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Part I

REPORTS, REVIEWS, AND PUBLICATIONS

REPORT OF THE CALCOFI COMMITTEE 2012

CDFG HIGHLIGHTS

The California Department of Fish and Game changed its name to California Department of Fish and Wildlife (CDFW) at the end of 2012. The Marine Region said good-bye and thank you to our former regional manager, Marija Vojkovich, after years of dedication and service and welcomed our interim region manager, Paul Hamdorf. In 2013, the Marine Region will have a new regional manager. Dale Sweetnam jumped ship from CDFW to NOAA Fisheries and so we wish him well in his new position and thank him for his hard work as editor of the status of the fishery reports for CalCOFI. Dianna Porzio of CDFW has taken over this role as well as assisting with hosting the CalCOFI symposium in 2012 and working with contracts. We said farewell to Emily Jones, our DFG scientific aid who helped sort invertebrate larvae in the CalCOFI samples, bolstering what we know about the distribution and density of lobster phyllosoma larvae and Dungeness crab megalopae; both species managed by the state. The CalCOFI lobster phyllosoma data in combination with Dr. Johnson's historic phyllosoma data was used by Drs Koslow, Rogers-Bennett, and Neilson in a paper quantifying the influence of oceanographic conditions on lobster recruitment, which was published in CalCOFI Reports.

CalCOFI 2012 Symposium: Harmful Algal Blooms

The CDFW hosted the 2012 CalCOFI conference at Asilomar in California. The symposium of the conference focused on Harmful Algal Blooms (HABs) in the California Current. HABs can have serious impacts on not only on human health but the health of marine populations. There is also some evidence that HABs may be expanding in geographic scope as well as severity. This symposium explored the state of the art in HAB work in the California Current Ecosystem as well as explored ways to incorporate collecting data useful for the study of HABs into the CalCOFI program.

Marine Regulatory Changes

In 2012, the California Fish and Game Commission undertook rule-making actions that addressed marine and anadromous species. The Commission adopted changes to commercial or sportfishing regulations that include ocean and inland salmon, greenling, groundfish, saltwater basses, herring, and abalone.

Sportfishing regulation changes: http://www.fgc.ca.gov/regulations/2012/index.aspx#sf.

Marine Life Protection Act

California completed planning for a revised network of marine protected areas (MPAs) in 2012 that now stretches along the entire coast including offshore islands. California's system of MPAs is the largest scientifically based network in the contiguous U.S., comprised of 124 protected areas covering approximately 852 square miles or 16 percent of coastal state waters (approximately nine percent of which is in no-take MPAs). The Department assigned staff to support outreach for California's network of MPAs and to build awareness of boundaries and regulations, facilitate compliance, support enforcement actions, and understanding of the significance and purpose of MPAs. The Department, in partnership with the California MPA Monitoring Enterprise (a program of the Ocean Science Trust), began long-term planning for the five-year review of baseline monitoring results from the central coast MPAs. In 2012, MPA baseline monitoring data collection for the north-central coast MPAs was completed and data analyses started. The south coast MPA baseline monitoring program completed its first year of data collection. In the north, baseline monitoring planning has begun for the north coast MPAs.

Ocean Protection Council (OPC)

The OPC provided a grant ($990,000) to support the creation of a spiny lobster fishery management plan for California. Funds have been used to contract for an independent peer review of the lobster stock assessment, a facilitation group to run the advisory committee meetings, an economic report on the commercial and recreational lobster fisheries, the creation of a management strategy model for the California lobster, creation of an electronic lobster log for commercial fishermen, and outreach materials for recreational lobster fishermen. A draft lobster FMP will be ready for scientific and public review early next year. OPC work continued on the California Sustainable Seafood Initiative, which is a voluntary seafood certification and marketing program. OPC is working in conjunction with the Ocean Science Trust to conduct rapid fisheries assessments to identify which fisheries may be eligible for the program.

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 just under 109,450 MT based on a biomass estimate of 988,385. For the third year in a row, the commercial market squid fishery was projected to reach the seasonal catch limit of 107,049.6 MT before the season's end. During the 2012–13 season the fishery was closed early on November 21, and catch totaled 99,573 MT. The past three years have seen favorable oceanographic conditions with very high squid landings well above the 20-year average (70,500 MT) and the fishery reached its harvest guideline before the end of the season each year.

Aquaculture and Bay Management

The project completed its annual assessment of the San Francisco Bay commercial Pacific herring fishery for the 2012–13 season. The spawning biomass estimate for the 2012–13 season is 79,500 MT, well above the historical average (1979–80 season to the present) of 52,000 MT. This is the fourth consecutive year of increased biomass since the historic low during the 2008–09 season of 4,800 MT. Since the fishery reopened during the 2010–11 season, harvest targets for Pacific herring have been set at five percent or below as a conservation safeguard to allow continued recovery. This allows 95 percent of the spawning stock to be available as forage for a variety of species dependent on Pacific herring.

Invertebrate Fisheries Management

The CDFW's Marine Region Invertebrate Project abalone staff presented papers on southern California abalone recovery. The papers describe translocation studies of pink (*Haliotis corrugata*) and green (*H. fulgens*) abalones for recovery and assessing recovery of pink abalone by incorporating aggregation into a matrix model, and are now published in the *Journal of Shellfish Research* (Vol. 32). The Invertebrate Project's northern California abalone staff initiated the regulation change process for the northern California recreational abalone fishery. Proposed changes were intended to maintain a healthy fishery, based on declines in survey densities at Abalone Recovery and Management Plan (ARMP) key fishery index sites. The Department initiated the development of a spiny lobster fishery management plan. A Lobster advisory committee was appointed representing commercial and recreational fishermen, marine scientists, non-consumptive stakeholders, environmental organizations, and a federal fisheries agency. Implementing regulations for the new commercial Dungeness crab trap limit program were developed with the cooperation of the Dungeness crab task force in 2012. The new regulations will require fishermen to affix tags to their specific tier allotment of crab trap buoys starting with the 2013 crab season.

Ocean Salmon

In 2012, California ocean salmon fisheries were less constrained by conservation objectives used to protect stocks than in recent years. Commercial salmon fisheries were open for a season total of 375 days, the most fishing opportunity since 2004. Total commercial landings exceeded 214,800 Chinook salmon (1,150 MT), caught in 14,400 days fished. Average nominal ex-vessel price was $11.40/kg ($5.17/lb), with an ex-vessel value of over $13 million. Recreational fishing opportunity also increased, for a season total of 754 days. In 2012, nearly 122,900 Chinook were landed in 146,500 angler-days.

Groundfish

The Groundfish Project prepared documents for modifications to federal regulations for the 2013–14 recreational fishery. Modifications included an increased sub-bag limit and removal of the minimum size limit for bocaccio rockfish, retention of shelf rockfish while fishing inside the Cowcod Conservation Areas during the open season for groundfish in depths shallower than 20 fathoms, and extending the Mendocino Groundfish Management Area season length through Labor Day. A 50-fathom depth restriction was also implemented in the Southern Groundfish Management Area. In addition, documents were prepared to inform fishery managers on the increased catch of Pacific halibut in the recreational fishery, and the abundance and distribution of Pacific halibut in California waters.

California Recreational Fisheries Survey

The California Recreational Fisheries Survey (CRFS) and the Recreational Fisheries Data Project continued to successfully transition California's saltwater sport angler intercept survey to a Department-staffed program. In 2012, the projects jointly developed web-based data entry and estimation programs for the commercial passenger fishing vessel (CPFV), and primary private/rental boat (PR1) fishing modes. Staff entered CPFV and PR1 data, and produced estimates of total catch and effort. Following the 2011 review of CRFS sampling methods and estimation procedures by NOAA Fisheries' Marine Recreational Information Program consultants, project staff worked towards improving the survey designs for the recreational fisheries at man-made structures and secondary private/rental boat sites.

Fisheries Independent Assessment Project

Amendments to the management of saltwater bass (barred sand bass, kelp bass, and spotted sand bass) fisheries were presented to the Fish and Game Commission. A combination of increased exploitation rates and cooler oceanographic conditions in the early 2000s led to depressed populations of saltwater bass in southern California. These declines, coupled with constituent input, lead the Commission to adopt an increase in the minimum size limit and a reduction in the bag limit in November 2012. Staff will continue to monitor fishery-dependent and independent data for the basses to assess the effectiveness of the new regulations. In addition, a collaboration between the Santa Monica Bay Restoration Commission and CDFW resulted in the successful use of an ultrasound machine to non-lethally identify the sex of California halibut, potentially identifying this as a monitoring tool for future studies.

Northern and Central California Finfish Research and Management Project

Ongoing project work included with sampling, research, and monitoring tasks such as: ageing of thin sections of halibut otoliths and whole surfperch otoliths; sampling and monitoring commercial halibut, hagfish, and white seabass fisheries; sampling and monitoring recreational halibut fisheries and fishing tournaments; conducting life-history studies of surfperch using fishery-independent hook-and-line sampling; and estimating recreational beach fishery effort through instantaneous angler counts in Monterey County. The project supervisor represents the Department at the Monterey Bay National Marine Sanctuary Advisory Council.

New project work included the following: determination of maturity and fecundity for central coast California halibut, obtaining sublegal-sized halibut using fishery-independent beach seines for maturity studies, estimating age of neonatal redtail surfperch otoliths, reviewing sportfishing regulatory proposals from the public submitted to the Fish and Game Commission, completing a guide for CRFS samplers to determination sex of surfperch, applying a Spawning Potential Ratio model to surfperch populations, completing draft chapters for a future halibut Fishery Management Plan, representing the Department on the Strategic Wildlife Action Plan revision and update, investigating incidental take of great white sharks in commercial gill net fisheries, and representing the Marine Region on a Department sturgeon task force. Staff completed halibut and surfperch status of fishery reports, a CalCOFI halibut fishery review, and an annual Sport Fish Restoration Act Progress Report.

NOAA HIGHLIGHTS

CalCOFI Ichthyoplankton Update

During the past year the SWFSC Ichthyoplankton Ecology group faced moving the laboratory and sample archive into the new SWFSC building after having occupied the same laboratory space in the old building for 49 years. This grand effort was simultaneously managed with processing current CalCOFI, spring sardine, and SaKe survey plankton samples and spending considerable time at sea. In addition, the group managed to continue their 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 1981 to the present.

Much of the laboratory effort 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 will be applied to ethanol-preserved CalCOFI samples to develop a time series for eggs from 1997 to the present. During the past year staff finished sorting eggs and larvae from ethanol-preserved samples from winter cruises in 2004 and 2011, adding these years to the list of completed ethanol-preserved samples from 1998, 1999, 2002–05, and 2011. The ichythoplankton lab continues to seek funds to hire a technician to sort all of the ethanol-preserved samples, and have submitted a proposal to NOAA's Fisheries and the Environment (FATE) program requesting one year of funding for a full-time technician that will focus exclusively on the ethanol samples. The lab has also gained a master's student from University of San Diego who will be 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, staff analyzed CalCOFI data together with ichthyoplankton and environmental data collected in Oregon between 1997 and 2011 by Oregon State University and the NWFSC. In collaboration with Toby Auth and Ric Brodeur from Oregon, staff prepared a manuscript currently under revision for the journal *Marine Ecology Progress Series*. This manuscript shows fluctuations in larval abundances of taxa common to both regions were not coherent between regions during that time, and that these fluctuations were well explained by environmental variability (measured as water depth, temperature, and salinity) off Oregon but not off southern California. A similar study using CalCOFI data together with IMECOCAL data is underway, in collaboration with Martín Hernández-Rivas and co-workers from CICIMAR. These studies should help inform NOAA's California Current Integrated Ecosystem Assessment program.

Staff also 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.

The highlight of the year was the group's move into the new ichthyoplankton laboratory and sample archive room, both great improvements over the old facility. The new lab features 12 microscope workstations, each with an adjustable snorkel and data portals, additional countertop work spaces with data portals, three computer workstations, a zooscan station, and separate hoods and sinks on opposite sides of the lab for processing ethanol- and formalin-preserved samples. The Ahlstrom library is housed along the west wall of the laboratory, and the reference collection is housed on high density shelving in an adjacent room. The sample archive is in a large, H3-rated controlled environment room equipped with high density shelving, a halon fire suppression system, and explosion-proof lighting.

Yet another benefit of the new SWFSC building is the state-of-the-art Pacific Room, which will act as the site for the 2013 CalCOFI conference from December 9–11 and mark the first CalCOFI conference to be held on SWFSC grounds. Unlike conference rooms of the previous SWFSC building, the Pacific Room boasts a 200 person capacity, allowing for larger conferences previously relocated to other NOAA sites. This provides an exceptional benefit for multinational interactions during larger functions, such as CalCOFI, as SWFSC's Mexican counterparts have greater access to San Diego than sites to the north.

Spring Coastal Pelagic Species Cruise

The spring Coastal Pelagic Species (CPS) cruise relies on a 25 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 of suite 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. This year's spring CPS survey began badly in the second week of April 2013. Acoustic calibration on *Ocean Starr* took place dockside on April 9 as planned; however, departure was delayed as a result of mechanical problems, including the winch metering and failure of the general/fire/man overboard/abandon ship alarm systems. The net effect of these problems was a loss of three and a half days of survey time. The lost time was shared with the following rockfish cruise, meaning that both cruises lost a day and a half of survey time. Weather was windy and rough both in the Southern California Bight and off the central coast during much of the survey. Numbers of sardine eggs were low but with a concentration of eggs on the central coast. *Shimada* made better progress than the *Ocean Starr*, despite an erratic cruise track brought on by poor weather. *Ocean Starr* leg 1 ended on Friday April 19 in Port San Luis, much to the relief of some of the staff aboard.

The near real-time sardine habitat model and overlaid CPS density and eggs from April 13 shows that there were considerable areas of favorable potential sardine spawning habit where no sardine eggs were found this year. Trawl catches yielded low numbers of sardine (which are needed for interpretation of both the DEPM and acoustic biomass estimates). *Shimada* leg 2 of the spring CPS cruise ended on April 30 in San Francisco, and leg 2 of *Ocean Starr* ended on May 4 in San Diego. Staff from *Shimada* ended the cruise with a successful outreach event arranged with the Exploratorium in San Francisco.

The spring ATM portion of the survey was conducted from NOAA FSV *Bell M. Shimada* and chartered FV *Ocean Starr*. The survey totalled ~2,000 nmi of trackline spanning over ~50,000 nmi^2 and the distribution of the northern stock of sardine predicted by a model of potential sardine habitat. Small catches of large sardine spanned the latitudinal extent of the survey, but they were mostly far offshore, north of Point Conception, whereas Pacific and jack mackerel were predominantly found to the south. The acoustic backscatter attributed to CPS was generally very low. The largest CPS backscatter was located towards the western ends of a couple of transects.

Summer Sardine and Hake Acoustic-Trawl Surveys (SaKe)

During the summer, the SWFSC conducted an acoustic trawl method based survey for small pelagic fish (henceforth referred to as CPS); e.g., Pacific sardine (*Sardinops sagax*), jack (*Trachurus symmetricus*) and Pacific mackerel (*Scomber japonicus*), northern anchovy (*Engraulis mordax*), and Pacific herring (*Clupea pallasii*). For this summer survey sampling is combined with survey personnel and survey objectives of the Northwest Fisheries Science Center to develop an acoustic-trawl based measure of hake abundance. This year the combined sardine-hake survey (SaKe) surveyed the nearshore extending to just beyond the shelf-slope break spanning from San Diego to northern Vancouver Island (VI), Canada. The ATM uses ship-based, multiple-frequency echosounders to map the distributions of CPS; and trawl catches to apportion the echo energy to species and convert those values to animal densities. During daylight, from sunrise to sunset, multifrequency echosounders (38, 70, 120, and 200 kHz) were used to sample acoustic backscatter from CPS and hake. During nighttime, surface trawls were used to identify the proportions of CPS and their lengths. The data were combined to estimate density-weighted fish-length distributions. This procedure resulted in maps of fish densities and estimates of their biomasses, by species and lengths (presented elsewhere).

The summer ATM survey was conducted solely from *Shimada*, over approximately 80 days during June–August. The survey totaled ~4,000 nmi of trackline spanning over ~45,000 nmi^2 and the expected distribution of the northern stock of sardine. North of Point Conception, transects were spaced 10 nmi, generally, extending from 40 to 1500 m depths, to at least 35 nmi offshore. During the summer survey, the habitat in the Southern California Bight was unsuitable for the northern stock of sardine. Some large sardine were caught far offshore between San Francisco and Humbolt, California, and nearshore between central Oregon (OR) and central Washington (WA). Anchovy were the only small pelagic fish caught south of Monterey Bay. Larval anchovy were caught offshore, just south of the Columbia River. Only a few mackerels were caught throughout the survey. Herring and smelt (family Osmeridae) were relatively abundant, however, with catches spanning from southern OR to the northern end of Vancouver Island. CPS backscatter was highest in the areas where sardine were caught (near San Francisco and between central OR and central WA), and nearshore off Vancouver Island, where herring were caught. This was the second year that a SaKe cruise has been conducted and refinements continue to be made.

