (Leigh and Hearn 2000). However, albacore in the eastern North Pacific are not confined exclusively to the California Current, so conditions beyond this area will also influence growth rates.

Foraging ecology and associated energy intake can also influence growth rates and likely play a significant role in regional size-at-age trends observed for albacore. For marine mammals and fishes, foraging on prey species lower in caloric content has significant impacts on intraspecific growth rates and population dynamics which could impact fish growth rates (MacFarlane and Norton 2001; Glaser 2010). Several studies have quantified diets of albacore in the eastern North Pacific (McHugh 1952; Graham 1959; Iversen 1962; Pinkas et al. 1971; Bernard et al. 1985; Glaser 2010). Albacore are considered generalists with a diet largely composed of Pacific saury (*Cololabis saira*), northern anchovy (*Engraulis mordax*), cephalopods and euphausiids (McHugh 1952; Graham 1959; Iversen 1962; Pinkas et al. 1971; Bernard et al. 1985). Additionally, it has been shown that the albacore diet in the eastern North Pacific varies with respect to region; decapods, euphausiids, and anchovy dominate the diets in the north; and hake, saury, and anchovy are more dominant in the south (Glaser 2010). A diet dominated solely by fish species will typically have a higher caloric content than a mixed diet of fish and crustaceans. The energy content of decapods and euphausiids ranges from 2.5 to 3.2 kJg<sup>-1</sup> in contrast to 3.5 to 7.9 kJg<sup>-1</sup> for the fish species found in albacore stomachs (Glaser 2010). Consequently, albacore in the north may need to consume more prey in order to obtain the same amount of calories. Consuming greater quantities of prey species may result in increased energetic costs (i.e., migration and effort) and can have indirect influences on fish growth

rates. Albacore in the northern region demonstrate extensive, horizontal movements to offshore areas with some individuals migrating into the central and western Pacific. In contrast, albacore in the southern region typically remain closer to the coast and often overwinter along the Baja peninsula, Mexico (Childers et al. 2011). The extensive migrations and reduced caloric content of the dominant prey items for fish in the northern region may have energetic costs that translate into less energy available for growth.

In addition to examining regional differences in growth, hatch dates can provide insight into temporal separation in spawning and stock structure. Albacore sampled in the eastern North Pacific were spawned during a protracted period from February through September with peak hatch dates (73%) occurring between April and July. This spawning period overlaps with previous estimates determined using otolith ageing and length-frequency analyses (Bigelow et al. 1993); however, Wetherall et al. 1987 reported evidence of winter spawning in the south region based on tag-recapture data of larger subadult (70–90 cm FL). A comparison of fish hatch dates between regions for the 2008 and 2009 cohorts did not yield any regional differences in this study. For both regions, sample sizes were limited and peak hatch dates were variable throughout spring and summer months suggesting that further collections over a longer time frame are needed to determine the potential for temporal separation in albacore spawning between regions.

This study demonstrates both the difficulty and the importance of understanding early life history characteristics of this commercially important fishery resource. Using otolith daily growth increment ageing, we have shown that juvenile albacore in the eastern North Pacific exhibit regional differences in length-at-age between the northern and southern regions, with larger fish in the south. Albacore size-at-age differences between regions may be a function of differing growth rates at earlier life stages since growth rates were similar over ages analyzed in this study. The spawning period of albacore in the eastern North Pacific was from February through September with 73% of all fish hatch dates occurring from April to July. Albacore growth is likely the result of multiple environmental (e.g., North Pacific Transition Zone, California Current System, El Niño–Southern Oscillation) and biological variables (e.g., migratory movements, diet) and may consequently vary based on region. These results support prior studies using alternative methods that suggest albacore in the two regions may represent different stocks; however, additional samples and information on spawning separation and how growth and recruitment are affected by temperature, productivity, and location of the TZCF are needed to

assess if two distinct stocks of albacore exist in the eastern North Pacific.

## ACKNOWLEDGEMENTS

Funding and samples were provided by NOAA Southwest Fisheries Science Center (SWFSC), American Fishermen's Research Foundation (AFRF), American Albacore Fishing Association (AAFA), and Sportfishing Association of California (SAC). Special thanks to Owyn Snodgrass for obtaining otoliths, Jenny McDaniel for assistance in the laboratory, and Emmanis Dorval and Suzy Kohin for comments on earlier drafts.

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## LIFE HISTORY AND HISTORIC TRENDS IN SALEMA (*HAEMULON CALIFORNIENSIS*) IN SOUTHERN CALIFORNIA

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### ABSTRACT

The Salema, *Haemulon californiensis*, is a small coastal marine fish whose southern California abundances vary considerably interannually. To better understand Salema biology and ecology, life history studies were executed and historic data reviewed to construct Salema's ecological profile in southern California, the northern extent of its biogeographic range. From these investigations, a von Bertalanffy growth model was developed for all fish ( $n = 475$ ):  $L_{\infty} = 159.367$  mm SL,  $k = 0.90$ ,  $t_0 = 0.047$ . The growth rate was fast with fish reaching  $L_{\infty}$  by six years of age with maximum age of 14 years. Reproductive studies confirmed summer spawning in southern California with a similar gonosomatic index in both males and females during spawning season,

averaging 8–9.5% of gonad-free body weight. Histological examination identified evidence of serial spawning, but no confirmatory studies were conducted. Scientific gill net sampling caught individuals as far north as Santa Barbara along the mainland coast and Santa Catalina Island, but the majority of catches occurred on the Palos Verdes Peninsula and south. Substantially more fish were taken near rocky reef habitat than soft-bottom open coastal or harbor habitats. Coastal sampling results were inconsistent as the two primary areas, Palos Verdes Peninsula and Newport. Recorded catch per unit efforts negatively correlated with each other over time. Long-term power plant entrapment monitoring in the area documented an increase in Salema abundance beginning in earnest in 1989 and continu-

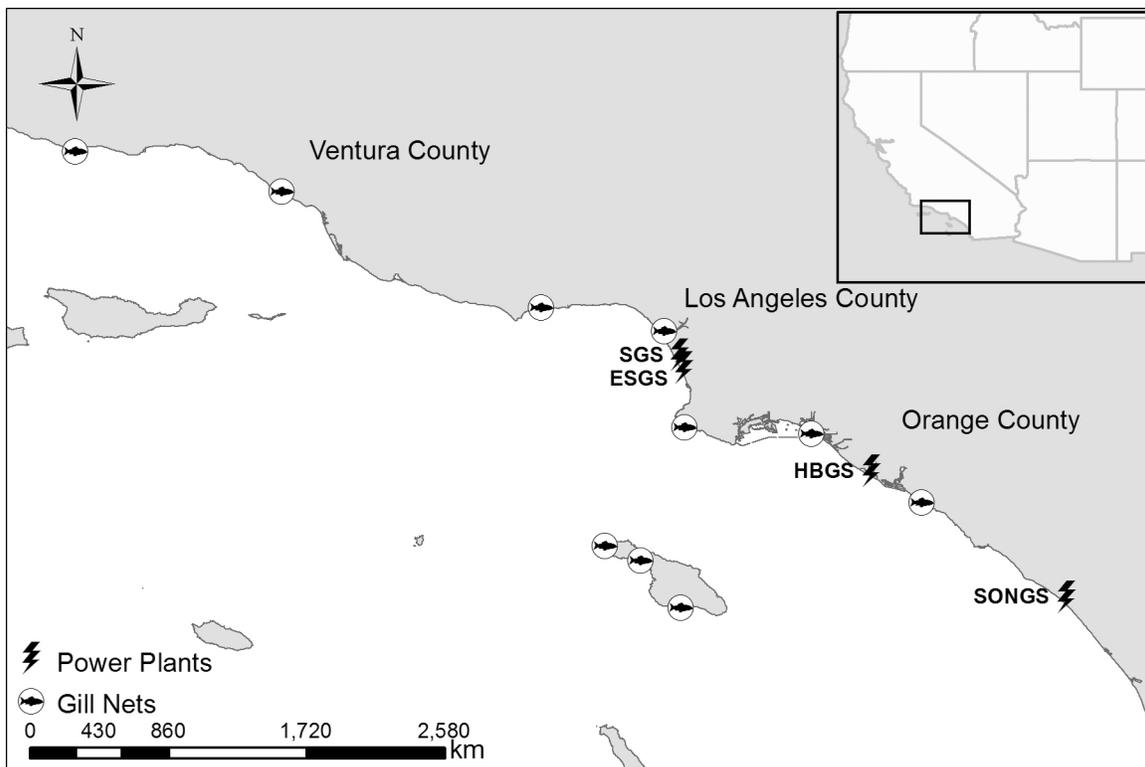


Figure 1. Map of the southern California sampling area indicating the location of each power plant and gill net sampling station providing Salema abundance data and life history samples. Power plants include Scattergood Generating Station (SGS), El Segundo Generating Station (ESGS), Huntington Beach Generating Station (HBGS), and San Onofre Nuclear Generating Station (SONGS).

ing through 2006 before abundance declined again. The area's population was dominated by year classes from 1994–95 and 2004–06. Juveniles remained in the area sampled by the power plants year-round until reaching 125 mm SL while larger individuals were rarely taken outside of the summer months when they became seasonally abundant.

## INTRODUCTION

Rocky reef communities are well known for their productivity and high biodiversity throughout the world (Stephens Jr. et al. 2006). This biodiversity, however, creates daunting challenges to adequately characterize many of the fishes in this community. While extensive effort has been expended on California rocky reef fishes, including surfperch (family Embiotocidae), bass (*Paralabrax* spp.), and California Sheephead (*Semicossyphus pulcher*), many of the lesser known species have not been rigorously examined (Cowen 1983; Carr 1994; Holbrook et al. 1997; Pondella et al. 2002; Erisman et al. 2011). Even less information on the life history and interannual variability was documented for many of these lesser-studied species.

Transient species that immigrate, either in a regular seasonal pattern or episodic events are linked to oceanographic conditions. Salema (*Haemulon californiensis*) likely represent a substantial contributor to southern California's marine environment. To date, no clear assessment of their abundance or distribution in California has been reported. Therefore, their inclusion as a resident or transient species cannot be fully evaluated and their role in the ecology of the southern California coastal ecosystem remains unclear. Salema range from northern Peru to the Monterey Bay in California and depths from the nearshore shallows out to 33 m (Love et al. 2005). Despite this distribution, surveys of the islands along the southern California and Baja California coast found Salema only at San Benito and Santa Catalina Islands, with two orders of magnitude more individuals at the more southern San Benito Island (Pondella et al. 2005).

Scientific gill nets and coastal power plant monitoring have been used in southern California to provide insight into similar, understudied species (Miller et al. 2008; Pondella et al. 2008; Miller et al. 2009; Miller et al. 2011; Miller and McGowan 2013). These sampling programs provide opportunities to assess trends in abundance over time, but also provide samples for life history analyses. Therefore, we executed a two-part investigation. The first aimed to characterize the Salema life history parameters including longevity, length at age, reproductive periodicity, and gonosomatic index. Second, we investigated spatiotemporal population effects of a changing environment on these trends.

## MATERIALS AND METHODS

### Data Sources

Life history samples were collected during nearshore scientific gill net surveys (described below) between April and November 2004; scientific purse seines in San Diego Bay in October 2004; and during southern California power plant entrapment monitoring (described below) at Scattergood Generating Station (SGS) in El Segundo, Huntington Beach Generating Station (HBGS) in Huntington Beach, and San Onofre Nuclear Generating Station (SONGS) in San Clemente between 2004 and 2007 (fig. 1). Spatial abundance indices were derived from the scientific gill net surveys. Temporal patterns were described from data collected during power plant entrapment surveys at El Segundo Generating Station (ESGS) in EL Segundo, California, HBGS, and SONGS.

Every April, June, August, and October 1995–2004, scientific gill nets were set overnight at three stations at Santa Catalina Island (west end, east end, and Catalina Harbor) while seven stations were sampled along the California coast: Santa Barbara, Ventura, Malibu, Palos Verdes, Seal Beach, and Newport (fig. 1). Sampling in Marina del Rey was added in October 1996. In 2005–07, all stations except the east end of Santa Catalina Island were sampled in June and October. Nets were set perpendicular to the shoreline at the open coast stations and parallel to the shoreline in bays and harbors to minimize impacts to navigation. Six horizontal gillnets were set on the bottom in 5–14 m of water outside of the surf zone at each station from dusk to dawn. Each net was 45.7 m long and 2.4 m deep, with two sets of three mesh-sized panels (25.4 mm, 38.2 mm, and 50.8 mm square mesh). The mesh sizes were chosen to target juvenile White Seabass (*Atractoscion nobilis*) and effectively captured 100–400 mm SL fishes.

These eight sampling sites (after combining all sites at Santa Catalina Island into one) represented a range of latitudes and habitats. The latitudinal distribution ranged from Newport at 33.5°N north to Santa Barbara at 34.4°N and offshore to Santa Catalina Island at 33.4°N. Sampled areas dominated by rocky reefs and often supporting kelp forests included Santa Catalina Island, Santa Barbara, Palos Verdes, and Newport. Ventura, Malibu, and Seal Beach were predominantly soft-bottom with hard substrate in the area, such as near a jetty in Seal Beach. Marina del Rey sampling occurred within the harbor at two locations, near the rocky riprap lining the entrance channel and near Mother's Beach located in a rear basin and dominated by soft-bottom sandy beach habitat. The three sites at Santa Catalina Island encompassed all three habitat types; rocky/kelp reef, soft-bottom near rocky substrate, and harbor.

Records from coastal power plant cooling water intake monitoring (entrapment data), were used both as a life history sample source and to characterize long-term abundance trends. Fish lengths (mm SL) were recorded only during the years 1992 to 2010. All fishes were exposed to lethal temperatures during routine heat treatment procedures at each the power plants listed above. Heat treatments were conducted to control biofouling growth in the cooling water system. Additional unique surveys (fish chase described below) at San Onofre Nuclear Generating Station (SONGS) were conducted since 1989. Both were surveys of opportunity and were conducted based on the plant's operational needs at a frequency of every 6–12 weeks, on average. At each power plant, intake conduits extended 500–900 m offshore terminating with a vertical intake riser along the 8–15 m isobaths extending 4 m above the seafloor. Inland, the conduits terminated in a forebay where water velocities slowed before passing through 1 cm square mesh traveling screens. Fishes > 10 mm SL were retained on the traveling screens until washed off and into a collection basket.

Forebay water velocities were low enough to allow fishes to take up residence until the next heat treatment, at which time all fishes within the forebay were exposed to temperatures >38°C and were subsequently impinged on the traveling screens and conveyed out of the forebay and deposited into a collection basket. All fish were identified, batch-weighed by species, and measured to the nearest mm SL (up to 200 individuals of each species only). The total abundance when >200 individuals were present was estimated by dividing the unmeasured fish aggregate weight by the mean weight of the 200-fish subsample (total weight/200). During a fish chase survey, forebay water temperatures were slowly raised to induce minimal, non-lethal stress in the fish. Once stressed, the fish accumulated in a hydrodynamically quiet area of the forebay where an elevator system was installed to raise the live fish that were in a steel tray of water and deposit them in a dedicated return conduit. All fishes in the tray were identified and a visual abundance estimate recorded by species prior to being released. No fish lengths were recorded during fish chases. Fish chases were limited to SONGS Units 2 and 3.

Annual Salema abundance offshore of SONGS was examined using lampara net sampling conducted from 1978 to 1986. Sampling methods were described in Allen and DeMartini 1983 but consisted of sampling in two areas offshore of the northern San Diego County coastline at depths of 5–11 m, 12–16 m, and 18–27 m with two lampara nets. The smaller net (4600 m<sup>2</sup>) was used at the two shallower isobaths while a larger net (6200 m<sup>2</sup>) was used at the deepest isobath with all nets fishing surface to bottom. Therefore, most sets were made over soft-bottom habitat. All nets had 15-cm stretch mesh

with a bag mesh of 1.25 cm. Nets were fished at night nearly monthly in all years.

Environmental indices over time periods and scales commensurate with the Salema studies were compiled. These environmental indices included sea surface temperature (SST) collected at the Scripps Institution of Oceanography Pier (SIO), sea surface density (SSD) derived from SST and sea surface salinity collected at SIO, Pacific Decadal Oscillation (PDO), North Pacific Gyre Oscillation (NPGO), and the Multivariate ENSO Index (MEI) (Mantua et al. 1997; Wolter and Timlin 1998; Di Lorenzo et al. 2008; Scripps Institution of Oceanography 2012).

### Life History Sample Processing and Analysis

The following morphometric parameters were recorded for nearly all life history specimens: SL, HL, FL, TL. All lengths (regardless of source or study component) were measured to the nearest mm and wet weight to the nearest g. The relationship between each length measurement was derived in addition to the SL-weight relationship via linear or nonlinear regression as appropriate. Sagittal otoliths from each fish were removed and one otolith from each specimen was mounted on a wood block using cyanoacrylate glue and sectioned (0.7 mm thick section) on the transverse axis through the focus using a Buheler Isomet™ low speed saw. Sections were viewed in a black-bottomed watch glass filled with water and read under a stereoscope at 25× magnification using reflected light. Each otolith was read twice by a single reader, at least four months apart. The value from two identical readings was accepted as the best estimate of age. When necessary, a third reading was made when two consistent values were not obtained. In the event a consistent value could not be obtained after three readings, the sample was excluded from further analysis. Nearly all samples were collected in 2004, and edge analysis was used to verify annual increment formation (Campana 2001). The proportion of edge type in summer and fall was used as an indication that each pair does in fact represent an annual mark. No further annuli formation studies were attempted. Von Bertalanffy growth model parameters were derived for all individuals combined and by sex using VONBIT (Stamatopoulos and Caddy 1989). Immature or sex-undetermined individuals were excluded from the sex-specific analysis. Differences between sex-specific growth rates were tested using a likelihood ratio test (Kimura 1980) using package fishmethods in R (Nelson 2014).

The gonosomatic index (GSI) was derived for each individual (Barbieri et al. 1994) using field measurements of body and gonad weight. The sex ratio was tested for deviation from an expected 50:50 gonochoric pattern and was done using a Chi square test in MS Excel. Indi-

viduals used for spawning seasonality analysis were sexed macroscopically. Gonads were weighed to the nearest 0.5 g and preserved in a 10% buffered formalin-seawater solution. Samples were dehydrated in an ascending series of ethanol, cleared in toluene, embedded in paraffin, and histological sections cut at 5  $\mu\text{m}$  using a rotary microtome. Sections were mounted on glass slides and stained with Harris hematoxylin followed by eosin counterstain. Female stages were assigned as: 1) pre-spawn, 2) spawning, 3) post-spawn, 4) regressing. Testes were histologically classified into four stages: 1) spermiogenesis (cycloid spermatids, lumina occluded with sperm, germinal cysts line lumina); 2) late spermiogenesis (ovoid spermatids, lumina occluded with sperm, germinal cysts line lumina); 3) regression (germinal cysts exhausted); and 4) recrudescence (proliferation of germinal cysts).

### Population Data Analysis

Spatial patterns in Salema abundance were evaluated using the 13-year gill net series (1995–2007). The mean catch/net was derived for each regularly sampled site. June and October were the only months sampled in all years at all open coast mainland sites, therefore only data from these months were included. Marina del Rey and Santa Catalina Island sites were excluded from further analysis since they were not consistently sampled in all years. Spearman's rank correlation was used to examine similarities in annual catches among sites. Temporal abundance patterns were examined using the entrapment series (1972–2012) and compared against the lampara net series to confirm, to the extent possible, the entrapment series represents coastal population trends. Data from the lampara net sampling was used to verify the use of the entrapment data as a measure of coastal fish population dynamics. August lampara sampling results were used for comparisons with the July–September entrapment data as it was only month sampled in all years. Three months were used for the entrapment series to account for the fact that heat treatments were not conducted monthly at SONGS, but the fish accumulated over time since the last heat treatment. Lampara catch data was standardized to count/net set. Similarity between the entrapment rate and lampara net collection data sets was determined by least squares regression. No such comparisons were made with the later gill net data due to the differences in sampled size distributions. The gill nets targeted fishes >100 mm SL while both the power plant and lampara net sampling caught juvenile and adult fishes of all size classes.

Fish chases preceded heat treatments at SONGS, therefore the data from each fish chase and its subsequent heat treatment were combined prior to standardization to cooling water flow volumes. An entrapment index was derived to represent survey-specific abun-

dance standardized to the volume of cooling water circulated (filtered) since the last heat treatment. Mean annual and monthly entrapment indices were derived to examine interannual and intra-annual variability in their occurrence. Significance of the long-term entrapment rate trend was tested using the Microsoft Excel add-in developed by Bryhn and Dimberg 2011. The program creates new time series by calculating the moving average over ever-increasing time intervals of the original time series. Linear regressions through each of the new time series are executed to calculate the coefficient of determination ( $r^2$ ) and  $p$  value for each regression. The trend is statistically meaningful if  $r^2 \geq 0.65$  at  $p \leq 0.05$  in any of the regressions.

Fish were measured during all scientific gill nets (1995–2007) and heat treatments (1992–2012). Length differences between island and mainland sampling sites were tested using a Kolmogorov–Smirnov test. The power plant surveys were used to derive a young-of-the-year index (YOYI) to represent the number of one-year-old, or less, individuals ( $\leq 75$  mm SL size class) entrapped each year. Size at age 1 was defined in the length at age portion of our study. All YOY were assigned to their appropriate year class assuming a birthday of June 1 based on ichthyoplankton data (MBC 2005). Therefore, all YOY collected between June 1 and December 31 were assigned to the year of collection for their year class while those collected between January 1 and May 31 were assigned to the year prior, or collection year–1. The proportion of the total number of measured Salema represented by individuals  $\leq 75$  mm SL size class was multiplied by the entrapment rate for the year to derive the YOYI (count/ $10^6$  m<sup>3</sup>). Long-term trends in the YOYI were tested for significance per Bryhn and Dimberg 2011.

Environmental indices were compared with the annual mean entrapment rate and YOYI using Spearman's rank correlation. All values were tested for autocorrelation using a Durbin–Watson test before comparing to climate data. When the data were autocorrelated, correlation analyses were adjusted using the Modified Chelton Method (Pyper and Peterman 1998).

## RESULTS

### Life History

Size conversions between HL, SL, FL, TL, and weight are presented in Table 1. A total of 475 Salema measuring 30–190 mm SL were used for the otolith analysis. Otolith edge analysis recorded a greater than 2:1 ratio of opaque (101) to translucent (50) edges in the summer months suggesting the banding observed on the otolith sections were annual increments. Salema grew to an average of 148 mm SL by their fourth year and  $L_{\infty}$  (159 mm SL) by age six (table 2 and fig. 2). The old-

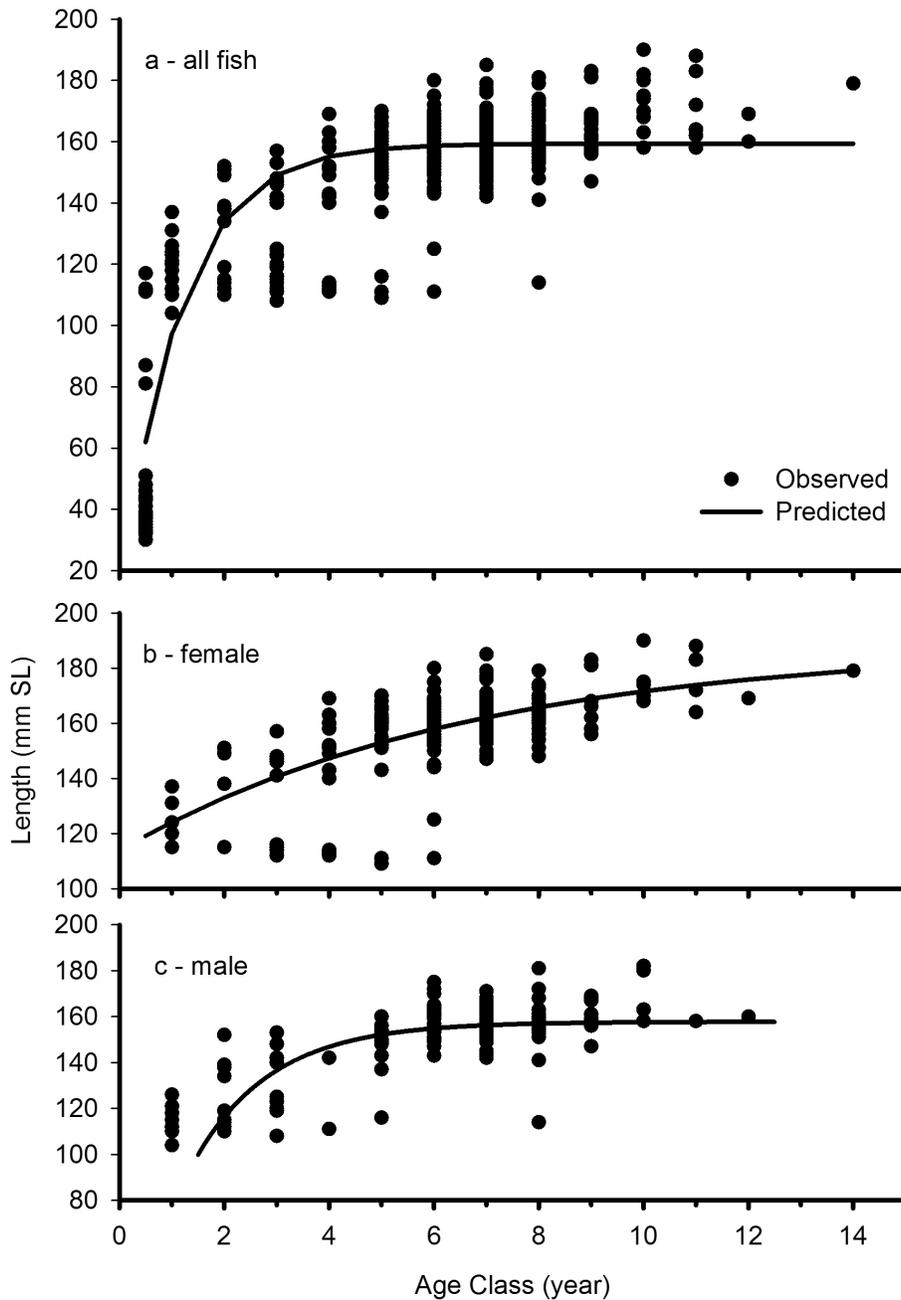
TABLE 1  
 Morphometric conversions between head length (HL), fork length (FL), standard length (SL), total length (TL), and weight (Wt), the best fit equation describing the relationship, goodness of fit ( $r^2$ ), and sample size for the relationship analysis.

Metrics	Equation	$r^2$	N
HL:SL	$SL = 3.0216HL + 10.198$	0.94	420
HL:FL	$FL = 3.5149HL + 9.6503$	0.94	415
HL:TL	$TL = 3.7995HL + 9.6036$	0.94	417
SL:FL	$FL = 1.1574SL - 1.4123$	>0.99	416
SL:TL	$TL = 1.2511SL + -2.3158$	0.99	418
FL:TL	$TL = 1.0787FL - 0.3871$	0.99	415
SL:Wt	$Wt = 7E-06SL^{3.2225}$	0.99	751

TABLE 2  
 Von Bertalanffy growth parameters for Salema sampled in southern California, 2004–07.

Parameter	All	Female	Male
k	0.90	0.15	0.26
$t_0$	0.047	-6.182	-3.254
$L_\infty$	159.367	188.155	168.805
n	475	228	169
$r^2$	0.82	0.44	0.60

Figure 2. Length at age for a) all samples, b) females, and c) males sampled in southern California, 2004–07. Von Bertalanffy growth parameters are listed in Table 2.



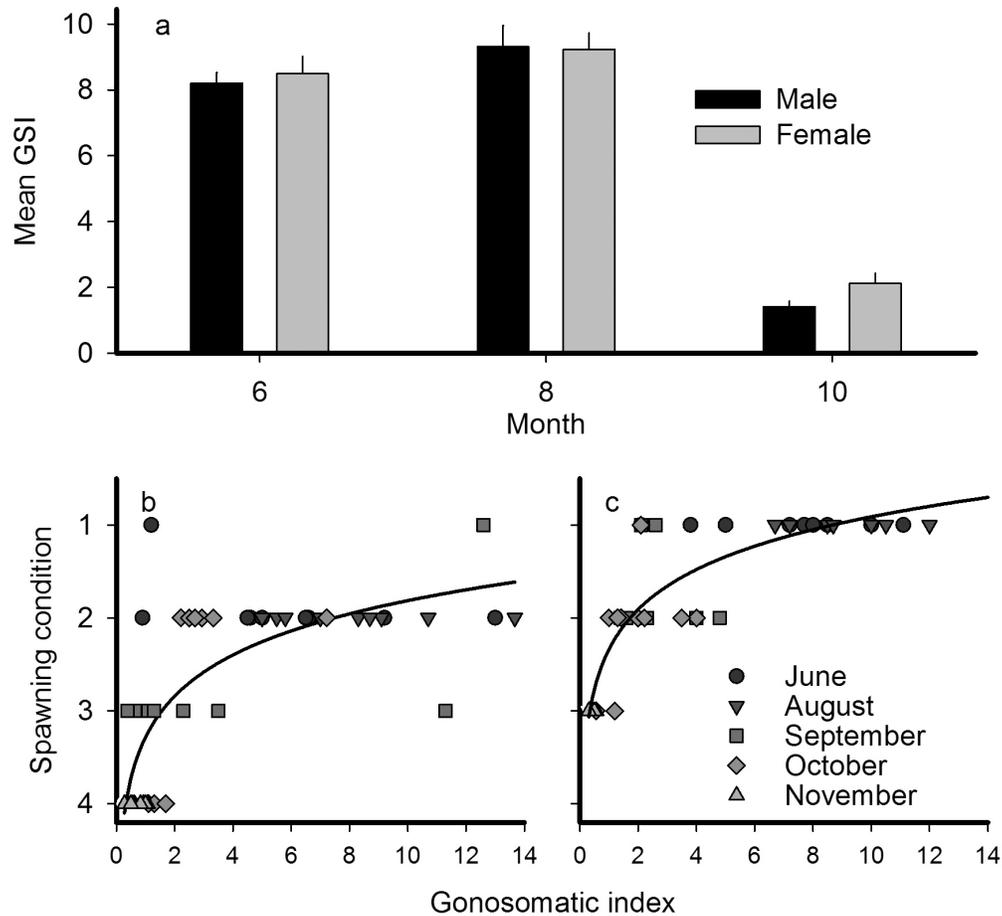


Figure 3. a) Gonosomatic Index (GSI) from the field processed (macroscopically sexed) samples. Histological preparations and analyses were conducted on 20 samples per month, when available. The GSI was derived for each sample and spawning condition assigned based on the histological preparations. Both parameters are presented by month as a function of each other for b) females and c) males. Spawning condition for females include: 1) pre-spawn, 2) spawning, 3) post-spawn, 4) regressing. Testes were classified into four stages: 1) spermiogenesis (lumina occluded with sperm, germinal cysts line lumina); 2) late spermiogenesis (lumina occluded with sperm, germinal cysts line lumina); 3) regression (germinal cysts exhausted); and 4) recrudescence (proliferation of germinal cysts). The line is the logarithmic curve through the data with a)  $r^2 = 0.54$  for females b) and  $r^2 = 0.82$  for males.

TABLE 3  
 Likelihood ratio test results comparing the von Bertalanffy model and parameters for 1) female and 2) male Salema.

Hypothesis	chisq	df	p
$L_{\infty}1 = L_{\infty}2$	3.78	1	0.052
$K1 = K2$	3.45	1	0.063
$t_01 = t_02$	5.35	1	0.021
$L_{\infty}1 = L_{\infty}2, K1 = K2, t_01 = t_02$	22.66	3	0.000

est fish was taken at Santa Catalina Island and was aged to 14 years and measured 179 mm SL. One individual measuring 190 mm SL was 10 years old and also taken at Santa Catalina Island. After age six, up to 31 mm SL was added by age 14. The rapid growth to  $L_{\infty}$  was represented in the von Bertalanffy growth parameters, especially the growth coefficient (k). Most of the 35 fish taken in 2004 that were nine years or older were larger the  $L_{\infty}$ . These were split nearly 50:50 between the island and mainland

sites. The two sex-specific growth curves were significantly different (table 3) driven by significant differences between in  $t_0$  ( $p = 0.021$ ). Differences in  $L_{\infty}$  were substantial, but not significant ( $p = 0.052$ ). There was no significant difference between the growth coefficients.

Salema could not be reliably sexed in the field in winter and spring months due to black tissue and fluid surrounding the gonads as well as the small size/biomass of the winter-spring gonads. Therefore the GSI was limited to collections in June, August, and October (fig. 3a). The GSI was slightly higher in August than in June, but both were significantly higher than the October values (Female:  $H = 73.729$ ,  $df = 2$ ,  $p < 0.001$ ; Male:  $H = 53.256$ ,  $df = 2$ ,  $p < 0.001$ ). The mean female GSI was higher than the male GSI in June and October, but not in August. Furthermore, females were significantly ( $p < 0.01$ ) more common (314/565 individuals sexed) than males (251/565).