SIO HIGHLIGHTS

Four quarterly CalCOFI cruises occurred on the RV *New Horizon* (NH), RV *Bell M. Shimada* (SH), and RV *Ocean Starr* (OS) in 2012: 1202NH (January 27–February 13), 1203SH (March 27–April 7), 1207OS (July 9–26), and 1210NH (October 19–November 5). 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, including routine sampling and observations of lower trophic levels and, led by Tony Koslow (SIO), of micronekton. Most data from these cruises have been rapidly made available on the Scripps CalCOFI, CCE-LTER, NOAA SWFSC, and CDF&G Web sites. More than 35 publications by SIO and other university scientists in 2012 were based on CalCOFI results. Selected papers are mentioned below.

Climate control of wind-forced upwelling in the southern California Current system was investigated by statistical analysis of observations (Macias et al. 2012a,b). The North Pacific Gyre Oscillation was shown to be an important modulator of upwelling in this region (Chenillat et al. 2012). CalCOFI data were used in a study of the effects of internal waves on the surf zone (Wong et al. 2012).

Nutrient and oxygen dynamics in the North Pacific, and their relation to climate and upwelling, were the subject of several papers (Deutsch and Weber 2012; Send and Nam 2012; and Pierce et al. 2012). Long-term variability of the species composition of the phytoplankton of the CalCOFI region was characterized by Venrick 2012. Bargu et al. 2102 suggest that domoic acid in toxic *Pseudo-nitzschia* may have caused a seabird frenzy that "eventually led [Alfred] Hitchcock to make his film [The Birds]." Two papers used satellite images of sea surface temperature and color (due to chlorophyll *a*) to document patterns of phytoplankton abundance in time and space (Kahru et al. 2012a,b).

Zooplankton collections were analyzed for nitrogen isotopes (Ohman et al. 2012) and to compute mortality rates (Ohman 2012). Time series of the abundance of phyllosoma larvae of spiny lobster (*Panulirus interruptus*) were studied and will be useful in its management (Koslow et al. 2012). Molecular methods were developed to identify eggs of fish in CalCOFI collections (Gleason and Burton 2012). CalCOFI data were used to study the spawning habitat of bocaccio (*Sebastes paucispinis*) within and around a marine reserve (Hitchman et al. 2012). On a larger scale, the spatial structure of ichthyoplankton assemblages was described for the central and southern California Current regions (Suntsov et al. 2012). Seabird hotspots (Suryan et al. 2012) and seabird relation to climate change (Sydeman et al. 2012) used CalCOFI observations.

A process study of fronts in the southern California Current system by the CCE-LTER program (Landry et al. 2012) made use of CalCOFI data. One paper focused on the use of inverse models of plankton trophic flows (Stukel et al. 2012). A study of the use of nonlinear time series analysis to infer about causation in complex systems (Sugihara et al. 2012) included CalCOFI results, with implications for understanding the dynamics of marine ecosystems and contributing to fisheries management.

Finally, Scripps CalCOFI leadership changed in 2013. Tony Koslow stepped down as Director of Scripps CalCOFI and was replaced by Dave Checkley on 1 July 2013. Tony directed Scripps CalCOFI from 2007 to 2013. During that time, despite fiscal challenges, CalCOFI thrived and was enhanced due to the efforts of Tony and colleagues at SIO, NOAA, CDF&G, and the CCE LTER program. Tony was instrumental in developing a scientific acoustic-trawl program ancillary to CalCOFI and the analysis of market squid paralarvae and spiny lobster phyllosoma in CalCOFI collections. Collectively, those efforts have valuably enhanced our understanding of midwater micronekton, market squid, and spiny lobster in the CalCOFI region, with implications for management. They also contributed to PhD research at Scripps. In 2012, the North Pacific Marine Science Organization, PICES, presented its Ocean Monitoring Service (POMA) Award to CalCOFI. Tony and Steven Bograd (PMEL, NOAA) accepted the POMA award on behalf of CalCOFI from PICES at its annual meeting in Hiroshima, Japan. Scripps expresses its appreciation to Tony for his leadership of Scripps CalCOFI.

The CalCOFI Committee
Laura Rogers-Bennett, CDFW
Sam McClatchie, NMFS
Dave Checkley, SIO

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REVIEW OF "REGIONAL FISHERIES OCEANOGRAPHY OF THE CALIFORNIA CURRENT SYSTEM AND THE CALCOFI PROGRAM" BY SAM McCLATCHIE

PAUL FIEDLER, 22 JULY 2013

We have all heard the accolades: CalCOFI is the "world's premier ocean monitoring program," based upon "extensive physical and chemical oceanographic studies, detailed observations of phytoplankton and zooplankton, and comprehensive analyses of fish eggs and larvae." (Ohman and Venrick 2003). John Isaacs called it a "profound and exciting experiment." (Behrman and Isaacs 1992). A review of the historical and scientific basis of the CalCOFI program would seem to be an ambitious endeavor. Sam McClatchie, SWFSC fisheries oceanographer and member of the CalCOFI committee, has taken on this task but appropriately constrained the scope and target audience of the review. The result is his recently published book, *Regional Fisheries Oceanography of the California Current System: The CalCOFI Program*. His expressed intent was "to extract themes relevant to current research rather than to prepare a compendious review of the literature," for use by "graduate students and researchers in oceanography with a special interest in the California Current System." The result is an enjoyable summary of the scientific principles behind the program, the history of the motivating questions and resulting sampling decisions, and the dedicated people involved.

The book is a comprehensive survey of the study of fisheries oceanography in a region with a long history of pioneering oceanographic investigations. It covers relevant scientific principles, regional fisheries, and the history and potential of applying this science to management problems, i.e., fisheries oceanography. The book is well organized, progressing from (1) a quick survey of fisheries, to (2) basic oceanography of the region, to (3) CalCOFI survey design and methodology, to (4) patterns of environmental variability affecting fish populations over a range of temporal scales, to (5) pioneering studies of predation on fish larvae, to (6) methods for assessing fish stock population parameters, to (7) new paradigms of fisheries science that will continue to evolve based on the CalCOFI data set and the history described in this book. The author does not shy from explicitly stating the limitations of shipboard sampling. He shows how much of our knowledge of this system has been gained by satellite remote sensing and is now being expanded and refined through data collected by drifters and gliders and assimilated into comprehensive physical/biological models.

The writing style is first-person and somewhat casual, so that the book is easier to read than the typical textbook. What really sets the book apart is the nearly fifty pages of "perspectives" contributed by 24 scientists and students who have been involved firsthand in CalCOFI. Unfortunately, many early contributors are no longer with us, but they are remembered here. The vignettes reveal the enthusiasm and dedication of those who work in this field, but more importantly give insight into the decisions, innovations, and compromises that have shaped CalCOFI over the years.

The book is both a valuable summary of regional fisheries oceanography and of the history of fisheries and applied science on the California coast. It will be a useful review and reference point for undergraduate and graduate school students, for practicing scientists, and even for the interested public.

Behrman, D., with J. D. Isaacs. 1992. John Isaacs and his Oceans. AGU ICSU Press. 230 pp.

Ohman, M. D. and E. L. Venrick. 2003. CalCOFI in a changing ocean. Oceanography 16(3): 76–85.

REVIEW OF SELECTED CALIFORNIA FISHERIES FOR 2012: COASTAL PELAGIC FINFISH, MARKET SQUID, PACIFIC HERRING, GROUNDFISH, HIGHLY MIGRATORY SPECIES, WHITE SEABASS, PACIFIC HALIBUT, RED SEA URCHIN, AND SEA CUCUMBER

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SUMMARY

In 2012, commercial fisheries landed an estimated 162,290 metric tons (t) of fish and invertebrates from California ocean waters (fig. 1). This represents a decrease of 12% from the 184,825 t landed in 2011, 18% from the 197,956 t landed in 2010, and a 36% decline from the peak landings of 252,568 t observed in 2000. The preliminary ex-vessel economic value of commercial landings in 2012 was $236.1 million, once again increasing 19% from the nearly $198 million generated in 2011, and $175 million in 2010.

Coastal pelagic species made up three of the top five volume fisheries in 2012. California market squid was once again the largest volume, and second highest value fishery in the state with over 97,077 t landed with an ex-vessel value of approximately $68.3 million. Although there was a 20% decrease in landings from 2011 (121,556 t), the fishery was closed for a third year in a row because landings were once again projected to reach the seasonal catch limit of 107,048 t. The Pacific sardine fishery has long been one of the largest in the state. In 2012 it was the second largest in volume and eighth largest in value, landing 23,037 t worth $5.1 million. This was a 17% decrease from 2011 (27,714 t). 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 California, Oregon, and Washington totaled 101,551 t, a 117% increase from the 46,745.5 t landed in 2011. The recommended HG for 2012 season was 109,409 t based on a biomass estimate of 988,385 t. Although the HG was not met, the fishery was temporarily closed during the second allocation period (1 July–14 September) which only lasted 54 days. Pacific mackerel was the fifth largest volume fishery with 3,485 t landed, increasing 157% from 2011 (1,357 t). Northern anchovy registered a slight increase, while jack mackerel registered a slight decrease in landings totals.

Dungeness crab was California's third largest volume fishery with 11,696 t landed, an increase from 9,344 t landed in 2011, but it emerged as the highest valued fishery in the state with an ex-vessel value of over $85.6 million, increasing from $51.5 million in 2011.

Red sea urchin was California's fourth largest volume fishery with 5,153 t landed, and the state's sixth largest value fishery worth $8.3 million. The proportion of yearly statewide catch was 77% in the south and 23% in the north. From 2003–07, the southern fishery has averaged 87% of the yearly statewide catch, but in the most recent five years (2008–12), average catch was 71%. An increase in the north and decrease in the south in recent years may be attributed to the addition of new active divers entering the northern fishery, and divers in the southern fishery participating in more lucrative dive fisheries such as sea cucumber. Sea urchin permit renewals totaled 305 in the 2012 season, and has been consistently near 300 since dropping from 340 in 2004 with a steady decline toward the "capacity goal" of 300 set by regulation in the early 1990s.

Fishing effort in California for Pacific herring in 2012 continued at reduced levels when compared to historic benchmarks. The fishery was closed during the 2009–10 season to allow for stock recovery after the fishery experienced one of the lowest landings in its 35 year history. During the 2012 sac roe season (January 2012–March 2012), the San Francisco Bay fleet landed 1,482.3 t, 94.6% of their 2011 landings (1,566.7 t) and 88.5% of the 1,673.8 t quota. Due to a decrease in base price, the statewide ex-vessel value of the herring sac roe fishery fell from $885,951 in 2011 to $493,468 in 2012. The San Francisco Bay herring eggs-on-kelp fishery landed 0 t during the 2012 season and has been inactive since the fishery closure in 2009–10. The commercial herring fishery is closely regulated through a catch-quota system to provide for adequate protection and utilization of the herring resource. The California Department of Fish and Wildlife (Department) conducts annual assessments of the spawning herring population in San Francisco Bay as part of its ongoing monitoring and management of the fishery. The spawning biomass estimate for the 2012 season in San Francisco Bay is 55,324 t, a 6.4% increase over last season's estimate of 51,785 t. This is the third consecutive year of increased biomass since the historic low of 4,394 t during the 2009–10 season when the fishery was closed for the first time ever by the California Fish and Game Commission (Commission).

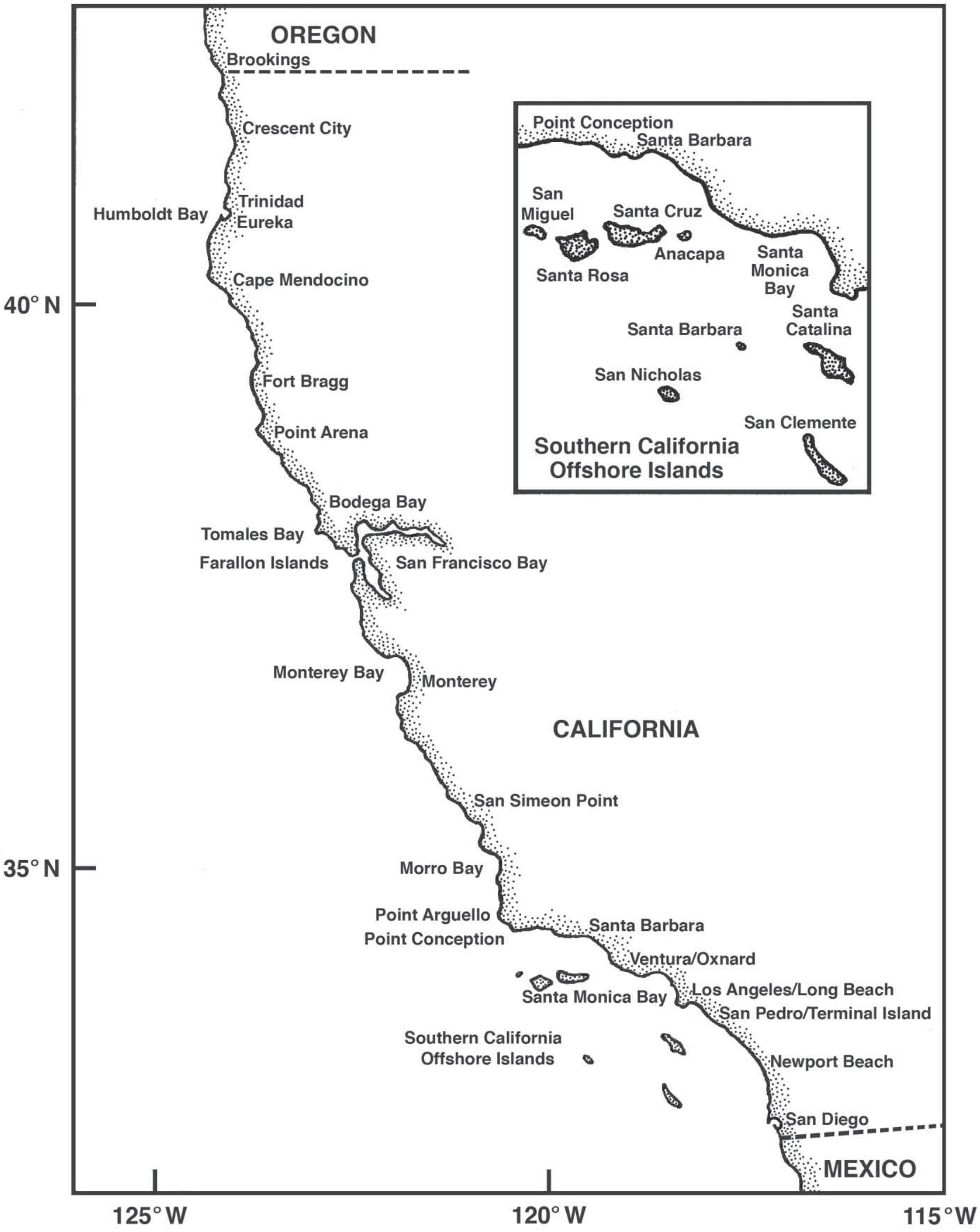

Figure 1. California ports and fishing areas.

More than 90 species of bottom-dwelling marine finfish are included in the federally-managed groundfish fishery. 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. In 2012, California's commercial groundfish landings totaled 6,085 t, with an estimated ex-vessel value of $17.8 million dollars. This represents a 14% decline in landings (7,113 t) and a 28% decline in ex-vessel value ($24.6 million) compared to 2011. In 2012, California recreational anglers participated in an estimated 867,000 trips targeting groundfish which represents a 4% increase from 2011 (830,000 trips). An estimated 1,656 t of groundfish were taken by the recreational fishery in 2012, a 4% increase from 2011 (1,534 t).

In Highly Migratory Species fisheries (HMS), the federal Shark Conservation Act of 2010 was signed into law January 4, 2011, specifying that no shark is to be landed without fins being naturally attached. Additionally, California passed AB 376—a bill banning the possession and sale of shark fins, beginning January 1, 2012.

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

Data Source: Commercial Fisheries Information System (CFIS)

While shark fisheries in California are still legal, and those possessing the proper license or permit are allowed to retain shark fins under California law, sales and distribution are prohibited.

In addition to being a popular sport fish, white seabass is also targeted by a commercial fishery. The commercial white seabass fishery landed 171 t in 2012, a 31% decrease from the 2011 total of 247 t. The total ex-vessel value in 2012 was $1,365,758, approximately 16% less than in 2011. The estimate of recreational take decreased by 13% to 107 t in 2012 from the previous year's total of 123 t. The combined commercial and recreational catch for 2012 was 278 t. In the 2011–12 fishing season, which runs from September 1 through August 31 the following year, the total recreational and commercial harvest was 302 t, 55% of the allowable catch which is set at 540 t.