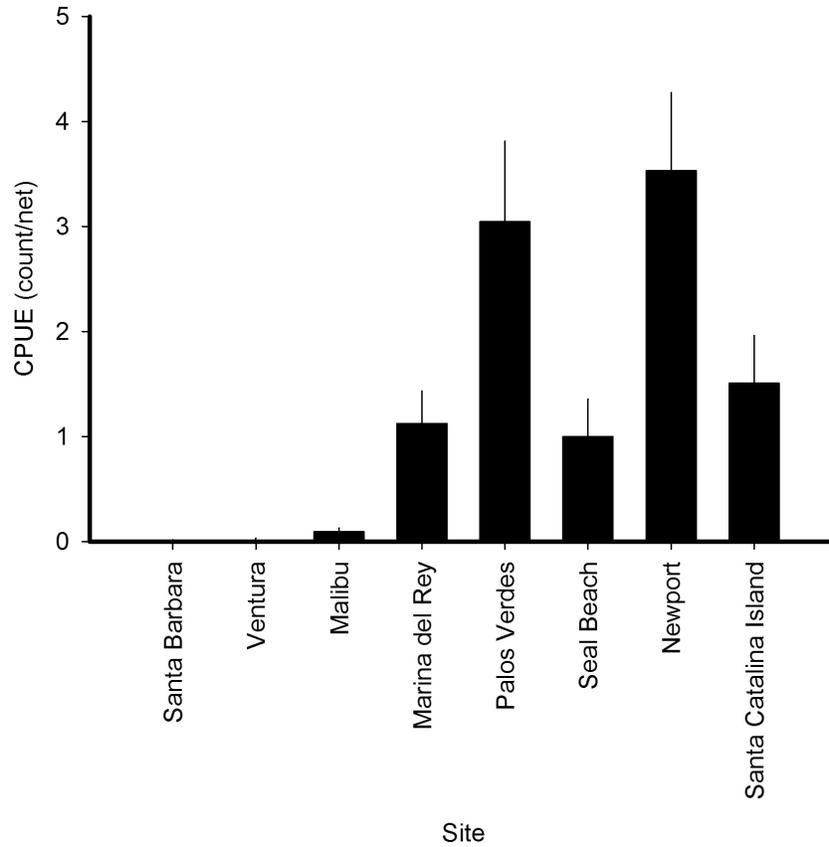


Figure 4. Mean catch per unit effort (CPUE; count/net) for all gill net sampling sites, 1995–2007. Standard error for each is presented. Santa Catalina Island includes three sites sampled, typically the west end, east end, and Catalina Harbor on the windward side of the island.

Female GSI for histologically examined individuals peaked in the summer months, coinciding with peak spawning while the minimal GSI was synchronous with no-spawning activity (fig. 3b). The GSI:spawning activity relationship followed a predictable logarithmic pattern ( $r^2 = 0.54$ ). While the number of spawning events for this species was not known, histological examination suggested serial spawning. Females were found to have both mature yolked oocytes (present spawn) and vitellogenic maturing oocytes (subsequent spawn). While samples were not available from all months, females in spawning condition were present in June (fig. 3b). The smallest female with yolk-filled ovarian follicles measured 144 mm SL and was collected in June. One female taken in June (149 mm SL) contained follicles with incomplete yolk deposition (accumulating yolk). The spawning period continued through August and concluded by September or October. The ovaries of five of eight females from September contained only rows of primary oocytes. Two September females contained atretic oocytes in the ovaries. One female from September collections contained hydrated eggs. Five of eight females collected at Seal Beach and one collected at Catalina Harbor in September were in spawning condi-

tion, suggesting some local geographic variation in the termination of spawning. All 13 Salema females collected in November had regressed ovaries containing primary oocytes.

Like the females, male GSI peaked during the summer spawning season (fig. 3c), again with a predictable logarithmic relationship between the two parameters ( $r^2 = 0.82$ ). All nine male Salema collected in June were undergoing spermiogenesis. Nine of ten from August were undergoing spermiogenesis with one exhibiting regression. September and October were transitional months indicating the male reproductive season was concluding. Two September males were undergoing spermiogenesis whereas five were in late spermiogenesis and seven of eleven males from October exhibited late spermiogenesis and three were regressed. All of the ten males from November contained regressed testes indicating the period of sperm formation had concluded.

#### Spatial Patterns

A total of 3750 Salema measuring 71–250 mm SL were caught in the gill net sampling program. Island samples were significantly larger (KS,  $F = 1.2638$ ,  $df =$

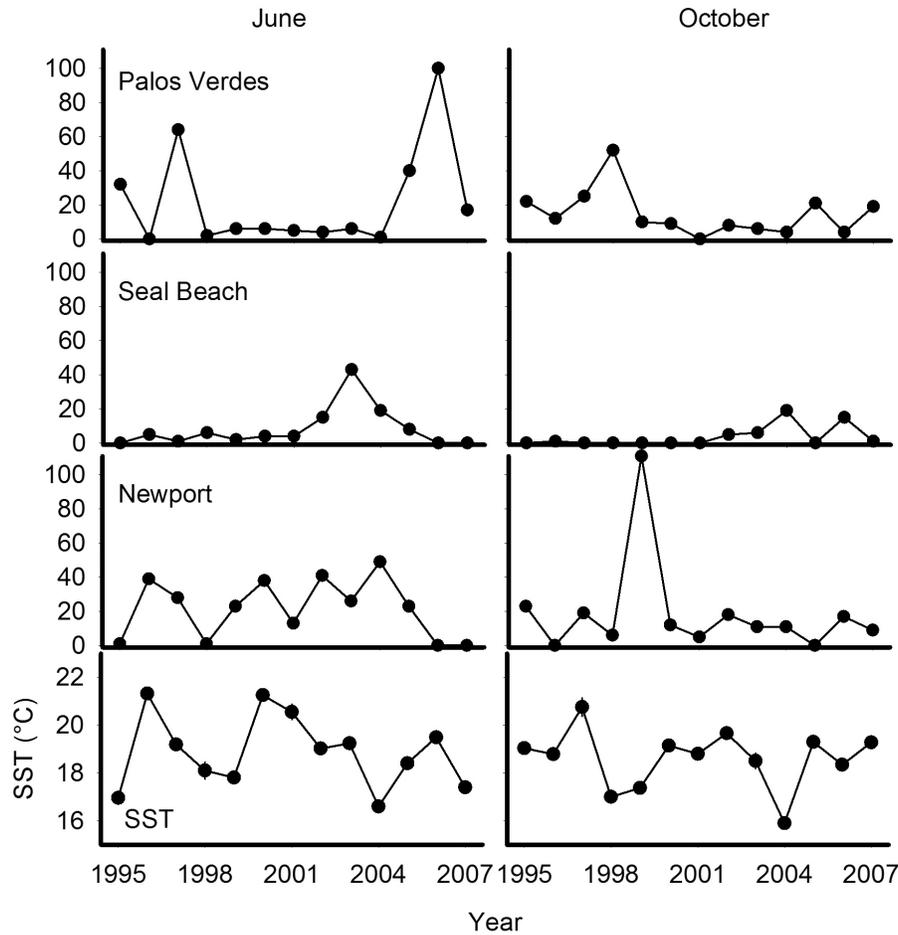


Figure 5. Total catch recorded at the three mainland gill net stations, with >5 fish caught in any year, by year for June and October. Six nets were set at each station in all years and nominally fished overnight. Mean sea surface temperature (SST °C) recorded during each net set across all sites is also presented.

2317, 1262,  $p < 0.001$ ) with a median length of 164 (0.3 standard error) mm SL while the median mainland fish length was 160 (0.2 standard error) mm SL. At least one individual was taken from all eight areas sampled by gill net, but their abundance substantially declined north of Marina del Rey (fig. 4). Peak catch per unit effort (CPUE) at sites from Malibu and southward occurred at Newport (3.5 fish/net) followed by Palos Verdes (3.0 fish/net) before a substantial decline to 1.5 fish/net, or less, at Santa Catalina, Marina del Rey, Seal Beach, and Malibu. Along the mainland, these sites segregated by habitat with the two rocky reef sites (Newport and Palos Verdes) numerically dominating the sampling while nets set at the soft-bottom areas (Marina del Rey and Seal Beach) caught substantially fewer individuals.

Of the six coastal sites, only sampling at Palos Verdes, Seal Beach, and Newport recorded CPUEs > 0 fish/net (fig. 5). Salema CPUE was not uniform at these three sites in both June and October; relatively elevated (depressed) CPUEs were not recorded at each site in the same years. June catches in Newport were the most

consistent, while catches at Palos Verdes in June were the most variable. Less than 10 fish/net were taken at Palos Verdes in June between 1998 and 2004 while the 1997 and 2005 CPUEs each exceeded 40 fish/net. During 1999–2004 period, above-average CPUEs were recorded at Seal Beach and Newport. Mean June CPUEs at Palos Verdes were negatively correlated with Seal Beach ( $r = -0.60$ ,  $p < 0.03$ ) and Newport ( $r = -0.54$ ,  $p = 0.05$ ). No significant correlation with SST was detected at any of the sites or for the cumulative annual means. In October, a similar pattern emerged, especially with the highest CPUE recorded at Newport in 1999. The Palos Verdes October annual CPUEs were negatively correlated to the Seal Beach CPUEs ( $r = -0.58$ ,  $p < 0.04$ ).

#### Temporal Patterns

Lampara net sampling over a shorter period than the power plant series (discussed below) corroborates the general appearance of Salema in the area with increasing numbers in 1980 with peak count/set in 1984 at

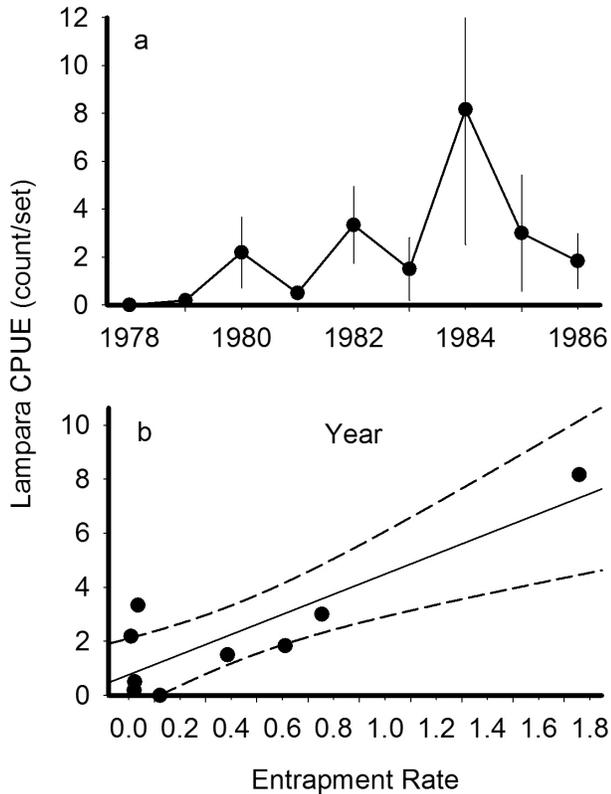


Figure 6. a) Mean August lampara catch per unit effort (CPUE; count/set) of Salema offshore of San Onofre Nuclear Generating Station during night sampling, 1978–86. b) Scatterplot and linear regression of mean August lampara CPUE versus mean annual entrapment rate during the overlapping years in both data sets. Dashed lines represent 95% confidence intervals.

8.2 fish/set (fig. 6a). Patterns in the power plant and lampara net data sets were significantly correlated ( $r^2 = 0.74$ ,  $p = 0.003$ ) during the brief period of overlapping sampling (fig. 6b). The power plant entrapment series recorded clear peaks during the summer months of July ( $3.5/10^6 \text{ m}^3$ ), August ( $5.3/10^6 \text{ m}^3$ ), and September ( $3.5/10^6 \text{ m}^3$ ) with CPUEs in the second one-half of the year considerably higher than five of the first six months. (fig. 7a). Looking at just the peak period, an entrapment rate  $> 1/10^6 \text{ m}^3$  was first recorded in 1983 (fig. 7b). The overall abundance remained low until the early 1990s after which it increased significantly over time ( $r^2 = 0.18$ ,  $p < 0.01$ ) and was statistically meaningful at a 4-year running mean ( $r^2 = 0.94$ ,  $p = 0.03$ ) despite substantial interannual variability. The increasing trend continued though 2006 before abundances declined substantially.

Power plant monitoring recorded 376,131 Salema during the 38 years included in this analysis. Measured individuals ranged 23–199 mm SL. The long-term pattern and multimodal distribution in the mean monthly entrapment rates suggested differential life stages occupying the nearshore waters at different times. The overall length-frequency distribution was dominated by fishes in

the 125-mm SL size class but additional large numbers ( $>15\%$  of the total) in the 75, 100, and 150 mm SL size classes were also taken (fig. 8a). Adults ( $>125 \text{ mm SL}$ ) were most common July–October with 17%, on average, of the total entrapped abundance occurring during these months versus 4% in the remaining months combined (fig. 8b). Monthly juvenile entrapment ranged from 5% to 13%, but averaged 8% of the total entrapped abundance each month.

Recruitment, or year-class strength, was estimated using the YOYI as a proxy. The YOYI was not autocorrelated ( $DW = 1.51$ ,  $p = 0.09$ ) with two clear peaks in the 18 years examined (fig. 9). The occurrence of two large year classes 11 years apart resulted in no significant trend in the long-term pattern ( $r^2 < 0.01$ ,  $p = 0.88$ ). Peak settlement occurred in 1995 ( $397/10^6 \text{ m}^3$ ) and 2005 ( $290/10^6 \text{ m}^3$ ) while the remaining years were commonly less than  $140/10^6 \text{ m}^3$ . Year class strength remained relatively high 2005–08 with each measuring at least  $105/10^6 \text{ m}^3$ . None of the five oceanographic or climate indices correlated with the YOYI after adjusting for autocorrelation in the climate index.

## DISCUSSION

Salema ranked among the 21 most commonly entrapped species in southern California power plants (1972–2010), and among the top ten since 1990 (Miller and McGowan 2013). Its diel behavior pattern created difficulties documenting their dynamics (Hobson and Chess 1976; Thomson et al. 2000). Salema are commonly taken using passive sampling devices such as scientific gill nets set overnight or coastal power plants operating cooling water intakes irrespective of diel period. Therefore, we used these two time series to assess Salema spatiotemporal patterns and collect samples for life history studies. As a result, the following overall profile emerges for Salema, with particulars discussed in further detail below. Salema is a fast-growing, summer-spawning species, potentially with high sperm competition, that lives to at least 14 years and exhibits clear preferences for rocky reef habitats in southern California. Salema became increasingly common in the area in the late-1980s with highly sporadic year-class strength, but evidence of juvenile residency. Adult Salema were seasonal transients in the sampling areas. Their recruitment patterns in the Southern California Bight were unrelated to generic climate indices such as water temperature or PDO, suggestive of more complex mechanisms regulating year-class strength (Asch and Checkley Jr. 2013).

Salema grow quickly through age six before stabilizing at approximately 190 mm SL with approximately 20 mm SL added during the remaining eight possible years of life. Our von Bertalanffy growth model  $L_\infty$  did not adequately represent fish older than eight years

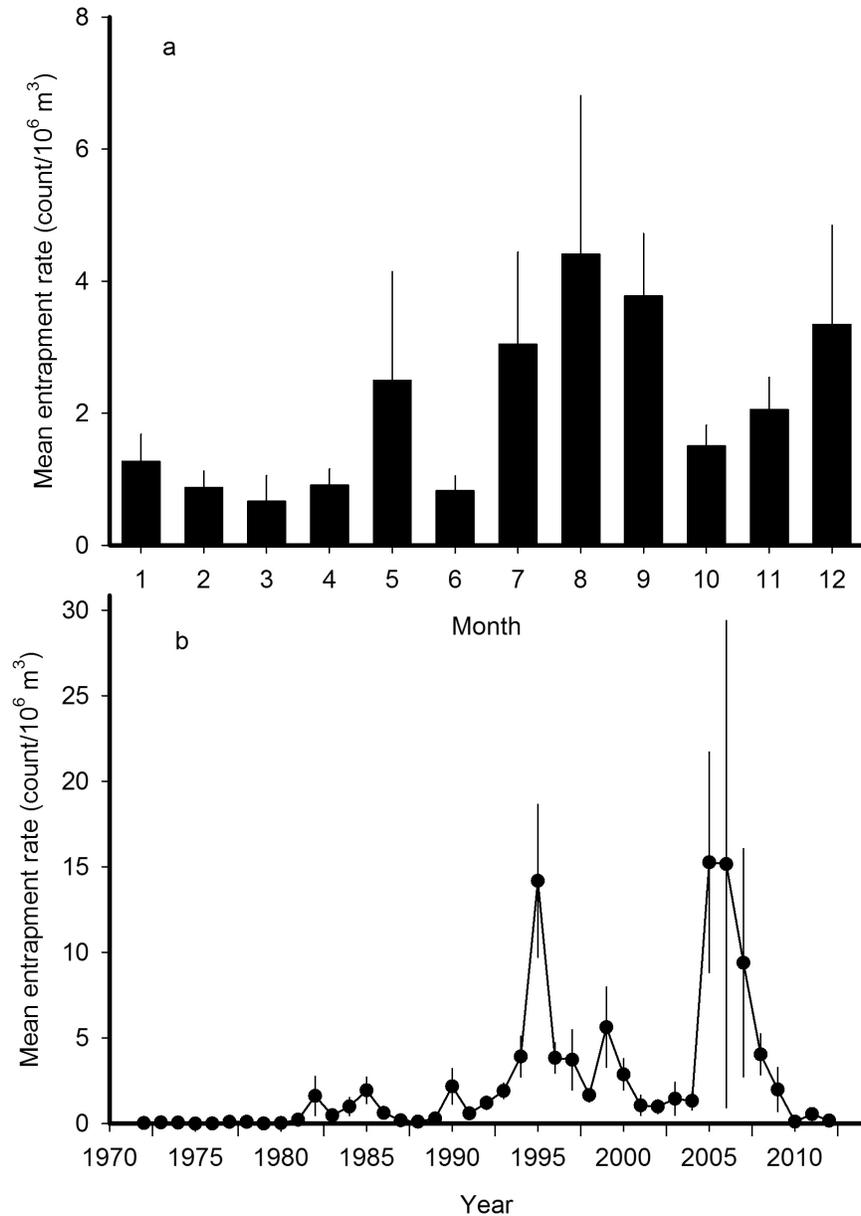


Figure 7. Mean ( $\pm$  standard error) power plant entrapment rates by a) month and b) year for Salema recorded during heat treatments at the three plants depicted in Figure 1, 1972–2012.

whose lengths exceeded the  $L_{\infty}$ . This may be an artifact of sampling location. The length at age samples in these older age classes were evenly sourced from island and mainland sampling sites in 2004. Over the full gill net time series, significantly larger Salema were taken at the island stations than those taken at the mainland stations. The possibility of spatial variation in growth is evident in Salema as has been found elsewhere (Schlosser and Angermeier 1995). Focused sampling targeting Salema from islands and the mainland is needed to better understand this process as a wide variety of biogeochemical factors can affect this, including: prey type and availability, water temperature, predator presence, etc.

The Salema growth coefficient was higher than most Southern California Bight species of similar maximum size, such as Queenfish (*Seriphus politus*) (Miller et al. 2009), but is consistent with other species in the family Haemulidae. Both the Bluecheek Silver Grunt (*Pomadysys argyreus*,  $k = 0.80$ ) and the Saddle Grunt (*P. maculatus*,  $k = 0.75$ ) common to the waters offshore of Brunei Darussalam have growth coefficients exceeding Salema's (Silvestre and Garces 2004). Rapid growth in early life is a common and well-founded theme in fish biology as size confers lower natural mortality (McGurk 1986). Salema reportedly grow to 300 mm TL (Thomson et al. 2000; Love et al. 2005) or approximately 238 mm SL

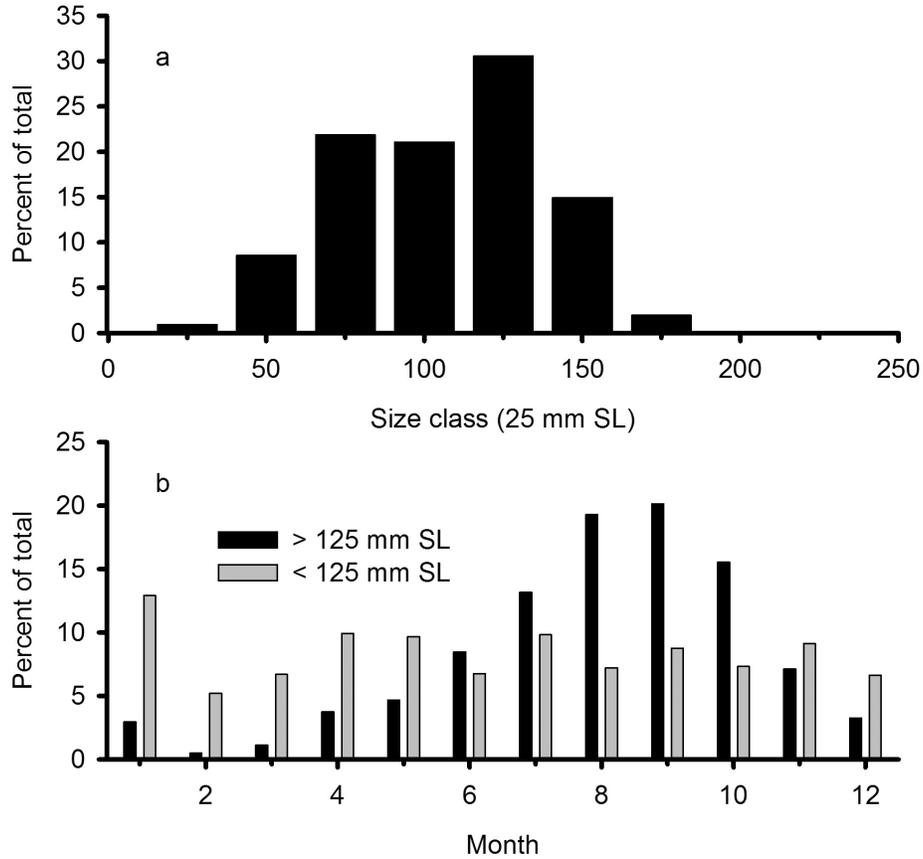


Figure 8. a) Length frequency of all Salema measured during surveys at the three coastal power plants depicted in Figure 1, 1992–2009. b) Percent of all measured Salema, 1992–2009, measuring > or < 125 mm SL by month.

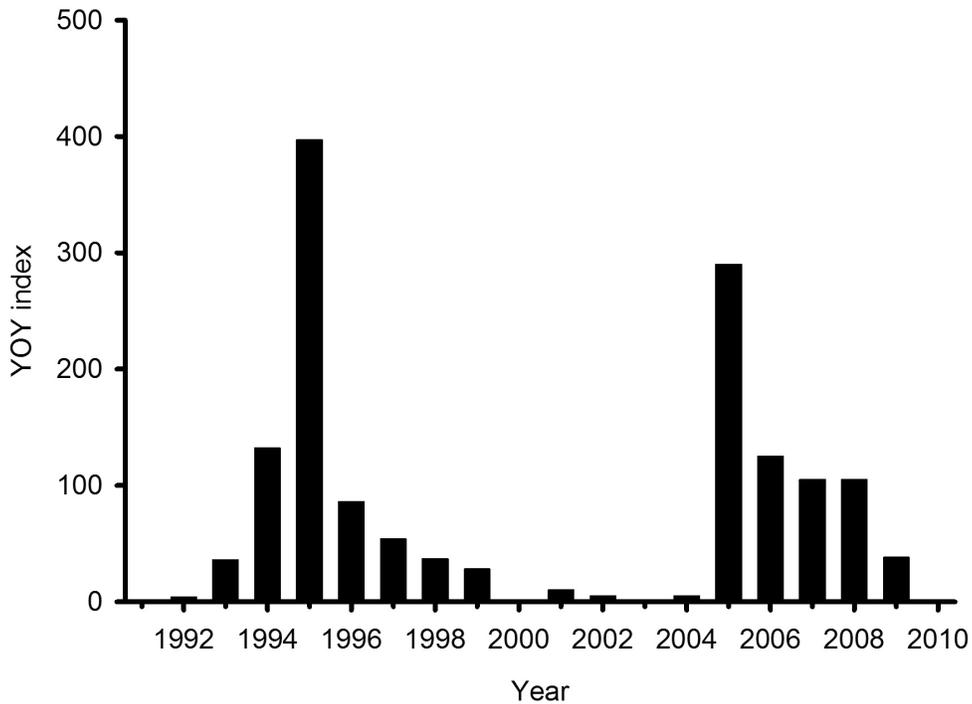


Figure 9. Annual young-of-the-year index (YOYI; count/10<sup>6</sup> m<sup>3</sup>) derived from power plant surveys.

after converting using our derived relationship. We did not have a fish this large in our age and growth sample, but the gill net sampling did catch one fish measuring 250 mm SL (315 mm TL) in August 2004 at Seal Beach, California. Out of the 3750 Salema caught in the 14 years of gill net sampling, only seven exceeded 200 mm SL. The largest fish recorded in the power plant monitoring was 199 mm SL. Salema up to 190 mm SL were included in the age and growth sample. Therefore, the age and growth sample encompassed most of the Salema documented size range.

Spawning occurred during the summer months, as may be expected in a southern distributed species at the northern extent of its range (Love et al. 2005). In Salema, the GSI was a significant predictor of spawning condition in both sexes with significantly higher levels of gametogenesis during the summer months as compared to the fall. Unfortunately, no adults for the life history analysis were successfully collected during the winter. The high GSI values observed in both sexes was surprising. Typically, in gonochoric species from southern California the female GSI far exceeds their male counterparts (Love et al. 1990; Allen et al. 1995; Miller et al. 2008). Salema mean male GSI was equivalent to the female GSI. This is commonly seen in species with high sperm competition (Stockley et al. 1997). While sperm competition has been identified in a variety of temperate fishes, especially those associated with reefs (Fischer and Petersen 1987), it has not been previously identified in fishes of the family Haemulidae. Unfortunately, field observations of Salema spawning have not yet been reported. Therefore, while the GSI values were consistent with sperm competition, we can only speculate as to its relevance to the undocumented Salema mating system. Females being significantly more common also discount the need for sperm competition by males.

Salema migration is undocumented, but the seasonal and interannual patterns in post-juvenile abundance found in this study were highly suggestive of migration. There were indications that larger fish repeatedly visited the areas sampled by the power plants on a seasonal cycle, but at intermittent annual frequencies. This was suggestive of an oceanographic cue, but none was identified here. Site-specific annual gill net CPUE were highest at gill net sampling sites centered near rocky reefs, consistent with Salema's known ecology. The negative correlations in site-specific annual gill net CPUE confirms that Salema was not uniformly distributed along the coast but exhibited high spatiotemporal variability. For instance, in 2006 Salema CPUE was well-above average in both June and October at Palos Verdes while the CPUE near Newport was well-below average. The same pattern emerged in October 1998. Each year was marked by anomalously warm waters caused by delayed upwelling (Goericke et

al. 2007) or a strong El Niño (Lynn et al. 1998). Otherwise, the CPUE at Newport was relatively stable in both months while the CPUE at Palos Verdes was substantially more variable.

Once spawned, Salema appeared to readily settle out of the plankton in the Southern California Bight, although no information was available to discern if these settlers are of local or distant (e.g., Baja California) origin. Ichthyoplankton surveys between 1978 and 1980 offshore of SONGS sporadically caught Salema larvae with the most taken in September 1978 (Walker et al. 1987). Similar surveys between 1982 and 1984 collected only two Salema larvae (McGowan 1993), despite a strong El Niño affecting the Southern California Bight between 1982 and 1983 (Fiedler et al. 1986). Finally, surveys in 2003–04 resulted in Salema collections ranking sixth in the nearly weekly sampling conducted offshore of HBGS; with most larvae taken in August 2004 (MBC 2005).

Regardless of where the Salema larvae were spawned, the presence of small, YOY size classes in the Southern California Bight indicates local recruitment. Smaller size classes appear to remain in the nearshore Southern California Bight areas sampled by the power plant intakes year-round. Reduced availability to the power plant intakes apparently begins with 125 mm SL size class as individuals >125 mm SL become seasonal migrants. This corresponds to an approximately one-year residence and partially contributes to our understanding of the interannual variation as these strong year classes residing in the area raise the overall annual mean entrapment rates. Once departed, they may only contribute to the annual total entrapment during the summer spawning period.

Factors regulating the observed larval settlement and total abundance patterns were not obvious. No evidence of a response to the 1976–77 regime shift (Miller et al. 1994) was found, despite the substantial biological reorganization in California waters in response to the altered oceanographic climate (Holbrook et al. 1997; McGowan et al. 2003; Miller and McGowan 2013). Salema abundances in the Southern California Bight increased initially during 1982–83 ENSO, with a sustained rise beginning in 1989, a year previously characterized as a regime shift outside of the PDO+/PDO– pattern (Hare and Mantua 2000; Bond et al. 2003; Miller and McGowan 2013). The 1989 regime shift reportedly influenced current patterns and productivity elsewhere (Polovina et al. 1995; Polovina 2005), but no investigations have looked for these changes in coastal southern California. Reasons for the post-2006 Salema abundance decline were unknown. It was unlikely that any anthropogenic impacts resulted in the decline as no fishery targeted Salema, no substantive

habitat loss occurred, and no demonstrative changes in wastewater or stormwater discharge has occurred in the recent years. Just as oceanographic changes associated with the 1989 regime shift likely resulted in the establishment of elevated (compared to previous years) seasonally resident populations in southern California, it was likely changes in oceanographic conditions led to their local decline. This question warrants continued investigation.

## ACKNOWLEDGEMENTS

We would like to thank the power plant owners and operators for their support of the impingement monitoring and use of the data here. The gill net sampling was supported by the California Department of Fish and Game's Ocean Resource Enhancement Hatchery Program. Many thanks to C.T. Mitchell for pushing to get the research completed and published. The manuscript was greatly improved by the comments of four anonymous reviewers.

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## USING IN SITU VIDEO ANALYSIS TO ASSESS JUVENILE FLATFISH BEHAVIOR ALONG THE OREGON CENTRAL COAST

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### ABSTRACT

We examined the feasibility of using a video beam trawl system to assess behavioral responses of juvenile flatfishes in relation to co-occurring habitat features, most notably dissolved oxygen (DO) concentrations. Sixteen samples were collected along a cross shelf transect in the central Oregon coast during summer 2008. We found that juvenile fish reaction duration, defined as the time in seconds from first reaction to capture, decreased with decreased DO. However, other variables such as bottom water temperature, fish size, and fish species composition by site are potentially confounding factors of the analysis. The dominant flatfish species shifted from English sole (*Parophrys vetulus*) to Pacific sanddab (*Citharichthys sordidus*) with increased depth. Escape behavior varied from “burying” in the shallows, to “hovering” at mid-depth stations, and “running” at the deepest site. Collectively, our results suggest that the video beam trawl effectively monitor behavioral metrics and community composition of nearshore flatfish assemblages.

### INTRODUCTION

In the eastern North Pacific along the central Oregon continental shelf, upwelling-driven coastal hypoxia (<1.43 ml DO l<sup>-1</sup> H<sub>2</sub>O) (Grantham et al. 2004; Chan et al. 2008) is a seasonal phenomenon, which also presents interannual variability in its intensity. Every year, northerly winds starting in late spring to early summer cause offshore Ekman transport. As the surface water moves offshore it is replaced with deep, nutrient-rich, oxygen-depleted water that has the potential to support phytoplankton blooms. The decomposition of organic matter sinking down from these phytoplankton blooms results in additional oxygen depletion (Pierce et al. 2012). Historically, hypoxia in the California Current System has not extended inshore past the 70 m isobath where important nursery grounds for economically and ecologically important fishes are located (Grantham et al. 2004).

In 2002 scientists began to detect seasonal nearshore hypoxic events on central Oregon’s continental shelf (Grantham et al. 2004). In the summer of 2002 hypoxic waters covering 820 km<sup>2</sup> were observed inshore of the 70 m isobath (Buck 2007). During this period, remotely

operated vehicle (ROV) surveys revealed areas void of live fish (dead zones) where long-lived benthic communities had previously existed, confirming decreased biodiversity (Grantham et al. 2004). In addition to scientific observation, the Oregon Department of Fish and Wildlife (ODFW) received increased reports of dead fishes washing up onshore. The hypoxic event in 2002 was not an isolated event. Four years later, in 2006, a more severe hypoxic event occurred (Chan et al. 2008). Some studies report that alterations in wind intensity and frequency due to climate change are affecting upwelling patterns (Grantham et al. 2004; Barth et al. 2007; Buck 2007) and contributing to their intensification in recent decades (Peterson et al. 2013). In 2006, anoxia (0.0 ml DO l<sup>-1</sup>) was detected inshore of the 50 m isobath with hypoxic water covering an area of approximately 3000 km<sup>2</sup> (Chan et al. 2008).

The nearshore regions affected by hypoxia include nursery grounds for commercially and ecologically important flatfish species such as the Pacific sanddab (*Citharichthys sordidus*), English sole (*Parophrys vetulus*), sand sole (*Psettichthys melanostictus*), and butter sole (*Isopsetta isolepis*) (Pattie 1969; Barss 1976; Krygier and Percy 1986; Rogers and Pikitich 1992; Buckley et al. 1999). During early life stages, flatfishes are important prey items for other species (Lassuy 1989), and if hypoxia negatively affects their behavior, there could be trophic implications for the local food web. On an ecological level, thresholds of hypoxia are taxon specific and can result in sublethal effects such as forced migration (Vaquer-Sunyer and Duarte 2008) resulting in shifts in biological communities and behavior-mediated death of individuals (Kolar and Rahel 1993; Breitburg et al. 1997). Organisms with restricted mobility, such as echinoderms, crustaceans, and early life stages of fishes, are typically some of the most heavily affected (Gray et al. 2002).

While the effects of anthropogenic hypoxia on fish communities in semi-enclosed systems such as Chesapeake Bay and the Gulf of Mexico have been well monitored (Buck 2007), similar effects in seasonal upwelling-driven nearshore hypoxic zones have not. Laboratory studies have revealed that low DO con-

TABLE 1  
 Date, station name, targeted and actual (in parenthesis) depths, number of tows, and video time (in minutes)  
 of the sampling events analyzed in this study. MB and NH station names indicate locations off of  
 Moolack Beach and along the Newport Hydrographic line (44.6517°N).

Date	Station	Depth (m)	No. of Tows	Video time (minutes)
07/26/08 & 08/11/08	MB 30	30 (30.0)	2	24.1
07/26/08, 08/11/08, & 08/26/08	MB 40	40 (42.8)	4	51.5
07/26/08, 08/25/08, 08/27/08, & 08/28/08	NH 05	60 (60.0)	4	48.7
08/11/08	NH 07	70 (73.0)	1	13.5
07/26/08, 08/11/08, 08/27/08, & 08/28/08	NH 10	80 (80.1)	5	75.4

centrations can affect marine organisms physiologically and behaviorally. For example, laboratory experiments with common sole (*Solea solea*) tracked behavioral and biochemical responses to gradual exposure to hypoxia, establishing a pattern of behaviors that correlated to shifts in metabolic response to oxygen concentration. With the onset of anaerobic metabolism, behavior shifted from reduced activity to inactivity and as tank conditions transitioned from hypoxia to anoxia fishes lifted their heads, exhibited escape responses (“panic swimming”), loss of balance, and paralysis (Dalla Via et al. 1998). Behavioral responses to low DO include alterations in activity (Dalla Via et al. 1998; Chabot and Dutil 1999; Brady and Targett 2010), reduced feeding rates (Chabot and Dutil 1999; Stierhoff et al. 2006), decreased predation efficiency (Tallqvist et al. 1999), altered predator-prey interactions (Kolar and Rahel 1993; Sandberg 1994; Breitbart et al. 1997; Long and Seitz 2008), and species specific avoidance techniques (Wannamaker and Rice 2000). Wannamaker and Rice (2000) found that juvenile spot (*Leiostomus xanthurus*), mummichog (*Fundulus heteroclitus*), pinfish (*Lagodon rhomboides*), menhaden (*Brevoortia tyrannus*), croaker (*Micropogonias undulatus*), white mullet (*Mugil curema*), and brown shrimp (*Penaeus aztecus*) could all respond to levels of 1 mg l<sup>-1</sup> DO, but the avoidance thresholds and responses varied from species to species. Some species avoided low DO by way of vertical migration while others increased surface breathing.

Ongoing improvements of environmental sensors, and in situ imaging and platforms have dramatically augmented our ability to monitor individual behavior of fish in response to environmental variability (Norcross and Mueter 1999; Kintisch 2013). Behavioral responses to external stimuli can have important consequences to the survival of an individual. By studying behavior one can reach a mechanistic understanding of the processes that affect the survival of individuals at very small spatial and temporal scales. However, there are analytical challenges in quantifying and analyzing behavioral metrics from in situ videos. Specifically, one needs to a-priori select a number of metrics that are quantifiable in video frames and that are truly representative of the behavior

under scrutiny (Laidig et al. 2013). Further, one needs to relate these behavioral metrics to species type and to changes that occur in the habitat.

The objective of this study was to assess the feasibility of using a video beam trawl system to assess the behavioral responses of juvenile flatfishes in relation to the physical and chemical properties of the water and the fish species community composition. We were particularly interested in assessing the responses of juvenile flatfishes to DO concentrations in a natural setting. To this end, we have added a video system to a beam trawl to allow for in situ behavioral observations. We hypothesized that the behavioral response of juvenile flatfishes to the approaching of the beam trawl is affected by DO concentrations and by community composition. If found to be true, our hypothesis could have implications for the survival of fishes within different ecological systems. Results from this study can thus shed light on the feasibility of applying in situ video technology in addressing the behavioral responses of organisms. Prior to this, there were a few studies to characterize the nearshore soft-sediment juvenile fish assemblages of the central Oregon coast (e.g., Pearcy 1978; Toole et al., 2011), but only for sites deeper than 50m. Given the nursery role of nearshore soft-sediment habitats (Laroche and Holton 1979), our study fills an important knowledge gap.

## MATERIALS AND METHODS

Juvenile flatfishes were sampled at five historical stations in central Oregon (table 1) off Moolack Beach (MB) and along the Newport Hydrographic (NH) line (fig. 1) during July and August of 2008. Data were collected during two 1-day cruises on the Oregon State University’s R/V *Elakha* and one 9-day cruise on the R/V *Wecoma*, for a total 16 tows. At each sample site, a conductivity, temperature, depth, and DO profiler (CTD-DO, Sea-Bird Electronics Model 25, Bellevue, WA, USA) was deployed to measure DO (ml l<sup>-1</sup>), temperature (°C), and salinity on the seafloor. The DO sensors are calibrated once to twice a year depending on availability of the gear and scheduled cruises of the R/V *Wecoma*. We sampled the flatfish community assemblage and measured their behavior using a 2 m wide beam

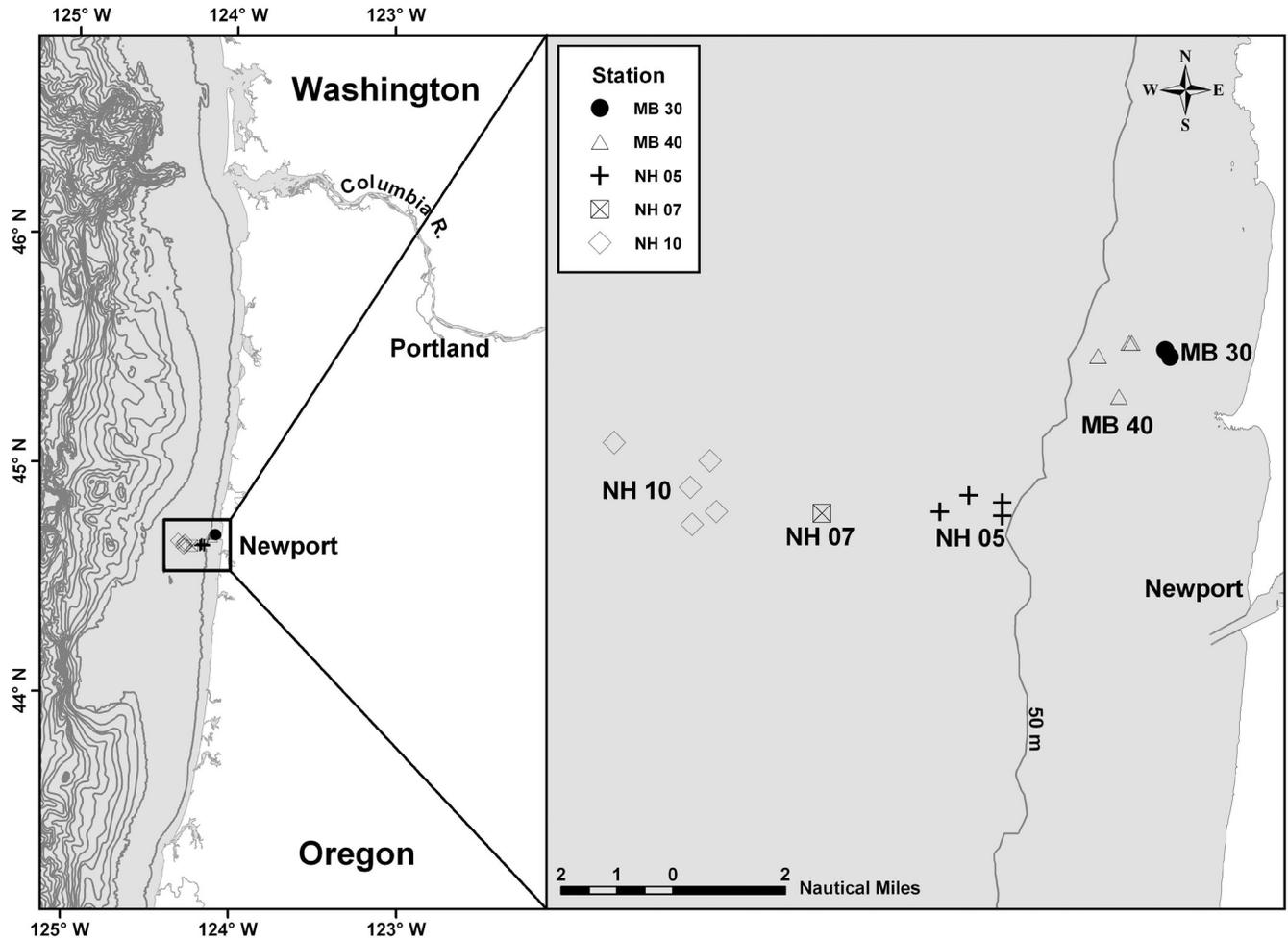


Figure 1. Locations sampled in 2008 with beam trawl and in situ video. Sampling took place along Newport Hydrographic line (NH) and at Moolack Beach (MB) stations.

trawl equipped with a 3 mm mesh liner throughout, 10-cm scaling laser, lights, tickler chain, and an NTSC high-resolution video camera mounted in a vertical downward orientation (fig. 2). Once the beam trawl made contact with the seafloor, it was towed for approximately 10 minutes at a target speed over the ground of 1 knot. The net was then brought on board and emptied. Fishes greater than 150 mm were identified to species, measured (total length [TL] in millimeters), and then released. Juvenile flatfishes less than 150 mm were frozen and subsequently thawed in the lab, identified to species, weighed (g) and measured (mm TL). Based on previous studies done in the area (Krygiar and Percy 1986), flatfishes equal to or smaller than 150 mm in length were considered juveniles (i.e., age-1 or younger). Fish length from the trawl samples was measured to the nearest mm.

In situ video obtained with the video beam trawl system was analyzed frame-by-frame using Quick Time Player version 7.6.4. For each tow, we recorded fish size

(to the nearest cm using the scaling lasers), tow duration, and the duration of actual bottom contact, as observed in the video. Intervals where the beam trawl was not in contact with the seafloor were removed from the inspected footage. The number of fishes observed was standardized by the total amount of time the beam trawl was in contact with the seafloor. This gave us the number of fishes caught per minute of towing effort. Video analysis began from the point the trawl runners and tickler chain made contact with the seafloor and ended when the sampling equipment no longer was in contact with the substrate. When the equipment first made contact with the seafloor a sand plume was generated. Once the beam trawl was in constant motion the disturbed sand remained behind the tickler chain leaving the undisturbed environment in front of the sampling equipment in clear view. Excerpts of videos collected during these operations can be viewed here: <http://www.fisheriesoceanographylab.org/photos-videos/beam-trawl-videos/>.

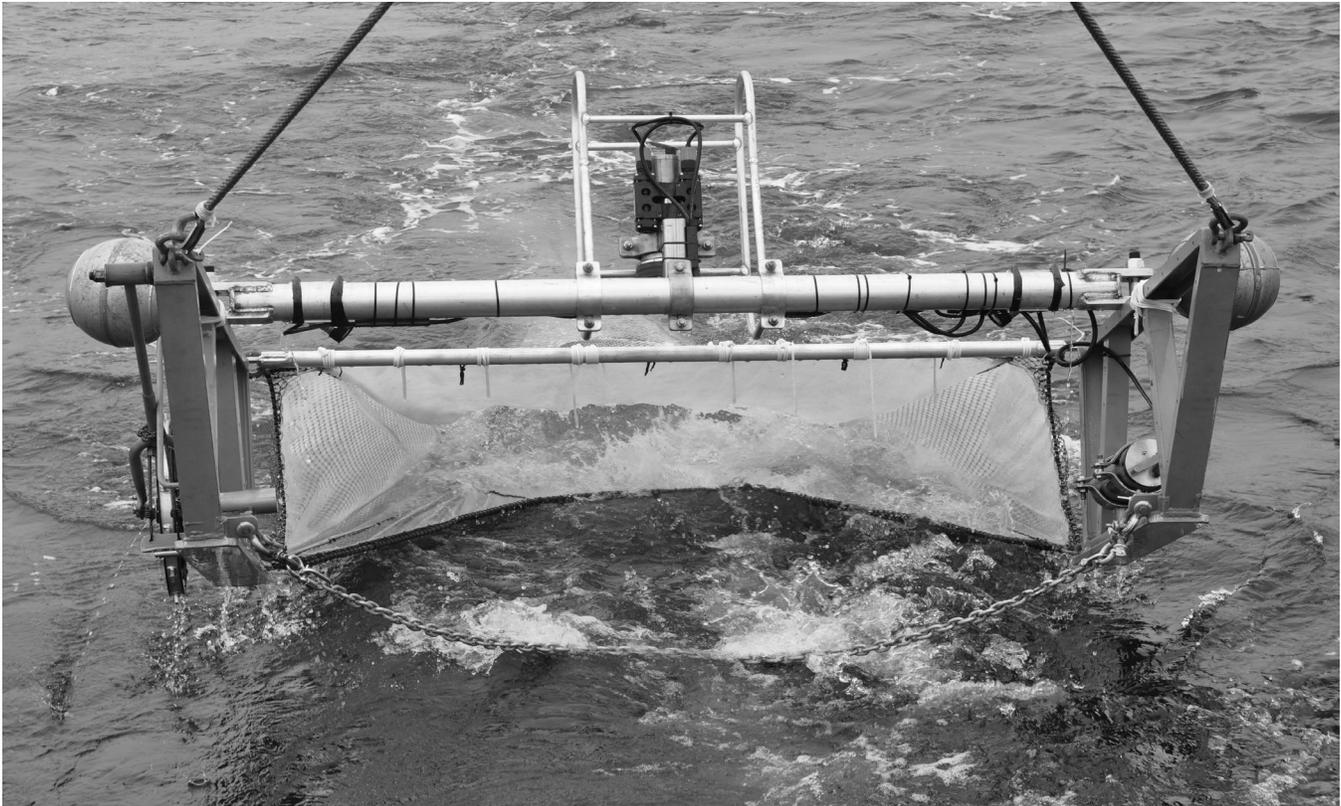


Figure 2. 2 m wide beam trawl equipped with tickler chain, 10 cm laser scaler, lights, 3 mm mesh net, and a NTSC high-resolution video camera.

During the analysis, the entire video frame was overlaid with a  $10 \times 7$  grid. The 10 cm scaling laser system generated a metric frame of reference. For each fish observed in the video frame, the following data were recorded: time first seen, location first seen (based on the overlying grid), length to the nearest cm (taken when the fish was flat over the bottom), and initially moving (1) or still (2). For fish that were not initially moving, we also recorded time of first reaction (i.e., a noticeable movement of the fish's body), distance from the tickler chain at the time it reacted, initial and post disturbance response behaviors (described below), time it fell behind the chain, time last seen, and location last seen. The time a fish fell behind the chain represents the time of capture. Fish that "out ran" the gear were classified as fish that escaped. Times were recorded in minutes and seconds. The total reaction time (total reaction time = time fish first reacted – time fish first appeared) and reaction duration (reaction duration = time fish fell behind – time fish first reacted) were calculated and recorded. Reaction duration was not recorded for fish that escaped the trawl (i.e., clearly left the video frame from the sides). In addition to the performance metrics listed above, we also quantified six initial and post disturbance response behaviors. Specifically: burying (buries in sediments), running (continuous swimming), hopping

(short bursts of swimming followed by short periods of rest), rising (rising out of sediments with no horizontal movement), hovering (hovers above sediments) and lastly, no visible reaction.

The in situ video footage was analyzed along with catch data to determine behavioral responses in relation to community composition, water DO, and other environmental conditions such as water temperature and bottom depth. Specifically, average reaction duration (time in seconds) for each tow was correlated against the respective values of bottom DO using Generalized Additive Models (GAM; Wood 2006). The average length of the fish per tow (measured from the videos) was also included in the analysis, to evaluate the effect of fish size on behavioral metrics. Initially both variables were included in the model, and removed one at a time, starting from the variables with the highest  $p$ -value. This analysis was restricted to juvenile fishes (length  $\leq 150$  mm). Analyses of variance (ANOVAs) were used to examine trends between fish size, standardized abundance (number of fish per minute of sample effort) and percent juvenile individuals observed and that escaped the tows, in relation to station. Linear regression was used to correlate DO values at each station with average fish size and with bottom temperature. All univariate analyses (ANOVA, GAM, and linear regression) were

TABLE 2  
**Average number of individual fish collected per minute at each station in the net data. The number of flatfishes per minute was calculated for net and video samples and includes individual of all sizes. The average percentage of juvenile flatfishes for net and video samples represents only flatfish that are 150 mm or less in TL.**

	MB 30	MB 40	NH 05	NH 07	NH 10
Speckled Sanddab ( <i>Citharichthys stigmaeus</i> )	1.17	1.90	0.47	0.07	0.00
Butter Sole ( <i>Isopsetta isolepis</i> )	2.38	1.22	0.10	0.07	0.09
English Sole ( <i>Parophrys vetulus</i> )	6.04	3.48	0.43	0.00	0.20
Pacific Sanddab ( <i>Citharichthys sordidus</i> )	0.04	2.02	2.61	1.85	0.86
Curlfin Sole ( <i>Pleuronichthys decurrens</i> )	0	0.02	0.00	0.00	0.00
Sand Sole ( <i>Psetichthys melanostictus</i> )	0	0.04	0.00	0.00	0.00
Dover Sole ( <i>Microstomus pacificus</i> )	0	0.00	0.12	0.00	0.07
Petrale Sole ( <i>Eopsetta jordani</i> )	0	0.02	0.00	0.00	0.00
Slender Sole ( <i>Lyopsetta exilis</i> )	0	0.02	0.02	0.00	0.08
Flathead Sole ( <i>Hippoglossoides elassodon</i> )	0	0.00	0.00	0.00	0.01
Rex Sole ( <i>Glyptocephalus zachirus</i> )	0	0.00	0.02	0.00	0.00
Number of flatfishes minute <sup>-1</sup> (net sample)	9.63	8.72	3.79	2.00	1.31
Number of flatfishes minute <sup>-1</sup> (video sample)	14.04	14.31	12.00	6.44	4.04
Average % of juvenile flatfishes (net sample)	91.2	59.3	50.9	7.4	19.8
Average % of juvenile flatfishes (video sample)	89.9	79.1	66.3	36.8	40.9

conducted in *R*, with cut off for significance set to 0.05. GAMs were conducted using the library “mgcv” (mixed gam computation vehicle; Wood 2006).

Species assemblages from the actual catch data were analyzed using multivariate techniques in PC-ORD v5 (McCune and Mefford 1999). Specifically, we used a species composition matrix and an environmental matrix including the following variables: depth, DO, temperature, mean length, mean reaction duration, mean reaction time, and percent of each behavior type. Data transformations and their effects on the summary statistics were examined prior to the multivariate analysis by comparing row and column skewness and coefficient of variation (CV) before and after data transformation (McCune and Grace 2002). Abundance data were natural log-transformed and rare species removed from the analysis (those which only occurred once), which greatly reduced row and column skewness and coefficient of variation (CV). Nonmetric Multidimensional Scaling (NMS; Kruskal 1964) was used to run an ordination of sample stations in species space to compare community composition at the various sample stations relative to the measured environmental variables. We used the Sorensen distance measure because it is less sensitive to outliers than some other distance measures. With NMS, the best solution for the ordination is defined by a particular starting configuration and number of dimensions. The NMS procedure uses an iterative search for the best possible positions of *n* entities on *k* dimensions, which minimizes the stress of the dimensional configuration (McCune and Grace 2002). To evaluate whether NMS extracted stronger axes than would be expected by chance, PC-ORD uses a randomization (Monte Carlo) procedure. PC-ORD performs runs with randomized data by shuffling the data from the main matrix and each run uses a different ran-

dom starting configuration. A “run” consists of a series of solutions, stepping down in dimensionality from the highest number of axes to one axis. The *p*-values of this test are calculated as the proportion of randomized runs with stress less than or equal to the observed stress. The dimensionality of the ordination is then evaluated by comparing the results of the NMS runs using real data to the results obtained using the Monte Carlo simulations with randomized data. Relationships between environmental variables and ordination scores are shown as a joint plot in which the angle and length of the lines indicate the direction and strength of the relationship. In order to test for differences in species composition between depth categories, we used a multiresponse permutation procedure (MRPP) (Mielke and Berry 2001; McCune and Grace 2002; Reese and Brodeur 2006).

## RESULTS

### Description of Habitat Characteristics

During the sampled period, hypoxic conditions occurred prevalently at the deeper sampling sites of our study area, while the shallower sites were characterized by high variability of DO values. At MB 30 for example, DO ranged from 1.99 to 8.11 ml l<sup>-1</sup>, while the range of DO concentrations became smaller and less variable with increasing station depth (fig. 3). We have questioned the validity of the highest DO value of at MB 30, because it appeared unrealistically high for this location and time of the year. However, the highest (8.11 ml l<sup>-1</sup>), lowest (1.11 ml l<sup>-1</sup>) and second lowest (1.30 ml l<sup>-1</sup>) DO values of our records were all measured on the same day—August 11, 2008, suggesting that an instrument malfunction was unlikely. On that day, the area close to shore was well mixed as indicated

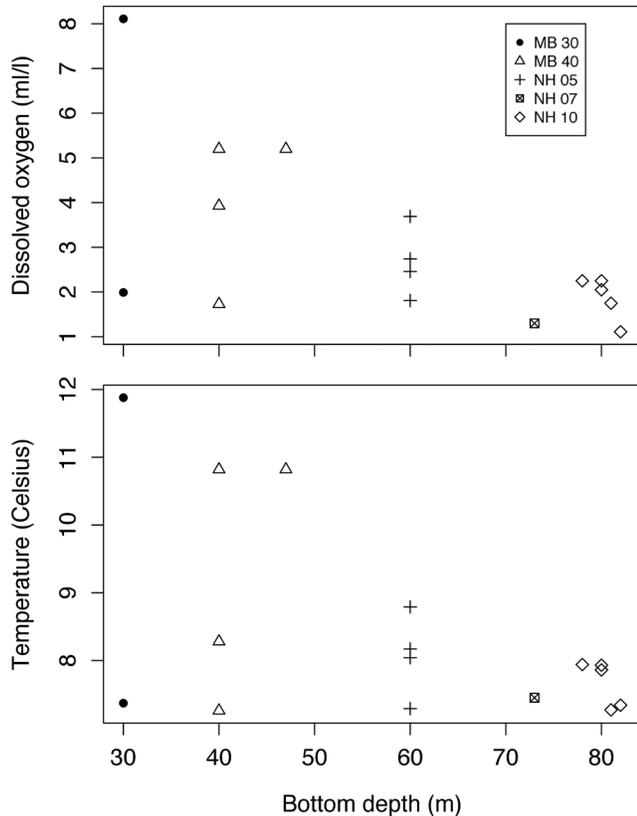


Figure 3. Dissolved oxygen concentration (top panel) and water temperature (bottom panel) measured just above the seafloor at each station (MB 30, MB 40, NH 05, NH 07 and NH 10) prior to towing the beam trawl.

by uniform temperature and salinity profiles at MB 30, while the area offshore was highly stratified. Thus, these extremes of DO values are likely the result of different hydrographic regimes of the coastal versus deeper sampled areas. At MB 30 bottom temperature ranged from 7.37 to 11.88°C, representing the largest difference in temperature of 4.51°C (fig. 3). The range and variability in temperature also decreased with depth at MB 30, MB 40, NH 05, and NH 10 (4.51°C, 3.56°C, 1.50°C, 0.67°C, respectively). Water temperature and DO were positively correlated ( $R^2 = 0.917$ ,  $p$ -value  $\ll 0.001$ ,  $n = 16$ ).

### Description of the Species Composition from the Catch Data

Flatfish species assemblages changed with the increasing of depth. At Moolack Beach (MB 30 and MB 40) the assemblage was primarily composed of English sole, speckled sanddab (*Citharichthys stigmaeus*), butter sole, and Pacific sanddab. The flatfish community composition on the deeper NH line was primarily composed of Pacific sanddab, speckled sanddab, English sole, and Dover sole (*Microstomus pacificus*) in order of decreasing abundance (table 2).

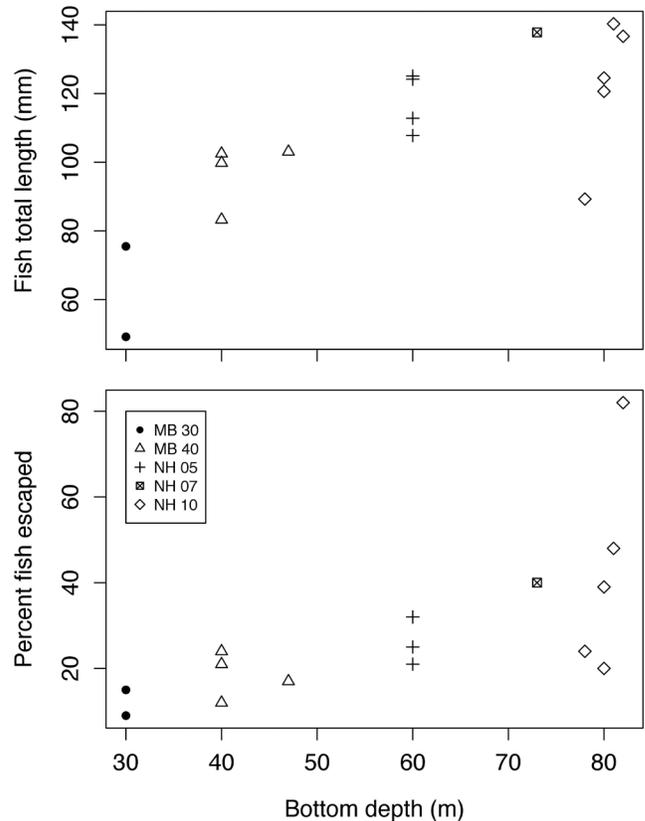


Figure 4. Fish total length (mm) and percentage of fishes escaped at each station (MB 30, MB 40, NH 05, NH 07, and NH 10). Fish total length is measured to the nearest 10 mm using scaled laser beams from video frames and it includes all fishes, not only the juvenile portion. Fishes that escaped the beam trawl were also assessed from inspection of the video frames.

### Description of Species Abundance and Size from the In Situ Video Observations

The abundance of flatfishes obtained from in situ video analysis was from 145.8 to 335.9% greater than that measured from the net data (table 2), indicating that many of the fishes that were detected in the video escaped the net. From the analysis of the video data, the average number of all flatfishes observed, standardized by effort, was highest at MB 40 (14.31 fish min<sup>-1</sup>) and decreased with depth in stations equal to and greater than 40 m. The smallest number of flatfishes was observed at NH 10 (4.04 fish min<sup>-1</sup>, table 2). The only significant difference in the number of fishes was observed between MB 40 and NH 10 ( $p = 0.05$ , Tukey HSD).

The average percentage of juveniles ( $\leq 150$  mm) with respect to all flatfishes caught decreased as depth increased from 30 m to 70 m. Interestingly, the percentage of juvenile fishes increased slightly at NH 10 (80 m), indicating the probable existence of deeper juvenile settlement locations for flatfish species that are associated with deeper habitats. MB 30 had the highest average percentage (89.9%) of juvenile fishes caught ( $< 150$  mm) while NH 07 had the lowest (36.8%, table 2). The aver-

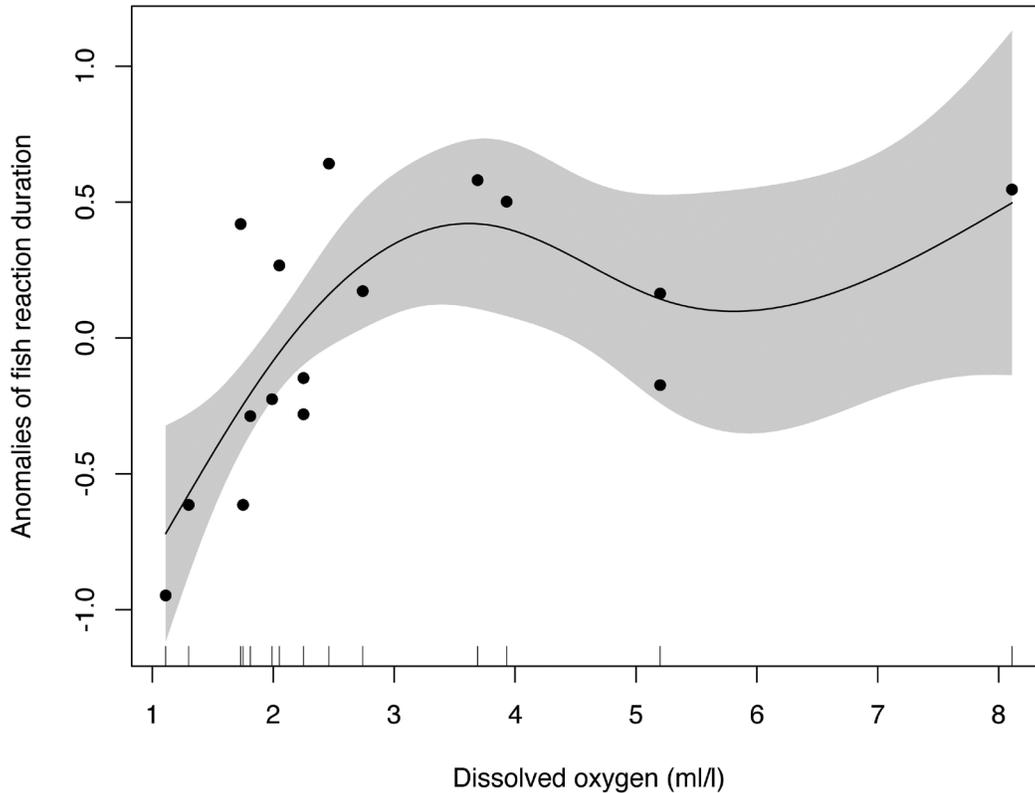


Figure 5. GAM estimated effects of dissolved oxygen (DO ml l<sup>-1</sup>) on average reaction duration (s) of juvenile flatfishes (length ≤ 150 mm) measured from the in situ video observations. The y-axis indicates the magnitude of the effect as anomalies with respect to the overall mean. Shaded regions are the 95% confidence intervals. The “rug” on the x-axis indicates the points at which observations were obtained.

age percentage of juvenile flatfishes at MB 30 was significantly different from NH 07 ( $p = 0.008$ ) and NH 10 ( $p < 0.001$ ) stations and MB 40 was significantly different than NH 07 ( $p = 0.020$ ) and NH 10 ( $p = 0.001$ ). The only significant difference between NH stations was between NH 05 and NH 10, with NH 05 having a greater percentage of juveniles ( $p = 0.020$ ). Average length (mm) of fishes had a positive trend in relation to station depth (fig. 4). The only non-significant difference in average fish size per station were found between NH 05 and MB 40 ( $p = 0.078$ ) and among all pair-wise combinations of station along the NH line.

#### Description of Juvenile Fish Performance and Behavioral Responses from In Situ Video Observations

The escape frequency increased with increased station depth (fig. 4), however, there were not statistically significant differences of escape frequencies among stations (ANOVA,  $p$ -value = 0.141). We compared the size of escaped and captured fishes at each station (two-way ANOVA) and found that the former were significantly larger (13.97 mm,  $p = 0.047$ ) than the latter. Reaction duration for all fishes and reaction time are a mea-

sure of performance. The GAM analysis indicates that the average reaction duration at each station decreased with decreasing DO concentrations ( $p = 0.018$ , fig. 5). A stronger (i.e.,  $p$ -value < 0.05) and positive relationship is found after removing the highest (8.11 ml l<sup>-1</sup>) and second highest (5.20 ml l<sup>-1</sup>) DO observations from the analysis. Average fish size per station did not have a significant effect and was removed from the model at the first iteration. The final fitted model only contained the DO term and explained 52.7% of the variance on a total of 16 stations sampled. However, there was a trend for negative correlation between station DO and average fish size ( $p = 0.065$ ,  $R^2 = 16.7\%$ ), therefore, due to their colinearity, it is not straightforward to disentangle effects of these two variables on fish reaction duration. No significant effects were observed between reaction time and DO concentration even after taking into account the distance from the chain when the fish was first seen. Running and hopping were the two most observed behavior types at all stations (combined 78.6%–90.4%, table 3).

Running was the dominant behavior at station MB 40 (50.9%), NH 05 (53.6%), NH 07 (70.6%), and NH 10 (54.2%). Hopping was the dominant behavior at

TABLE 3  
 Percentage of behavior type (burying, running, hopping, rising, hovering, and no reaction)  
 at stations MB 30, MB 40, NH 05, NH 07, and NH 10.