Pacific halibut is a desirable commercial and recreational target species ranging from the Bering Sea in Alaska to central California. The entire North Pacific halibut resource is internationally managed through the Halibut Treaty (Treaty) between the United States and Canada. The International Pacific Halibut Commission (IPHC) was established to conduct research and management activities in the waters of the parties to the Treaty. In California, both the commercial and recreational Pacific halibut fisheries have experienced large fluctuations in catch over the last century. The Pacific Fishery Management Council (Council) and the National Marine Fisheries Service (NMFS) are authorized by the Treaty to manage Pacific halibut in what is known as "Area 2A" which includes the waters off of the three West Coast states (Washington, Oregon, and California). The IPHC annually allocates a portion of the harvestable Pacific halibut to Area 2A, which the Council divides among the tribal, commercial, and recreational fisheries through a Catch Sharing Plan (CSP). From 2000–12 the directed commercial fishery in California averaged landings of 0.08 t net weight per year. Trace amounts of Pacific halibut were landed in California from the directed commercial fishery during 2012. Estimated recreational catch of Pacific halibut in California during 2012 was 11.7 t net weight. Recent

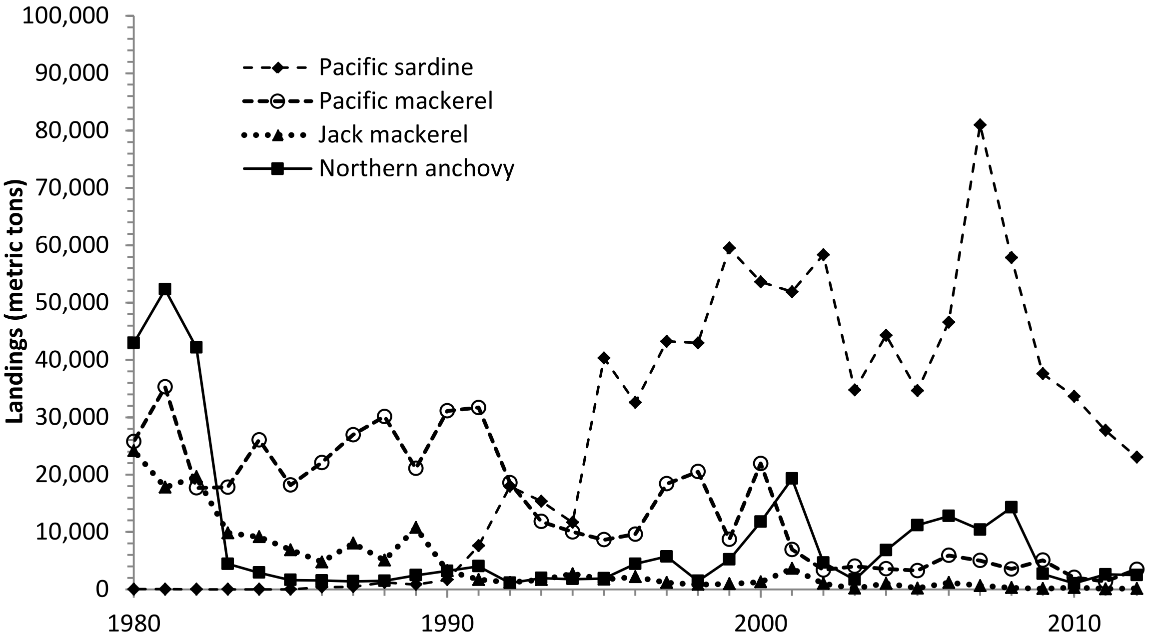

Figure 2. California commercial landings of Pacific sardine (*Sardinops sagax*), Pacific mackerel (*Scomber japonicus*), jack mackerel (*Trachurus symmetricus*), and northern anchovy (*Engraulis mordax*), 1980–2012.

catches have exceeded the recreational catch quota set by the IPHC by an average of 7.4 t and the highest recent catch occurred in 2009 when an estimated 15.8 t were caught. It is not known whether increased catch reflects an increase in Pacific halibut abundance, angler interest, or effort due to limited angler opportunities in the recreational salmon and groundfish fisheries. The 2012 Pacific halibut stock assessment indicated that biomass was stable, although less than previously thought. The 2012 stock biomass is above the harvest policy threshold precautionary level, but is approximately 33,566 t, or 28% less than was estimated in the 2011 assessment.

Commercial harvesting of warty sea cucumber and giant red sea cucumber has increased dramatically in California over the last decade in response to growing foreign demand from Chinese and Korean based markets. In 2012, there were 83 dive and 16 trawl permits issued, with dive landings reaching 123 t with an ex-vessel value worth $1.2 million. This was a 50% reduction in landings when compared to 2011 (247 t), despite the fact that the average price reached a record high of $8.50/kg ($3.85/lb) in 2012. In 2011, the fishery set an all-time record ex-vessel value of $2.2 million. The 2012 dive landings were the lowest since 2005 when most of the fishery began to sell their product in a cut/processed state. Although the dive fishery mostly targets warty sea cucumber, dive landings of giant red sea cucumber reached a record high in 2012 of 23 t, which comprised 19% of all dive landings. In 2012, trawl landings reached 89 t with an ex-vessel value of $728,469, a 37% reduction in landings when compared to the 142 t landed in 2011, valued at a record high of $1.2 million (ex-vessel).

Coastal Pelagic Finfish

Managed jointly by the Pacific Fishery Management Council (PFMC) and the National Marine Fisheries Service (NMFS) under the Coastal Pelagic Species Fisheries Management Plan (CPS FMP), Pacific sardine (*Sardinops sagax*), Pacific mackerel (*Scomber japonicus*), jack mackerel (*Trachurus symmetricus*), and northern anchovy (*Engraulis mordax*) form a finfish complex known as the Coastal Pelagic Species (CPS). These fisheries bring millions of dollars in revenue to the economy every year. In 2012, total commercial landings for these species equaled 26,805 t (table 1), with a combined ex-vessel value of over $6.4 million. When compared to landings in 2011, 2012 saw a 15.5% and 0.3% decrease in volume and value, respectively. Once again, the Pacific sardine fishery was the largest of these four in 2012, comprising 85.9% of the total volume and 80% of the total value.

Pacific Sardine. The Pacific sardine fishery in California has long been one of the largest in the state. In 2012 it was the second largest in volume and eighth largest in value, landing 23,037 t worth $5.1 million. This was a 17% decrease from 2011 (27,714 t). Commercial landings of sardine averaged 44,990 t over the twelve-year period from 2001–12 (fig. 2). Nearly all (95.8%) of California's 2012 sardine catch was landed in Los Angeles (77.4%, 17,838 t) and Monterey (18.4%, 4,241.4 t) port areas (table 2).

TABLE 2
Landings (metric tons) of Pacific sardine (*Sardinops sagax*) and Pacific mackerel (*Scomber japonicus*) at California port areas in 2012.

	Pacific sardine		Pacific mackerel	
Area	Landings	% Total	Landings	% Total
Monterey	4,241.4	18.4	100.2	2.9
Santa Barbara	962.2	4.2	53.2	1.5
Los Angeles	17,838.0	77.4	3,331.8	95.6
Total	23,041.6	100	3,485.2	100

*Los Angeles totals include Oceanside/SoCal landings

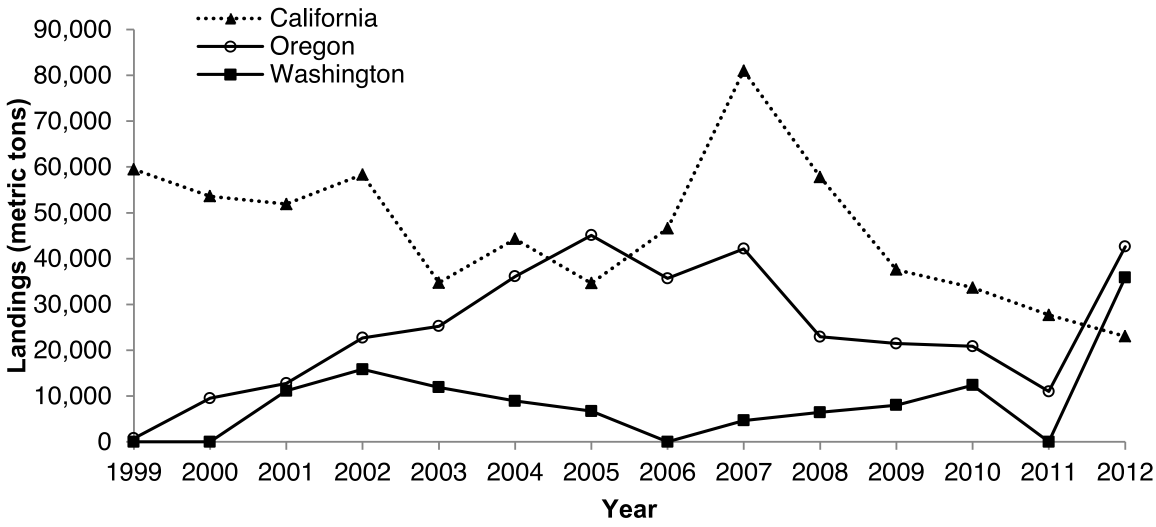

Figure 3. Commercial landings of Pacific sardine (*Sardinops sagax*) in California, Oregon, and Washington, 1999–2012.

Landings of sardine have steadily increased in the Pacific Northwest and Canada since the recent expansion of the sardine fishery in 1999. 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. Combined landings of Pacific sardine for California, Oregon, and Washington totaled 101,551 t, a 117% increase from the 46,745.5 t landed in 2011 (fig. 3). The Pacific sardine harvest guideline (HG) for each calendar year is determined from the previous year's stock biomass estimate (of >=1-year-old fish on 1 July) in U.S. and Mexican waters. The recommended HG for 2012 season was 109,409 t based on a biomass estimate of 988,385 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.

The U.S. West Coast fisheries harvested a large portion (93%) of the HG, same as the previous year (93%). The 1st allocation period (1 Jan–30 June) lasted through the entire allocation period, 181 days. The 2nd period (1 July–14 September) lasted 54 days; the fishery was officially closed on August 23rd. The 3rd allocation period (15 September–31 December) also lasted the entire allocation period, 107 days.

Oregon landings appeared to be leveling off since 2008, but experienced a large jump in 2012. Landings totaled 42,618 t, an increase from 2011 (11,023 t). In 2012, Oregon exported 218 t of sardine product worth $324,809.

Washington landings totaled 35,891.5 t in 2012, after landing no Pacific sardine in 2011. They exported 76,986.3 t of sardine product to 32 countries, totaling $63.9 million in revenue.

The recreational Pacific sardine catch as sampled from the California Recreational Fisheries Survey (CRFS) was 62 t (854,000 fish), much larger than the 22 t (469,000 fish) in 2011 (82% increase, in number of fish). The majority (91%) of the fish landed were from man-made structures, such as piers.

Pacific Mackerel. In 2012, landings of Pacific mackerel jumped 157% from 2011. Landings in California totaled 3,485 t (table 1, fig. 2), generating $872,820 in ex-vessel revenue. Industry exported 660.5 t of mack-

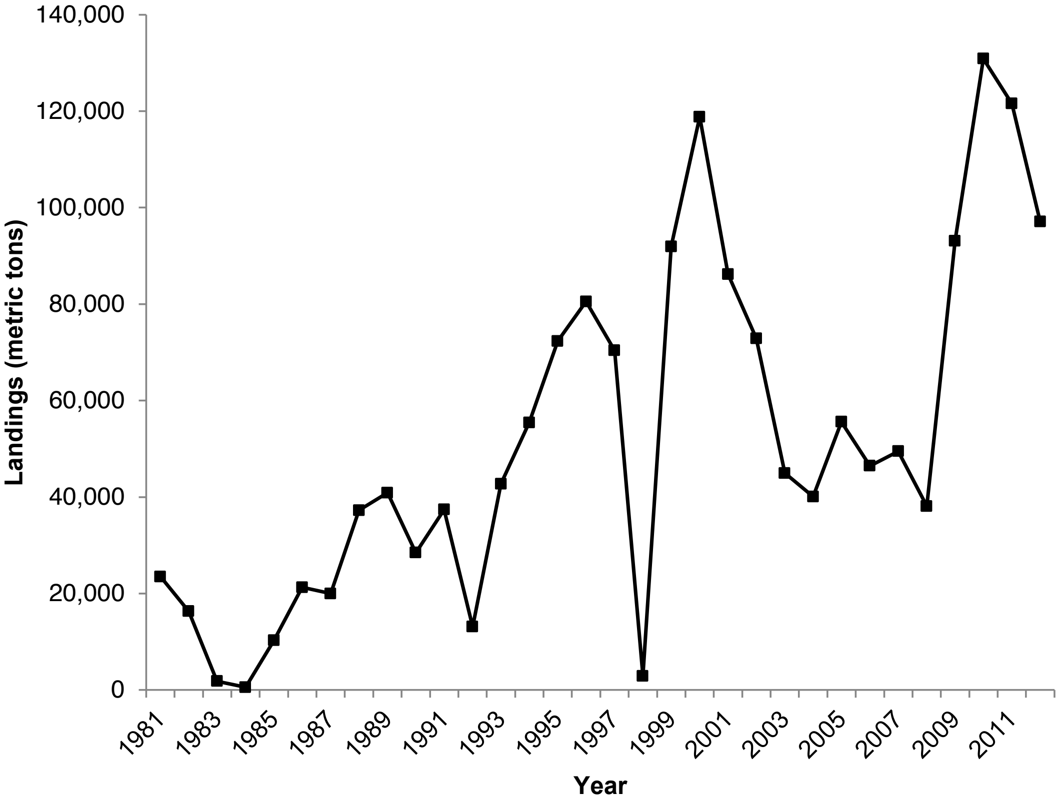

Figure 4. California commercial market squid (*Loligo (Doryteuthis) opalescens*) landings, 1981–2012.

erel product, mainly for human consumption, valued at nearly $604,250, to 13 countries. The Philippines (234.4 t), Australia (113.1 t), and Egypt (94 t) received over 66% of this product.

Oregon reported 1,779 t of Pacific mackerel landed for 2012, with an ex-vessel value of $171,178. This is a 253% increase from the 2011 catch of 7 t. For Washington in 2012, 691.6 t were landed with an ex-vessel value of $159,487, the first landings of mackerel since 2005. Exports showed that 165.6 t were exported to three countries, valued at $189,275. Washington landings of Pacific mackerel have been typically low, with the greatest landings having occurred in 2012.

At the start of the 2012–13 season, which runs from 1 July to 30 June the following year, the PMFC set the HG at 30,386 t, with a 10,128 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 2012 recreational Pacific mackerel catch as sampled from CRFS was 144 t (847,000 fish), a 13% (24% by number of fish) decrease from 2011. A total of 33,000 fish were reported landed on CPFVs.

Jack Mackerel. Representing 0.5% of the total catch of federally managed CPS finfish landings in California for 2012, jack mackerel has long been the smallest of these federally managed fisheries. Landings of jack mackerel totaled 145 t last year, with an ex-vessel revenue of just $28,230 for California. Landings in Oregon jumped dramatically with 95 t landed in 2012, bringing an ex-vessel value of $5,383. Washington reported no landings of jack mackerel during 2012.

The 2012 recreational jack mackerel catch as sampled from CRFS was 5 t (28,000 fish), a 0.17% (54% by fish) decrease from 2011. A total of 11,000 fish were landed on CPFVs.

Northern Anchovy. Composed of three stocks, southern, central and northern, the northern anchovy have been a part of California's fisheries since the early 1900s. While studies of scale deposits on the sea floor suggest that their abundance has historically been quite large, current landings are moderate at best. 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. 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. During periods of low sardine abundance, anchovy landings increased, hitting a peak in the mid-1970s at over 100,000 t.