Station	Burying	Running (R)	Hopping (H)	R+H	Rising	Hovering	No reaction
MB 30	10.5%	37.0%	41.6%	78.6%	5.1%	0.4%	5.4%
MB 40	4.4%	50.9%	37.5%	88.4%	5.6%	0.2%	1.4%
NH 05	1.2%	53.6%	31.7%	85.3%	7.5%	1.6%	4.4%
NH 07	0.0%	70.6%	17.6%	88.2%	11.8%	0.0%	0.0%
NH 10	0.0%	54.2%	36.1%	90.4%	8.4%	0.0%	1.2%

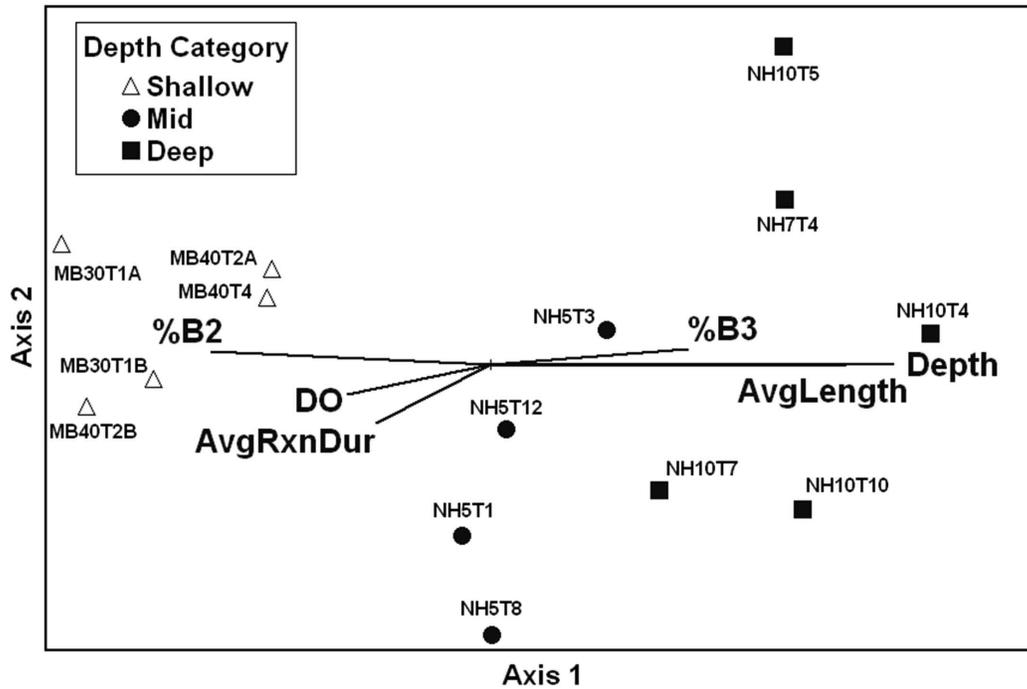


Figure 6. Multivariate analysis comparing the species composition of the catch data to environmental conditions (stress = 9.10). Behavioral values were added to the environmental matrix (B2 is burying and B3 is running). Stations were named using station names (MB 30, MB 40, NH 05, NH 07, and NH 10) and tow (T) number. DO: dissolved oxygen (ml l<sup>-1</sup>).

MB 30 (41.6%). Burying occurred only at stations MB 30, MB 40, and NH 05 (table 3). Hovering was the least common behavior and only observed at mid depth (NH 05).

The non-metric multidimensional scaling (NMS) ordination of the catches data revealed three distinct species assemblages separated by depth (fig. 6). Most of the variance in the community composition was captured by two dimensions containing 78.8% and 11.6%, respectively, of the information in the analytical data set (cumulative for the two-dimensional solution = 90.5%; stress = 9.10). The three community groups suggested by the ordination analysis were tested for similarity between the depth categories as indicated in Figure 6 with a multi-response permutation procedure (MRPP). Results from the MRPP analysis found high within-group agreement ( $A = 0.36, p < 0.001$ ). In community ecology, values for  $A$  are commonly below 0.1, so an  $A > 0.3$  is determined to be high (McCune and Grace 2002).

These results indicate that community composition varied between the three depth categories. English sole, speckled sanddab, and butter sole dominated numerically at the shallower Moolack Beach stations. Along the NH stations, Pacific sanddab dominated numerically, however, flatfish diversity was generally higher at the shallower NH 05 station than further offshore at the NH 07 and NH 10 stations (table 2).

Of the variables measured several showed strong levels of correlation to axis 1, depth ( $r^2 = 0.929$ ), average fish length ( $r^2 = 0.818$ ), DO concentration ( $r^2 = 0.329$ ), and average reaction duration ( $r^2 = 0.264$ ) (fig. 6). Thus, community composition was found to vary with geographic location of the sampled stations and the environmental characteristics occurring within these areas. In addition, average fish length increases with increasing depth whereas DO concentration decreases. The deepest stations (NH 07 and NH 10) have larger fishes and lower DO concentrations.

A relationship between the community composition found at the shallowest depths and burying was observed ( $r^2 = 0.645$ ) (B2 in fig. 6). This behavior was primarily noted at stations off Moolack Beach (table 3). At the deepest stations (NH 07 and NH 10), a relationship was found between the flatfish community composition and running ( $r^2 = 0.455$ ) (B3 in fig. 6) indicating that species in this community tended to run when disturbed rather than bury as the species did in shallower locations at Moolack Beach (table 3; fig. 6).

## DISCUSSION

From the analysis of the in situ video, we have quantified a number of fish performance and behavioral metrics that correlated with water hydrographic properties and species community composition. Because behavior is likely the first trait affected by adverse environmental conditions, we were particularly interested in relating the in situ behavioral response of fishes to DO. Indeed, results from previous laboratory studies indicate that fishes exposed to hypoxia encounter changes in behavior (i.e., panic swimming, reduced spontaneous activity, and paralysis) (Dalla Via et al. 1998; Brady and Targett 2010), in turn affecting predator-prey interactions (Tallqvist et al. 1999), recovery time from exposure to diel-cycling hypoxia (Brady and Targett 2010), and reductions in growth and feeding rates (Stierhoff et al. 2006). However, prior to our work there were no other studies that have looked at the effect of hypoxia on juvenile flatfish species in the nearshore region of the US Pacific coast.

We found that reaction duration, representing the length of time fishes responded to an approaching of the sampling gear, decreased with decreased DO concentration. The effect was particularly strong up to bottom DO concentrations of 3 ml l<sup>-1</sup> and then leveled off. Decreased reaction duration with decreased DO indicates that fishes responded sluggishly at lower levels of DO. The beam trawl is dragged across the seafloor at approximately 0.5–1 knots. This means that fishes that respond sluggishly fall behind the chain quickly and are captured. On the other hand, fishes that respond more energetically have the ability to stay in front of the chain for a longer period of time or outrun the chain and escape. There are at least three potentially interacting reasons that contribute to this result. First, as suggested above, lower DO may cause fishes to reduce the length of their sustained swimming following disturbance. Second, lower reaction duration may be driven by changes in species composition and fish size. We found a clear shift of species assemblages and an increase of fish size with depth where DO levels are lower. However, it is somewhat counterintuitive that increased fish size causes a reduction of reaction duration at low DO

levels, because one would expect that larger fishes are able to perform longer and faster swimming bouts. In our analysis we also found that fish size did not significantly contribute to reaction duration, but fish size and DO are both correlated to depth, so their effect on reaction duration is hard to disentangle. Third, other environmental covariates, in addition to DO, may affect the fish reaction duration. For example, we found that bottom DO was strongly and positively correlated with bottom temperature ( $R^2 = 0.917$ ,  $p$ -value  $\ll 0.001$ )—a result that limits our ability to discern between a DO and a temperature effect on fish behavior.

We found no significant relationship between DO and reaction time (time fish reacted minus time fish was first seen). This neither supports nor rejects the idea that DO affects the ability of juvenile flatfishes to respond to a disturbance. During this study, reaction time ranged from 0–3 seconds and the time the fish was first seen and time the fish first reacted were recorded in one-second increments. This increment may be too limiting, and in future applications it would be more appropriate to use time increments smaller than a second. Other factors to consider are the orientation of fishes to the chain, the direction of the initial response to the disturbance, substrate composition, and whether to redefine the circumstance of initial response time. By redefining the stimuli of an initial response time researchers could take into account circumstances such as fish response to sand plumes generated by sampling equipment and reactions to disturbances by organisms that had previously reacted.

We found differences in juvenile flatfish in situ behavior over the stations sampled. Running and hopping were the two most common behavior types and when combined made up between 78.6% to 90.4% of the observed behaviors at all stations, with increasing percentages toward deeper sites. Because the percentages of fishes that escaped the trawl also increased going offshore, it is clear that running and hopping are effective disturbance avoidance behaviors. Burying on the other hand was only observed at MB 30, MB 40, and NH 05. The multivariate analysis indicated that burying had a strong relationship to the species composition at the shallower stations MB 30 and MB 40. The prevalence of burying at shallow stations may also be related to substrate type, which in this area is dominated by fine sand at depths shallower than 40 m and increases to medium sand for deeper stations. The flatfish communities of the shallower stations were largely composed of small English sole, butter sole, and speckled sanddab in order of dominance.

Besides variations of species composition, we showed that fish size also changed with depth, with the percentage of juvenile fishes being higher at the shallower stations. This trend would suggest a possible nursery role of

inshore locations and an ontogenetic shift toward deeper habitats. While this certainly applies to some of the species we sampled, like English sole (Laroche and Holton 1979; Kryger and Pearcy 1986), it is difficult to conclude that larger individuals of all species move offshore, given that we could not discriminate among species with our video samples. For example, butter sole and speckled sanddab are also abundant at the shallower stations (table 2), but their size does not change in relation to depth (Johnson 2012). It is possible that for these species, shallower habitats (i.e., <30 m) than those sampled here (i.e., >30 m) may serve as nursery habitats. Although not statistically significant from other NH stations, we found that the percentage of juvenile fish decreased slightly at NH 10 compared to NH 07. It is possible that deeper locations may serve as nursery habitats for flatfish species that are deeper in their adult distribution range, such as Pacific sanddab, petrale sole, and Dover sole.

## CONCLUSION

Juvenile flatfishes are an important component of the ecosystem and as they grow into adults and move into deeper waters they become part of the economically important flatfish fishery. The ability for juveniles to escape predation and capture food is key to their survival. If behavioral performance is affected by low DO or temperature values, there can be ecological consequences on the survival of fishes. These effects can be species specific. Benthic species that have low thresholds to DO and experience sublethal effects such as reduced activity (Chabot and Dutil 1999), loss of balance, panic swimming, inactivity, or paralysis (Dalla Via et al. 1998) are consequently vulnerable to predation by species with lower DO thresholds in hypoxic waters (Long and Seitz 2008).

The objective of this study was to examine the feasibility of using an in situ video system and sampling gear to assess behavioral responses of juvenile flatfishes in relation to the physical and chemical properties of the water and the species community composition. We were particularly interested in assessing the responses of juvenile flatfishes to DO concentrations. When looking at the flatfish behavioral metrics we found a positive trend between DO and reaction duration. This result suggests that the ability of juvenile flatfishes to escape predation could be affected by DO concentrations, but this result may be confounded by the covariation of water temperature and species assemblages. Abundance of flatfishes obtained from in situ video analysis was 143% to 322% greater than that measured from the net data (table 2) and has expanded our ability to quantify individual performance and behavioral metrics of juvenile flatfishes. In situ video has proven to be an effective tool to complement trawl survey data (Norcross and Mueter 1999).

The video data allows us to observe greater numbers of organisms and their behavioral responses while the net data provides us with the community composition. An ideal development would be that of identifying species from the video data. However, with the camera system used in this study it was not possible without a considerable margin of error. Newer technologies and higher definition cameras may provide better results. In addition to improved equipment, more data on substrate physical and chemical characteristics could also prove useful in understanding behavioral and abundance metrics of the nearshore flatfishes in relation to hypoxic events. Finally, findings from the analysis of catch data contribute to our current understanding (Pearcy 1978; Toole et al. 2011) of the nearshore juvenile fish assemblages in the Oregon central coast. We have identified clear changes of species assemblages along a depth gradient. Of interest was the fact that while there was a clear trend to larger fishes from inshore to offshore stations, the average size of fishes observed at the deepest station (NH 10) was not the largest. It is possible that deeper locations along the shelf edge may serve as nursery habitats for slope flatfishes like Dover and petrale sole. Our sampling design was developed to monitor coastal habitats, thus additional studies over greater temporal and spatial extent are needed to corroborate this hypothesis and to further characterize the juvenile fish assemblages.

## ACKNOWLEDGEMENTS

This research was sponsored by Oregon Sea Grant under award number NA06OAR4170010, project number R/ECO-23 from the National Oceanic and Atmospheric Administration's National Sea Grant College Program, U.S. Department of Commerce, and by appropriations made by the Oregon State Legislature. The statements, findings, conclusions, and recommendations are those of the authors and do not necessarily reflect the views of these funders. Amy Stinton was funded through the DOD Assure, and NSF. Special thanks goes to three anonymous reviewers for their insightful comments and to Angela Johnson, Natalie Ehrlich, Chris Toole, Cathleen Vestfals, Jason Phillips, Matthew Yergey and Bobby Ireland for intellectual and field support. Cathleen Vestfals and Lorey Stinton developed Figure 1.

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## COMPARISON OF LONG-TERM TRENDS OF ZOOPLANKTON FROM TWO MARINE ECOSYSTEMS ACROSS THE NORTH PACIFIC: NORTHEASTERN ASIAN MARGINAL SEA AND SOUTHERN CALIFORNIA CURRENT SYSTEM

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### ABSTRACT

Long-term trends of zooplankton biomass (1968–2009) and major zooplankton taxa (1978–2009) were examined across the North Pacific in the Northeastern Asian Marginal Sea (NeAMS) and the Southern California Current System (SCC) to test for evidence of basin-scale synchrony. Zooplankton biomass showed contrasting long-term patterns in the two regions: an increasing trend (as wet mass) in the NeAMS, but a decreasing trend (as displacement volume) in the SCC. Zooplankton biomass covaried with the Pacific Decadal Oscillation in the NeAMS, but with the North Pacific Gyre Oscillation in the SCC. In the NeAMS, increasing zooplankton biomass was closely associated with increases of all major zooplankton groups (copepods, chaetognaths, euphausiids, and hyperiid amphipods). In the SCC, decreasing zooplankton biomass was caused by declining tunicates and chaetognaths. Seasonal cycles and responses to El Niño also differed between the two regions. In this cross-basin comparison, zooplankton showed differing patterns that reflect region-specific physical and biotic processes rather than synchronous responses to large-scale atmosphere-ocean forcing.

### INTRODUCTION

Climate change has begun altering ecosystems on a global scale (IPCC 2013). Atmosphere-ocean interactions alter sea surface temperature, calcium carbonate saturation, dissolved oxygen concentrations, ocean circulation, nutrient supply, sea level, and other properties, leading to changes of marine ecosystems in various ways. In addition, relatively abrupt changes in marine ecosystems in response to climate variables have been reported from a number of regions (Hare and Mantua 2000; Rebstock and Kang 2003; Hunt et al. 2008; Drinkwater et al. 2009), although the mechanisms underlying these changes are under discussion (Bestelmeyer et al. 2012; Di Lorenzo and Ohman 2013).

The North Pacific experiences large-scale atmosphere and ocean forcing on various timescales, including the Pacific Decadal Oscillation (PDO), the North Pacific Gyre Oscillation (NPGO), and El Niño-Southern Oscil-

lation (ENSO; Mantua et al. 1997; Di Lorenzo et al. 2008). However, the same large-scale forcing may impact geographically separated regional ecosystems in different ways. In a comparative study of four marine ecosystems (two in the Pacific and two in the Atlantic Ocean), the four systems revealed similar patterns of variability in adjacent regions or subregions, but little similarity across the Atlantic or between high latitude regions in the Atlantic and Pacific (Drinkwater et al. 2009).

Within the North Pacific, the eastern Bering Sea and Gulf of Alaska show warming coupled with the Pacific Decadal Oscillation (PDO; Drinkwater et al. 2009) and altered marine ecosystems consistent with the timing of change of sign of the PDO (Hare and Mantua 2000; Benson and Trites 2002). On the other hand, in the southern California Current, Lavaniegos and Ohman 2007 showed that zooplankton were markedly affected by El Niño and La Niña, but apart from a long-term decline in pelagic tunicates (especially salps), these authors did not detect long-term trends in aggregated biomass in response to climate shifts (cf., McGowan et al. 2003). At the species level, Brinton and Townsend 2003 and Di Lorenzo and Ohman (2013) working with euphausiids, Keister et al. 2011 and Bi et al. 2012 with copepods, and Ohman et al. 2012 with stable *N* isotopes of selected zooplankton species have suggested zooplankton responses to PDO-related climate forcing in the North Pacific. In the western North Pacific, changes in the Oyashio Current and the Tsushima Warm Current regions have been associated with changes in ecosystem conditions (Rebstock and Kang 2003; Sakurai 2007; Kang 2008). Di Lorenzo et al. 2013 illustrate how regional forcing can differentially influence zooplankton populations in the Kuroshio-Oyashio-Extension region and the California Current System.

Contrasting with these regional ecosystem responses to regional physical forcing is the apparent basin-scale synchrony in fluctuations in biomass of some clupeoid fishes. Kawasaki 1983, Lluch-Belda et al. 1992, Schwartzlose et al. 1999, Alheit and Bakun 2010 and others have called attention to the apparent in-phase variations of geographically separated populations of small, epipe-

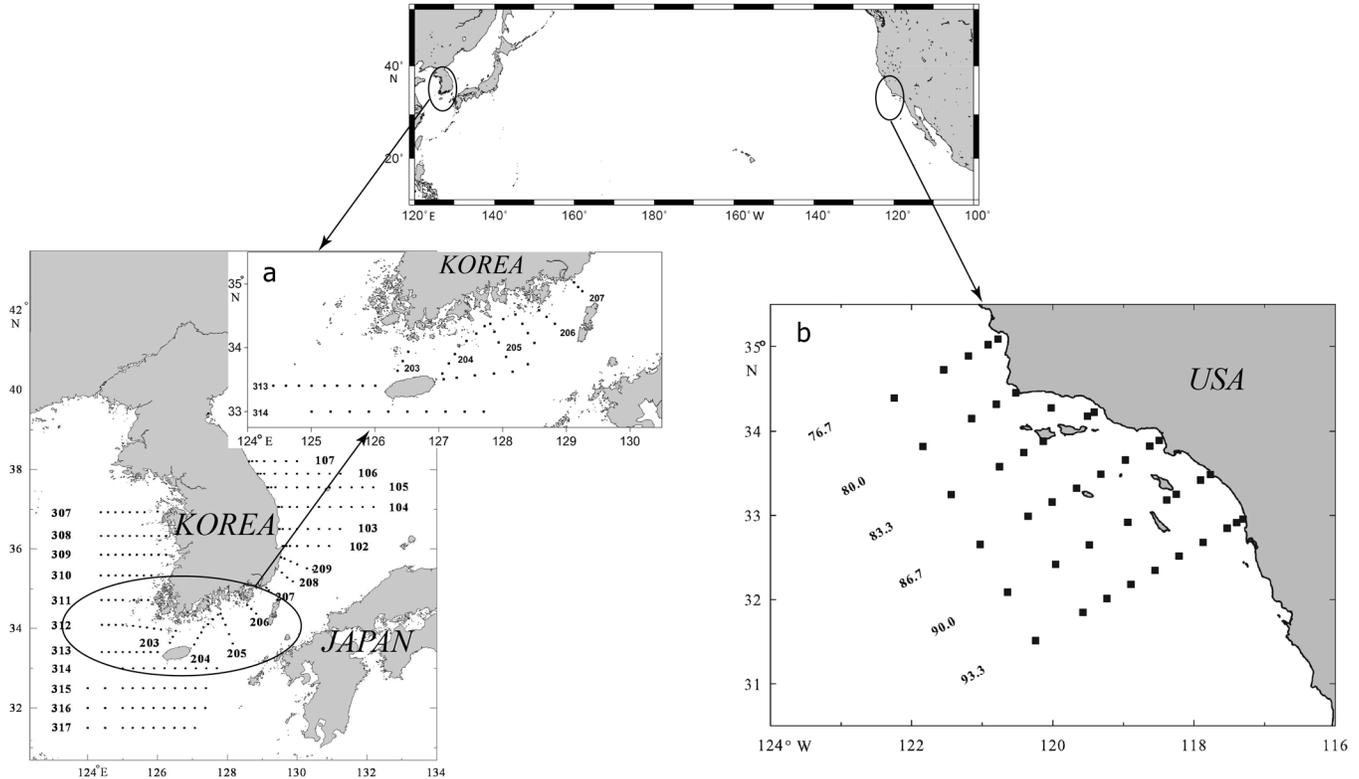


Figure 1. Research regions: the Northeastern Asian Marginal Sea (NeAMS) and the Southern California Current System (SCC), and sampling stations considered in this study: (a) NeAMS and (b) SCC.

lagic planktivorous fishes. Sardine populations off the coast of California and Japan, for example, are thought to vary in-phase with one another (Lluch-Belda et al. 1992), in relation to climate forcing (Hollowed et al. 2001). If planktivorous fishes exhibit such synchrony, this leads to the question whether their zooplanktonic prey do as well. Perry et al. 2004 could not identify rigorous and statistically robust global synchronies of zooplankton from multiple sites in several ocean basins. Mackas and Beaugrand 2010 suggested, based on preliminary data, that there might be significant synchrony in decadal variations of zooplankton among regions and across ocean basins, but not globally. The more comprehensive results of Batchelder et al. 2012 suggest there may be synchronous zooplankton biomass and/or abundance fluctuations at scales up to ca. 1000–3000 km, but that the synchronous patterns observed in the sardine and anchovy are unlikely connected with lower trophic level production (e.g., zooplankton biomass/abundance). However, while Batchelder et al. 2012 presented metrics of bulk zooplankton biomass, they did not analyze variations in any of the constituent zooplankton taxa.

Here we were motivated by the result of synchrony of small clupeoid fishes like sardines across the North Pacific to address the extent to which mesozooplankton on the western and eastern sides of the North Pacific

might also show common (or different) responses. We sought to conduct a comparative study between Korean coastal waters and the southern California Current System to improve our ability to understand, predict, and prepare for the expected large-scale variations in the atmosphere–ocean forcing across the North Pacific basin.

This study focuses on 1) comparing long-term and seasonal variations of zooplankton biomass and major zooplankton taxa with environmental variables from these two regions across the North Pacific, and 2) assessing the extent to which regional or basin-scale processes better account for the variations observed in the mesozooplankton.

## DATA AND METHODS

### Geographical Areas and Hydrographic Characteristics

The Northeastern Asian Marginal Sea, in the western Pacific, is defined as the southern region adjacent to the Korean Peninsula and the northern East China Sea (EC) between approximately 33°–35°N, 124°–130°E (fig. 1a). The Northeastern Asian Marginal Sea (NeAMS) is a representative continental shelf region less than 100 m deep and directly influenced by the Tsushima Warm Current as a branch of the Kuroshio Warm Current.

Low salinity, high turbidity water from the Yangtze River reaches the EC and gradually mixes with the Tsushima Warm Current in the NeAMS (An 1974; Hong et al. 2002). We restricted our analyses to this southern region within the larger survey region analyzed (fig. 1), because of contrasting hydrographic and plankton conditions in the southeastern Yellow Sea and southwestern East/Japan Sea (Kang et al. 2012). The Southern California Current System (SCC) is here defined as the California Current System between approximately 31°–35°N, 117°–122°W, from Point Conception to the border with Mexico (fig. 1b). The SCC includes the southward extension of the California Current proper, the Inshore Countercurrent, and the California Undercurrent (Lynn and Simpson 1987) and the seasonally formed southern California eddy (Checkley and Barth 2009). The continental shelf is narrow (<5–10 km) in most of the region. Wind-driven coastal boundary upwelling and offshore wind-stress curl upwelling are important regional physical characteristics in the SCC. The SCC is often influenced by medium-to-larger ENSO events (Ohman et al. 2012; Ohman et al. 2013).

#### Data

We sought similar data sets in order compare long-term changes of zooplankton in response to physical forcing in both ecosystems. Data were obtained from the Korea Oceanographic Data Center (KODC) in the NeAMS and the California Cooperative Oceanic Fisheries Investigations (CalCOFI) in the SCC.

Although the CalCOFI record extends to 1949, data analyzed were restricted to the time period since 1968 for comparability between the NeAMS and SCC regions. Temperature and salinity data at 10 m depth from 1968 to 2009 were analyzed to remove the transient effects of surface ocean-atmosphere exchange. Near-surface chlorophyll *a* data were available from 1983 in the SCC and 1995 in the NeAMS. Mesozooplankton biomass from 1968 to 2009 was examined from both regions. Total biomass was determined by wet weight in the NeAMS and by displacement volume in the SCC. The abundance of major zooplankton groups from 1978 to 2009 was obtained in the both regions but with a difference in the major zooplankton groups analyzed. Microscope enumerations of copepods, hyperiid amphipods, euphausiids and chaetognaths were available in both regions, while tunicates (here the sum of doliolids and salps) were available only in the SCC. Pelagic tunicates are a major zooplankton taxon in the SCC, but less so in the NeAMS. There were differences in collection methods of zooplankton and estimation of zooplankton biomass. Zooplankton were sampled vertically in the NeAMS with a NORPAC net (0.45 m diameter ring net with 0.33 mm mesh) from 100 m to

the surface, bottom depth permitting, otherwise from near-bottom depths to the surface. In the SCC, zooplankton were sampled with a double oblique tow with a 1 m diameter ring net with 0.55 mm mesh from 140–0 m from 1951 to 1968, a 1 m diameter ring net with 0.505 mm mesh from 210–0 m from 1969–77, and a 0.71 m diameter bongo net with 0.505 mm mesh from 210–0 m depth after December 1977 (Ohman and Smith 1995).

In the NeAMS, zooplankton biomass was calculated by wet weight, following exclusion of large organisms >3 cm in size and extraction of excess water with filter paper. In the SCC the wet displacement volume was determined after removal of large (>5 mL individual biovolume) organisms. Displacement volume can give different results from carbon biomass, especially when pelagic tunicates are prevalent (Lavaniegos and Ohman 2007), but we analyze displacement volume here for comparability with the NeAMS region. To intercompare methods between the SCC and NeAMS, both wet weight and displacement volume were determined for 50 samples taken in the NeAMS region in October 2009, using the CalCOFI methodology for the latter. The resultant average density of the zooplankton was 1.25 g mL<sup>-1</sup>, which is reasonable for preserved zooplankton and provides an approximate measure of comparability between methods.

Data from February, April, August, and October were used as the representative of each season in the NeAMS, while means were calculated from March–May, June–August, September–November, and December–February in the SCC. There were limited data in some months, so we used means over three months closely related to each season in the SCC. For comparison of numerical abundances of zooplankton taxa in the two regions, only spring data were used because these provide the most complete record and best interannual coverage. The spatial coverage was limited to the region described in Figure 1b and analyzed by Lavaniegos and Ohman 2007. Spring is an important time period for fish spawning in both regions.

#### Data Analysis

Zooplankton biomass and abundances of major zooplankton groups were log<sub>10</sub> transformed. The annual mean was determined from the data averaged in each season. If there were no data in a particular season, the annual mean was not calculated. Anomalies of temperature, salinity, and zooplankton biomass from mean values for 1968–2009 were standardized by dividing by the standard deviation of the long-term mean. Anomalies of major zooplankton groups were calculated relative to the mean during 1978–2009, because taxonomic data were not available from the NeAMS for earlier years.

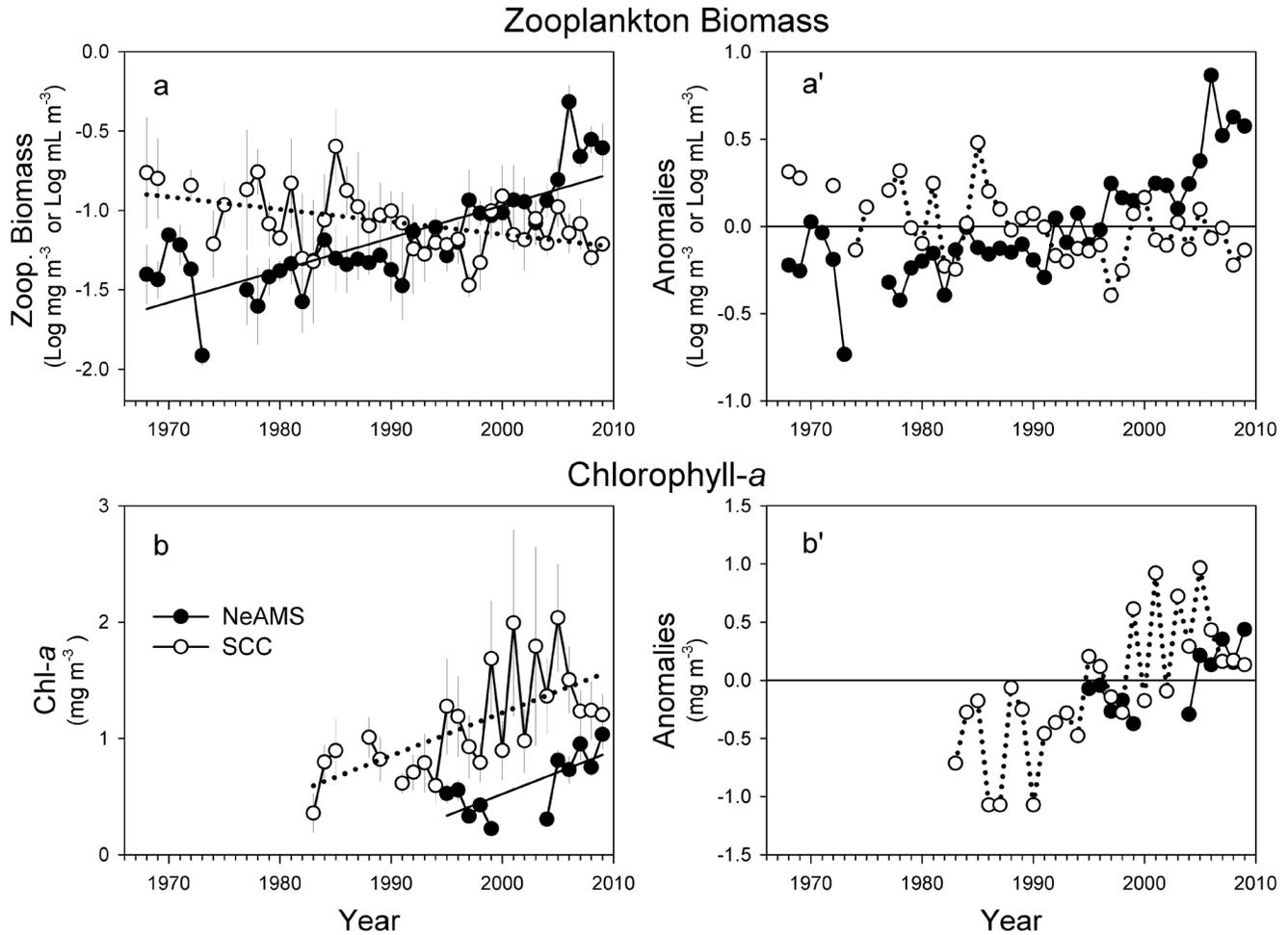


Figure 2. Time series of annual mean of log<sub>10</sub>-transformed zooplankton biomass and chlorophyll a, and their normalized anomalies in the Northeastern Asian Marginal Sea (NeAMS, filled symbols) and the Southern California Current System (SCC, open symbols). (a) Zooplankton biomass (NeAMS:  $r^2 = 0.624$ , SCC:  $r^2 = 0.228$ ,  $p < 0.01$ ), (a') normalized zooplankton biomass anomalies, (b) chlorophyll a (NeAMS:  $r^2 = 0.519$ , SCC:  $r^2 = 0.422$ ,  $p < 0.05$ , and (b') chlorophyll a anomalies. Error bars in this and subsequent figures indicate 95% confidence limits.

Linear regression analyses fitted by the ordinary least squares method were carried out to analyze temporal trends. No correction was made for autocorrelation because the data are annual and essentially independent. To identify long-term trends of covarying major zooplankton groups, Principal Components Analysis was carried out with spring mean data, including tunicates in the SCC. Correlation analysis was conducted with Spearman rank correlations. We chose not to apply the Bonferroni correction for multiple testing, as this is an exceedingly conservative criterion that can increase the probability of Type II error.

## RESULTS

### Long-term Trends

**Zooplankton biomass** The time series of the annual mean of zooplankton biomass revealed an obvious contrast between the two regions (figs. 2a, a'). The

NeAMS showed a significant increasing trend ( $r^2 = 0.624$ ,  $p < 0.001$ ), with a decreasing trend in the SCC ( $r^2 = 0.228$ ,  $p < 0.01$ ). In the NeAMS, zooplankton biomass increased sharply after the early 1990s compared to prior years. Zooplankton biomass was initially lower in the NeAMS than in the SCC, but this pattern reversed in the 2000s (figs. 2a, a'). In comparing biomass values, it must be recalled that the sampling and biomass determination methods were different. In the SCC, declines in annually averaged zooplankton biomass were found for the strongest El Niños (1972–73, 1982–83, 1991–92, 1997–98, 2003–04,  $P < 0.05$ , Mann-Whitney U test; fig. 2a') but these El Niño-related decreases reversed within one to two years. In the SCC, biomass increased abruptly in the La Niña of 1999, but thereafter continued a slow rate of decline. In the NeAMS there was no consistent response of zooplankton biomass to the strongest El Niños ( $p > 0.50$ ). Over the entire time series, there was an inverse corre-

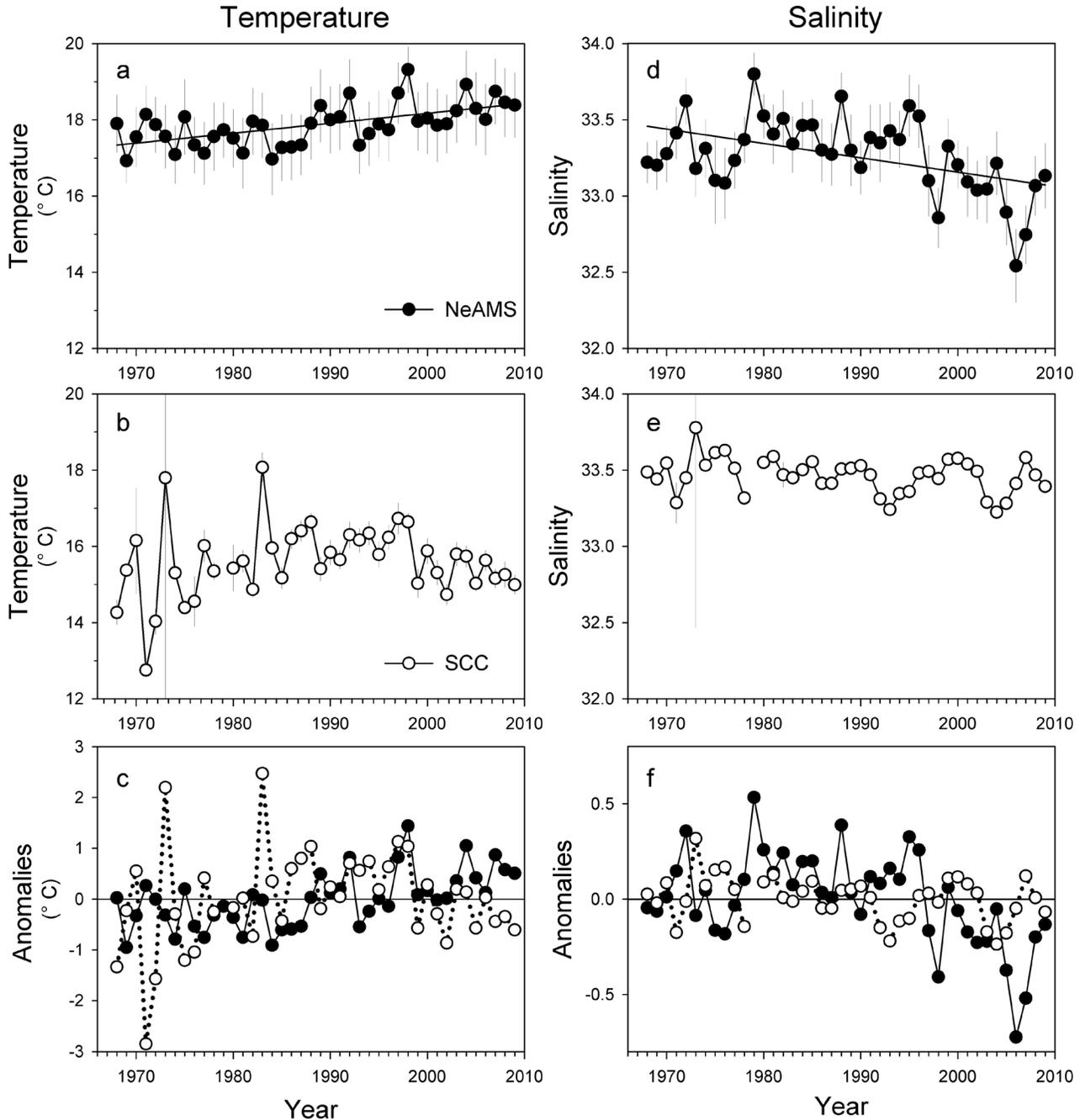


Figure 3. Time series of annual mean of temperature and salinity, and their normalized anomalies in the Northeastern Asian Marginal Sea (NeAMS, filled symbols) and the Southern California Current System (SCC, open symbols). (a) Temperature (NeAMS:  $r^2 = 0.342$ ,  $p < 0.001$ ), (b) Temperature (SCC:  $r^2 = 0.022$ ,  $p > 0.3$ ), (c) NeAMS and SCC temperature anomalies, (d) Salinity (NeAMS:  $r^2 = 0.221$ ,  $p < 0.01$ ), (e) Salinity (SCC:  $r^2 = 0.091$ ,  $p > 0.05$ ), and (f) NeAMS and SCC salinity anomalies.

lation of biomass between the two regions ( $r = -0.430$ ,  $p < 0.01$ ), however, once the linear trend in both regions is removed there is no remaining correlation of the residuals ( $p > 0.50$ ).

**Chlorophyll a** Chlorophyll *a* concentrations were consistently higher in the SCC than the NeAMS (fig. 2b). Annual mean chlorophyll *a* data were very limited for comparisons between regions, but they generally showed increasing trends in both (figs. 2b,b'; NeAMS:  $r^2 = 0.519$ ,

SCC:  $r^2 = 0.422$ , both  $p < 0.05$ ). Chlorophyll *a* concentrations were uncorrelated in the two regions, both before and after removal of the linear trend ( $p > 0.10$ ).

**Temperature** Mean annual temperature was usually higher in the NeAMS than in the SCC (fig. 3a,b). The long-term annual mean of temperature increased somewhat in the NeAMS (figs. 3a,c;  $r^2 = 0.342$ ,  $p < 0.001$ ), while no detectable trend was found in the SCC (figs. 3b,c;  $r^2 = 0.022$ ,  $p > 0.30$ ). Intrannual tempera-

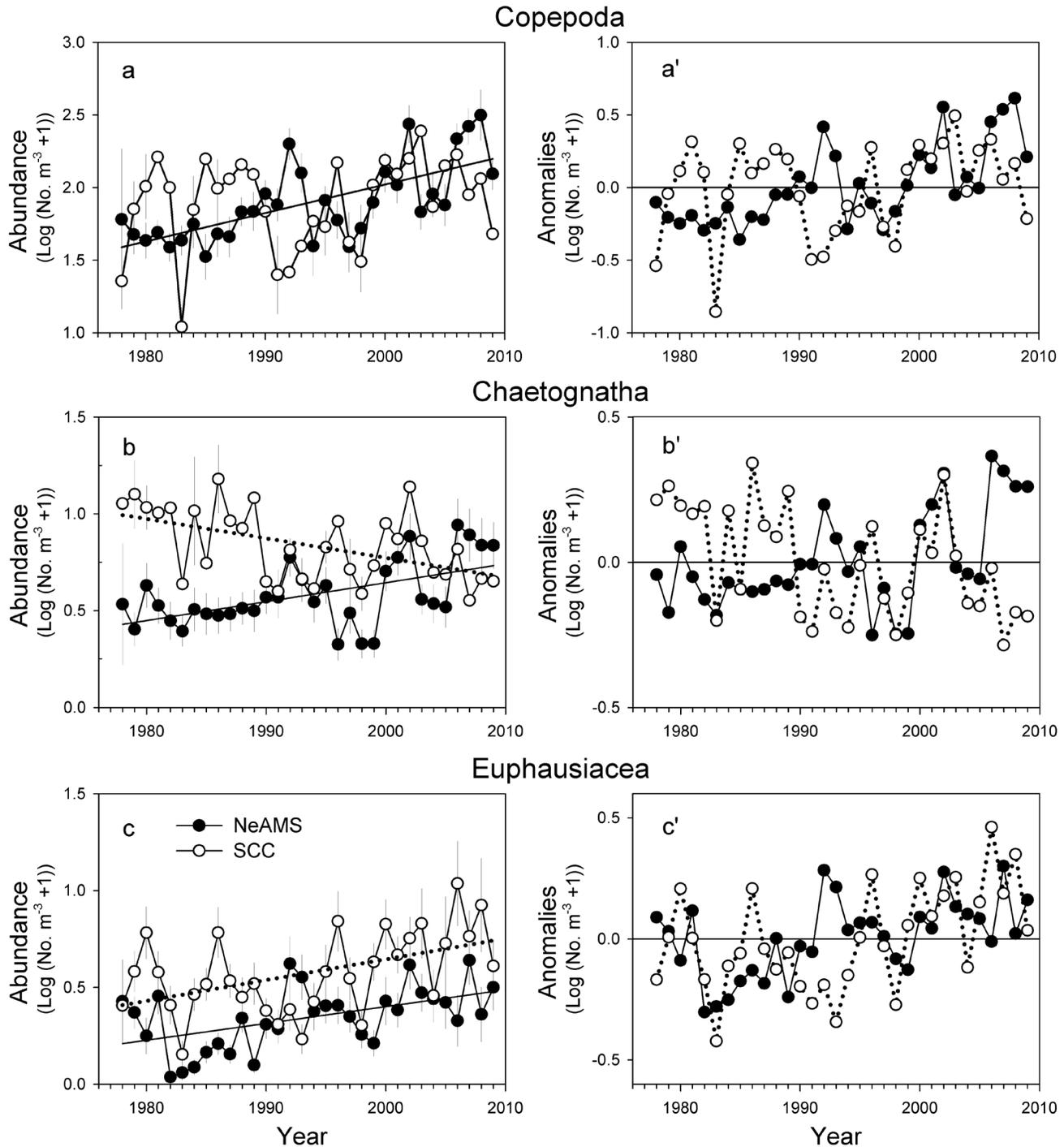


Figure 4. Time series of annual mean of log<sub>10</sub>-transformed abundance of zooplankton groups and their anomalies in the Northeastern Asian Marginal Sea (NeAMS, filled symbols) and the Southern California Current System (SCC, open symbols). (a) Copepoda (NeAMS:  $r^2 = 0.463$ ,  $p < 0.001$ ; SCC:  $r^2 = 0.063$ ,  $p > 0.10$ ), (a') Copepoda anomalies, (b) Chaetognatha (NeAMS:  $r^2 = 0.291$ , SCC:  $r^2 = 0.257$ ,  $p < 0.01$ ), (b') Chaetognatha anomalies, (c) Euphausiacea (NeAMS:  $r^2 = 0.256$ ,  $p < 0.01$ ; SCC:  $r^2 = 0.230$ ,  $p < 0.01$ ) and (c') Euphausiacea anomalies.

ture variability was higher in the NeAMS than in the SCC (fig. 3a,b).

**Salinity** Salinity was generally lower in the NeAMS than in the SCC (fig. 3d,e). Annual mean salinity revealed a significant decreasing trend in the NeAMS (figs. 3d,f;  $r^2 = 0.221$ ,  $p < 0.01$ ), but no significant trend in the

SCC (figs. 3e,f;  $r^2 = 0.091$ ,  $p > 0.05$ ). Intrannual salinity variability was higher in the NeAMS than in the SCC (fig. 3d,e). Neither temperature nor salinity, nor the residual of these variables after removing the long-term trends, were correlated between the NeAMS and the SCC ( $p > 0.10$ ).

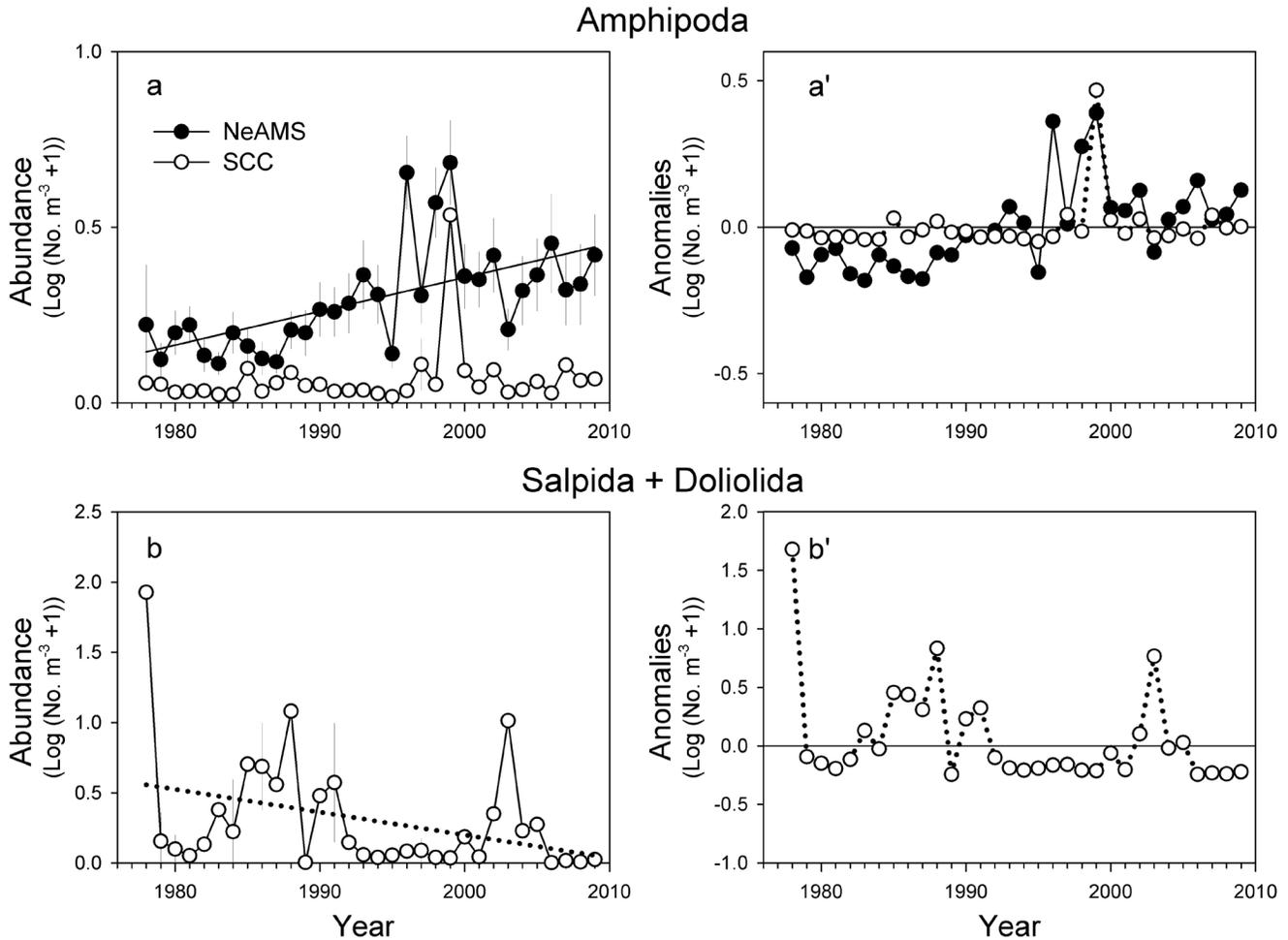


Figure 5. Time series of annual mean of  $\log_{10}$ -transformed abundance of zooplankton groups, and their anomalies in the Northeastern Asian Marginal Sea (NeAMS, filled symbols) and the Southern California Current System (SCC, open symbols). (a) Amphipoda (NeAMS:  $r^2 = 0.372$ ,  $p < 0.001$ ; SCC:  $r^2 = 0.034$ ,  $p > 0.30$ ), (a') Amphipoda anomalies, (b) Tunicata (SCC:  $r^2 = 0.134$ ,  $p < 0.05$ ) and (b') Tunicata anomalies.

**Zooplankton groups** The long-term mean abundance of copepods was generally similar in both regions (figs. 4a,a'). The mean abundance of copepods in spring increased from 1978 to 2009 in the NeAMS ( $r^2 = 0.463$ ,  $p < 0.001$ ) but not in the SCC ( $r^2 = 0.063$ ,  $p > 0.10$ ). Interannual variations were largely independent in both regions during 1978–97 but became somewhat more correlated after 1998 (fig. 4a').

The time series of chaetognath abundance showed contrasting trends between regions (figs. 4b,b'). Abundance increased over time in the NeAMS ( $r^2 = 0.291$ ,  $p < 0.01$ ), but decreased in the SCC ( $r^2 = 0.257$ ,  $p < 0.01$ ). Chaetognaths showed elevated abundance in 2002 in both regions, while in the SCC, a similar high abundance was found in 1986. The long-term mean of chaetognath abundance was usually higher in the SCC than the NeAMS, but approached a similar mean in both regions at the end of 2008.

The mean abundance of euphausiids was consistently higher in the SCC compared to the NeAMS

and showed increasing trends in both the NeAMS ( $r^2 = 0.256$ ,  $p < 0.01$ ) and the SCC ( $r^2 = 0.230$ ,  $p < 0.01$ , figs. 4c,c').

Hyperiid amphipods were more abundant in the NeAMS, in particular after the late 1980s compared to the long-term mean (figs. 5a,a'). They showed an increasing trend in the NeAMS ( $r^2 = 0.372$ ,  $p < 0.001$ ) but not in the SCC ( $r^2 = 0.034$ ,  $p > 0.30$ ). High positive anomalies were found in 1993, 1996, 1998–99, 2002, and 2006 in the NeAMS, and in 1999 in the SCC.

Tunicates (Doliolida+Salpida) showed a slightly decreasing trend ( $r^2 = 0.134$ ,  $p < 0.05$ ), and showed low abundance continuously after 1992, except around 2003 (figs. 5b,b').

None of the four taxonomic groups analyzed in both regions showed correlations between regions, either before or after removal of long-term trends ( $p > 0.05$ ).

**PCA** Principal Component Analysis was used to identify dominant modes of community structure of major zooplankton groups. The 1st and 2nd principal

TABLE 1  
**Eigenvectors of 1st and 2nd principal components  
 in the Northeastern Asian Marginal Sea (NeAMS)  
 and the Southern California Current (SCC).**

	TWC		SCC	
	PC 1	PC 2	PC 1	PC 2
Copepoda	<b>0.762</b>	-0.319	<b>0.608</b>	-0.065
Amphipoda	<b>0.680</b>	<b>0.699</b>	0.266	0.483
Euphausiacea	<b>0.816</b>	0.014	<b>0.576</b>	-0.329
Chaetognatha	<b>0.717</b>	-0.340	0.471	0.084
Tunicata			0.076	<b>0.804</b>
Cumulative variance	55.6%	73.2%	45.3%	70.2%

Boldface indicates values  $> |0.5|$ . Cumulative variance is the cumulative percentage of the total variance explained by PCA.

components (PC 1 and PC 2) calculated from the matrix of spring means of major zooplankton groups explained 73.2% of the total variance in the NeAMS and 70.2% in the SCC. In the NeAMS, PC 1 accounted for 55.6% of the variance, and showed a strong positive association with copepods, amphipods, euphausiids, and chae-

tognaths (table 1). PC 2 described 17.1% of the variance, showing a high positive relationship with amphipods. In the SCC, PC 1 accounted for 45.3% of total variance, with high positive loadings on copepods and euphausiids. PC 2 explained 24.9% of the variance, with the highest positive loading on tunicates and weaker loading on amphipods.

The time series of PC 1 showed a statistically significant increasing trend in the NeAMS ( $r^2 = 0.508$ ,  $p < 0.001$ ) with the most notable peaks in 1993 and 2002 (fig. 6a). Conversely, PC 2 decreased over time (fig. 6b,  $r^2 = 0.154$ ,  $p < 0.05$ ). In the SCC, there were no significant temporal trends in either PC1 or PC2 (figs. 6c,d;  $r^2 = 0.022$  and  $0.039$ , respectively,  $p > 0.10$ ).

**Seasonal Variation**

It should be recalled that the availability of data necessitated rather coarse temporal resolution for these seasonal comparisons.

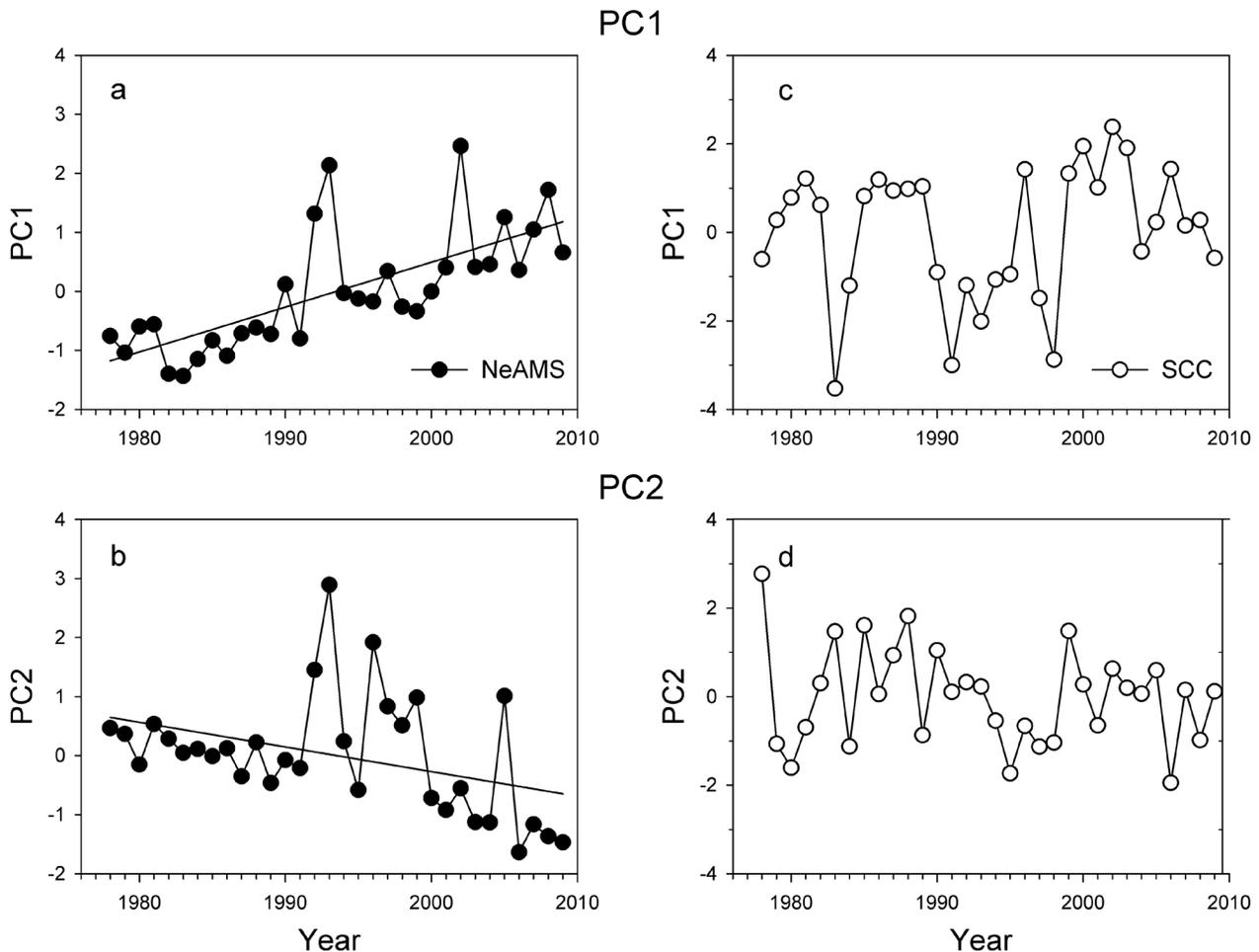


Figure 6. Time series of the 1st and 2nd principal components (PC) in the Northeastern Asian Marginal Sea (NeAMS, filled symbols) and the Southern California Current System (SCC, open symbols). (a) PC1 of NeAMS ( $r^2 = 0.508$ ,  $p < 0.001$ ), (b) PC2 of NeAMS ( $r^2 = 0.154$ ,  $p < 0.05$ ), (c) PC1 of SCC ( $r^2 = 0.022$ ,  $p > 0.10$ ) and (d) PC2 of SCC ( $r^2 = 0.039$ ,  $p > 0.10$ ).

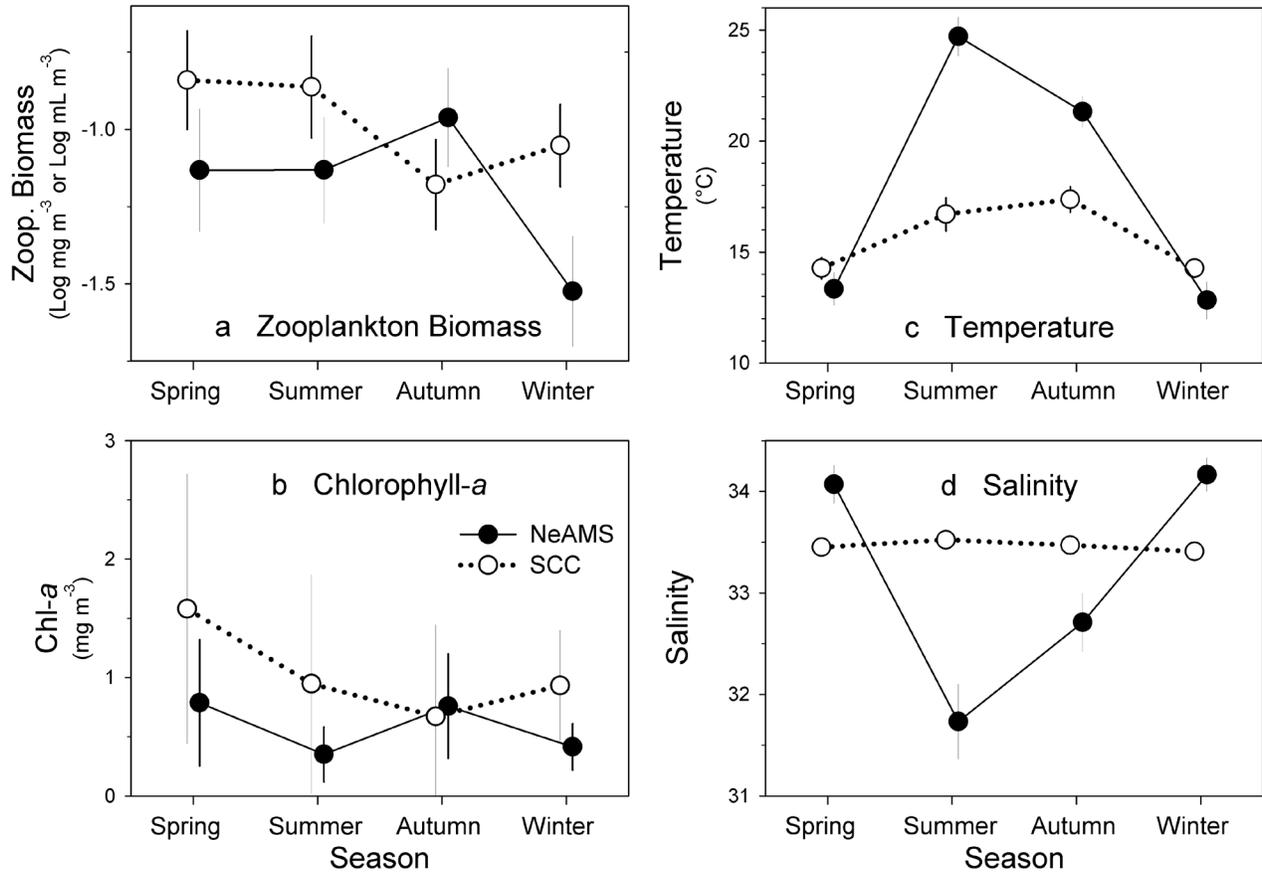


Figure 7. Seasonal variations of (a) zooplankton biomass, (b) chlorophyll a, (c) temperature, and (d) salinity in the Northeastern Asian Marginal Sea (NeAMS, filled symbols) and the Southern California Current System (SCC, open symbols).

**Zooplankton biomass** Zooplankton biomass showed different seasonal cycles with different peaks in the two regions (fig. 7a). A small seasonal peak occurred in autumn in the NeAMS, while the maximum occurred in spring–summer in the SCC. The lowest zooplankton biomass was found in winter in the NeAMS and in autumn in the SCC.

**Chlorophyll a** The seasonal peak of chlorophyll a appeared in autumn and, to a lesser extent, in spring in the NeAMS, while values peaked in spring in the SCC (fig. 7b). The lowest value was found in summer in the NeAMS, but in autumn in the SCC.

**Temperature** There was a substantial seasonal difference in mean temperature in the NeAMS, with a smaller range in the SCC (fig. 7c). The SCC showed similar temperatures between summer and autumn, and spring and winter differed less than 1°C. In contrast, the NeAMS exhibited high differences between spring and summer (11.3°C), and autumn and winter (8.5°C). Seasonal peaks were found in the summer in the NeAMS and in the autumn in the SCC.

**Salinity** Salinities were similar in winter and spring in the NeAMS, but appreciably lower in summer and

autumn (fig. 7d). The SCC showed no detectable seasonal differences.

### Correlation Between Environmental Variables and Zooplankton

**Northeast Asian Marginal Sea (NeAMS)** Total zooplankton biomass exhibited a significant positive correlation with three major zooplankton groups: copepods, chaetognaths, and euphausiids ( $p < 0.05$ , table 2). Of the environmental variables, biomass showed a significant negative correlation with the PDO and positive correlation with temperature ( $p < 0.05$ ).

Copepods were closely positively related with chaetognaths and euphausiids ( $p < 0.05$ ). They were negatively correlated with the PDO as the representative oceanic variable in the North Pacific ( $p < 0.05$ ). Amphipods showed no significant relation with environmental variables, but covaried with euphausiids ( $p < 0.05$ ). Chaetognaths were significantly related to copepods ( $p < 0.05$ ). Similar to amphipods, euphausiids had no significant relations with any of the physical variables, while they were associated with other zooplankton groups.

TABLE 2  
 Correlations (bold values  $p < 0.05$ ) among environmental variables and zooplankton  
 in spring in the Northeastern Asian Marginal Sea (NeAMS).

	Zooplankton biomass	Temperature	Salinity	NPGO	PDO	Copepoda	Amphipoda	Chaetognatha
Temperature	<b>0.545</b>							
Salinity	-0.337	0.081						
NPGO	0.066	0.052	<b>-0.504</b>					
PDO	<b>-0.397</b>	-0.275	0.252	<b>-0.405</b>				
Copepoda	0.430	0.182	-0.340	0.255	<b>-0.374</b>			
Amphipoda	0.332	0.276	0.127	-0.170	0.070	0.322		
Chaetognatha	<b>0.634</b>	0.237	-0.347	0.268	-0.209	<b>0.407</b>	0.320	
Euphausiacea	<b>0.425</b>	0.241	-0.138	-0.119	-0.150	<b>0.516</b>	<b>0.438</b>	<b>0.428</b>

TABLE 3  
 Correlations (bold values  $p < 0.05$ ) among environmental variables and zooplankton  
 in spring in the Southern California Current System (SCC).

	Zooplankton biomass	Temperature	Salinity	NPGO	PDO	Chl. <i>a</i>	Copepoda	Amphipoda	Chaetognatha	Euphausiacea
Temperature	0.063									
Salinity	<b>0.346</b>	-0.261								
NPGO	<b>0.341</b>	-0.222	<b>0.345</b>							
PDO	0.142	<b>0.643</b>	-0.332	-0.212						
Chl. <i>a</i>	-0.030	<b>-0.499</b>	0.039	0.0005	-0.054					
Copepoda	<b>0.424</b>	<b>-0.422</b>	<b>0.410</b>	<b>0.342</b>	-0.060	<b>0.415</b>				
Amphipoda	0.124	<b>-0.447</b>	<b>0.484</b>	0.277	<b>-0.416</b>	0.105	0.162			
Chaetognatha	<b>0.698</b>	0.252	0.091	0.108	0.177	0.023	<b>0.406</b>	-0.081		
Euphausiacea	0.243	<b>-0.491</b>	0.277	0.123	-0.123	<b>0.418</b>	<b>0.694</b>	0.143	0.320	
Tunicata	<b>0.444</b>	0.264	-0.172	-0.004	<b>0.356</b>	-0.085	-0.032	0.008	0.251	-0.267

**Southern California Current (SCC)** Zooplankton biomass was significantly correlated with the NPGO and salinity ( $p < 0.05$ , table 3), but there no relationships were found with temperature and the PDO. Of the biotic variables, copepods, chaetognaths, and tunicates showed significant correlations with zooplankton biomass ( $p < 0.05$ ). In contrast to zooplankton biomass, chlorophyll *a* was inversely associated with temperature among environmental variables, and positively associated with copepods and euphausiids among biotic components ( $p < 0.05$ ).

From the major zooplankton groups, copepods were significantly related with chaetognaths and, especially, with euphausiids ( $r^2=0.694$ ,  $p < 0.05$ ). In addition, copepods were inversely related to temperature and positively related to salinity and the NPGO. Conversely, amphipods did not show any significant relationships with the other zooplankton groups examined in this study. However, they showed significant negative relations with temperature and the PDO, and a positive relation with salinity. Chaetognaths exhibited no identifiable correlations with environmental variables, but they were significantly related to copepods ( $p < 0.05$ ). Euphausiids were negatively related with temperature ( $p < 0.05$ ). Tunicates showed no detectable relations with other zooplankton groups. In terms of the environmental variables, they showed a significant positive relationship with the PDO.

## DISCUSSION

### Contrasting Long-term Changes in Zooplankton Biomass and Major Taxa

Zooplankton biomass in two regions on opposite sides of the North Pacific basin revealed contrasting responses to atmosphere-oceanic forcing and no evidence of in-phase fluctuations over the 40 year period analyzed here. Zooplankton biomass showed an increasing long-term trend in the Northeastern Asian Marginal Sea (NeAMS), with interannual variability related to the PDO, while a decreasing trend was evident in the Southern California Current (SCC), where interannual variability is related to the NPGO. Despite the presence of basin-scale forcing that influences both ecosystems, there were pronounced differences in regional expression of this climate forcing.

Di Lorenzo et al. 2013 illustrate that region-specific transport processes associated with large-scale forcing may influence zooplankton on eastern and western sides of the North Pacific differently. The present results are also in accord with the broader comparisons among many zooplankton time series from diverse ocean regions reported by Batchelder et al. 2012. Those authors reported that zooplankton biomass/abundance have 50% decorrelation length scales of ca. 700–1400 km and scales of significant coherence that extend to separation dis-

tances of ca. 3000 km, although only biomass time series were available for Pacific sites. For comparison, the distance between our two study sites is approximately 9,500 km. Batchelder et al. 2012 also observed low correlations between biomass fluctuations in different sites within the California Current System and sites in the Kuroshio-Transition-Oyashio region off Japan. Our results extend those findings for direct comparison between the SCC and NeAMS, and for key higher taxa of zooplankton taxa (rather than total biomass alone).