Landings of northern anchovy in California for 2012 amounted to 2,488 t with an ex-vessel value of nearly $371,150 (table 1). This is a 4% decrease from 2011 land-

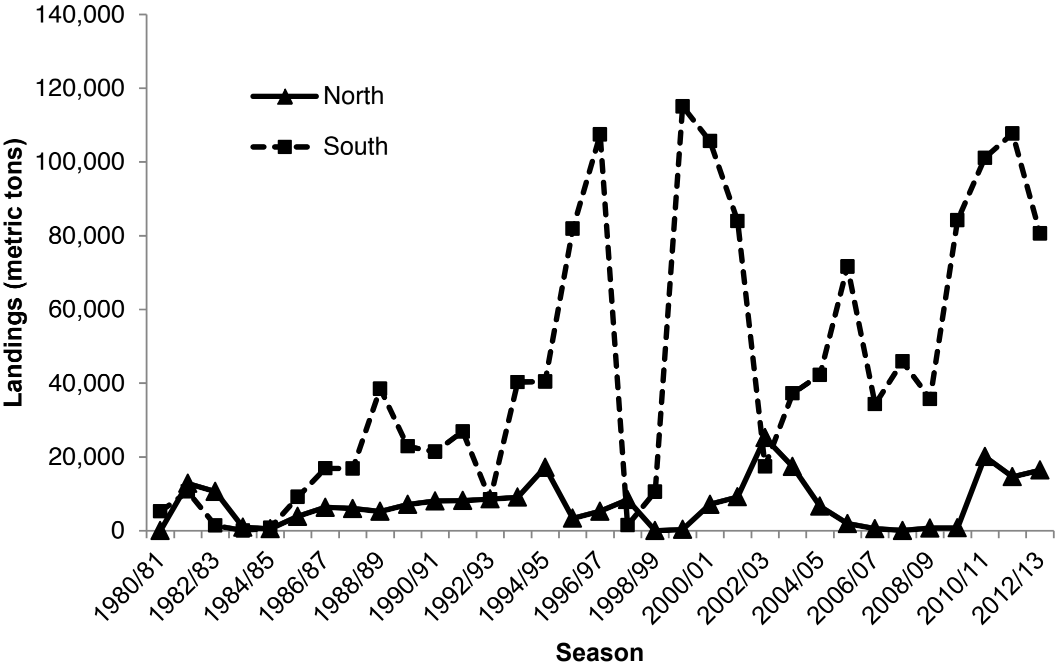

Figure 5. Comparison of market squid (*Loligo (Doryteuthis) opalescens*) landings for northern and southern fisheries by fishing season (1 April–31 March), from 1980/81 to 2012/13 seasons.

ings (2,601 t). Exports of northern anchovy product from California totaled 177.6 t for an export value of $849,594. Six countries received anchovy product from California; South Korea received the majority at 65%.

Both Oregon and Washington reported no northern anchovy landings for 2012, although Washington exported 11.7 tons of preserved northern anchovy product worth $54,859.

California Market Squid

In 2012, market squid (*Loligo* (*Doryteuthis*) *opalescens*) continued to dominate commercial landings of marine species in California, contributing about 61% of the total tonnage and 28% of total ex-vessel value of all species landed. Landings of market squid in 2012 decreased 20% compared to 2011 landings, from 121,558 t to 97,076 t (fig. 4). Ex-vessel value remained relatively stable, only slightly declining from $68.5 million in 2011 to $68.3 million in 2012. California fish businesses exported 84,832 t of market squid to 45 countries for a value of $121 million in 2012. The majority (90%) was shipped to just four countries but most (72%) went to China.

For the third season in a row, since the inception of the Market Squid Fishery Management Plan 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 21 November 2012, with a total of 95,243 t landed for the open portion of the 2012/13 season.

Commercial fishing for market squid is limited by fishery control rules set forth in the Market Squid Fishery Management Plan. Vessels are required to have a permit to possess or land over 1.8 t of squid, except when fishing for use as live bait. Permits are valid for the management season, from 1 April to 31 March the following year. In 2012, there were 77 market squid vessel (purse seine), 36 light boat (attracting), and 42 brail (or dip net) permits issued. Of the 77 vessel permits, 77 vessels were active in the fishery with 54 vessels contributing 95% of the landings. Other fishery control rules include a seasonal catch limit, 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 three 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 and logbooks are voluntary so total catch is unknown. The live bait fishery is likely a low-volume, high-value endeavor, as recreational anglers are willing to pay up to $60 for a "scoop" of live squid.

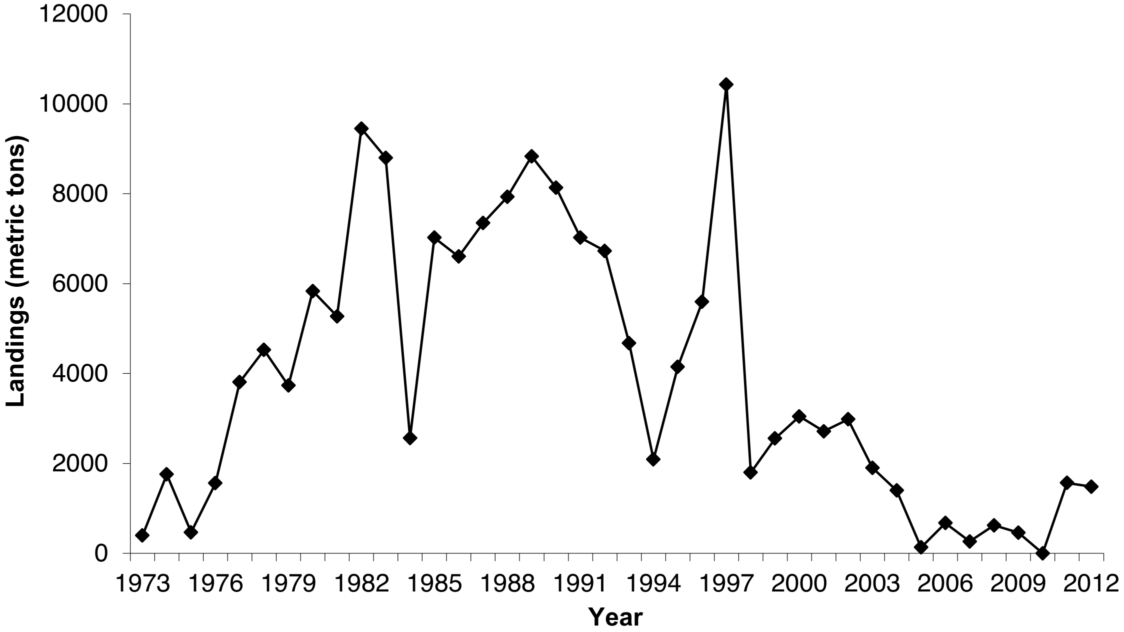

Figure 6. San Francisco Bay commercial Pacific herring (*Clupea pallasi*) sac roe landings, 1972–2012.

Pacific Herring

Fishing effort in California for Pacific herring (*Clupea pallasi*) in 2012 continued at reduced levels when compared to historic benchmarks. The fishery was closed during the 2009–10 season to allow for stock recovery. During the 2012 sac roe season (January 2012–March 2012), the San Francisco Bay fleet landed 1,482.3 t, 94.6% of their 2011 landings (1,566.7 t) (fig. 6) and 88.5% of the 1,673.8 t quota. There was no fishing effort in Tomales Bay, Humboldt Bay, or Crescent City Harbor during the 2012 season. It should be noted that no commercial fishery has taken place in Tomales Bay since 2007, since 2005 in Humboldt Bay, and since 2002 in Crescent City Harbor.

The forecast base price for roe herring is a good indicator of the economic status of the fishery and determines whether fishermen will participate in the fishery. Ex-vessel prices for roe herring are set using a base price with an additional roe percentage point bonus. The base price is set per short ton of roe herring with a minimum roe percentage of 10%. Roe herring that are landed which exceed the minimum roe recovery level are given a bonus for each percentage point exceeding 10%. Ex-vessel prices in the herring sac roe fishery can vary greatly based on roe recovery rates. The 2012 base price for roe herring with 10% or greater roe recovery was $200/st landed, with an additional $20 paid for each percentage point above the 10% baseline. The average roe count for the 2012 season was 15.1% resulting in an ex-vessel value of $302/st. Due to a decrease in base price, the statewide ex-vessel value of the herring sac roe fishery fell from $885,951 in 2011 to $493,468 in 2012.

The San Francisco Bay herring eggs-on-kelp fishery landed 0 t during the 2012 season and has been inactive since the fishery closure in 2009–10. Price paid for eggs-on-kelp typically ranges from $6–18 per pound depending on the quality of the product.

During the 2012 season the California Department of Fish and Wildlife (Department) conducted spawn deposition surveys in San Francisco Bay to estimate the spawning biomass of the herring stock. The spawning biomass estimate for San Francisco Bay is 55,324 t, a 6.4% increase over last season's estimate of 51,785 t. This is the third consecutive year of increased biomass since the historic low of 4,394 t during the 2009–10 season. The average biomass for San Francisco Bay 1979–2012 equals 46,458 t. No spawning biomass estimates were made for Tomales Bay, Humboldt Bay, or Crescent City in 2012.

The commercial herring fishery is closely regulated through a catch-quota system to provide for adequate protection and utilization of the herring resource. The Department conducts annual assessments of the spawning herring population in San Francisco Bay as part of its ongoing monitoring and management of the fishery. The Department also examines age structure, growth and general condition, biological aspects of the catch, and environmental conditions. These data serve as the basis for establishing fishing quotas for the following season. The quota range is based on the determination of the Department's assessment of the stock status and utilizing the best science available. The best available science includes, but is not limited to, recent fishery-independent field surveys, commercial catch and age

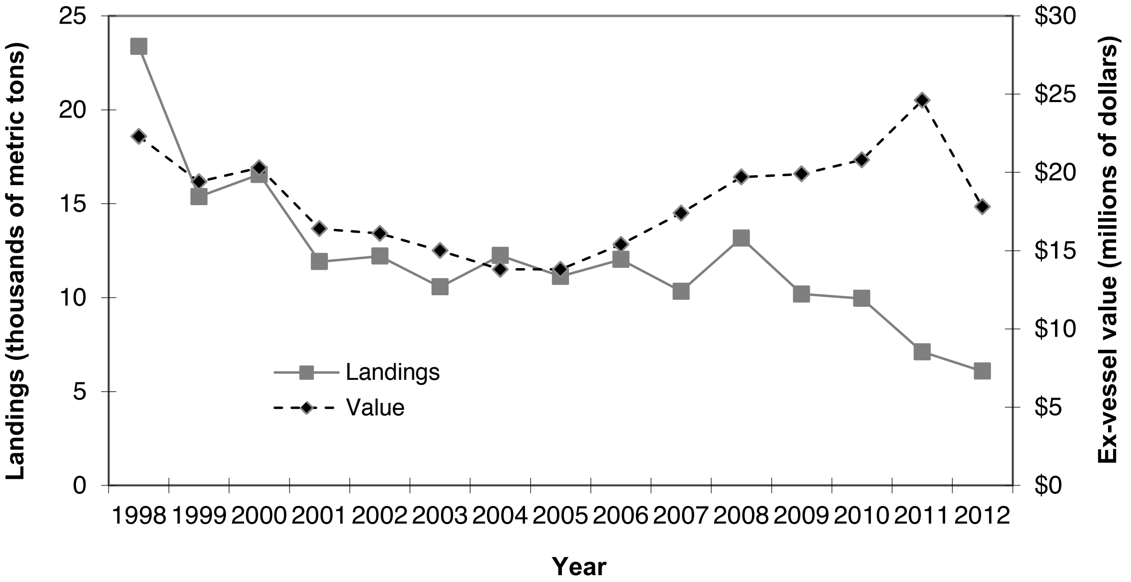

Figure 7. California landings of total groundfish by all gears, 1998–2012.

composition analysis, and environmental data. Quota recommendations for San Francisco Bay are primarily based on the most recent assessments by the Department of the size of the spawning population of herring in San Francisco Bay. The recommendation also takes into account additional data collected each season, including ocean and bay conditions, growth rates of herring, strength of individual year-classes, and predicted size of incoming year-classes (i.e., recruitment).

In response to poor recruitment, indication of population stress, and/or unfavorable oceanographic conditions, harvest percentages in recent years have been set at or below 10%. Since the 2003–04 season, harvest targets have allowed over 90% of the spawning biomass to return to the ocean, after spawning in the bay. The Department and the Director's Herring Advisory Committee (composed of fishing industry representatives) recommended a no fishery option for the 2009–10 season, when the herring spawning biomass in 2008–09 fell to a new low of 4,394.4 t. The Commission adopted this recommendation and no commercial fishery was held in San Francisco Bay for the 2009–10 season. Since the fishery reopened during the 2010–11 season, the Department has recommended harvest rates at 5% or less of the spawning biomass. Based on accepted fishery management principles, these harvest rates are conservative and represent a precautionary approach to safeguard the population as forage and to provide a robust reproductive base to allow for continued stock rebuilding.

Groundfish

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. "Groundfish" species include all rockfishes in the Scorpaenidae family, flatfishes such as Dover sole (*Microstomus pacificus*) and petrale sole (*Eopsetta jordani*), 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 2012, California's commercial groundfish landings totaled 6,085 t, with an estimated ex-vessel value of $17.8 million dollars. This represents a decline in both landings (14%; 7,113 t) and ex-vessel value (28%; $24.6 million) compared to 2011. During the last decade, groundfish landings have declined by 50% (7,113 t in 2012 versus 12,207 t in 2002); yet the ex-vessel value has increased nearly 11% ($16.1 million in 2002 versus $17.8 million dollars in 2012). Although annual landings have declined over the past years, the fishery experienced an increase in value over the past decade (fig. 7). The area from the California/Oregon border to the Monterey Bay port complex accounted for 73% (4,421 t) of the groundfish landed in California and 54% of the ex-vessel value ($9.6 million). In the groundfish fishery the majority of landings by weight comes from trawl gear (71%), followed by hook and line and trap gear (29%), yet the majority of trips are made with hook and line and trap gear (89%). Trawl gear is used to a lesser extent (9%), with gill net and seine gear comprising the remainder. Dover sole, sablefish, the thornyhead complex (*Sebastolobus altivelis* and *S. alascanus*) and chilipeper rockfish (*Sebastes goodei*) continued to domi-

TABLE 3
California commercial groundfish landings (in metric tons) and ex-vessel value in 2012 with comparisons to 2011. The top species by weight for the Flatfishes and Rockfishes are represented in the table.

	2012		2011		% change from 2011 (t)	% change from 2011 ($)
	Harvest (t)	Value ($)	Harvest (t)	Value ($)		
Flatfishes						
Dover sole	2,099	$1,895,274	2,412	$2,264,815	–13	–16
Petrale sole	222	$697,323	174	$536,140	28	30
Arrowtooth flounder	99	$23,752	86	$53,534	15	–56
Rex Sole	47	$40,490	68	$115,136	–31	–65
English sole	23	$20,987	19	$17,301	21	21
Sand sole	17	$48,701	13	$55,414	31	–12
Other flatfishes	10	$22,724	13	$35,332	–23	–36
Total Flatfishes	2,517	$2,749,251	2486	$2,948,794	–10	–11
Rockfishes						
Chilipepper	236	$362,174	293	$413,006	–19	–12
Blackgill rockfish	127	$369,358	126	$359,333	1	3
Group slope rockfish	102	$152,643	59	$85,126	73	79
Brown rockfish	26	$363,624	29	$383,712	–10	–5
Black rockfish	24	$105,557	27	$111,303	–11	–5
Gopher rockfish	23	$370,588	30	$462,849	–23	–20
Vermilion rockfish	17	$103,475	17	$102,968	0	1
Other rockfishes	88	$694,500	67	$650,810	31	7
Overfished species						
Bocaccio	12.34	$28,625	7.56	$18,373	63	56
Canary rockfish	0.56	$818	0.33	$473	70	73
Cowcod	0.08	$98	0.01	$19	700	416
Darkblotched rockfish	6.5	$9,725	3.38	$6,617	92	47
Pacific ocean perch	0.07	$71	0.07	$73	0	–3
Yelloweye rockfish	0	$12	0	$16	0	–25
Total Rockfishes	663	$2,516,817	647	$2,594,678	0	–1
Roundfishes						
Sablefish	1,623	$8,996,968	2,407	$15,159,279	–33	–41
Lingcod	48	$208,341	33	$148,329	45	40
Cabezon	30	$362,457	32	$387,731	–6	–7
Kelp greenling	5	$68,821	2	$29,171	150	136
Pacific whiting	4	$11,830	5	$14,419	–20	–18
Total Roundfishes	1,710	$9,648,417	2,479	$15,738,929	–31	–39
Scorpionfish, California	4	$41,671	5	$38,537	20	8
Sharks & Skates	182	$160,833	176	$140,376	3	15
Thornyheads	909	$2,634,386	922	$3,086,208	–1	–15
Other Groundfish	99	$52,604	87	$41,030	14	28
Total Groundfish	6,084	$17,848,430	7,113	$24,717,430	–14	–28

Data Source: CFIS (CMASTR) Extraction Date: 05-29-2013

nate as the top five species in 2012 with 2,099 t, 1,623 t, 499 t, 409 t and 236 t landed, respectively. These five species comprised 80% of the total groundfish landings. The amount of total groundfish landed in 2012 was mostly comprised of flatfishes (41%), followed by roundfishes (28%), and rockfishes (26%). The majority of rockfish was comprised of the thornyhead complex (58%). The "other" groundfish species category was comprised of grenadier (Macrouridae) which accounted for 99 t (table 3). The highest volume rockfish was chilipepper with landings of 236 t an ex-vessel value of $362,174. Unlike high-volume, high-priced species such as sablefish, nearshore rockfishes are generally a low-volume, high-priced commodity in California—gopher rockfish (*Sebastes carnatus*), brown rockfish (*S. auriculatus*) and grass rockfish (*S. rastrelliger*) earned a combined ex-vessel value of $969,338 with landings of 23 t, 26 t and 12 t respectively. Over the last decade, management measures such as limiting access and restricting landings have been used to protect vulnerable nearshore rockfish stocks. These measures, combined with the live fish market, help contribute to the high market value of the nearshore fishery. For nearshore species with 2012 landings in excess of two metric tons, grass rockfish was valued at approximately $20,250/t followed by black-and-yellow rockfish (*S. chrysomelas*) with an approximate value of $16,300/t and gopher rockfish worth approximately $15,600/t. By contrast, chilipepper rockfish (a non-nearshore rockfish) was valued at approximately $1,500/t.