Within the California Current System, Mackas et al. 2006 found different responses of both zooplankton biomass and key species groupings to an extreme year of delayed upwelling in the far northern and southern sectors of the California Current System (CCS), separated by ca. 2,250 km. However, on the scale of separation of the southern and central California sectors of the CCS (ca. 400 km), much of the variability in zooplankton higher taxa (Lavaniegos and Ohman 2007) and zooplankton stable *N* isotope content (Ohman et al. 2012) is shared between regions. Of the three seas surrounding the Korean peninsula, the East/Japan and East China Seas showed similar time series of some zooplankton taxa, while the Yellow Sea differed (Rebstock and Kang 2003).

Therefore we do not find evidence from either total zooplankton biomass or abundance of major taxa that could account for the correlated fluctuations of clupeoid fishes across the North Pacific (e.g., Lluch-Belda et al. 1992). Although our study site in the NeAMS is displaced somewhat westward of the locations of catch of Japanese sardine during times of low sardine abundance, during times of high abundance the regions of primary sardine catch overlap our study location off the southern Korean peninsula (Lluch-Belda et al. 1989). Our study site off southern California is a primary site of sardine spawning in the California Current System.

**The NeAMS** In the NeAMS, increased temperature in winter creates early phytoplankton blooms and extends the duration of the phytoplankton outbreak in the East/Japan Sea (Chiba and Saino 2002). Lower salinity indicates elevated river discharge and accompanying dissolved nutrients (Hong et al. 2002) in the East China Sea. Consequently, warmer and less saline waters enhance the production of phytoplankton, thus fostering increased zooplankton biomass. The limited data available suggest chlorophyll *a* increased somewhat in recent years. In addition to total zooplankton biomass, all four major zooplankton taxa increased in abundance, and their correlated responses were corroborated by the consistent high positive loadings of all four taxa on PC 1. Thus, in the NeAMS, zooplankton biomass appears to be controlled from the bottom-up, and closely linked with physical forcing.

The NeAMS is a marginal sea exposed to two dominant currents, the Tsushima Warm Current as a branch of the Kuroshio Warm Current. Plankton variations of the NeAMS are closely related to fluctuations of these currents (An 1974; Hong and Cho 1983). Anomalously high zooplankton biomass can be caused by strong intrusions of the Tsushima Warm Current (Kang and Rebstock 2004). The PDO is closely correlated with characteristic pressure, wind, temperature and precipitation patterns in the North Pacific (Latif and Barnett 1994; Zhang et al. 1997; Mantua et al. 1997). Thus, the PDO is also indirectly or directly connected to the Tsushima Warm Currents, and precipitation. Density stratification is also an important physical variable related to production of phytoplankton and zooplankton in the NeAMS (Chiba and Saino 2002; Chiba et al. 2008; Kim et al. 2007).

**The SCC** In the SCC there were no detectable long-term linear trends in temperature and salinity over the duration of the data analyzed here, even though zooplankton biomass showed a decreasing trend. Lavaniegos and Ohman 2007, who analyzed a longer record from 1951–2005, noted that zooplankton biomass expressed as displacement volume declined because of a long-term decrease in contribution of pelagic tunicates. The decline in displacement volume was not detectable as a change in carbon biomass because of the disproportionate contribution that large, gelatinous tunicates make to displacement volume without corresponding contributions to C biomass (Lavaniegos and Ohman 2007). In that study, the decline in pelagic tunicates was accompanied by a long-term increase in water column stratification, and the species of salps that declined tended to be those introduced into the region from higher latitudes (Lavaniegos and Ohman 2003; 2007). In the present study, both tunicates and chaetognaths showed a long-term declining trend over the shorter period from 1978–2008. The decline in these taxa appears to be dominated by the decreasing contribution of large biovolume zooplankton, in particular salps, although the more recent spring of 2012 was again a period of high salp biomass (Smith et al. 2014).

The relationship between zooplankton displacement volume and the NPGO is evidence that interannual variations in this metric of zooplankton biomass are associated with upwelling in the SCC. The NPGO is related to wind-driven upwelling and horizontal advection, and is related to fluctuations of salinity and nutrients (Di Lorenzo et al. 2008; 2013). Variations in nutrients influence phytoplankton production and then appear to connect to higher trophic levels. Therefore, fluctuations of zooplankton biomass are affected by fluctuations of phytoplankton under the influence of the NPGO.

The correlations observed with copepods suggest they are related to variations in upwelling. Analyses

of fish populations and chlorophyll-*a* calculated with satellite data also suggest that the CalCOFI region is under bottom-up forcing (Ware and Thomson 2005; Rykaczewski and Checkley 2008). Euphausiids were also significantly correlated with chlorophyll *a* and inversely related to temperature.

Amphipods showed significant relations with the PDO, as well as temperature and salinity. Most species of hyperiid amphipods are known to be parasitoids on gelatinous zooplankton hosts (Madin and Harbison 1977; Lavaniegos and Ohman 1999). However, we did not find a relationship between total hyperiids and total tunicates, even though the latter include important host taxa. In contrast, Lavaniegos and Ohman 2007 found significant correlations between total biomass of hyperiids and medusae, salps, doliolids, and physonect+cystonect siphonophores. The differences in findings may be attributed to the longer data record and larger sample sizes in the Lavaniegos and Ohman 2007 study, and to the treatment of salps and doliolids together as tunicates in the present study.

Chaetognaths showed a significant relationship only with copepods in this study. Chaetognaths are known as carnivores mainly feeding largely on planktonic copepods (Feigenbaum and Maris 1984). Thus, the relation between copepods and chaetognaths suggests a prey-predator relationship.

### Variability in Zooplankton

#### Biomass Response to El Niños

The SCC, in particular, shows interannual variability in physical processes associated with specific El Niño events (Lavaniegos et al. 2002; Todd et al. 2011). In the present study, annually averaged zooplankton biomass decreased in strong El Niño events in the SCC, apparently via reduced upwelling and phytoplankton production (Kahru and Mitchell 2000), supplemented by advection of lower biomass subtropical waters in some events (Lavaniegos and Ohman 2007). In the NeAMS, Kang and Rebstock 2004 reported anomalously high zooplankton biomass in 1997 caused by the increase of thaliaceans, especially the warm-water species *Doliolum nationalis*, transported by the Tsushima Warm Current. The present results suggest no consistent response across all El Niño events in the NeAMS.

#### Contrasting Seasonal Cycles

In the NeAMS, the discharge of freshwater from rivers is the most important nutrient source (Hong et al. 2002). Low salinities in summer and autumn, due to heavy rainfall, are associated with the supply of nutrients into the sea. Consequently, phytoplankton increase, and then zooplankton increase. On the other hand, the zooplankton peak was found in spring in the SCC. The

SCC in the southern region of the California Current System is a major region of coastal upwelling, which is closely related to plankton production. The spring peak of zooplankton biomass arises from the main seasonal forcing of coastal and curl-driven upwelling.

Therefore, seasonal variation in zooplankton biomass in the SCC is associated with variations in coastal upwelling, together with regional circulation, while biomass in the NeAMS is linked with large scale currents and river discharge. Biotic and abiotic seasonal cycles are related to different physical processes in the two regions.

### Conclusions

The NeAMS and the SCC experience different regional physical and biotic forcing even though they are exposed to the same large-scale climate forcing. The regionally important physical forcing includes river discharge and large-scale currents in the NeAMS, in contrast to upwelling and large-scale currents in the SCC. The dominant regional physical characteristics associated with variations in total zooplankton biomass are the PDO in the NeAMS and the NPGO in the SCC. There were long-term biomass trends of contrasting signs in the two regions. Zooplankton biomass responses to seasonal cycles showed opposite patterns between the two regions, and El Niño's have a depressive effect on zooplankton biomass in the SCC, but less consistent effects in the NeAMS.

There is no evidence for correlated fluctuations of zooplankton that would account for the coherent variability in clupeoid fishes between the eastern and western North Pacific. More detailed process studies that focus at the species level, rather than aggregated higher taxa of zooplankton, are needed to understand the differential responses of zooplankton between these ocean provinces.

### ACKNOWLEDGEMENTS

We thank the generations of seagoing personnel who have sustained a commitment to data quality in the two field sites studied here. We also thank the anonymous referees for their comments. B. Lavaniegos and A. Townsend contributed to CalCOFI sample analysis. MDO was supported by the U.S. National Science Foundation via the California Current Ecosystem LTER site. A contribution from the SIO Pelagic Invertebrates Collection and the CCE-LTER site.

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## PHYTOGEOGRAPHY ASSOCIATED AT SPECTRAL ABSORPTION SHAPES IN THE SOUTHERN REGION OF THE CALIFORNIA CURRENT

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### ABSTRACT

The phylogeographic association of nano-micro-phytoplankton was characterized during April 2008 in the southern region of the California Current with 21 diatom and 11 dinoflagellate genera. Hierarchization of the diatom community ( $>5 \mu\text{m}$ ) revealed 12 persistent genera throughout the study area. Two bloom events were detected: one in San Quintín Bay dominated by *Eucampia zodiacus* ( $646 \times 10^3 \text{ cells L}^{-1}$ ) and another of lesser intensity off Punta Eugenia dominated by *Pseudo-nitzschia* spp. Both blooms were attributed to upwelling events in the region when the  $25\sigma_\theta$  surface was inclined from between 80 and 30 m. The intrusion of two water masses was observed: high-nutrient low-chlorophyll Subarctic Water, influencing the stations off Ensenada and San Quintín Bay; and California Current water, influencing the stations off Punta Eugenia. The magnitude of the specific absorption coefficient of phytoplankton ( $a_{\text{ph}}^*$ ) showed large variability in the blue Soret band (440 nm), while the blue/red ratio of absorption ( $a_{\text{ph}440}/a_{\text{ph}674}$ ) ranged from 1.7 to 7.4, both with high values at offshore stations. Our  $a_{\text{ph}440}^*$  and b/r ratio results indicated an inverse behavior in the community size distribution. The diatom community ( $>5 \mu\text{m}$ ) showed four phylogeographic provinces with six different pattern curves from normalized spectral absorption shapes ( $a_{\text{ph}n}/440 \text{ nm}$ ). We concluded that the southern region of the California Current consists of a basic structure composed of smaller cells and few microphytoplankton cells that maintains a balanced community periodically, an extra diatom population is superimposed on the basic structure, resulting in high values of the absorption coefficient of phytoplankton and a better hierarchical phytoplankton structure in the upwelling system.

### INTRODUCTION

Phytoplankton community size structure and primary production are the two main factors defining the importance of a pelagic ecosystem. This information provides knowledge of the biogeographic association and the coupling between biological and environmental factors at different scales. Recently, marine scientists have

indicated the need for improved techniques to detect the variability in plankton ecology at small and interannual time series, since changes in the community structure of organisms are controlled primarily by local or regional processes. Pelagic ecosystem response to interannual variability off Baja California has been previously described (Gaxiola-Castro et al. 2008), and an acceptable compatibility was found using climate indices such as the Pacific Decadal Oscillation (PDO; Mantua et al. 1997), and Multivariate ENSO Index (MEI; Wolter and Timlin 1998). During the period 2002–06, under weak El Niño conditions, a decrease in plankton organisms of the pelagic system was observed in the southern region of the California Current (Venrick et al. 2003; Durazo 2009; Millán-Núñez and Millán-Núñez 2010); whereas an increase in organisms was observed in 2001 and 2008, under La Niña conditions (Millán-Núñez et al. 2004; Baumgartner et al. 2008). This study thus aims to contribute to the knowledge of the phytoplankton geography association in the southern region of the California Current under La Niña conditions.

### METHODS

The Mexican California Current research program (IMECOCAL, acronym for Investigaciones Mexicanas de la Corriente de California) monitors 91 stations distributed from northern transect 100 off Ensenada to southern transect 137 to the south of Punta Abreojos; however, only 45 stations were surveyed during the cruise conducted from 16 to 30 April 2008 due to the prevailing weather (fig. 1). Temperature and salinity were measured to 1000 m depth (depending on the topography) using a SeaBird SBE-911 CTD fitted with a rosette holding 5-L Niskin bottles. The biological samples were taken at 10 m depth. Phytoplankton samples were stored in 250 mL dark bottles, preserved in 4% formaldehyde, and neutralized with sodium borate at pH between 7.5 and 8 (Thronsen 1978). To obtain the light absorption coefficients of phytoplankton ( $a_{\text{ph}}$ ), one litre of seawater was filtered through Whatman glass fiber filters (GF/F, 25 mm), which were stored in HistoPrep® capsules and deposited in a liquid nitrogen container for subsequent analysis in the laboratory.

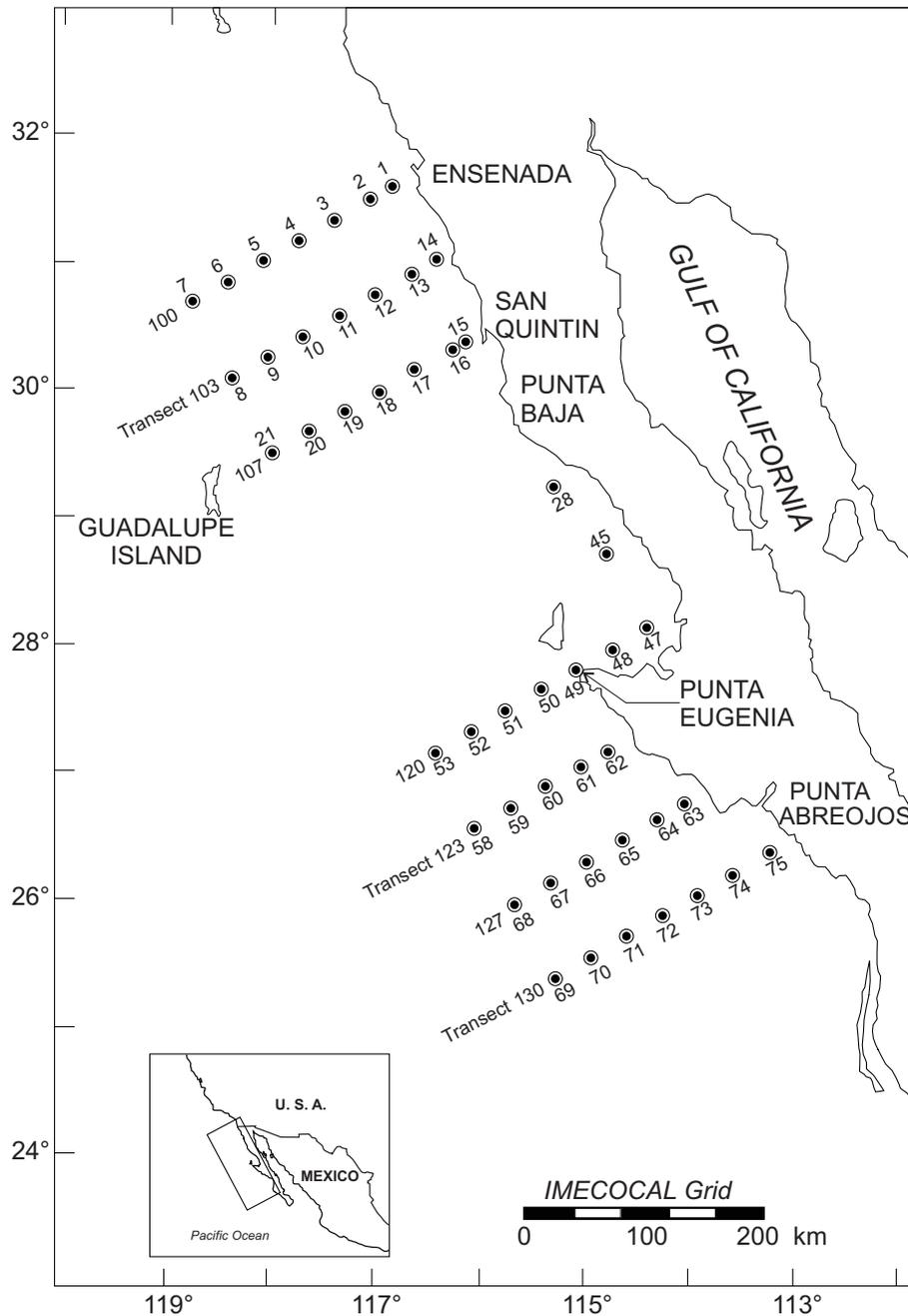


Figure 1. Study area and location of the stations sampled during April 2008 off Baja California. Samples were taken at 10 m depth.

**Nano-microphytoplankton (>5  $\mu\text{m}$ ).** The analysis of nano-microphytoplankton was carried out within the first two months after the cruise, using an inverted microscope at 160 $\times$  and 400 $\times$  magnification (Utermöhl 1958) with a sedimentation chamber of 50 mL. The qualitative and quantitative classifications of nano-microdatoms were made to the genus level and whenever possible to the species level (Moreno et al. 1997; Tomas 1997). The genera were sorted according to the Niche Amplitude Index (Levins 1978), where the level posi-

tion of the taxa represent the major spatial distribution between the sampling stations. The association between nano-microdiatoms was then determined using dendrograms based on the unweighted pair group method with arithmetic mean (UPGMA; Sokal and Rohlf 1962) in relation to the first 12 genera present in the Table 1a and Table 1b.

**Absorption coefficient of phytoplankton ( $a_{ph}$ ).** The GF/F filters were analyzed in the first two weeks after the cruise. The reference and sample filters were kept sat-

TABLE 1A  
 Spatial distribution of the Niche Amplitude Index from nano-microphytoplankton genus at 10 m depth during April 2008.  
 The lowest fraction number represents the dominant cells. Station 1–47.

Stations	1	2	3	4	6	7	9	10	11	12	13	14	15	16	17	18	19	28	45	47	
<b>Diatoms</b>																					
1. <i>Nitzschia</i>	0.091		0.018	0.007	0.102	0.008	0.010	0.025		0.038	0.076	0.013	0.053	0.020	0.131			0.009	0.069		
2. <i>Coscinodiscus</i>			0.051	0.019	0.102		0.028					0.004	0.005	0.083	0.041			0.003	0.024		
3. <i>Navicula</i>			0.071			0.162						0.302	0.034		0.060			0.002			
4. <i>Chaetoceros</i>													0.059					0.103	0.007		
5. <i>Thalassionema</i>	0.037			0.039		0.036							0.005	0.075	0.225			0.003	0.028	0.079	
6. <i>Pseudo-nitzschia</i>														0.012	0.000			0.001		0.014	
7. <i>Rhizosolenia</i>													0.339	0.017				0.469	0.130		
8. <i>Eucampia</i>													0.157					0.023	0.761		
9. <i>Thalassiosira</i>																					
10. <i>Actinopterychus</i>												0.023									
11. <i>Guttardia</i>																				1.000	
12. <i>Pseudoecunofia</i>																				0.129	
<i>Hemiaulus</i>												0.098	0.364					0.122	0.105	0.061	
<i>Dietylum</i>																			1.000		
<i>Leptocylindrus</i>																				0.264	
<i>Asterionella</i>																					
<i>Gramatophora</i>																					
<i>Corethron</i>																					
<i>Planktoniella</i>																					
<i>Skeletonema</i>													1.000						1.000		
<b>Dinoflagellates</b>																					
<i>Gymnodinium</i>	0.009	0.161	0.027	0.010	0.054	0.012	0.029	0.036	0.080	0.020	0.080	0.007	0.002	0.014				0.003	0.003	0.003	
<i>Ceratium</i>			0.039	0.205			0.085	0.052	0.078	0.058		0.015	0.007	0.024		0.067		0.002	0.001		
<i>Gyrodinium</i>				0.044	0.235		0.064	0.078		0.088		0.005	0.002		0.064			0.005	0.003		
<i>Prorocentrum</i>	0.059											0.007	0.004	0.035				0.005			
<i>Scrippsiella</i>								0.223				0.013			0.182			0.005	0.008		
<i>Protoperidinium</i>			0.161				0.351	0.214	0.241				0.005					0.003	0.008		
<i>Gonyaulax</i>			0.062	0.046			0.135	0.083	0.124	0.093	0.186	0.010	0.002	0.013				0.003	0.008		
<i>Dinophysis</i>				0.215					0.431									0.001			
<i>Oxytoxum</i>				0.109		0.249			0.291									0.002	0.009		
<i>Peridinium</i>													0.008			0.918					
<i>Pyrocystis</i>													0.058	0.779							

TABLE 1B  
 Spatial distribution of the Niche Amplitude Index from nano-microphytoplankton genus at 10 m depth during April 2008.  
 The lowest fraction number represents the dominant cells. Station 48-75.

Stations	48	50	51	52	53	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	BI(%)
<b>Diatoms</b>																								
1. <i>Nitzschia</i>	0.017	0.002	0.001	0.048	0.004	0.022		0.009	0.064	0.065	0.061	0.051	0.042	0.018		0.047	0.037		0.032		0.041	0.083	0.031	73.294
2. <i>Coscinodisais</i>	0.005	0.001	0.001	0.019	0.001	0.061				0.005	0.028	0.116					0.153						0.046	2.006
3. <i>Navicula</i>		0.002	0.002	0.018	0.009		0.113			0.002	0.004	0.283	0.087			0.119			0.041				0.009	0.723
4. <i>Chaetoceros</i>			0.026	0.005		0.014	0.197				0.013	0.046		0.105									0.063	0.330
5. <i>Thalassionema</i>	0.003	0.006	0.002	0.039						0.014	0.039	0.269		0.124									0.014	0.292
6. <i>Pseudo-nitzschia</i>	0.036	0.165	0.236	0.016	0.212			0.104		0.077	0.050	0.047				0.013							0.007	0.312
7. <i>Rhizosolenia</i>	0.460	0.012	0.004	0.044	0.030			0.058		0.011	0.009	0.094		0.233		0.018								0.123
8. <i>Eucampia</i>		0.044																						0.057
9. <i>Thalassiosira</i>		0.059																						0.041
10. <i>Actinopterychus</i>																								0.034
11. <i>Guinardia</i>											0.035										0.599	0.401		0.941
12. <i>Pseudoecinothia</i>																								0.026
<i>Hemiaulus</i>		0.177	0.090									0.570												0.027
<i>Ditylum</i>		0.250																						0.028
<i>Leptocylindrus</i>			0.078						0.082			0.576												0.024
<i>Asterionella</i>																								0.025
<i>Grammatophora</i>		1.000			1.000																			0.021
<i>Corethron</i>																								0.021
<i>Planktoniella</i>																								0.021
<i>Skeletonema</i>																								0.024
<b>Dinoflagellates</b>																								
<i>Gymnodinium</i>	0.001	0.001		0.010				0.054	0.027	0.001	0.002	0.022	0.025	0.040	0.032	0.004		0.080	0.092		0.040	0.013	0.008	20.553
<i>Ceratium</i>	0.005	0.003	0.001			0.094	0.063					0.025			0.094	0.025					0.058			0.948
<i>Gyrodinium</i>	0.002			0.088	0.002	0.141			0.059	0.008	0.002	0.038	0.054										0.016	0.356
<i>Prorocentrum</i>	0.005			0.063	0.201			0.084			0.003		0.078				0.335				0.126			0.142
<i>Scrippsiella</i>		0.005							0.334	0.008		0.054										0.167		0.064
<i>Proteroperidinium</i>			0.002							0.015														0.064
<i>Gonyaulax</i>																	0.248							0.219
<i>Dinophysis</i>										0.007				0.345										0.055
<i>Oxytoxum</i>														0.348										0.062
<i>Peridinium</i>		0.015																						0.030
<i>Pyrocystis</i>		0.108	0.055							0.049														0.023

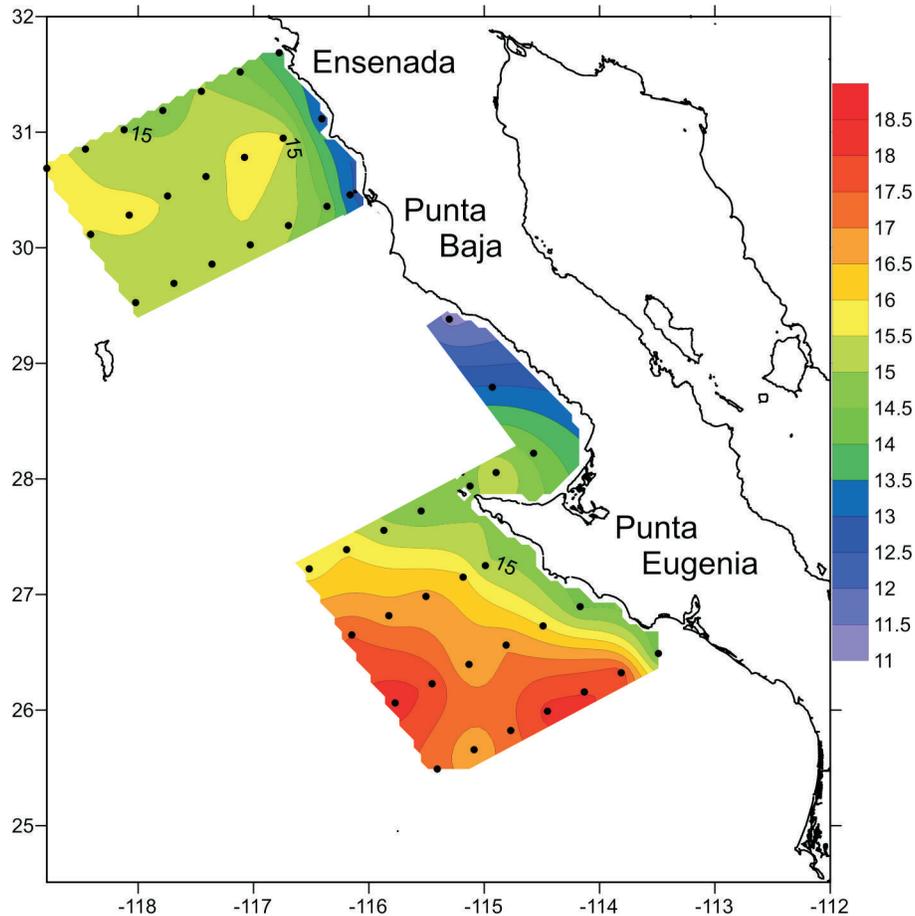


Figure 2. Spatial distribution of temperature (°C) at 10 m depth during April 2008.

urated during the analysis with filtered seawater (0.2 μm) and measured in a Shimadzu UV-2401 PC spectrophotometer equipped with an integrating sphere (Cleveland and Wiedemann 1993). The samples were measured between 400 and 750 nm with 1 nm sampling interval, 2 nm slit width, and medium speed of 330 nm min<sup>-1</sup>; the filters were then rinsed in methanol for 15 minutes (Kishino et al. 1985). The spectral curves of the absorption coefficient were corrected by two factors: baseline correction (reference filter) and path-length amplification (β) by adjusting the optical density of the filtered samples (OD<sub>fil</sub>(λ)) to the optical density of samples in suspension (OD<sub>sus</sub>(λ)) (Mitchell 1990) (equation 1). The a<sub>ph</sub> was taken to be the difference between the absorption coefficient of total particulate matter (a<sub>p</sub>) and the absorption coefficient of detritus (a<sub>det</sub>), and the specific absorption coefficient of phytoplankton (a\*<sub>ph</sub>, m<sup>2</sup> (mg Chl a)<sup>-1</sup>) was obtained by normalizing the phytoplankton absorption data (m<sup>-1</sup>) by the concentration of chlorophyll a (Chl a, mg m<sup>-3</sup>) extracted with 90% acetone by fluorometric analysis. The phytoplankton spectral shape (a<sub>phn</sub>) was obtained by analyzing a<sub>ph</sub> (m<sup>-1</sup>) normalized by the area below the curve between 400

and 750 nm (equation 2). To determine the homogeneity of slopes between 440–550 nm we used a linear model fitted by least squares (Macías-Carballo 2011).

$$OD_{sus} = 0.3385 OD_{fil} + 0.4770 (OD_{fil})^2 \quad (1)$$

$$a_{phn} = \frac{a_{ph}(\lambda)(m^{-1})}{\int_{400}^{750} a_{ph}(\lambda)(m^{-1})\delta\lambda(nm)} \quad (2)$$

## RESULTS

**Oceanographic characterization.** Authors such as McClatchie et al. 2009 have reported oceanographic conditions in the California Current System along the West Coast of North America in 2008 and 2009. During this period, the principal oceanographic forcing on the California Current was determined to be a La Niña event, its main characteristics prevailing since mid-2007 to early 2009. A cold phase was detected in relation to El Niño-Southern Oscillation (ENSO), as was also observed during 1998–99 (Bjorkstedt et al. 2010). A new phase of El Niño-La Niña conditions occurred in the

TABLE 2

Trans = transects showing a subset of the original CalCOFI grid, sta = stations, temp (T °C), salinity, diatoms (cells L<sup>-1</sup>), dinoflag (cells L<sup>-1</sup>), specific absorption coefficient of phytoplankton (a\*<sub>ph</sub>, m<sup>2</sup> (mg Chl a)<sup>-1</sup>) at 440 nm, blue/red ratio (a<sub>ph440</sub>/a<sub>ph674</sub> nm), chlorophyll a (mg m<sup>-3</sup>) from 10 m samples collected during April 2008.

Trans	Sta	Temp	Salinity	Diatoms	Dinoflag	a* <sub>ph440</sub>	Ratio	Chl a
100.30	1	13.59	33.732	2063	552	0.053	2.35	4.89
100.35	2	15.07	33.596	0	0	0.038	2.76	1.19
100.40	3	15.06	33.452	966	690			
100.45	4	14.68	33.301	414	1794		2.96	0.42
100.50	5	14.99	33.247					
100.55	6	15.35	33.361	138	276	0.050	3.04	0.17
100.60	7	15.73	33.444	1514	414	0.024	7.40	0.15
103.60	8	15.48	33.304			0.050	2.74	0.17
103.55	9	15.62	33.361	276	1242			0.18
103.50	10	15.48	33.332	276	966	0.048	3.64	0.21
103.45	11	15.30	33.345	0	826			0.23
103.40	12	15.68	33.461	141	828			0.25
103.35	13	15.63	33.588	138	414			0.52
103.30	14	12.91	33.885	18565	2342	0.002	1.61	5.46
107.32	15	13.05	33.883	1021677	42624	0.023	1.79	15.2
107.35	16	14.41	33.749	6326	1654			4.32
107.40	17	15.10	33.552	1240	276	0.027	3.03	0.72
107.45	18	15.47	33.525	414	414	0.037	2.74	0.45
107.50	19	15.10	33.340	688	276	0.038	3.82	0.34
107.55	20	15.10	33.346					
107.60	21	15.10	33.343					
113.30	28	11.32	33.753	197735	3850	0.015	1.83	7.43
117.30	45		33.765	111448	4125	0.009		11.2
120.30	47	14.33	33.714	108627	10999	0.042	1.89	11.4
120.35	48	15.56	33.678	27026	690	0.040	1.88	0.18
120.40	49	14.78	33.690					7.87
120.45	50	14.67	33.733	129972	3270	0.030	1.69	0.12
120.50	51	15.40	33.718	223312	1100	0.032	1.72	3.78
120.55	52	15.96	33.689	1652	552	0.042	2.47	1.24
120.60	53	15.71	33.690	53489	138	0.031	2.47	2.01
123.60	58	17.49	33.730	276	552			0.23
123.55	59	16.71	33.525	1787	276	0.049	4.94	0.17
123.50	60	16.65	33.542	963	688			0.30
123.45	61	16.09	33.720	962	1100	0.036	2.79	1.13
123.40	62	15.05	33.818	68572	2750	0.029	1.94	7.05
127.35	63	14.38	33.683	67143	1145	0.036	2.14	6.03
127.40	64	15.96	33.661	14025	1377	0.038	2.29	1.00
127.45	65	16.97	33.674	1237	552	0.046	4.06	0.44
127.50	66	16.52	33.605	1238	412	0.037	3.76	0.38
127.55	67	17.92	33.750	138	552			0.15
127.60	68	18.22	33.778	3700	316	0.027	6.33	0.14
130.60	69	14.23	33.553	138	276	0.016	5.57	0.23
130.55	70	16.65	33.706	138	138	0.052	5.82	0.19
130.50	71	17.34	33.645	414	0			0.31
130.45	72	18.15	33.744	552	690	0.033	5.55	0.30
130.40	73	17.99	33.721	552	552	0.053	5.73	0.28
130.35	74	17.81	33.689	1375	276	0.030	2.79	0.31
130.30	75	14.23	33.883	23098	1784	0.022	2.17	9.49

southern region of the California Current during late 2006–07 and 2007–08, respectively, depicted by a transition from moderately positive temperature and salinity anomalies during winter 2006–07, to slightly cool and fresh conditions giving place to La Niña conditions that continued until spring 2008. Likewise, results from biological indicators suggest an increase in the abundances of life cycles and composition of phytoplankton communities (Durazo 2009; Millán-Núñez 2010).

In this study, water temperatures at 10 m depth ranged

from 11.32°C to 18.22°C and were distinguished as: temperate waters of ~15.2°C off Punta Eugenia and northern Baja California, cold waters of ~11.5°C (this indicates active upwelling) to the south of San Quintín and Punta Baja; and warm waters of ~17.5°C in the oceanic area off Punta Eugenia (fig. 2). Salinity at 10 m depth ranged from 33.25 to 33.90, with low salinity water detected at stations off the coast of northern Baja California (table 2). In this cruise, three water masses have been documented off Baja California (García-

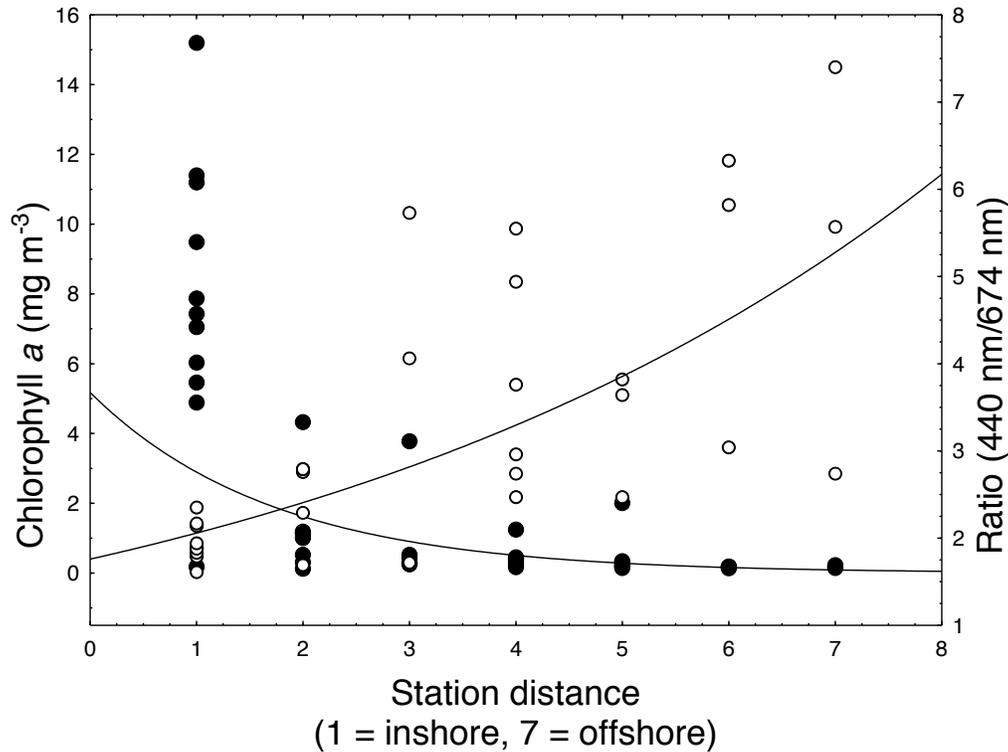


Figure 3. The absorption coefficient phytoplankton ratio at two wavelength (440 nm/674 nm) (clear circles), and chlorophyll a concentration (dark circles). The stations are numbered as: #1 nearshore station; #7 offshore station.

Córdova, 2008), except at 10 m depth, where only two were detected: Subarctic Water (SAW) and California Current Water (CCW).

**Nano-microphytoplankton (>5 μm).** The spatial distribution of nano-microphytoplankton in San Quintín Bay showed a maximum of  $1064 \times 10^3$  cells L<sup>-1</sup> (sta. 15), while the mean values of diatoms and dinoflagellates were  $\sim 154 \times 10^3$  cells L<sup>-1</sup> and  $\sim 4.6 \times 10^3$  cells L<sup>-1</sup>, respectively (table 2). The taxonomic composition of phytoplankton comprised 21 diatoms genera, 11 dinoflagellates, and 2 silicoflagellates (scant presence of *Dicthyocha* sp. and *Distephanus* sp.) (table 1a and 1b). The most abundant diatom genera throughout the study area were *Nitzschia* sp., *Coscinodiscus* sp., *Navicula* sp., *Chaetoceros* sp., *Thalassionema* sp., *Pseudo-nitzschia* sp., *Rhizosolenia* sp., *Eucampia* sp., *Thalassiosira* sp., *Actinopterychus* sp., *Guinardia* sp., and *Fragilariopsis* sp. The dominant dinoflagellate genera were *Gymnodinium* sp., *Ceratium* sp., *Gyrodinium* sp., and *Prorocentrum* sp. The genus *Nitzschia* spp. was the most persistent, showing five species: *N. closterium* Ehrenberg (or *Cylindrotheca closterium*), *N. seriata* Cleve, *N. sigmaidea*, and two unidentified species. The abundance of the genera *Nitzschia* spp. and *Pseudo-nitzschia* sp. were observed with high values of  $\sim 210 \times 10^3$  cells L<sup>-1</sup> in the area off Punta Eugenia, as was the abundance of *Eucampia zodiacus* Ehrenberg and *Eucampia cornuta* (Cleve) Grunow, showing values of  $\sim 646 \times 10^3$  cells L<sup>-1</sup> and

$\sim 80 \times 10^3$  cells L<sup>-1</sup>, respectively, to the north of Punta Baja (table 2).

**Specific absorption coefficient of phytoplankton ( $a_{ph}^*$ ).** Values of  $a_{ph}^*$  440 nm ranged from 0.002 to 0.053 m<sup>2</sup> (mg Chl *a*)<sup>-1</sup> (table 2). The spectral curves with lower  $a_{ph}^*$  440 nm were located at inshore stations to the north of San Quintín and south of Punta Baja, respectively. In station 47 the absorption coefficient of phytoplankton ( $a_{ph440}$ ) ranged from 0.003 and 0.489 (m<sup>-1</sup>), and at 674 nm it showed a maximum of 0.258 (m<sup>-1</sup>) ( $a_{ph674}$  data not shown). The B/R ratios ( $a_{ph440}/a_{ph674}$ ) ranged from 1.6 to 7.4, with high values at offshore stations (fig. 3).

**Phytoplankton associations and spectral absorption shapes.** This study shows four clusters when the stations were associated on the abundance of the 12 main genera of nano-microdiatoms (fig. 4). After the cluster it is transformed as a map or phytogeographic provinces (PGPv) (fig. 5). The first PGPv (A) was dominated by *Eucampia* spp., while PGPv (B) was dominated by *Pseudo-nitzschia* spp. The third PGPv ( $C_{North}$ ,  $C_{South}$ ) was formed by a mixture of species of diverse genera (*Thalassiosira* sp., *Chaetoceros* spp., *Nitzschia* spp.), as was the fourth PGPv ( $D_{North}$ ,  $D_{South}$ ) (*Thalassionema* sp., *Coscinodiscus* spp., *Guinardia* sp., *Actinopterychus* sp., *Rhizosolenia* spp., *Fragilariopsis* sp., *Navicula* spp.). Figure 6 shows six pattern curves (M1–M6) associated at 32 spectral absorption shapes

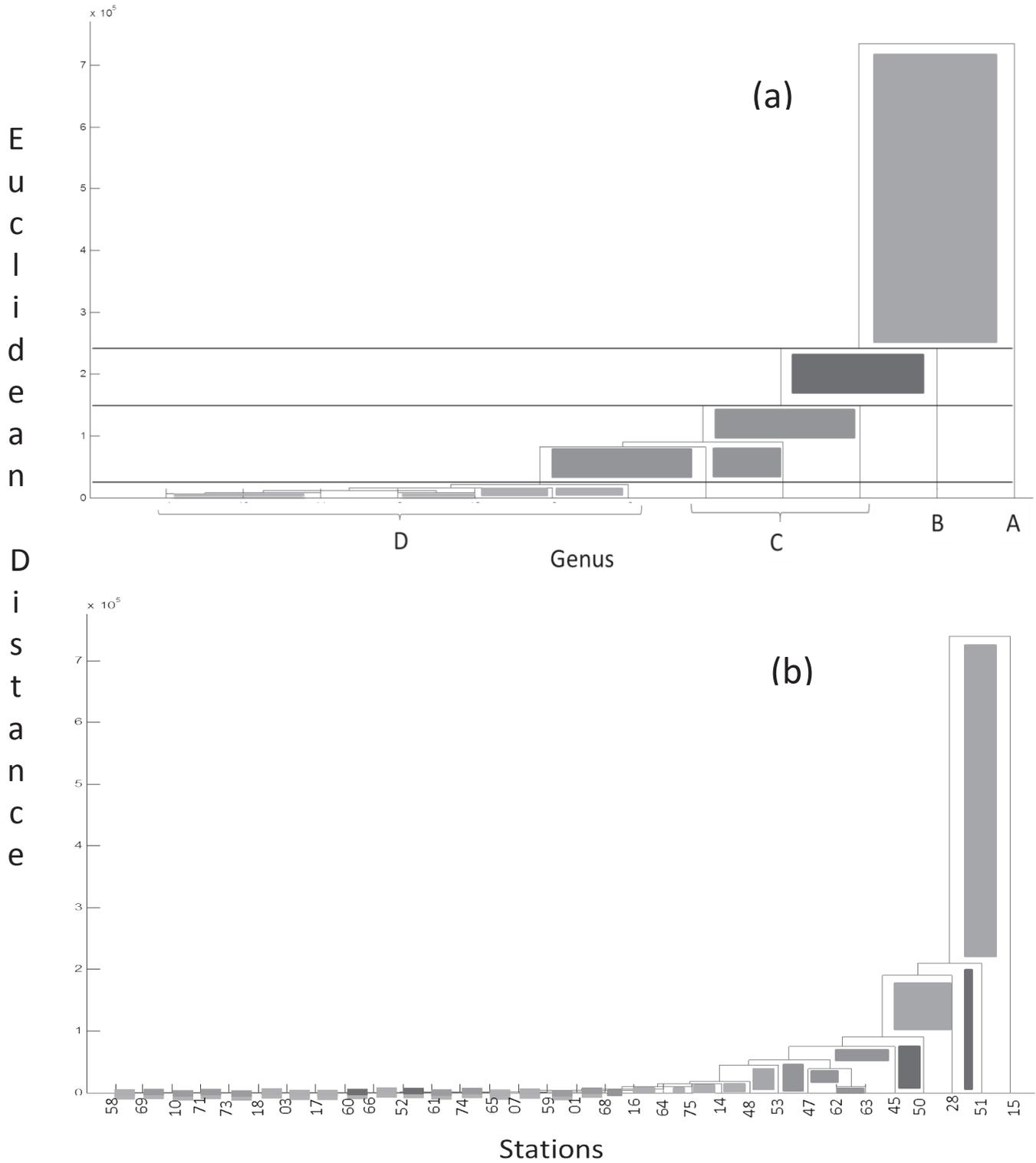


Figure 4. Hierarchical cluster dendrogram based in twelve dominants genus from Amplitude Niche Index and stations. The samples were taken at 10 metre depth during April 2008.

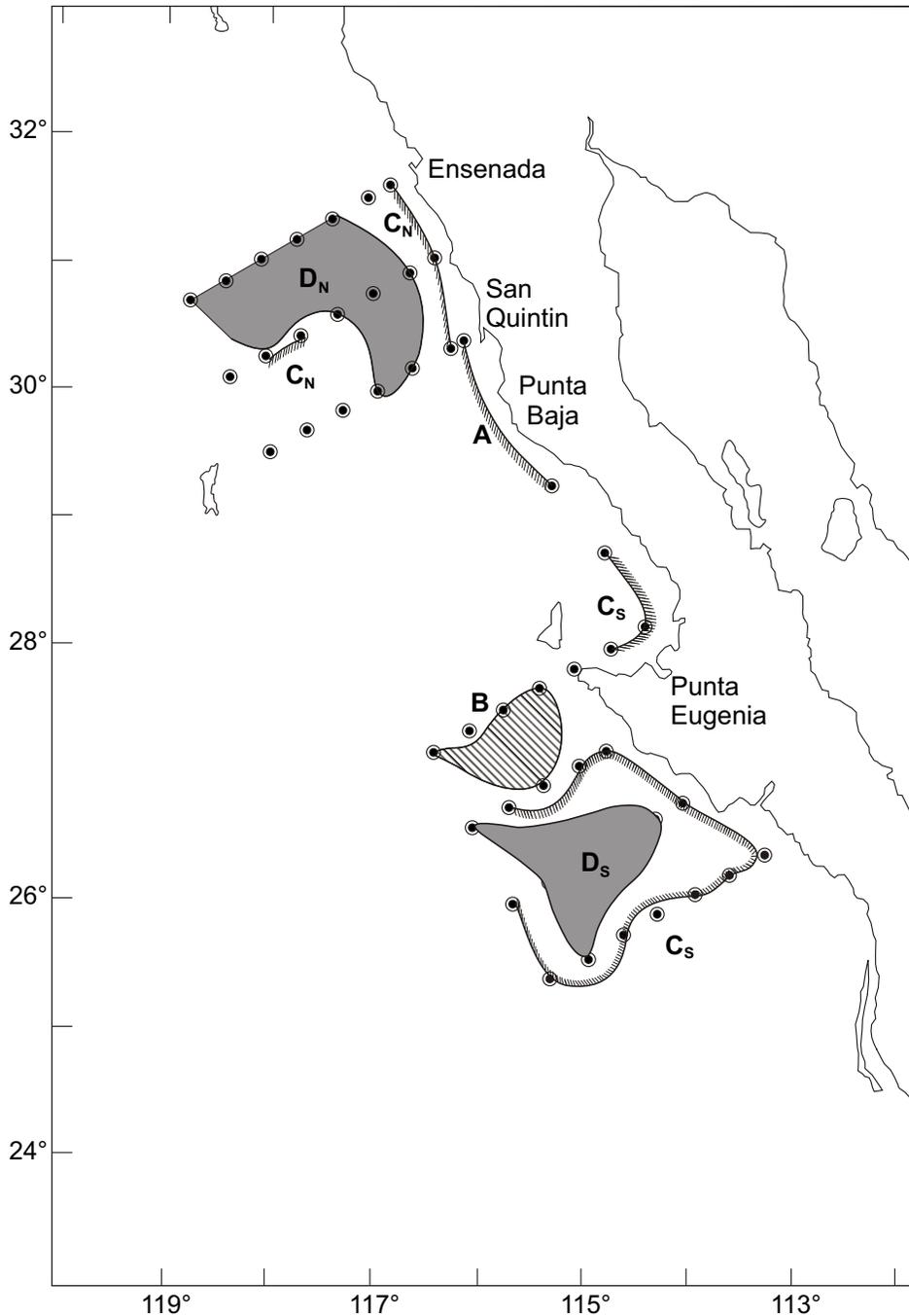


Figure 5. Phylogeographic provinces off Baja California: A (dominant *Eucampia* spp., bloom), B (weak *Pseudo-nitzschia* spp., bloom), C<sub>NORTH</sub> and C<sub>SOUTH</sub> (*Thalassiosira*, *Chaetoceros*, *Nitzschia*, *Fragilariopsis*, *Rhizosolenia*), and D<sub>NORTH</sub> and D<sub>SOUTH</sub> (*Thalassionema*, *Coscinodiscus*, *Guinardia*, *Actinopterychus*, *Navicula*). The samples were taken at 10 m depth during April 2008.

from the homogeneity of slopes between 440–550 nm (fig. 7). The PGPv A, PGPv B, and PGPv Cs show similar curves (fig. 6a, 6b, and 6d) with small differences in the shoulder between 440–550 nm (table 3), these three spectral shapes are related to upwelling events with the dominant group of diatoms (81%, 97%, and 99%). Conversely, to the PGPv CN, DN, and DS that showed a

decrease of the diatom group (<71%), and less homogeneity of slopes and high diversity of nano-microphytoplankton (table 3).

## DISCUSSION

The southern region of the California Current off Baja California presents productive oceanographic con-

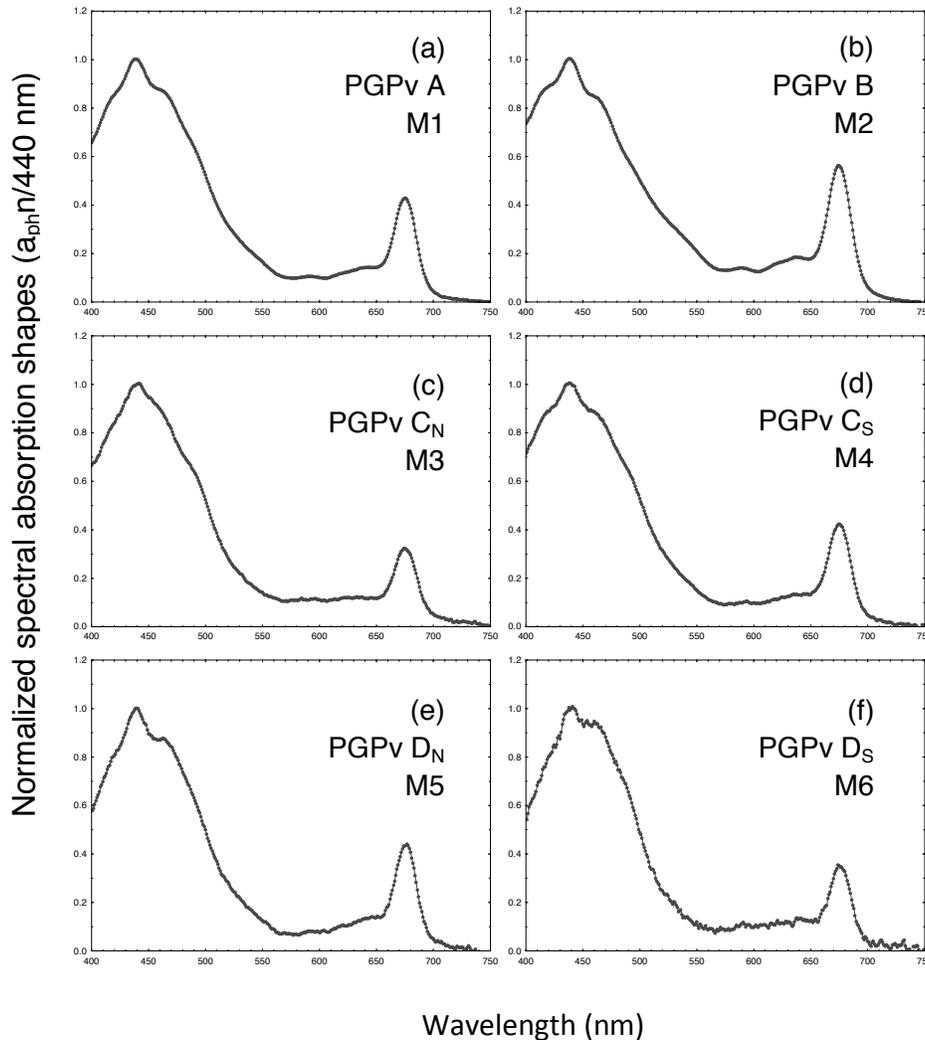


Figure 6. Normalized spectral absorption shapes ( $a_{phn}/440$  nm). The pattern curves represent the phyto-geographic provinces: (a) M1 (PGPv A); (b) M2 (PGPv B); (c) M3 (PGPv C<sub>NORTH</sub>); (d) M4 (PGPv C<sub>SOUTH</sub>); (e) M5 (PGPv D<sub>NORTH</sub>); (f) M6 (PGPv D<sub>SOUTH</sub>). The spectral shapes are representative of 10 m depth during April 2008.

ditions, mainly in areas where upwelling events occur. In this study, two important upwelling events were detected in relation to the inclination of the mean  $25\sigma_\theta$  surface. This inclination technique has been used off Baja California because the depth of mixing in the IMECOCAL area is found close to the pycnocline (Jerónimo-Moreno and Gómez-Valdéz 2006). The most intense upwelling event occurred off San Quintín Bay with the surficial part ( $25\sigma_\theta$ ) near the coast, between stations 16 and 17, and the deepest part offshore, reaching ~80 m depth (fig. 8a). These data are similar to those reported off Baja California during the period 1998–2005 by Jerónimo-Moreno and Gómez-Valdéz 2006, where the deep inclination of  $25\sigma_\theta$  reached 74 m. The second upwelling event showed oceanographic characteristics corresponding to weak upwelling conditions off Punta Eugenia, with the surficial part in the stations 47 and 50 and the

deepest part offshore, reaching ~30 m depth (fig. 8c). Both these events produced phytoplankton blooms. The first event was dominated by *Eucampia* spp., with an abundance of  $726 \times 10^3$  cells  $L^{-1}$  and an approximate biomass of  $2657 \mu g C L^{-1}$ , whereas species of *Nitzschia* were observed in the weak event, with an abundance of  $213 \times 10^3$  cells  $L^{-1}$  and a biomass of  $\sim 400 \mu g C L^{-1}$  (table 2, phytoplankton biomass not data show).

Based on temperature-salinity diagrams and chemical-biological data, authors such as Venrick et al. 2003, Baumgartner et al. 2008, Millán-Núñez and Millán-Núñez 2010, and Durazo et al. 2010 have detected that the SAW water mass off southern California shows high-nutrient, low-chlorophyll characteristics ( $NO_3 = 10 \mu M$ ,  $PO_4 = 1 \mu M$ ,  $Chl a = 0.2 mg m^{-3}$ ) and that it extends to  $28^\circ N$ , as observed in the present study, where salinity  $< 33.5$  reached transects 107 and 120 (fig. 8b, 8d). The

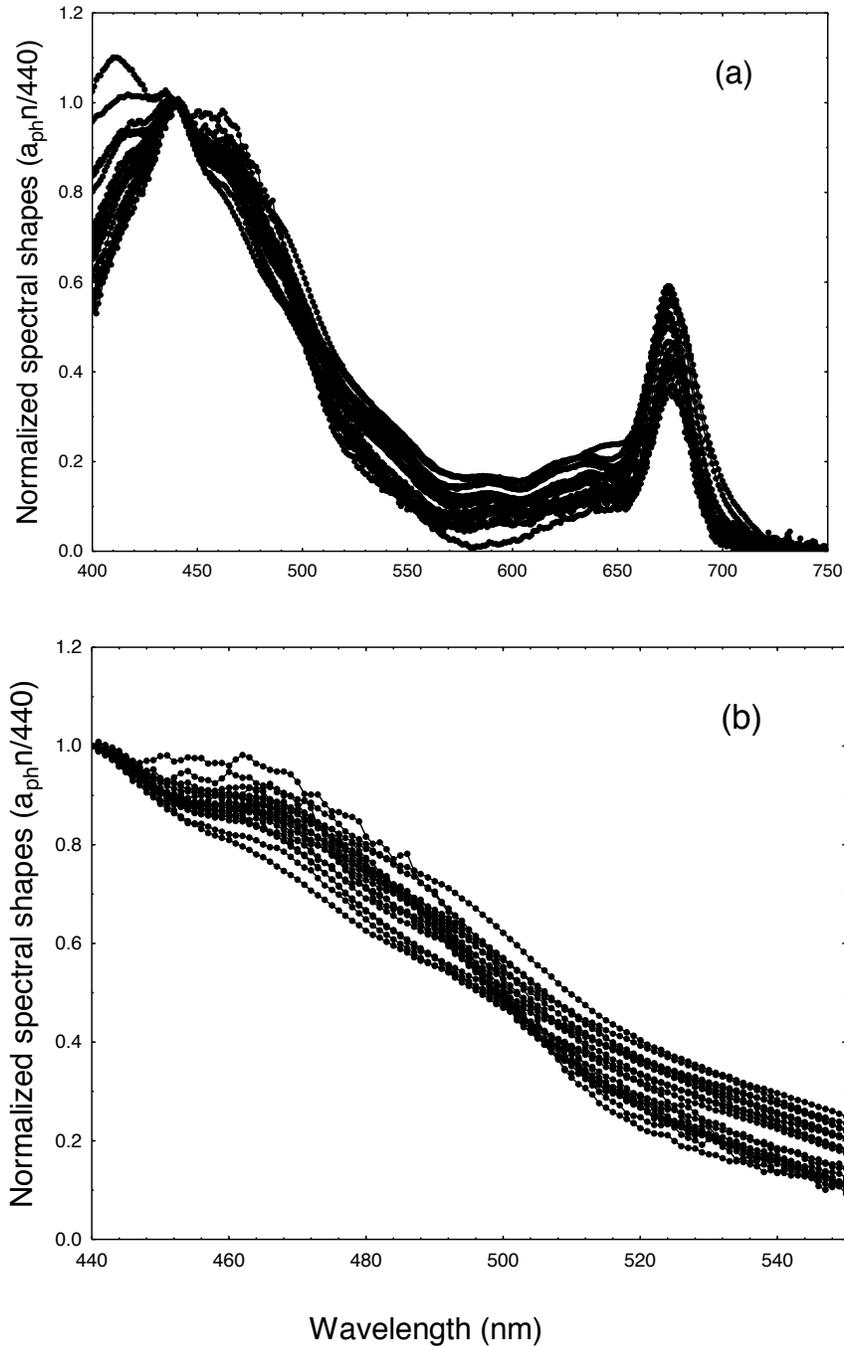


Figure 7. Normalized spectral shapes ( $a_{ph,n}/440$  nm) and homogeneity of slopes. a) All spectral shapes (400–750 nm), b) 440–550 nm.

geographic position of Punta Eugenia allows the observation of trajectory-effects of SAW off Baja California, hence, it should be possible to detect mixing processes of the hierarchical structure of the pelagic community, such as phytoplankton/zooplankton and fish eggs/larvae relationships. Here, we observed that SAW impacted the southern region of the California Current off Baja California (trans. 100, 103, 107), with an impoverished nano-

microdiatom structure at offshore stations, as opposed to coastal ones that were favored by local upwelling events. According to Tetsuichi et al. 2009, the Subarctic North Pacific is one of the major regions of the global ocean, with  $\sim 0.4$   $\text{mg m}^{-3}$  of Chl *a* concentration throughout the year; this value is similar to our offshore data of  $\sim 0.26$   $\text{mg m}^{-3}$  (table 2). All stations nearest to shore had very high chlorophyll ( $\sim 7.84$   $\text{mg m}^{-3}$ ), as shown in Fig-

TABLE 3  
 Phylogeographic provinces (PGPv) associated from stations, phytoplankton groups, and spectral absorption shapes. Pattern curves that conformed the spectral absorption shapes, dinoflagellates/diatoms rates (%), homogeneity of slopes (440–550 nm) from 10 m samples collected during April 2008.

Phylogeography Provinces (PGPv)	Spectral Shapes pattern curves	Stations	Taxonomic Groups (%) Diatoms/Dinoflag Mean Rates	Homogeneity Slopes (440–550 nm)
A	M1	15,28	97	-0.0081
B	M2	50,51,53	99	-0.0080
C <sub>N</sub>	M3	1,9,10,14	53	-0.0074
C <sub>S</sub>	M4	47,48,59,61,62,63,73,74	81	-0.0083
D <sub>N</sub>	M5	4,6,17,18	47	-0.0091
D <sub>S</sub>	M6	64,65,66,70	71	-0.0098

TABLE 4  
 Vertical distribution of nano-microdiatoms genera (>5 µm) at stations 6, 11, 18, 50. The numbers represent the natural logarithm of the cells L<sup>-1</sup>. Data collected at 0, 10, 20, 50, 100 m depth during April 2008.

Stations	( 6 )					( 11 )					( 18 )					( 50 )																									
Depth	0	10	20	50	100	0	10	20	50	100	0	10	20	50	100	0	10	20	50	100																					
Diatoms																																									
<i>Nitzschia</i>		5.62		6.30	4.92	6.87	6.02	4.92	5.62	4.92	4.92	4.92	4.92	7.00	7.48	7.69	9.56	8.44	7.69	6.68																					
<i>Coscinodiscus</i>	4.92	5.62						4.92	7.12						5.62	4.92	6.31	8.75	8.32	8.44	6.71	4.92																			
<i>Pseudonitzschia</i>																6.31																									
<i>Ditylum</i>																					4.92	7.91	9.11	7.40	6.71	4.92															
<i>Thalassiosira</i>																					7.69	8.38	7.56	5.61																	
<i>Chaetoceros</i>																					6.31	9.97	9.40	8.01	6.71																
<i>Rhizosolenia</i>																					4.92	5.62	9.08	9.87	10.19	8.87															
<i>Eucampia</i>																										9.60	10.10	9.33													
<i>Skeletonema</i>																															8.10	7.40									
<i>Thalassionema</i>																										6.02	5.62	5.61	6.71												
<i>Stephanophycis</i>																															5.61										
<i>Navicula</i>	6.02						4.92	6.53	6.31	5.62	4.92						4.92	4.92	5.62						5.61																
<i>Hemialus</i>																															5.62										
<i>Asterionella</i>																															6.10										
<i>Planktoniella</i>																															5.62										
<i>Fragilariopsis</i>																															7.56	6.53									
<i>Bacteriastrum</i>																															5.62										
<i>Guinardia</i>																																				6.02					

ure 3 where the Chl *a* is clearly related to distance from shore; the station that is numbered as #1 is the near-shore station, and #7 the offshore station. On the other hand, the vertical distribution of nano-microdiatoms at stations 6, 11, and 18 supports the idea of SAW input, with low phytoplankton abundance and low Chl *a* off Baja California (table 4).

In general, the spectral shapes of the PGPv showed similar pattern curves (fig. 6), with slight homogeneity slopes at the shoulder between 440–550 nm attributed to the different photosynthetic pigments of the associated organisms. A particular spectral shape was observed at station 15 and 28 (fig. 6a), with a slight difference in slope relative to Figure 6b stations 50, 51, and 53 (table 3). This was due to the dominance of *Eucampia* spp. (72%), and we thus consider that the spectral shape observed in Figure 6a is a reflection biomarker of the dominant pigment species; similar to the case of

*Pseudo-nitzschia* spp., which had a predominance of 95% (fig. 6b).

The absorption Blue/Red ratios and Chl *a* concentrations in this cruise showed significant changes at 10 m of depth (table 2). In the offshore stations B/R ratios were greater than 3.5 with Chl *a* lower than 0.5 mg m<sup>-3</sup> (fig. 3). This implies the predominance of picoplankton cells in the size structure of phytoplankton communities (Stramski and Morel 1990; Wu et al. 2007; Millán-Núñez and Millán-Núñez 2010; Goericke 2011). The inshore stations were different, with the B/R ratios (station 15, 28, 61, 62, 63, 64) dropping from 2.8 to 1.6, suggesting an increase in the proportion of nano-microdiatoms in the size structure of phytoplankton communities and Chl *a* concentration. We concluded that the southern region of the California Current off Baja California consists of a basic structure composed of smaller cells and scant microphytoplankton cells that maintains a balanced

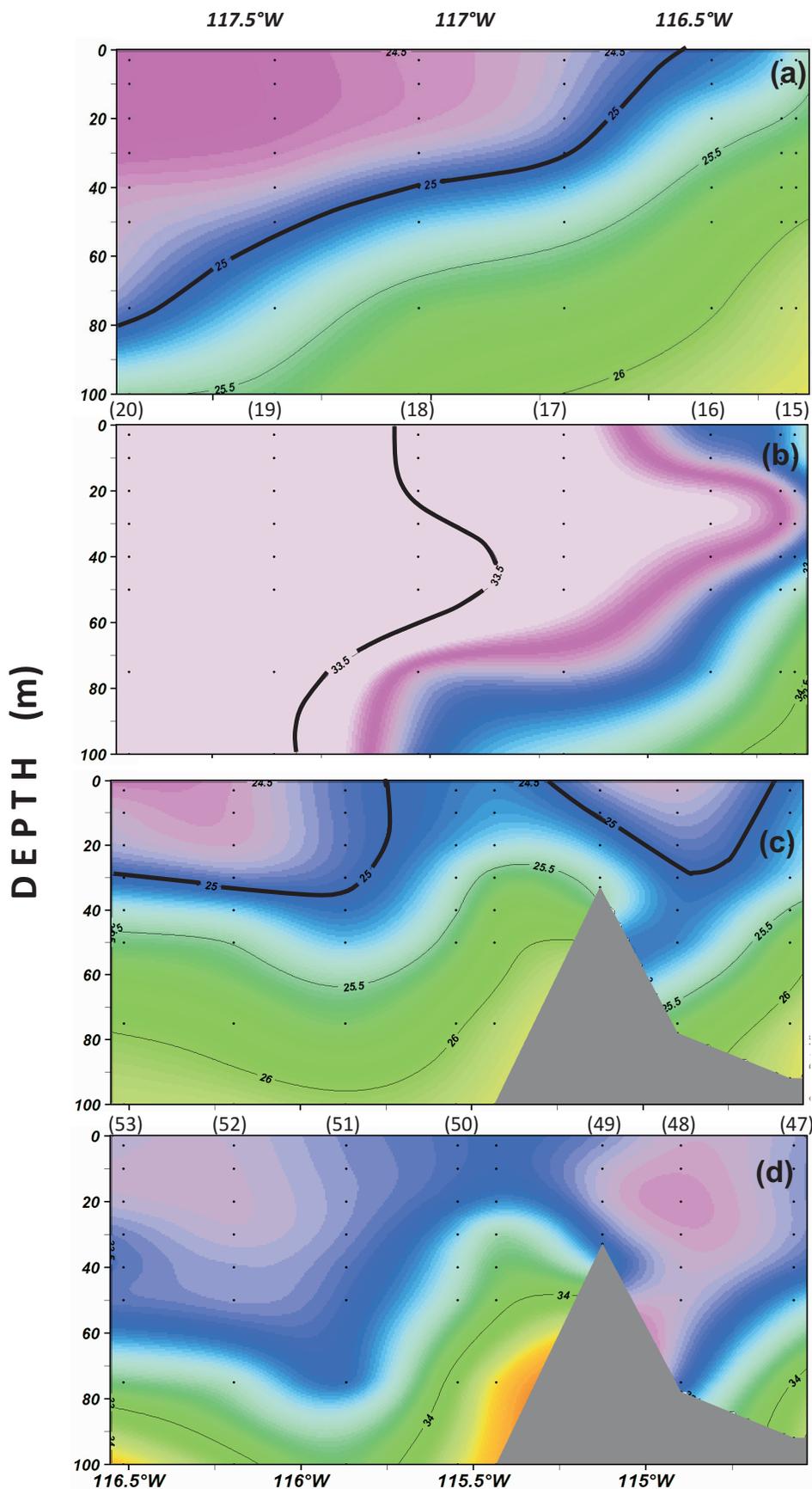


Figure 8. Vertical sections: (a) potential density (b) potential salinity along transect 107, and (c) potential density (d) potential salinity along transect 120. Numbers on top represent the station number along each transect.

community; periodically, an extra diatom population is superimposed on the basic structure, which results in high values of the absorption coefficient of phytoplankton and a better hierarchical phytoplankton structure in the upwelling system off Baja California.