Overfished rockfish species landings, which account for less than 1% of the total landings in 2012, increased in 2012 compared to 2011 (20 t versus 11 t). In both years

TABLE 4
California recreational groundfish landings (A+B1) greater than 5 metric tons in 2012 with 2011 comparisons.

	2012 Harvest (t)	2011 Harvest (t)	% Change from 2011
Lingcod	281	230	22
Vermilion rockfish	220	195	13
Black rockfish	210	178	18
Bocaccio	125	103	21
CA scorpionfish	116	100	5
Copper rockfish	80	67	19
Brown rockfish	70	86	–19
Pacific sanddab	66	81	–19
Yellowtail rockfish	53	46	15
Gopher rockfish	52	72	–28
Blue rockfish	52	62	–16
Cabezon	43	40	8
Leopard shark	35	25	40
Olive rockfish	32	24	33
Starry rockfish	23	24	–4
Grass rockfish	21	11	90
Kelp rockfish	19	18	6
Greenspotted rockfish	18	18	0
Flag rockfish	14	9	56
China rockfish	14	15	–7
Canary rockfish	13	16	–19
Kelp greenling	13	23	–43
Treefish	11	12	–12
Speckled rockfish	10	8	25
Chilipepper	8	5	60
Quillback	6	4	50
Honeycomb rockfish	6	10	–40
Rosy rockfish	6	7	–14
Other rockfishes	38	45	–14
Total Groundfish	1,656	1,534	8
Angler Trips			
Bottomfish Effort	867,096	830,058	4

Rockfish species of concern including yelloweye rockfish (1.6 t), cowcod (0.8 t) are included in the "Other" category. (A1+B1)—Fish caught and either identified or not available for identification.
Data source: RecFIN Date Extracted: 6-4-2013

the predominant species was bocaccio rockfish (*S. paucispinis*), which accounted for 60% and 73% of the total overfished species landings in 2012 and 2011, respectively. Overfished species landings have been greatly reduced from previous years due to management measures designed to protect these species.

Recreational Fishery. The Recreational Fisheries Information Network (RecFIN) Program houses recreational data from California, Oregon, and Washington. California data, available from 1980 to the present, represent the best available information regarding recreational catch off California. RecFIN incorporates data from two recreational fishery sampling programs—the Marine Recreational Fisheries Statistical Survey (MRFSS), which operated from 1980 to 2003, and the California Recreational Fishery Survey (CRFS) initiated by the Department of Fish and Wildlife in 2004. CRFS data queried through RecFIN indicates that in 2012, California anglers participated in an estimated 867,000 trips targeting groundfish which represents a 4% increase from 2011 (830,000 trips). The predominant gear type used in the California recreational groundfish fishery is hook and line.

An estimated 1,656 t of groundfish were taken by the recreational fishery in 2012 (table 4), a 4% increase from 2011 (1,534 t). The top five species were: lingcod, vermilion and black rockfishes (*S. miniatus* and *S. melanops*), bocaccio rockfish, and California scorpionfish (*Scorpaena guttata*) accounting for approximately 57% of the total groundfish estimated catch by weight. The same five species dominated catches in 2011, but accounted for only 53% of the total weight. In 2012, 43% of the groundfish catch occurred in southern California (south of Point Conception) and California scorpionfish and vermilion rockfish dominated the catch. Central California (Point Conception to Cape Mendocino) accounted for 47% of the total catch and was dominated by lingcod. Lastly, northern California (Point Mendocino to the California-Oregon border) accounted for 10% of the estimated catch, with black rockfish comprising the majority of rockfish taken.

Trawl Rationalization. In 2011, a new federal program was implemented for the West Coast Groundfish Trawl fleet which changed how fish were harvested in California. This is one of the most complex "catch share" programs in the nation, encompassing 21 species and three species complexes. Under the Individual Fishing Quota (IFQ) program (also known as trawl rationalization), quota for species or species groups are issued to individual limited entry trawl permit holders instead of to the fleet as a whole. This allows individuals to harvest quota at their discretion, eliminating a derby style fishery. Among other benefits, the IFQ program will ideally improve individual accountability, increase the profitability of the fishery, promote efficiency of the fleet, and reduce regulatory discards. Under this program, individuals are responsible for covering both catches and discards with quota. As such, it is their responsibility to ensure they have the correct amount of quota to cover both target and incidentally caught species before fishing. While quotas may be leased or bartered, a provision was made prohibiting the sale of quota shares until 2013 so that participants could become familiar with the new program (selling of quota shares has been delayed and is expected to resume in 2014). Another provision of trawl rationalization allows IFQ vessels to use non-trawl gears or fixed gear (e.g. hook and line or trap) to harvest their quota. This provision is known as gear switching and is primarily used to harvest sablefish and to a much lesser extent blackgill rockfish (*S. melanostomus*).

Trawl Rationalization in California. California groundfish landings and ex-vessel value from the limited

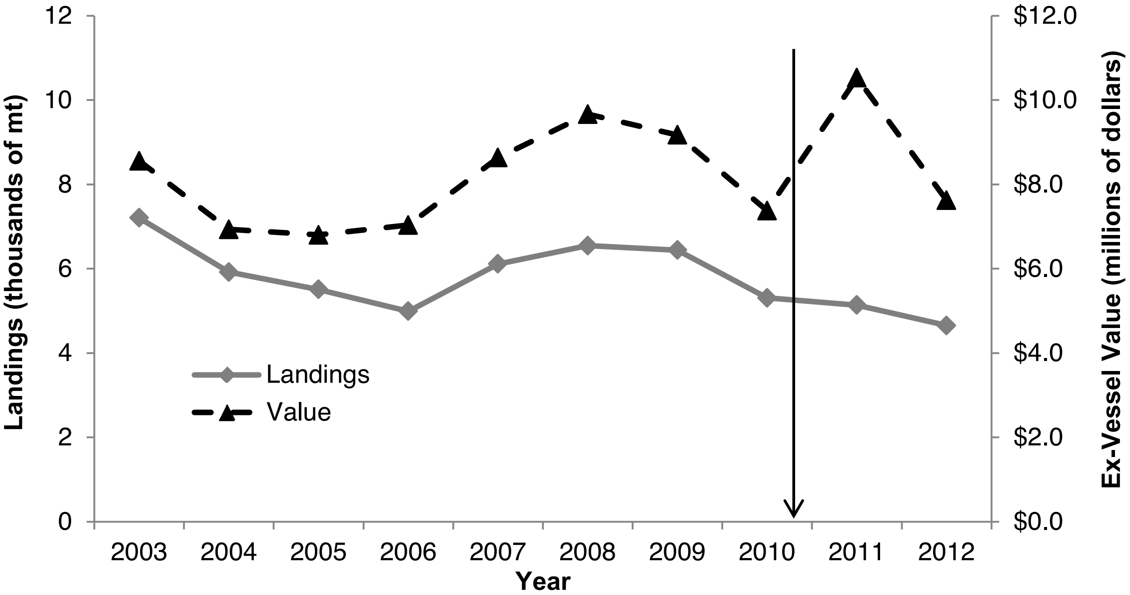

Figure 8. California landings of the limited entry trawl fleet, 2003–2012. The arrow indicates when the trawl rationalization program was implemented.

entry trawl fleet (2003 through 2010) and the rationalized trawl fishery (2011 and 2012) are shown in Figure 8. To identify early trends in the fishery as a result of the program, landings from pre- and post-rationalization (2009 through 2012) were compared. Landings of Pacific whiting (*Merluccius productus*) varied substantially between the two years before and after the program began. A total of 4,219 t were landed in the two year period prior to implementation of the program, compared with only 8 t landed in the years following the start of the IFQ fishery; as a result Pacific whiting was excluded from this analysis (Pacific whiting has a more northern distribution and it is likely that program participants fishing off California traded their shares of Pacific whiting for a more lucrative species such as sablefish). The average annual landings in the IFQ fishery decreased by 17% from 2009–10 (pre-rationalization) to 4,896 t for 2011–12 (post-rationalization). However, in spite of a depressed sablefish market starting in late 2011 and continuing through 2012, ex-vessel value increased 10% ($9.1 million) post-program implementation, compared to $8.3 million dollars in 2009–10.

Total encounters (landings plus discards) of overfished rockfish species have declined since the fishery was rationalized, decreasing from 51 t (2009) and 19 t (2010), to 8 t (2011) and 16 t (2012). Bocaccio rockfish accounted for 62% and 56% of the total overfished rockfish species encounters in 2011 and 2012, respectively.

Since rationalization, the Eureka and Fort Bragg port complexes continue to have the highest annual landings, accounting for 66% of annual California IFQ landings. While the program has had marginal effects on some port complexes, differential effects on annual landings are most apparent between the Crescent City and Morro Bay port complexes. Prior to implementation of the program, the Crescent City port complex contributed nearly 11% to annual landings, which has decreased by 6% post-rationalization.

Conversely, prior to the IFQ program the Morro Bay port complex had relatively few landings accounting for roughly 1% of annual landings, and since rationalization landings to the Morro Bay port complex have increased—contributing 14% to annual landings, largely due to the sablefish fishery.

Trawl Rationalization and the Sablefish Fishery. The sablefish fishery is the most important groundfish fishery in California, and as a result, it is also the most important species in the IFQ fishery. Prior to trawl rationalization, landings of trawl caught sablefish were 850 t (2009) and 710 t (2010), with an ex-vessel value of $3.3 million and $3.0 million dollars, respectively. Under the IFQ program, sablefish is now caught with a variety of gear (trawl and fixed gear, including hook and line and trap). In 2011, 1,069 t of sablefish were landed, with an ex-vessel value of $5.9 million dollars; 732 t were landed in 2012 with an ex-vessel value of $3.0 million dollars. It should be noted that the decrease in landings and ex-vessel value seen in 2012 is due to depressed sablefish market conditions, which began in late 2011, continuing through 2012. The average price per pound increased from $1.88 in 2009 and 2010 to $2.34 in 2011 and 2012. Of the IFQ vessels harvesting sablefish quota in 2012, roughly 41% utilized fixed gear (gear switching), with 13 out of 15 vessels using only fixed gear to land sablefish;

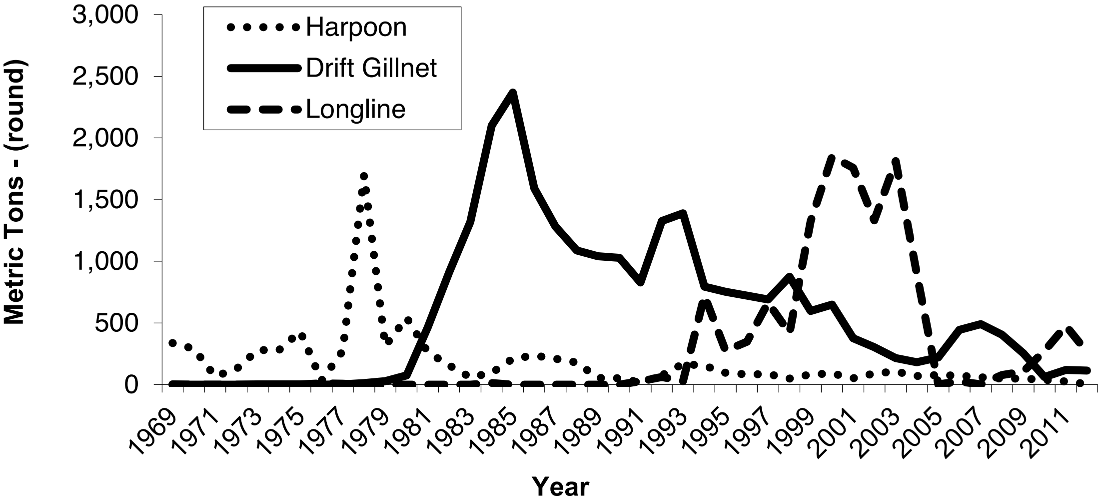

Figure 9. California commercial swordfish (*Xiphias gladius*) landings by gear type.

the other two vessels used a combination of both trawl and fixed gear. Vessels that "gear switched" primarily used trap gear which had the highest price per pound of all gear types in 2012, averaging $2.26 dollars. By contrast, in 2011 approximately the same percentage of IFQ vessels utilized fixed gear, however, earned less, averaging $2.44/lb opposed to those made by trawl gear (approximately $2.90 per pound).

Although data are preliminary and may be subject to change, data from 2011 and 2012 indicate some positive benefits as a result of trawl rationalization, the full impact of which may not be fully realized for several more years.

Highly Migratory Species

Swordfish. Swordfish (*Xiphias gladius*) is the most valuable highly migratory species (HMS) taken off California in both price-per-kilogram and total revenue; most landings take place in California. In 2012, 397 t of swordfish with an ex-vessel value of $3.4 million were landed on the West Coast, a 36% decline from landings in 2011 of 619 t. For 2012, 6% were taken by harpoon gear, 28% were taken by drift gill net gear, and 66% were taken by hook and line gears (mostly Hawaiian vessels fishing outside the United States Exclusive Economic Zone [EEZ]). Harpoon and drift gill net landings of swordfish on the West Coast take place entirely within California as Washington does not authorize drift gill net gear, and Oregon discontinued a drift gill net permit program in 2009. Commercial swordfish landings have been affected dramatically by the changes in fishing gear used and management measures implemented over the decades. As shown in Figure 9, the 1970s were dominated by harpoon, the 1980s and 1990s by drift gill net gear, and the 2000s by longline gear. Longline gear landings for the last few years, however, have been made by vessels permitted by the Hawaiian longline fishery; longline is not an approved gear for swordfish off the West Coast. Revenues for swordfish peaked in 2000 at $11.7 million and have varied with management measures and gear type. Generally, annual revenues have averaged about $800,000 for harpoon since starting in the 1970s, $2.9 million for drift gill net since in the 1980s, and $2.2 million for longline since the 1990s (fig. 10).

Eastern Pacific Ocean swordfish populations are healthy; according to recent stock assessments, biomass levels are above the levels necessary to achieve maximum sustainable yield and the stock is in good condition. However, in recent years, West Coast swordfish landings continue to decline. In 2011 the NOAA Fisheries Southwest Fisheries Science Center (SWFSC) sponsored a workshop entitled "Working Towards Sustainability" as a means of enhancing the economic viability of the swordfish fishery. The Pacific Fisheries Management Council (PFMC) directed the Highly Migratory Species Management Team (HMSMT) to analyze all new information presented in the workshop to determine if changes can be made to the swordfish fishery, especially in terms of a modification of the borders or closure dates of the Pacific Leatherback Sea Turtle Conservation Area (PLCA). This conservation area, initiated in 2001, closed the drift gill net fishery to an area off central California to mid-Oregon August 15–October 31, at a time when leatherback sea turtles commonly feed in that area, coinciding with historical swordfish drift gill net fishing. New information, such as determination of sea turtle critical habitat, migration patterns, and vertical distribution may inform such a decision.

Recreationally caught swordfish are uncommon along the West Coast. Since 2003, swordfish have only been documented in the recreational catch in state fishing and federal fishing surveys in California in 2007; none were recorded in 2012 from either recreational Commercial

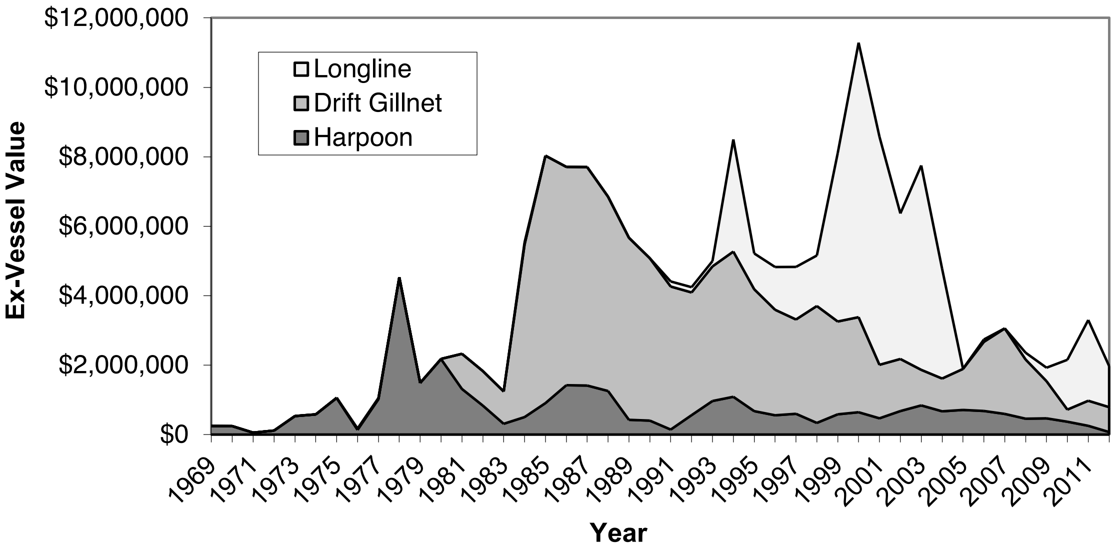

Figure 10. California commercial swordfish (*Xiphias gladius*) revenue by gear type.