## ACKNOWLEDGEMENTS

I am grateful to the crew of the R/V *Francisco de Ulloa* for their efficient help on board: J. F. Moreno-Higareda, J. L. Cadena-Ramírez, M. E. De la Cruz-Orozco. We also want to thank J. M. Dominguez and E. J. Ponce for improving the drawings, and C. Harris for fine-tuning the English. The research was supported by a grant from IMECOCAL program and the Mexican Council for Science and Technology (CONACyT #23804 and #99252).

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## AGE AND GROWTH MODELLING FOR EARLY STAGES OF THE JUMBO SQUID *DOSIDICUS GIGAS* USING MULTI-MODEL INFERENCE

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### ABSTRACT

Age and growth were estimated for early growth stages of the jumbo squid *Dosidicus gigas* in the Gulf of California, based on daily growth increments in statoliths. Three individual growth functions that showed non-asymptotic patterns (two cases of the Schnute general model, and Tanaka model) were fitted to length-at-age data. Using Akaike's Information Criterion and multi-model inference, we selected the best model to describe the growth pattern. We found that the Schnute general model was the best growth function describing mantle length-at-age data for paralarvae and juveniles of *D. gigas*, showing a power pattern. Absolute daily growth rate ranged from 0.03 to 1.66 mm day<sup>-1</sup>, with lower values for paralarvae and higher values for juveniles.

### INTRODUCTION

*Dosidicus gigas* is the most abundant commercial squid in the central Gulf of California. Although the fishing activity is well known in this area, life-history parameters of *D. gigas* have not been fully assessed and are critical for understanding squid biology, as well as for proper management through stock assessment modelling (Morales-Bojórquez et al. 2001; Morales-Bojórquez and Nevárez-Martínez 2010). Thus, knowledge of *D. gigas* has been limited to fishery-dependent data, and several aspects of recruits and adult squid population. In contrast, little is known about the demography of the paralarvae of *D. gigas*, and how their parameters vary spatially and seasonally in the Gulf of California, although recent information about this issue has been reported by Camarillo-Coop et al. 2010, 2013; and Rosa et al. 2013.

Rapid growth appears to enhance survival of paralarvae due to high predation during the early life stages (Boyle and Rodhouse 2005). Studies have suggested that individuals that grow rapidly and achieve a larger body size spend less time in the most vulnerable early life stages (Cushing 1982). Understanding the factors responsible for differences in growth during the early

life stages of *D. gigas* can be used to assess important factors regulating survival, as well as recruitment success (Boyle and Rodhouse 2005), it is defined as the number of individuals that reach a specified stage of the life cycle (e.g., metamorphosis, settlement, selected by the fishery). The scarcity of information on age and growth of early life stages of *D. gigas* is presently an impediment to describing spawning locations, hatch dates, and transport from offshore to recruitment areas (advection), and availability for the fishing fleets in the Gulf of California.

Growth rates are critical to survival of paralarvae, as well as the dynamics of recruitment (Vidal et al. 2005). In general, if squid have several phases of early development or the number and duration of stages are large, then natural mortality increases. According to Nesis 1979, the limits of these phases or stages are defined by body size, and not the age at which the change happens. For example, the cephalopod *Spirula spirula* has a single discontinuity in growth of its mantle, arms, tentacles, and fins. The discontinuity is characterized by morphological changes expressed through relative growth (Nesis 1979). These changes correspond to the transition from paralarval to juvenile phase (Clarke 1966). For the short fin squid *Illex argentinus*, the first discontinuity in growth coincides with the transition from the paralarval to juvenile phase, which occurs in a narrow range of 14–17 mm ML (Vidal 1994). Between 25 and 35 days the larval growth rate of *Stenoteuthis pteropus* shows a decreasing trend when the species changes from larvae to juvenile (Laptikhovskiy et al. 1993). Vidal 1994 explained that, to be efficient predators, rhyntoteuthions must be good swimmers. Fast growth and slendering of the body is a result of relatively slow growth of mantle weight, which causes the loss of the spherical shape and favors the development of the cylindrical shape, which increases the efficiency of jet propulsion. Paralarval growth in length of *Ommastrephes bartramii* is typically described by an

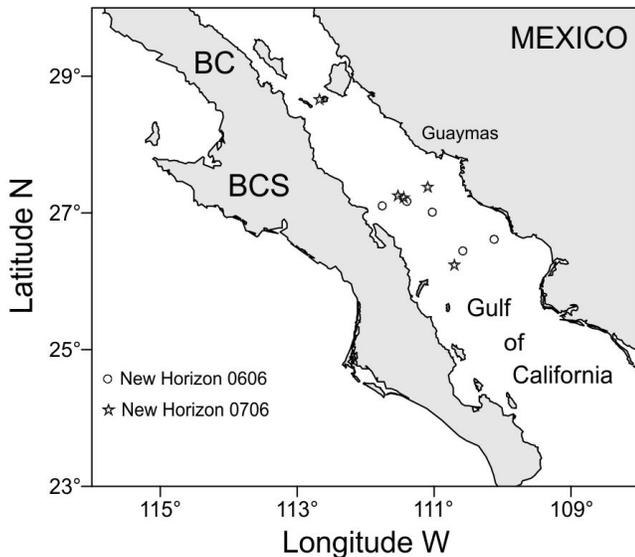


Figure 1. Study area in the central Gulf of California, Mexico. Sampling sites of two field surveys are shown.

exponential equation (Bigelow and Landgraf 1993). Arkhipkin 2004 analyzed the diversity in growth of squids (suborder Oegopsina), reporting that the tropical species show non-asymptotic growth in comparison to polar and deepwater species where the asymptotic growth is commonly observed. Fast growth has clear benefits in allowing paralarvae to pass more quickly through its most vulnerable life history stages and to develop faster physically and physiologically in order to improve its ability to detect and capture prey, as well as predator avoidance and resistance to environmental variability (Bigelow 1992).

Fishery management and conservation of *D. gigas* in the Gulf of California is very important. Lack of basic biological information of early stages of *D. gigas* reduces our understanding of the population dynamics of recruits and adult stock (Camarillo-Coop et al. 2010, 2013; Zepeda-Benitez et al. in press). In this study an appropriate growth model was identified to fit length-at-age data for early stages of *D. gigas* in the Gulf of California based on multi-model inferences and generalized growth models. The implications of these growth models, as well as the choice of models, are discussed in relation to the new population biology of early stages of *D. gigas*.

## MATERIAL AND METHODS

### Squid sampling data collection

Two research surveys on board the RV *New Horizon* were conducted in the central Gulf of California in June 2006 and June 2007 (fig. 1). Samples of the early life stages of *D. gigas* were collected in the Guaymas and del Carmen Basins; paralarvae were captured with a 500  $\mu\text{m}$

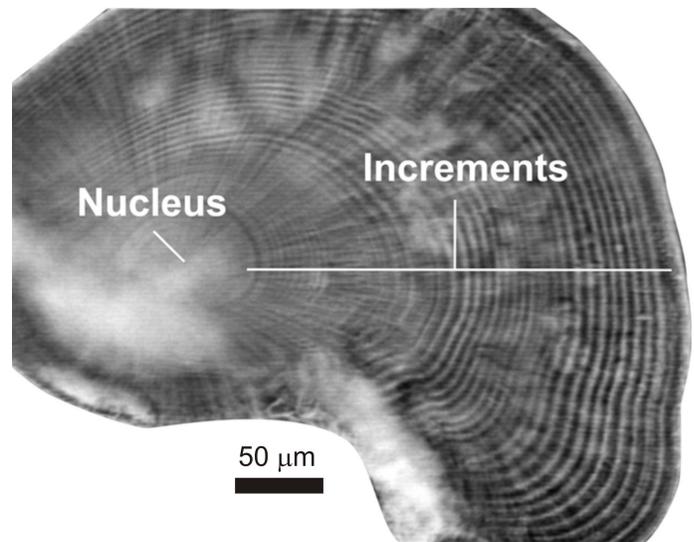


Figure 2. Microstructure of a statolith of a juvenile (18.6 mm ML) of *Dosidicus gigas*.

mesh bongo net (Diekmann and Piatkowski 2002) and juveniles with a dipnet. A total of 12 paralarvae and 93 juveniles were fixed in 95% ethanol. Measurements of mantle length (ML) and body weight (BW) were taken to the nearest 0.01 mm and 0.1 g, respectively. Statoliths from each specimen were extracted and stored in 95% ethanol for age determination. Sizes ranged from 2.8 to 67.8 mm ML; the most common size frequency interval was identified as a mode at 24–26 mm ML.

### Statolith reading

The statoliths were mounted on microscopic slides for reading growth increments on the dorsal dome based on the Arkhipkin method (Dawe and Natsukari 1991). For juveniles, the statoliths were ground and polished, since in this development stage the concave and convex regions of statolith are not well developed. Consequently, any side can be used for grinding in juveniles. González et al. 2010 explained that for paralarvae (*Loligo vulgaris*) the concave and convex surfaces must be ground. The procedure is not clearly defined; however both techniques allow the observation of growth lines. Paralarvae statoliths required only polishing. Increment counting started at the nucleus and proceeded to the edge of the dorsal dome. Counts were carried out independently by two readers where they read the increments with transmitted light at 400 $\times$  (fig. 2). Each increment was assumed to be deposited daily, as has been determined to occur for other squid of the family Ommastrephidae (Dawe et al. 1985; Nakamura and Sakurai 1991). The age of each individual was defined to be the average of the two independent counts. The index of average percent-age error (IAPE) and coefficient of variation (CV) were

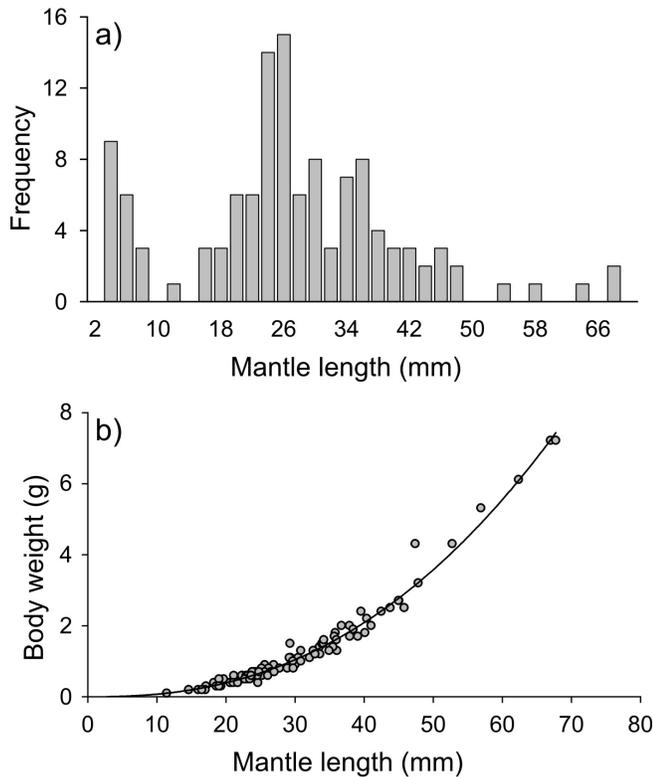


Figure 3. (a) Mantle length interval and (b) Mantle length to body weight relationship analyzed for early growth stages of *Dosidicus gigas*.

calculated to assess the reliability of the counts between readers (Campana et al. 1995).

**Growth modelling**

We used models that do not show an asymptotic growth because the early development of the *D. gigas* has accelerated growth. We used two cases of the non-asymptotic models proposed by the Schnute general growth model (Schnute 1981): a)  $\rho = 0, \eta \neq 0$ , and b)  $\rho = 0, \eta = 0$ , where  $\rho$  is the constant relative rate of the relative growth rate and  $\eta$  is the incremental relative rate of the relative growth rate. We also used an indeterminate growth model (Tanaka 1982). These models were fitted to length-at-age data, and specific details about the growth function are in Appendix 1.

**Parameter estimation and confidence intervals**

The  $\theta_i$  parameters represent the estimated parameters in the non-asymptotic models (Schnute or Tanaka models), and were estimated using a negative log-likelihood function:

$$-\ln L(\theta_i | data) = \sum_i \left[ -\frac{1}{2} \ln(2\pi) \right] - \left[ \frac{1}{2} \ln(\sigma^2) - \left( \frac{\ln L(t) - \ln \hat{L}(t)^2}{2\sigma^2} \right) \right]$$

The parameters were estimated by maximizing the negative log-likelihood estimator (Hilborn and Mangel 1997) using the Newton algorithm (Neter et al. 1996). For the standard deviation ( $\sigma$ ), the analytical solution is:

$$\sigma = \sqrt{\frac{1}{n} \sum_{t=1}^n [\ln L(t) - \ln \hat{L}(t)]^2}$$

where  $n$  is the number of ages observed in the early stages of *D. gigas*. Confidence intervals were estimated using the bootstrap method described by Fournier and Archibald 1982.

**Model selection**

We compared the fits of the different candidate growth models using Akaike’s information criterion (*AIC*) (Burnham and Anderson 2002). The small-sample *AIC<sub>c</sub>* was determined as follows:

$$AIC_c = 2 \times -\ln L(\theta_i | data) + 2 \times \theta_i + \frac{2 \times \theta_i (\theta_i + 1)}{n - \theta_i - 1},$$

where  $\theta_i$  is the number of estimated parameters,  $n$  is the number of observations, and  $-\ln L(\theta_i | data)$  is the objective function for each candidate growth model. The model with the lowest *AIC<sub>c</sub>* value was selected as the best model (Haddon 2001).

**Growth rates**

Absolute daily growth rates (DGR), and instantaneous growth rate (G) were calculated for each 5-day interval (Forsythe and Van Heukelem 1987; González et al. 2010), with data that included paralarvae and juveniles.

**RESULTS**

The mantle length-body weight relationship was estimated for juveniles ( $R^2 = 0.97$ ) and total weight varied from 0.1 to 7.2 g (figs. 3a, 3b). Power coefficient was analyzed using a Student’s *t*-test to determine the type of growth. It was estimated as a value of 2.41, which was statistically different from the theoretical value of 3.0 ( $p < 0.05$ ), indicating that growth in juvenile of *D. gigas* is faster in length than in body mass.

Statoliths were measured from the rostrum to the dorsal dome. Length varied from 0.09 to 0.63 mm, corresponding to mantle length of 4.1 mm (paralarvae) and 67.8 mm (juvenile), respectively. The mantle length-statolith length (ML-SL) showed correlation between the two variables ( $R^2 = 0.85$ ), which indicates that there is a proportionality between somatic growth and statolith growth of paralarvae and juveniles. The results of the index of average percent error and the coefficient of variation were 2.03% and 2.87%, respectively, indicating that the readings carried out by the two readers were similar. Estimated age varied from 1 to 59 days,

TABLE 1  
 Parameters and confidence intervals estimates by Monte Carlo simulations for different growth models.

Model	Parameter	Value	Mean	S.E.	CV	Bias	%Bias	Lower 5%	Upper 95%
Schnute ( $\rho = 0, \eta \neq 0$ )	$\eta$	0.334	1.171	0.088	0.075	0.837	71.497	1.012	1.351
	$\lambda_1$	3.331	2.784	0.146	0.052	-0.548	-19.669	2.495	3.022
	$\lambda_2$	46.093	34.912	0.996	0.029	-11.181	-32.027	33.131	37.047
	$\tau_1$	1							
	$\tau_2$	59							
Schnute ( $\rho = 0, \eta = 0$ )	$\lambda_1$	4.030	8.319	0.725	0.087	4.289	51.559	7.072	9.877
	$\lambda_2$	54.328	84.084	23.630	0.281	29.756	35.388	62.684	213.587
	$\tau_1$	1							
	$\tau_2$	59							
Tanaka	$\gamma$	0.737	0.049	0.094	1.929	-0.689	-1419.267	0.002	0.854
	$\chi$	49.760	20.956	2.329	0.111	-28.804	-137.451	16.185	25.646
	$\delta$	70.204	22.302	0.587	0.026	-47.903	-214.793	21.527	23.774
	$\varphi$	0.004	0.211	0.154	0.733	0.207	98.127	0.084	0.761

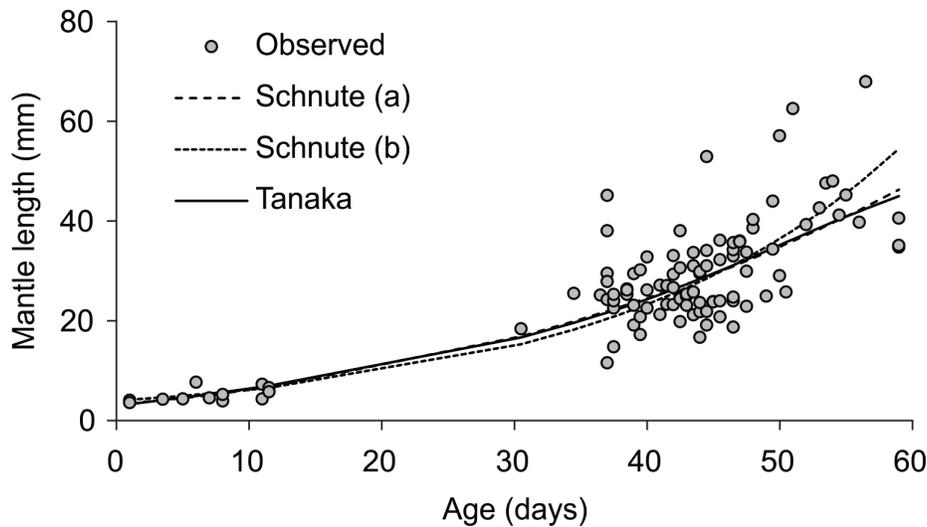


Figure 4. Growth models fitted to mantle length-at-age data for *Dosidicus gigas*. Tanaka model, and two cases of Schnute model assuming  $\rho = 0, \eta \neq 0$  (a), and assuming  $\rho = 0, \eta = 0$  (b). The best candidate growth model was Schnute (b).

which corresponds to paralarvae of 3.4 mm ML (the age paralarvae interval varied between 1 and 12 days; and the larger specimen was 7.5 mm) and juveniles of 34.9 mm ML, respectively. The parameters of the non-asymptotic growth models fitted to the length-at-age data are shown in Table 1.

The Schnute general model, assuming  $\rho = 0, \eta \neq 0$  (fig. 4), described an empirical power function; consequently, biological parameters about individual growth were not estimated.

For each candidate model  $AIC_c$ ,  $\Delta_i$  and  $w_i$  values are shown in Table 2. Based on the lowest  $AIC_c$  (-10.64) and the highest  $w_i$  (0.984) values, the Schnute general model ( $\rho = 0, \eta = 0$ ) was the function that describes the best fit the mantle length-at-age data. The other candidate models showed  $AIC_c$  differences ( $\Delta_i$ ) greater than 9, which indicates that these functions should not be considered.

TABLE 2  
 Growth model selection for *Dosidicus gigas*.

	$\theta$	$AIC_c$	$\Delta_i$	$w_i$
Schnute ( $\rho = 0, \eta = 0$ )	2	-10.64	0.00	0.984
Schnute ( $\rho = 0, \eta \neq 0$ )	3	-1.28	9.36	0.009
Tanaka	4	-0.79	9.85	0.007

The highest absolute daily growth rates (DGR) for the paralarval stage was 0.16 mm day<sup>-1</sup>, which occurred during the first five days of life, followed by a gradual decrease to 0.03 mm day<sup>-1</sup> (fig. 5a). Individuals between 12 and 31 days were not available. Juveniles at 35 days increased their absolute daily growth rate to a maximum of 1.66 mm day<sup>-1</sup> in individuals at 55 days. The estimations showed an increment in absolute daily growth rate, and a subsequent fall that probably can be explained by the smaller sample of size-at-age of organisms greater than 55 days old, although a linear trend was observed

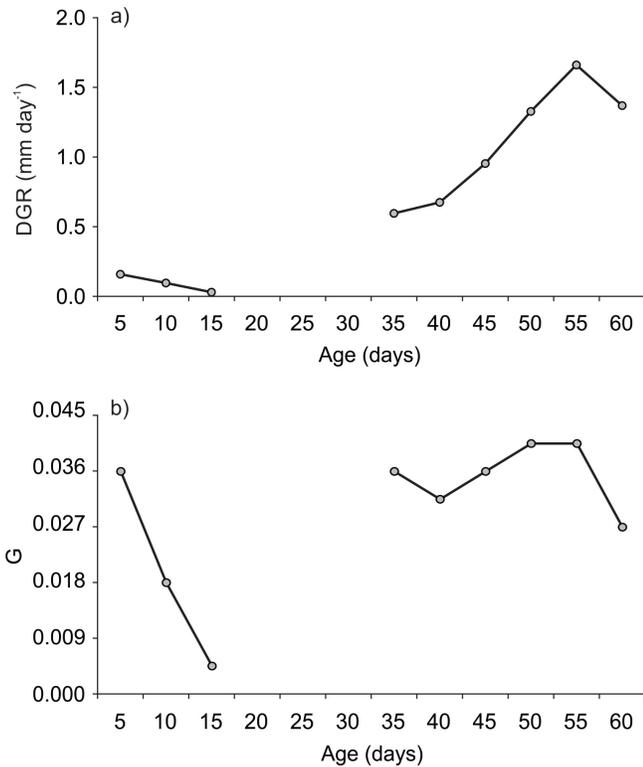


Figure 5. (a) Absolute daily growth rate (DGR), and (b) Instantaneous growth rate (G) of statoliths during early growth stages of *Dosidicus gigas*.

from 35 to 60 days old. The instantaneous growth rate decreases through the calculated range for paralarvae, decreasing from 0.036 (at age 1–5 days) to 0.005 (at age 11–15 days) (fig. 5b). For individuals from 35 days and older the instantaneous growth rate showed a new increment with an average of 0.035.

## DISCUSSION

The central Gulf of California is known as a spawning region for *Dosidicus gigas* (Gilly et al. 2006a). This region is also the main fishing area during autumn and winter and is near the coastal city of Guaymas in the State of Sonora. During spring and summer fishing intensity of this resource moves westward near Santa Rosalía in the State of Baja California Sur (Markaida et al. 2005; Gilly et al. 2006b). This seasonal pattern is characterized by the presence of mature males and females, which is routinely reported in the Gulf of California (Ehrhardt et al. 1986; Velázquez-Abunader et al. 2012). Hernández-Herrera et al. 1998 concluded that the spawning season of the *D. gigas* occurs from February to May off Guaymas, Sonora. However, Ehrhardt et al. 1986 concluded that the spawning seasons are not well defined and vary annually, based on changing oceanographic conditions. From the mantle length-body weight relationship, juveniles have power coefficient less than 3. A similar pattern was reported by Laptikhovskiy et al. 1993 for the

paralarvae of *Sthenoteuthis pteropus*. It was found that during early-stages development, the length and weight proportions changed and mantle length increased faster than weight. Consequently, organisms were found to be slimmer as they grew, and this shape change is related to muscle growth playing a role in improving paralarval locomotion in order to enhance survivability.

The growth increments in paralarvae and juvenile statoliths were clearly visible, for all individuals ages were determined, however an older age (59 days) was estimated for a juvenile of 34.9 mm ML, and the age of the larger organism (67.8 mm ML) was 57 days; the youngest organism aged corresponds to a paralarvae of one day and 3.4 mm ML. Rosa et al. 2013 described results found by Arkhipkin and Murzov 1986 explaining that individuals of *Dosidicus gigas* between 28 and 32 increments (4–4.5 weeks) had a mantle length between 9 to 10 mm, showing an exponential growth in these age classes. Yatsu et al. 1999 conducted artificial fertilization experiments of *Dosidicus gigas*; they did not report increments in the statoliths, suggesting that this was an effect of artificial rearing; they also reported mantle length at hatching measured 0.9–1.3 mm based on frozen specimens, and explained that the mean mantle length gradually increased, observing high variability within and among ages for this ontogenic development stage. In contrast, our observations were based on wild paralarvae and the individuals were not frozen. Comparatively, the morphological characteristics of wild organisms cannot be similar to those individuals obtained by artificial fertilization and captivity.

Absolute growth refers to the total increase in body material or body dimensions, while the absolute growth rate is defined as absolute growth over a given time period. If this rate is constant over time, then we have linear growth. Comparatively, an exponential growth is represented by the instantaneous growth rate (Pitcher and Hart 1982). According to Arkhipkin 2004, early stages of *D. gigas* have higher instantaneous growth rates than other members of the Ommastrephidae; their growth rate declined from 5%–8% in paralarvae and juveniles, and between 0.2%–0.4% in adults. These growth rates are influenced by different biotic and abiotic factors and cause changes throughout the life cycle of squid. The most important factors are availability of food and temperature (Forsythe 1993; Jackson and Moltschanivskiy 2001a). During ontogenetic development at the paralarvae stage, the proboscis begins its division between 5 and 6 mm ML (Nesis 1970, 1983). In our study, squid at this size decline in their absolute daily growth rate to 0.03 mm day<sup>-1</sup>. In our study all the paralarvae were in process of the proboscis division, and the decline in DGR possibly attributable to this morphological change; during this morphological reorganization the yolk sac

is absent and the capture apparatus (tentacles) begins to develop to make way for a more complex feeding that is mainly composed of crustaceans (Balch et al. 1985; Vecchione 1991; Laptikhovskiy et al. 1993; Vidal and Haimovici 1998).

The growth curve that was derived from the Schnute general model ( $\rho = 0, \eta \neq 0$ ) is equivalent to a linear or quadratic growth model. However, our data does not show this tendency; consequently, this growth model was not the best candidate. For the Schnute general model, the  $\tau_0$  parameter could be estimated; nonetheless, the parameter is undefined; and does not have the usual significance related to size 0 (Schnute 1981). The  $\Delta_i$  of this model ( $\rho = 0, \eta \neq 0$ ) was greater than 9, which means that this growth function should not be considered as a candidate growth model. A similar value was estimated for the Tanaka growth model. According to Burnham and Anderson 2002, if  $\Delta_i > 10$ , then the candidate growth model can be omitted because it did not represent the observed growth pattern; if  $4 < \Delta_i < 7$ , there was partial support for the model, and the candidate growth model could explain the individual growth pattern; and if  $\Delta_i < 2$ , then the candidate growth model had substantial support to explain the early growth pattern of *D. gigas*. The Schnute general model ( $\rho = 0, \eta = 0$ ) describes a power function and was identified as the best growth model candidate, where the Akaike weight was 0.984. This solution ( $\rho = 0, \eta = 0$ ) describes a curve that starts at the  $t$ -axis ( $t$  is time in days) and continues upward with unbounded, accelerated growth, which is restricted to the early development stages (Schnute 1981). This model has also been used for other squid species. For adult *Loligo noctiluca* (Jackson and Moltschanivskiy 2001b) only the Schnute model was used. For juvenile and adult *Illex argentinus* (Schwarz and Alvarez-Perez 2010), four growth functions (exponential, potential, Gompertz, and Schnute) were used; the authors concluded that the Gompertz growth model described females, and the Schnute growth model was the best growth model for males. For both models, the existence of two growth phases was observed, an initial rapid growth and a subsequent decline in growth rate.

Cephalopods show plasticity in their growth rates and thus identifying a pattern of growth is not easy (Jackson 2004). From our results, paralarval and juvenile *Dosidicus gigas* grow following a power function; it represents a special case of the Schnute growth model ( $\rho = 0, \eta = 0$ ) and was used in this study. During these early stages, the squid did not show a specific age where growth rate changes or length-at-age growth inflection. Consequently, Schnute ( $\rho = 0, \eta \neq 0$ ) and Tanaka models did not adequately describe growth within early stages for this species because they did not identify the change

from one period of growth to another. These changes are usually characterized by a discontinuity in development, which is commonly associated with major ontogenic events, such as transformation of the body shape (Balch et al. 1985; Vecchione 1991; Arkhipkin and Roa-Ureta 2005). Our study showed that the early stages of wild paralarvae of *Dosidicus gigas* grow following the Schnute growth model ( $\rho = 0, \eta = 0$ ).

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## ACKNOWLEDGMENTS

We thank Ira Fogel of CIBNOR for detailed English editorial services, Brad Seibel (responsible of both cruises) for logistic support on board *New Horizon* surveys, and Susana Camarillo-Coop for paralarvae and juvenile identification. C.Q.V. is a fellow of Comisión de Operación y Fomento de Actividades Académicas del Instituto Politécnico Nacional, and Programa de Estímulos al Desempeño de los Investigadores del Instituto Politécnico Nacional. V.Y.Z.B. is a recipient of a fellowship (CONACYT 224240). E.M.B. thanks to Consejo Nacional de Ciencia y Tecnología of México (CONACYT grant CB-2012-01 179322). We appreciate the comments of three anonymous reviewers and wish to extend our thanks to them.

APPENDIX 1

The Schnute general growth model (Schnute 1981), assuming  $\rho = 0, \eta \neq 0$  is:

$$L(t) = \left[ \lambda_1^\eta + (\lambda_2^\eta - \lambda_1^\eta) \times \frac{t - \tau_1}{\tau_2 - \tau_1} \right]^{1/\eta}$$

The case, assuming  $\rho = 0, \eta = 0$  is:

$$L(t) = \lambda_1 \times \exp \left[ \ln(\lambda_2/\lambda_1) \times \frac{t - \tau_1}{\tau_2 - \tau_1} \right]$$

where  $\tau_1$  is the first specified age,  $\tau_2$  is the second specified age,  $\lambda_1$  is the size at age  $\tau_1$ , and  $\lambda_2$  is the size at age  $\tau_2$ . Using  $\rho = 0, \eta \neq 0$ , we estimated age of theoretical zero size ( $\tau_0$ ) as:

$$\tau_0 = \tau_1 + \tau_2 - \left[ \frac{(\tau_2 \times \lambda_2^\eta) - (\tau_1 \times \lambda_1^\eta)}{\lambda_2^\eta - \lambda_1^\eta} \right]$$

The Tanaka model (Tanaka 1982) assumes a non-asymptotic growth phase based on indeterminate growth. The model has four parameters with an initial period of slow growth, a period of exponential growth, followed by an indefinite period of slow growth. The parameterized form of the model is:

$$L(t) = \frac{1}{\sqrt{\phi}} \ln | 2\phi(t - \chi) + 2\sqrt{\phi^2(t - \chi)^2 + \phi\gamma} | + \delta$$

where  $\phi$  is the rate of change of the growth rate,  $\chi$  is the age at which the growth rate is maximum,  $\gamma$  is the maximum growth rate, and  $\delta$  is a parameter that shifts the mantle length at which growth is maximum (Ebert 1999).

## INSTRUCTIONS TO AUTHORS

*CalCOFI Reports* is a peer-reviewed journal. Papers submitted for publication in the “Scientific Contributions” section are read by two or more referees and by arbiters when necessary; “Symposium” papers are invited by the convener of the annual symposium and are reviewed and edited at the convener’s discretion. The “Reports, Review, and Publications” section contains newsworthy information on the status of stocks and environmental conditions; the papers in this section are not peer reviewed; the CalCOFI Editorial Board will not consider unsolicited review papers.

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.

### Submission Guidelines

Submissions must be received no later than March 15 of the year in which publication is sought. Please submit manuscripts as MS word documents in electronic format via email to: calcofi\_coordinator@coast.ucsd.edu. (use Word; see “Manuscript Guidelines” below for more details on preparing tables and figures).

### The manuscript should contain the following parts:

1. A title page containing the manuscript’s title, your name, your institutional affiliation and contact information (address, telephone and fax numbers, e-mail address), and a word count
2. An abstract of no more than 150 words that succinctly expresses only the manuscript’s most central points, using the active voice
3. Body of the text, including any footnotes
4. Literature cited, in alphabetical order
5. Acknowledgments, if any
6. Tables
7. Figures and captions

### Manuscript Guidelines

**Length.** Unless previously approved by the Scientific Editor, manuscripts should not exceed 6,000 words, including title page, abstract, text body, footnotes, acknowledgments, and literature cited but excluding figures and tables.

**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. Indi-

cate 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.”

**Tables.** Use your word-processor’s *Table* feature, rather than spaces or tabs, to create the columns and rows. Use *minimal* formatting, and do not insert vertical or horizontal rules. Double-space the tables and use a standard font, such as Times or Times New Roman. Number the tables consecutively, and provide a brief title for each. Place explanatory material and sources in a note beneath the table. Place the tables in a separate file labeled, for example, “Smith tables.doc,” and place this on the disk with the text file. Provide one printout of each table, gathered together at the end of the text printout submitted. Be sure each table is specifically referred to in the text.

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For matters of editorial style, contributors should consult recent editions of *CalCOFI Reports*. Contributors may also refer to *The Chicago Manual of Style*, 15th ed. Whenever possible, write

in the first person, and use active verbs. Use the full name of a person, organization, program, or agency when mentioning it for the first time in your manuscript. Double-check the spelling of non-English words, and include special characters such as accents and umlauts. Use correct SI symbols for *units of measure* in figures, tables, and text (other units may be given in parentheses). Prepare *equations* in accordance with similar expressions in the printed literature.

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**BOOK:**

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