Passenger Fishing Vessel (CPFV) logs or RecFIN data. California RecFIN data for 2012 comes from the California Recreational Fisheries Survey (CRFS), and represents observed and angler reported landed catch for private boats in all waters off California. All CPFV and CFRS data are from California waters only.

Albacore. Albacore (*Thunnus alalunga*) is the most abundant tuna caught in commercial fisheries and recreational fisheries in California and along the West Coast. In the commercial fishery albacore are caught primarily using hook and line gear (jigs, bait, or trolling), but they are also taken in drift gill nets or round haul gear. Along the West Coast 13,852 t were landed commercially in 2012, an increase of 26% coastwide from 10,964 t landed in 2011. California landings increased slightly to 611 t from 570 t in 2012. In 2012 the ex-vessel value in California was $2.1 million with a price of $3.70/kg ($3,700/t), about thirty cents higher than the coastwide average. Washington landed 63% of West Coast albacore with 8,757 t, its only HMS landed, while Oregon landed 32% with 4,484 t. About 58 t of fresh and frozen albacore were exported from the West Coast to Canada, Japan and Thailand; 80% was exported from Washington. Albacore makes up 96% of all HMS commercially landed on the West Coast.

Recreational Commercial Passenger Fishing Vessel (CPFV) logs reported anglers taking 4,338 albacore in 2012 in California waters. RecFIN estimates indicate that anglers caught about 32,000 albacore off California, out of 150,000 caught coastwide, by private and rental boats.

Yellowfin tuna. Commercial landings of yellowfin tuna (*Thunnus albacares*) have continued to decline over 2009's low of 45 t to less than 2 t landed in 2012 (only 7 t total in the last three years), with an ex-vessel value of $13,245; however, the price was $8.49/kg presumably because of scarcity ($1.11/kg in 2009, when 45 t were landed). All yellowfin was landed in California; the majority by longline gear. About 8 t of fresh yellowfin was exported to Mexico and Thailand. Recreational CPFV logbooks reported anglers caught 4,338 yellowfin tuna off California in 2012, more than six times as much as taken in 2011 (681 fish). CRFS reported an estimated 1,027 yellowfin tuna taken by private and rental boaters in 2012, while none were reported in 2011.

Skipjack tuna. There was 1 t of skipjack tuna (*Kastuwonus pelamis*) in each of the past two years; there have not been commercial landings over 10 t since 2006 (48 t). No skipjack tuna was estimated caught in the last three years in shore or private boat modes off California, although California CPFV logs reported 66 fish taken in California waters. This is a 70% decrease from 2011, when nearly 222 skipjack were taken by CPFVs in California.

Bluefin tuna. Commercial landings of bluefin tuna (*Thunnus thynnus*) declined in 2012 to 43 t landed in California. Landings in 2011 had increased to 118 t from only 1 t the previous year. Ex-vessel price increased slightly to $2.24/kg in 2010, from 2.09/kg in 2011. The majority of the landings were taken in purse seine gear for the last two years (83 to 86%). Two tons of frozen bluefin tuna was exported to Canada in 2011; there were no exports in 2012. CRFS estimates sport anglers took only 10 bluefin tuna in 2012 off California by private boaters, whereas in 2011, 30 were estimated landed. CPFV logs report about 5,627 bluefin taken in 2012, almost twice as much as in 2011, when anglers took 2,743 fish in California waters.

Common thresher shark. Common thresher shark (*Alopias vulpinus*) is the most common and most valuable shark taken in HMS commercial fisheries off California. As in 2011, 95% of commercially-caught thresher shark was taken in gill net fisheries in 2012. Landings of common thresher shark declined by 10% from 64 t in 2011, to 63 t in 2012. Ex-vessel value was $112,000 at an average of $2.90/kg dressed weight ($1.32/lb), decreasing from $2.35/kg ($1.07/lb) in 2011. California CPFV logs reported 37 threshers caught in 2012. CRFS landings, the majority of which come from private boats, estimate anglers landed about 372 thresher sharks in California in 2012.

Shortfin mako shark. Shortfin mako shark (*Isurus oxyrhincus*) is the second most common commercially landed shark in California HMS fisheries, 64% of which was taken by gill net gear in 2012, with 36% taken by hook and line gear, much of which was Hawaiian longliner landing on the West Coast. Mako shark landings increased 37% from 2011 landings of 19 t to 26 t in 2012. Ex-vessel revenue was $49,761, with an average price of $2.79/kg ($0.88/lb) dressed weight, a slight decrease from $2.86/kg ($0.90/lb) in 2011. CPFV logs reported 139 mako sharks taken in 2012, almost three times the amount taken in 2011. CRFS reported an estimated 648 taken by private vessels in 2012, about twice as much as the previous year.

Dorado (dolphinfish). All commercial landings of dorado (*Coryphaena hippurus*) occurred in California on the West Coast of the U.S. Commercial landings of dorado increased to 10 t in 2012, more than three times the amount landed in 2011 (3.2 t). The ex-vessel revenue was $35,643, at $3.52/kg, 3% higher than 2011's price of $3.42/kg, but 46% less than 2009's high of $6.27/kg. CPFV logs also recorded an increase in landings in 2012, with 6,337 fish landed, 38 times the previous year, when anglers took 166 fish. CRFS reported an estimated 8,785 dorado taken by private vessels in U.S. waters.

HMS Management. The federal Shark Conservation Act of 2010 was signed into law January 4, 2011, specifying that no shark is to be landed without fins being naturally attached. Additionally, California passed AB 376—a bill banning the possession and sale of shark fins, beginning January 1, 2012. While shark fisheries in California are still legal, and those possessing the proper license or permit are allowed to retain shark fins under California law, sales and distribution are prohibited. Restaurants and retailers were allowed to sell stock on hand as of the implementation until July 1, 2013. There is also an exception for taxidermy.

The Pacific Fishery Management Council (PFMC) made recommendations to international regional management organizations on bluefin tuna overfishing, supporting existing management measures but strengthening them to reduce the take of juvenile fish by other countries; additional domestic measures were not considered necessary because of the negligible impact of U.S. fisheries. The Council tasked the HMSMT to begin developing recommendations for an albacore precautionary management framework in case of future poor assessments, for recommendations at the international level. The Council also made recommendations to U.S./Canada Albacore Treaty fishing regime negotiations, and in 2012, supported the U.S. industry in suspending of reciprocal access privileges to each other's waters until investigation of economic and landings data was completed.

White Seabass

The white seabass (*Atractoscion nobilis*) is the largest member of the Sciaenid family found in California waters. In addition to being a popular sport fish, white seabass is also targeted by a commercial fishery. The commercial white seabass fishery landed 171 t in 2012 (fig. 11), a 31% decrease from the 2011 total of 247 t. In 2012, the average ex-vessel value paid by dealers was $3.61/lb. The total ex-vessel value in 2012 was $1,365,758, approximately 16% less than in 2011. Estimates of recreational take for 2012 are generated from the California Recreational Fisheries Survey (CRFS) for the private boat and shore-based modes and from Commercial Passenger Fishing Vessel (CPFV) logbook data. The estimate of recreational take decreased by 13% to 107 t in 2012 from the previous year's total of 123 t. The recreational catch estimates prior to 2004 are from a different survey and are not directly comparable to the estimates from the CRFS. However, historical trends in the recreational catch of white seabass can be determined from CPFV logbook data (fig. 12). The combined commercial and recreational catch for 2012 was 278 t.

Commercial and recreational fisheries for white seabass in California have existed since the 1890s. Historically, commercial landings have fluctuated widely, including landings of white seabass taken in Mexican waters by California commercial fishermen. In 1959, the white seabass commercial take in Mexican waters made up 1% of California's white seabass annual landings, while in 1981, it reached 89% of the total annual catch. Since this time, the Mexican government has prohibited access permits to the U.S. commercial fleet.

Beginning in 1994, the use of set and drift gill nets within 3 nautical miles of the mainland shore from Point Arguello to the U.S./Mexico border and in waters less than 70 fathoms or within 1 mile (whichever is less) of the Channel Islands was prohibited. In April 2002, the use of gill and trammel nets in depths of 60 fathoms or less was prohibited from Point Reyes (approximate latitude 38.0°N) to Point Arguello (approximate latitude

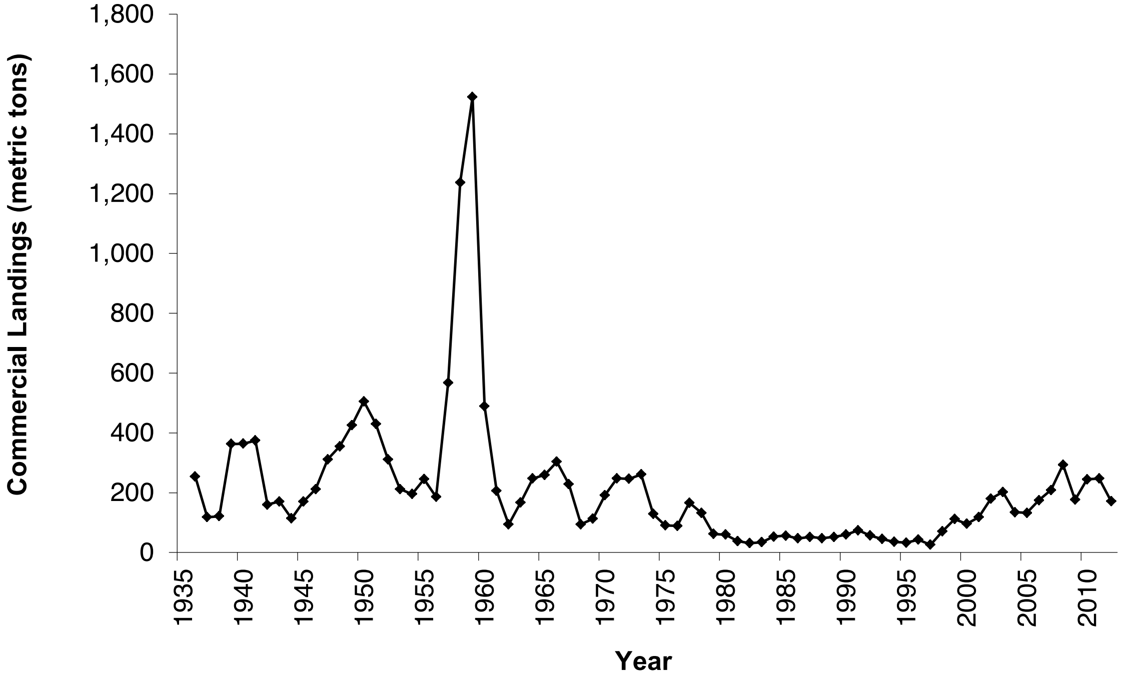

Figure 11. California commercial white seabass (*Atractoscion nobilis*) landings, 1936–2012.

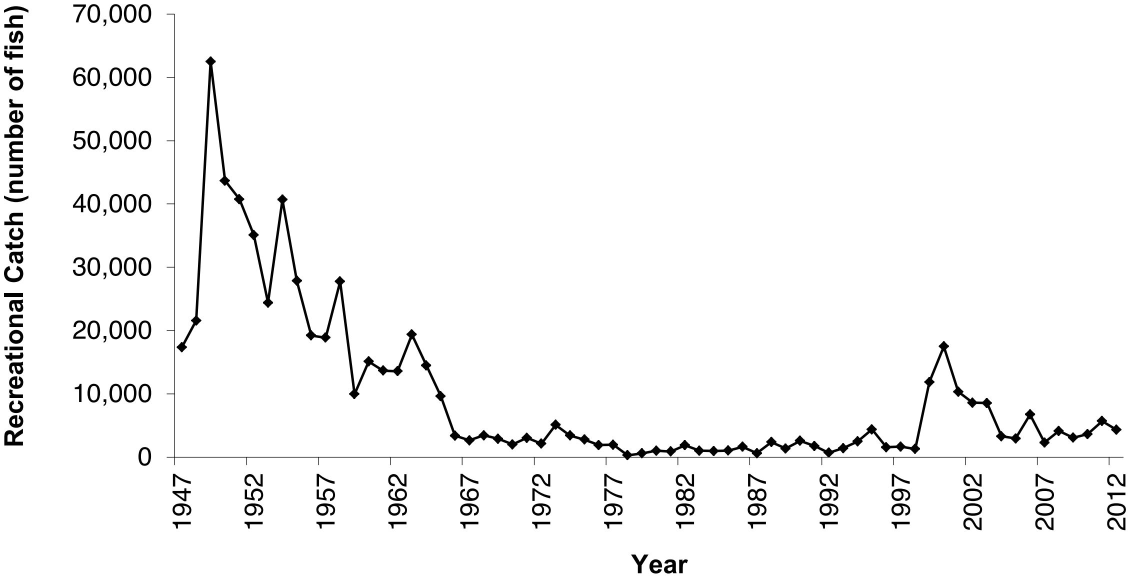

Figure 12. California recreational white seabass (*Actractoscion nobilis*) landings, from Commercial Passenger Fishing Vessel logbooks, 1947–2012.

34.6°N). Despite restrictions, most commercial white seabass landings are still taken with set and drift gill nets. In 2012, set and drift gill nets accounted for 62% of the commercial landings by weight, while hook and line vessels accounted for 38%. Almost half of these vessels, however, made less than three landings in 2012, indicating that the majority of hook and line vessels opportunistically catch white seabass when available along the coast. Much of the hook and line catch occurs within Monterey Bay. The shift in catch distribution as evidenced by the increase in northern California landings (fig. 13) and, therefore, hook and line gear usage could be attributed to changes in oceanic conditions or distribution of forage fish.

The minimum legal size limit for white seabass in the commercial fishery is 28 inches (710 mm). The commercial fishery for white seabass is closed between Point Conception (approximate latitude 34.45°N) and

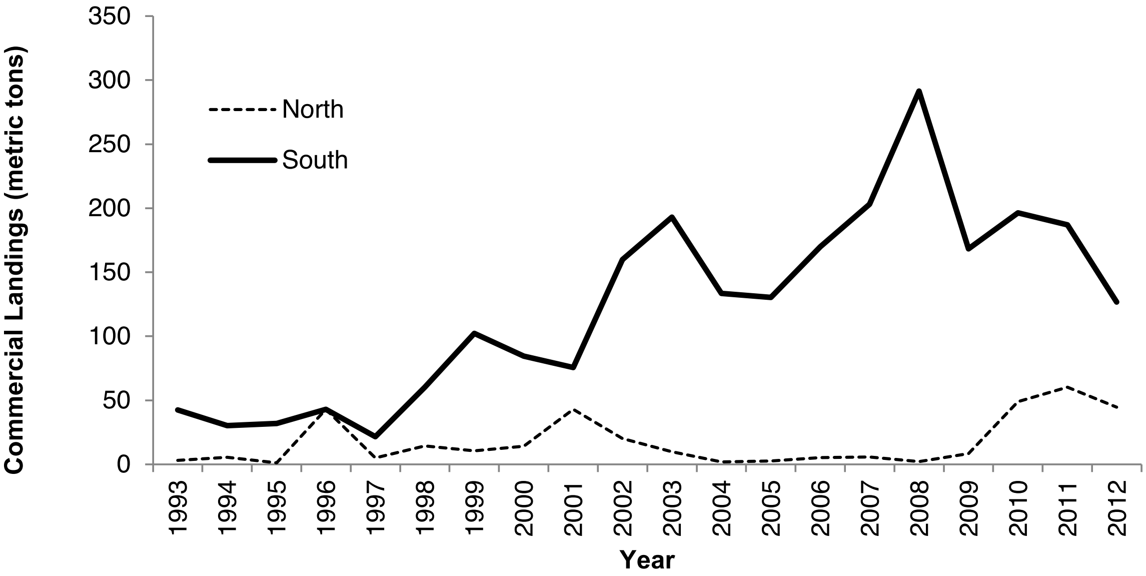

Figure 13. California commercial white seabass (*Atractoscion nobilis*) landings north and south of Pt. Arguello, 1993–2012.

the U.S./Mexico border from 15 March to 15 June, except one fish not less than 28 inches in total length may be taken, possessed, or sold by a vessel each day if taken incidental to gill and trammel net fishing operations. In 2012, the average ex-vessel value paid by dealers was $3.61/lb.

The recreational fishery for white seabass usually occurs almost entirely south of Point Arguello (approximate latitude 34.6˚N). Typically, 95% to 99% of the catch is caught south of this point; however, starting in 2010, there has been an increase in catch in central and northern California. In 2012, only 81% of the catch occurred south of Point Arguello, while 19% occurred north of this point. The change in distribution of catch is attributed to an increase in the numbers of white seabass available within Monterey Bay. The fishery is open all year, but the majority of the recreational take occurs between March and September. The minimum legal size limit for white seabass in the recreational fishery is 28 inches (710 mm), and the daily bag limit is three fish, except from 15 March through 15 June when the daily bag limit is one fish. Most fish are caught by hook and line anglers onboard CPFVs and private boats.

In 1982, the California Legislature established the Ocean Resources Enhancement and Hatchery Program (OREHP). The legislation was adopted to fund research into the artificial propagation of marine finfish species whose populations had become depleted. The ultimate goal of the legislation is to enhance populations of marine finfish species important to California for their recreational and commercial fishing value. Initially, research was focused on California halibut and white seabass; however, white seabass was eventually chosen as the primary species to focus on because of the depressed condition of the stock at the time and its higher value to recreational and commercial fishermen.

The California Department of Fish and Wildlife (Department) manages the OREHP with the assistance of an advisory panel that consists of academic and management agency scientists, representatives of both commercial and recreational fishing groups, and the aquaculture industry. The program is funded through the sale of recreational and commercial marine enhancement stamps for all saltwater anglers south of Point Arguello. In 1995, the OREHP completed construction of the Leon Raymond Hubbard, Jr. Marine Fish Hatchery in Carlsbad, California. The primary function of the hatchery, which is operated by the Hubbs-SeaWorld Research Institute (HSWRI), is to provide juvenile white seabass, approximately 4 inches (100 mm) total length (TL), to growout pens operated by volunteer fishermen and non-profit organizations. Currently, the hatchery and growout pens may release up to 350,000 juvenile white seabass per year.

There are 13 growout pens located in bays and marinas from Santa Barbara to San Diego in southern California. At the growout pens, juvenile white seabass are reared to 200–250 mm TL before they are released at or near the growout site. In 2012, 108,749 hatchery-raised white seabass were released, an increase of approximately 12% from last year's release of 97,444 fish. Since 1986, over 1.9 million white seabass, each implanted with a coded wire tag (CWT), have been released from the OREHP facilities.

Since the mid to late1980s, the OREHP has contracted with researchers to develop juvenile and adult sampling programs to assess the proportion of hatchery-raised fish to the wild population. From 1988 to

2008, researchers conducted a standardized gill net sampling survey designed to capture 1- to 4-year-old juvenile white seabass in shallow waters off southern California. Initially, the survey focused on determining the distribution of young fish but switched in 1996 to look at recruitment of 1-year-old fish and recovery of tagged fish. The juvenile gill net sampling program was cut in 2009 due to limited funding availability; however, the Department was able to reinstitute sampling in 2012 in a limited capacity. In the late 1990s, HSWRI researchers developed a sampling program to recover adult hatchery-raised white seabass from the commercial and recreational fisheries. The program, which is ongoing, is aimed at scanning white seabass for the presence of a CWT. Since the inception of both programs, 1,416 hatchery-raised juvenile white seabass have been recovered in the juvenile gill net studies while 181 tagged adult white seabass (legal-size) have been recovered from the recreational and commercial fisheries. The results of both the juvenile and adult sampling programs will be used in evaluating the success of the OREHP. In addition to both juvenile and adult sampling programs aimed at determining survival rates and recruitment of hatchery raised white seabass, a stock assessment will be completed in 2014 and will be used as part of the program evaluation.

In 2006, the California Legislature passed SB 201 (Simitian) Marine Finfish Aquaculture, which amended the statute related to marine aquaculture [FGC §15000 et. seq.]. The statute requires the preparation of an enhancement plan for any recovery, restoration, or enhancement of native fish stock projects carried out under either a scientific collecting permit, research permit, or the OREHP [FGC §15400(b)(10)(c)]. Legislation also designates the Fish and Game Commission (Commission) the authority to approve an enhancement plan.

In June 2010, the Department submitted the White Seabass Enhancement Plan (WSEP) to the Commission, which it approved on 21 October 2011. The WSEP provides a framework for managing the OREHP in an environmentally sustainable manner and establishes best management practices (BMPs) for hatchery and growout operations, fish health, genetics, and benthic monitoring. It also outlines methods on which to evaluate the OREHP and is designed to be flexible and adaptable to a wide range of future conditions. Minor changes can be made to the BMPs without the need to amend the WSEP by revising the other guidance documents for the OREHP. However, future research, environmental, biological, or economic changes of significance may create a need to amend the WSEP to ensure that the enhancement of white seabass is conducted in a responsible manner.

Since its inception, the OREHP has conducted research designed to provide a new tool for resource management while preventing adverse impacts to the environment or the wild fisheries. In July 2012, the Department adopted the Initial Study and Negative Declaration for the OREHP per California Environmental Quality Act (CEQA) guidelines. The initial study indicated that the program does not have a significant impact on the environment.

To manage the state's commercial and recreational fisheries for white seabass, the Commission adopted a White Seabass Fishery Management Plan (WSFMP) in 1996. To implement the WSFMP, the Commission adopted regulations in 2002 to establish a fishing season of September 1 through August 31 of the following year. The Commission also adopted an optimum yield (OY) in 2002. The OY is based on a maximum sustainable yield proxy of the unfished biomass and is currently set at 540 t. The OY has never been reached since its implementation, but came close in the 2001–02 fishing season when combined landings reached 530 t. In the 2011–12 fishing season, the total recreational and commercial harvest was 302 t, 55% of the allowable catch.

Pacific Halibut

Pacific halibut (*Hippoglossus stenolepis*) is a desirable commercial and recreational target species ranging from the Bering Sea in Alaska to central California. The entire North Pacific halibut resource is internationally managed through the Halibut Treaty (Treaty) between the United States and Canada. The International Pacific Halibut Commission (IPHC) was established to conduct research and management activities in the waters of the parties to the Treaty. In California, both the commercial and recreational Pacific halibut fisheries have experienced large fluctuations in catch over the last century.

During the first half of the 20th century, a substantial commercial fishery for Pacific halibut existed in California. Landings data from 1916–60 (reported in the California Department of Fish and Game Fish Bulletin No. 74) show annual landings as high as 348 t net weight (fish are headed and gutted) occurring in 1934 (fig. 14). Despite the magnitude of Pacific halibut landings occurring in California during this time, the fishery was a minor portion of the overall fishery for Pacific halibut, with approximately 1% of Pacific coast commercial landings occurring in California, and the fishery was considered of minor importance to the state of California. Most of California's commercial Pacific halibut landings were made in Eureka, with smaller amounts in Fort Bragg and San Francisco; however, not all catch was by California vessels, nor was all the catch occurring in California waters. Point Arena (38°57.5'N lat) was considered the southern limit of the commercial fishing grounds. After 1945, regulations restricting the fishery

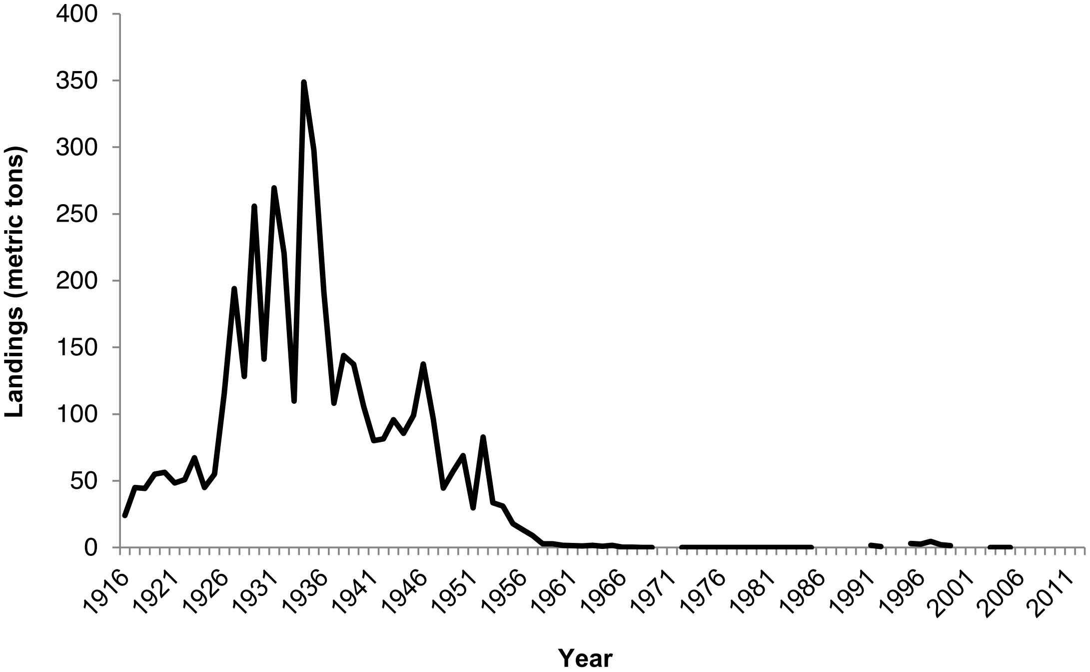

Figure 14. Annual commercial landings of Pacific halibut (*Hippoglossus stenolepis*) in California from 1916–2012. Missing data points are due to confidentiality concerns. Data from CDFW Fish Bulletin Number 74 and CFIS.

were implemented and landings in California experienced a drastic decrease.

The Pacific Fishery Management Council (Council) and the National Marine Fisheries Service (NMFS) are authorized by the Treaty to manage Pacific halibut in what is known as "Area 2A" which includes the waters off of the three West Coast states (Washington, Oregon, and California). The IPHC annually allocates a portion of the harvestable Pacific halibut to Area 2A which the Council divides among the tribal, commercial, and recreational fisheries through a Catch Sharing Plan (CSP). California's recreational subquota is within the South of Humbug Mountain (SoH) subarea of Area 2A which includes southern Oregon and all of California. In 2012, the SoH subarea subquota was 2.75 t (fig. 15) or approximately 0.62% of the Area 2A Total Allowable Catch (TAC).

From 2000–12 the directed commercial fishery in California averaged landings of 0.08 t net weight per year. Trace amounts of Pacific halibut were landed in California from the directed commercial fishery during 2012. The directed commercial fishery for Pacific halibut in Area 2A is a derby fishery consisting of one-day open periods 10 hours in duration scheduled every other week by the IPHC, generally beginning in the second half of June. Due to the derby nature of the directed commercial fishery, in combination with a quota shared by all three West Coast states, the season generally consists of two to five 10 hour open periods per year. Commercial fishermen are required to obtain an IPHC permit to participate in the directed fishery and are prevented from participating in any other Pacific halibut fishery for that year.

A coastwide Pacific halibut incidental allowance to the commercial salmon troll fishery is permitted but no legal landings in California have been made since the start of that fishery in 1995, primarily because the incidental fishery has reached its quota prior to the start of the commercial salmon fishery in California. Vessels choosing to operate in this fishery are also required to obtain an IPHC permit and are restricted from participating in any other Pacific halibut fishery for that year. Pacific halibut are also encountered as bycatch in other commercial fisheries, such as the groundfish trawl and Limited Entry longline sablefish fisheries, but they must be discarded.

A small recreational fishery targeting Pacific halibut existed in northern California prior to 2007, although only minimal amounts were caught. Since 2007, catches have increased and Pacific halibut is now actively targeted in northern California (north of Point Arena). Based on information from the California Department of Fish and Wildlife (CDFW), estimated recreational catch of Pacific halibut in California during 2012 was 11.7 t net weight (fig. 15). Recent catches have exceeded the recreational catch quota set by the IPHC by an average of 7.4 t and the highest recent catch occurred in 2009 when an estimated 15.8 t were caught. It is not known whether increased catch reflects an increase in Pacific halibut abundance, angler interest, or effort due to

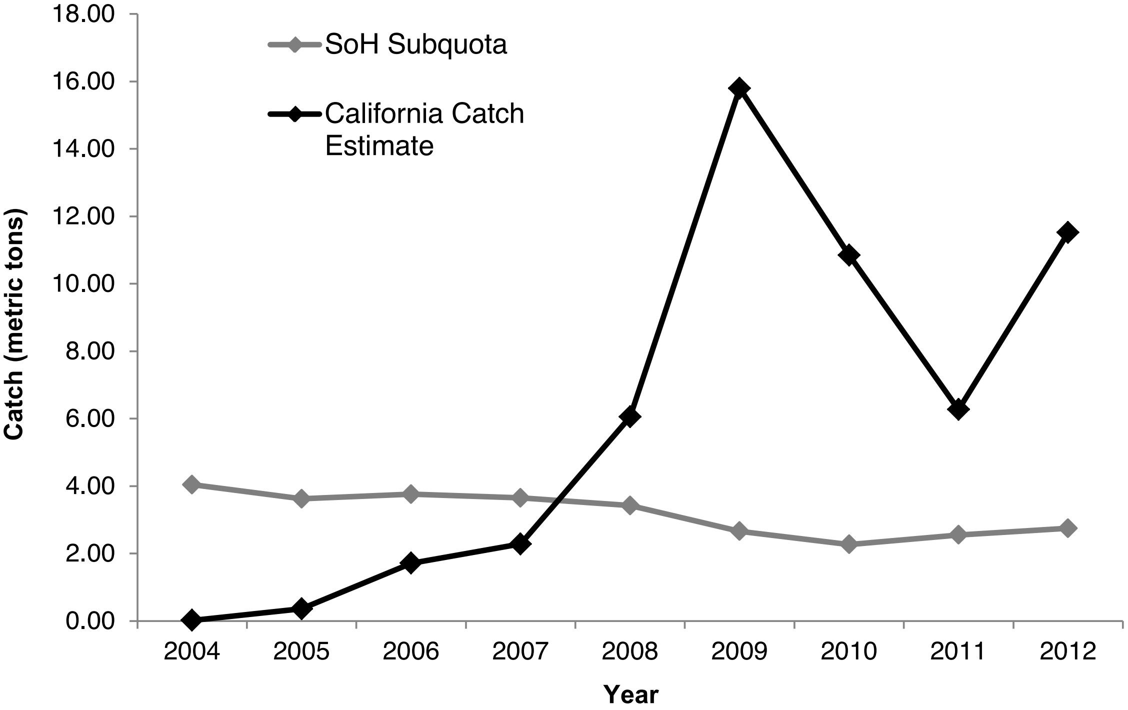

Figure 15. California Pacific halibut (*Hippoglossus stenolepis*) recreational catch and SoH subquota from 2004–2012. Catch estimates for 2012 are preliminary. Data from CRFS and CDFW.

limited angler opportunities in the recreational salmon and groundfish fisheries. Recreational regulations for Pacific halibut in California during 2012 provided for an open season from May 1 through October 31, with a one-fish bag and possession limit and no minimum size limit.

The IPHC is responsible for conducting the annual stock assessment, developing information on current management issues, and adding to the knowledge of the biology and life history of the Pacific halibut. According to the IPHC, Pacific halibut can live up to 55 years, and have been reported to reach 267 cm (9 ft) in length and up to 318 kg (900 lbs). Few males attain weights greater than 36 kg (80 lbs) and almost all fish over 45 kg (100 lbs) are females. Each year the IPHC surveys and assesses the North Pacific stock from the Bering Sea to the Oregon/California border, determines the available coastwide exploitable biomass, then allocates the available harvest among subareas in Alaska, Canada, Washington, Oregon, and California. The 2012 Pacific halibut stock assessment indicated that biomass was stable, although less than previously thought. The 2012 stock biomass is above the harvest policy threshold precautionary level, but is approximately 33,566 t, or 28% less than was estimated in the 2011 assessment.

In response to the recreational catches of Pacific halibut in the SoH subarea exceeding the SoH subarea subquota, the IPHC, NMFS, Council, and West Coast states began gathering information on Pacific halibut in the SoH subarea. Specific objectives were to: develop a common understanding of Pacific halibut management and allocation history in California; develop methods to more accurately estimate the recreational catch in California; find alternative data sources to estimate abundance and distribution of Pacific halibut in California for use in stock assessments; collaborate and develop a range of management options to reduce the recreational catch in California; and explore the possibility of expanding the IPHC annual research survey into California waters. These efforts are ongoing, and already resulted in plans to extend the annual research survey into California waters for the first time in 2013. Future regulation changes to the Pacific halibut fishery in California may occur as more information on the Pacific halibut resource in the SoH subarea becomes available.

Red Sea Urchin

Statewide landings of red sea urchins (*Strongylocentrotus franciscanus*) in 2012 were estimated at 5,153 t, with an ex-vessel value of $8.3 million (fig. 16). The catch represents a small decrease from 2011 landings of 5,270 t, but also represents a small increase in value from $8.2 million, with little or no change in catch and value for both the northern and southern California regions.

In 2012, effort in the southern fishery was 8,210 landings and 2,451 landings in the northern fishery. The southern fishery over the last decade peaked in 2004 to 11,065 landings and dropped to a range of 7,600–9,500

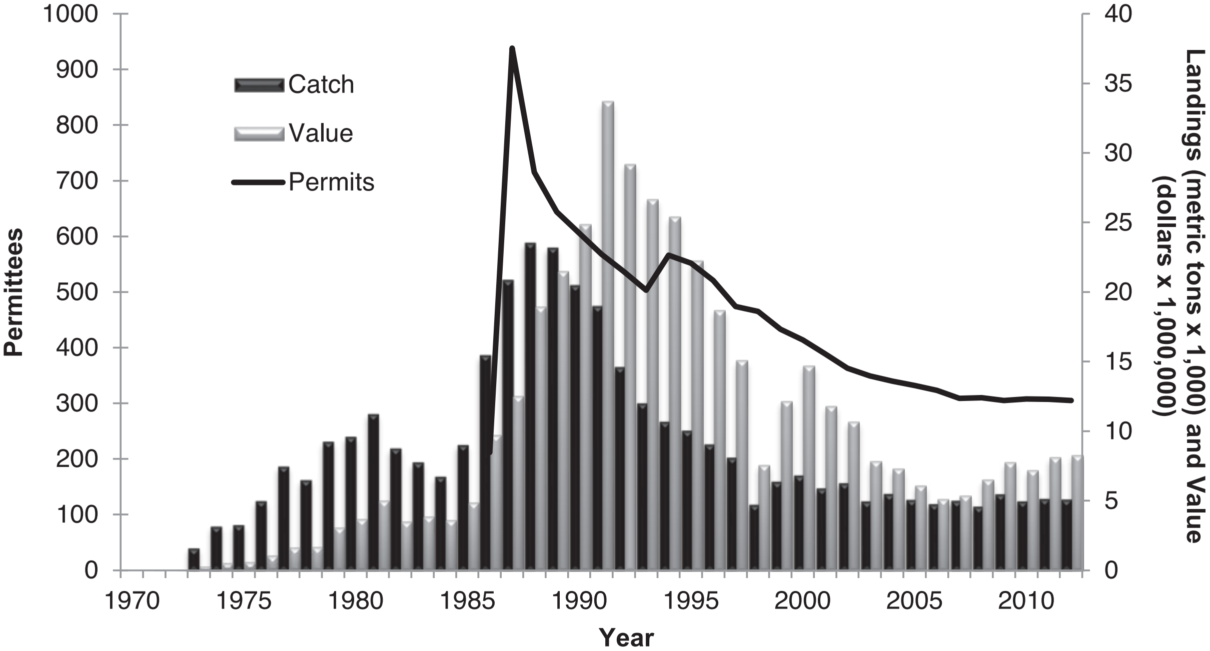

Figure 16. Catch, value, and number of permits for the California commercial red sea urchin (*Strongylocentrotus franciscanus*) fishery, 1970–2012.

annually over the next 8 years. The northern fishery effort in 2003 was 2,275 landings and declined to about 1,000–1,400 until 2008. From 2009–12, effort increased to 2,000–2,600 landings annually.

The proportion of yearly statewide catch was 77% in the south and 23% in the north. From 2003–07, the southern fishery has averaged 87% of the yearly statewide catch, but in the most recent five years (2008–12), average catch was 71%. An increase in the north and decrease in the south in recent years may be attributed to the addition of new active divers entering the northern fishery, and divers in the southern fishery participating in more lucrative dive fisheries such as sea cucumber. Many of the sea cucumber permit holders are also sea urchin divers, and recent increases in demand and value for sea cucumbers may be contributing to the shift.

For the last decade (2003–12), the average southern fishery catch was 4,029 t, and for the last two years was around 3,700 t. The Santa Barbara port continues to have the highest landings in the state, making up approximately 50% of the southern fishery landings in 2012 at 2,035 t, up from 1,835 t in 2011. Over the last decade a high percentage of the landings have originated in a few regions including the Channel Islands (mainly San Miguel and Santa Rosa Islands), San Diego, and San Clemente Island. In 2012, these regions continue to be the areas of concentration in the southern fishery.

A significant increase in the northern fishery catch occurred from 2008 at 1,201 t to 2009 at 1,802 t, and catch continues to stay near the 1,500 t level in 2012. This is up from previous years in the fishery where catch was generally below 1,000 t and only 476 t in 2006. Fort Bragg port consistently has the highest northern fishery contribution at 68% in 2012 with 1,007 t, up slightly from 940 t in 2011.

The 5,207 t California sea urchin fishery yielded $8.3 million ex-vessel in 2012, for an average of $1.61/kg of landed urchin. This unit value was well below the highest average on record of $2.36/kg in 1994, but similar to unit values since 2008. Over the last decade, unit value has averaged $1.36/kg. When adjusted for inflation using the 2012 consumer price index figures, $1.61/kg in 2012 is worth $1.04 in 1994, a 56% drop in value to the fishermen. It should be noted that some buyers in southern California began writing lower estimated prices on the market receipt at the time of unloading starting in about 2003, which was a result of regulations requiring buyers to record a price paid at the time of landing. This was not necessarily the ultimate price since the actual price is not paid to the fishermen until the quality of the product is assessed. The effect is that price and value data are likely an underestimate of the actual price paid to fisherman for red sea urchins in southern California during this time period. The California Department of Fish and Wildlife (Department) is working with the industry to rectify this problem.

Sea urchin permit renewals totaled 305 in the 2012 season, and has been consistently near 300 since dropping from 340 in 2004 with a steady decline toward the "capacity goal" of 300 set by regulation in the early 1990s. In 2004, the California Sea Urchin Commission (CSUC) was formed, and operates under state law to

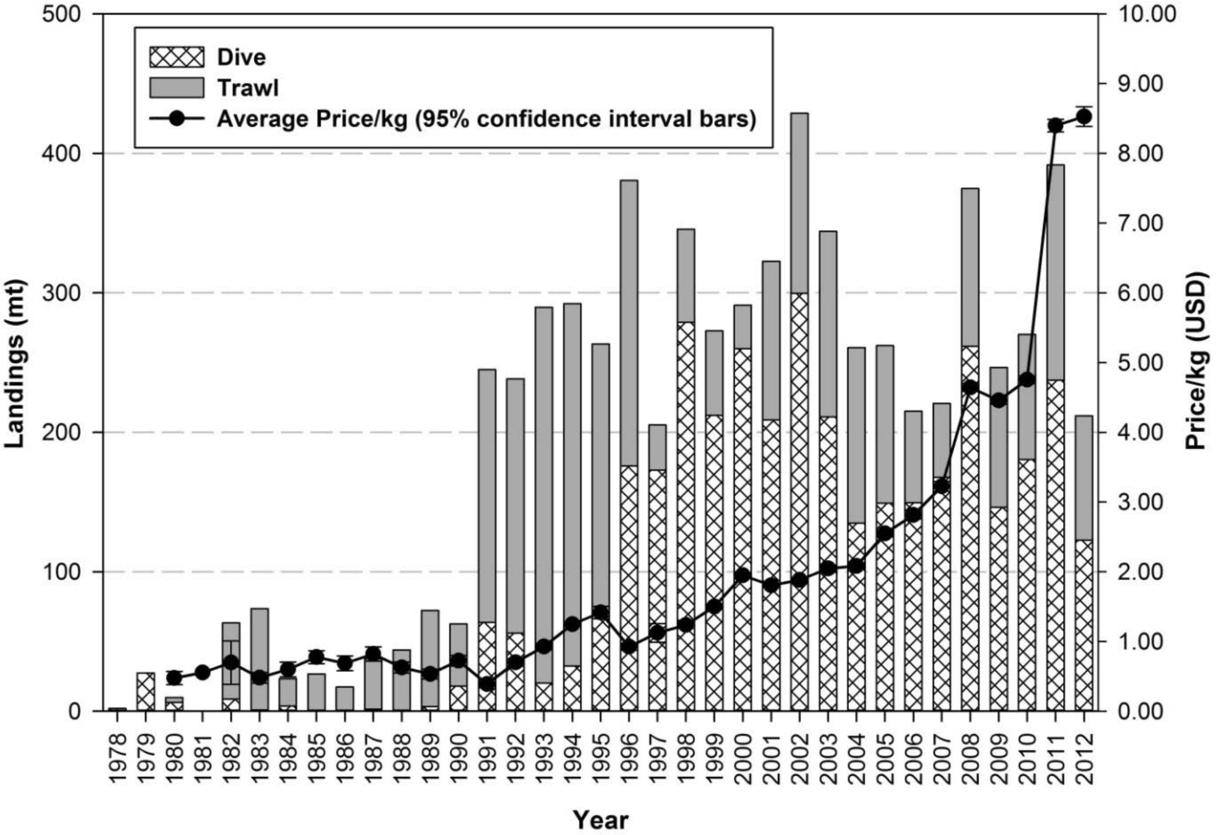

Figure 17. Commercial sea cucumber landings by dive and trawl fisheries from 1978–2012.

ensure a sustainable sea urchin resource and a reliable supply of quality seafood product for domestic consumption and export. The industry is currently working with the Fish and Game Commission and the Department to propose a regulatory package that includes a reduction in permit capacity goal, transferability, and the addition of fishing days.

In 2012, 50% of the catch was taken by the 40 top divers, and 80% of the catch was taken by 85 divers. In the northern fishery, 11 of the 41 active divers took 50% of the catch. In the event of an improvement in worldwide urchin markets, the latent fishery capacity could activate and drive catches considerably higher than those under our present management scheme. The capacity goal issue has increased in urgency due to the aging of the sea urchin diver population with the average diver age over 50 years old, and most of the catch coming from the older divers. The issue of permit transferability is being debated more actively as older divers look to retirement and hope to sell their permit or pass it on to younger family members.

Sea Cucumber

Commercial harvesting of warty sea cucumber (*Parastichopus parvimensis*) and giant red sea cucumber (*P. californicus*) has increased dramatically in California over the last decade in response to growing foreign demand from Chinese and Korean based markets. The giant red sea cucumber, also known as California sea cucumber, ranges from Alaska to Baja California, Mexico and mainly occurs in depths ranging from the low intertidal to 91 m (300 ft). Giant red sea cucumbers are primarily targeted by the trawl fishery in southern California and, to a limited extent, the dive fishery in northern California, with commercial dive landings recently increasing in southern California. Established dive fisheries targeting giant red sea cucumbers also exist in Washington and Alaska. The warty sea cucumber ranges from Monterey, California to Baja California, Mexico and is most commonly found in depths ranging from the low-intertidal to 30 m (90 ft). Due to the shallower distribution of the warty sea cucumber compared to the giant red, it is principally targeted by the dive fishery in southern California and Mexico.

The commercial and recreational take of sea cucumbers are managed by the California Fish and Game Commission. Starting in the 1992–93 commercial fishing season, a general "sea cucumber" permit was required to harvest sea cucumbers commercially. In order to qualify for this permit, individuals were required to meet a minimum landing requirement of "50 pounds" during a four year "window" period. In 1997, legislation

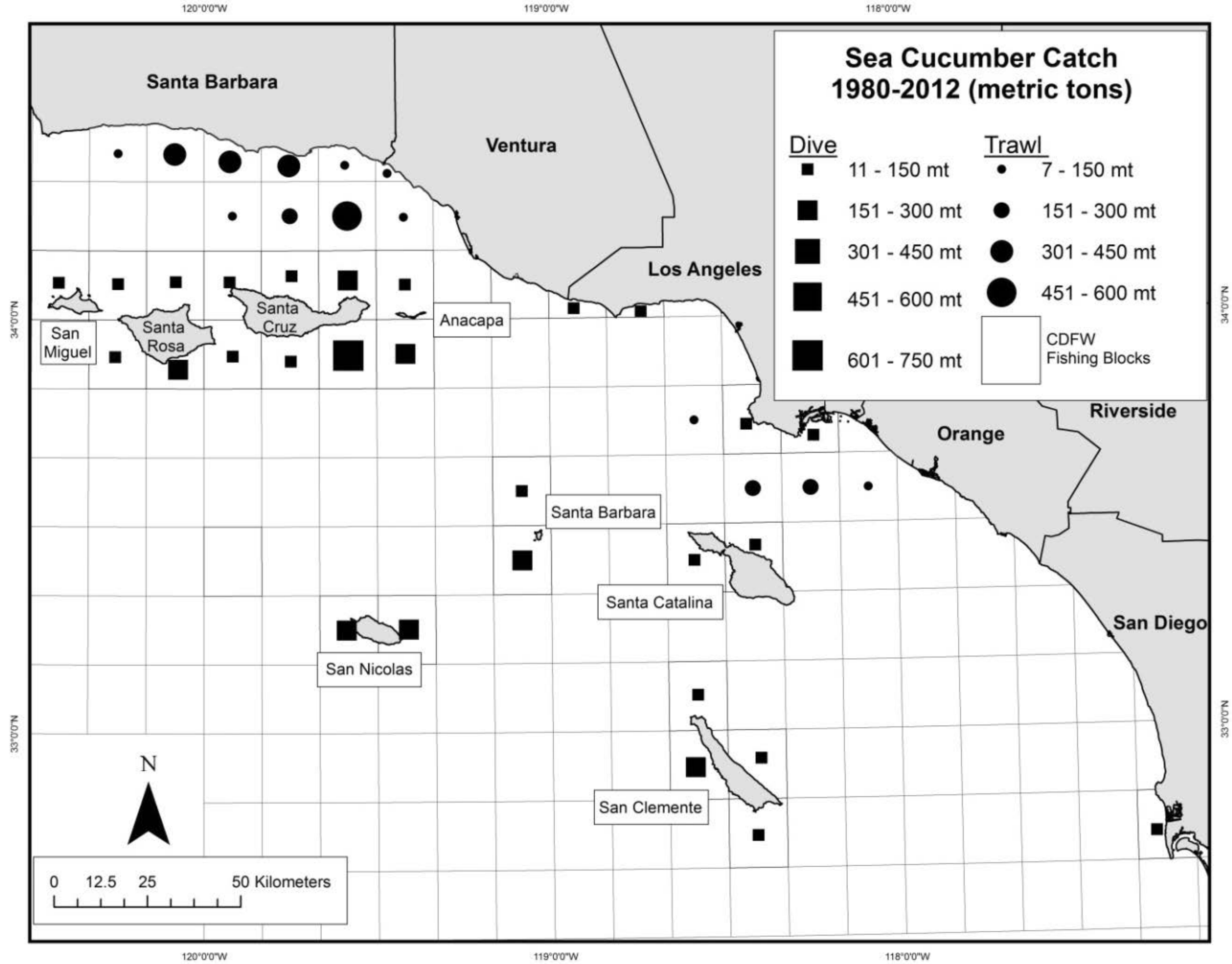

Figure 18. Commercial sea cucumber dive and trawl catch by origin (CDFW commercial fishing blocks) in southern California from 1980–2012. Commercial fishing blocks are approximately 256 km^2 (100 mile^2).

was passed creating separate "sea cucumber trawl" and "sea cucumber dive" permits. Another major regulatory change to this fishery at this time was the capping of the total number of available permits based on the number that were issued during the 1997–98 permit year (116 dive; 36 trawl), and the meeting of a minimum landing requirement. The transferability of sea cucumber trawl and sea cucumber dive permits was also initiated by the 1997 legislation. This allows sea cucumber fishermen to transfer their permits by selling them to other qualified individuals. Sea cucumber trawl permits can be transferred as either a trawl or dive permit, but dive permits can only be transferred as dive permits. Sea cucumber dive and trawl fishermen are required to fill out a California Department of Fish and Wildlife (Department) logbook detailing their daily fishing activities. The sport take of sea cucumbers is minimal at this time, with regulations consisting of a daily bag limit of 35 individuals that must be harvested by hand and greater than "1000 ft" from shore.

The sea cucumber fishery began in southern California in 1978, with divers targeting warty sea cucumber around Santa Catalina Island (fig. 17). In 1980, the trawl fishery began targeting giant red sea cucumber, and from 1980–94 trawl landings dominated sea cucumber landings, accounting for 84% over this period (fig. 17). In 1995, the average price per kilogram for sea cucumber reached a then all-time high of $1.40/kg ($0.64/lb), which led to increased dive effort starting in 1996. From 1996–12, the dive fishery has accounted for a majority of sea cucumber landings (67%), with most harvest occurring at offshore island locations (fig. 18). Most trawl catch occurs off the coast of Santa Barbara and Ventura counties, with minor landings originating off Los Angeles and Orange counties (fig. 18). Seasonally, dive landings generally peak from spring through early

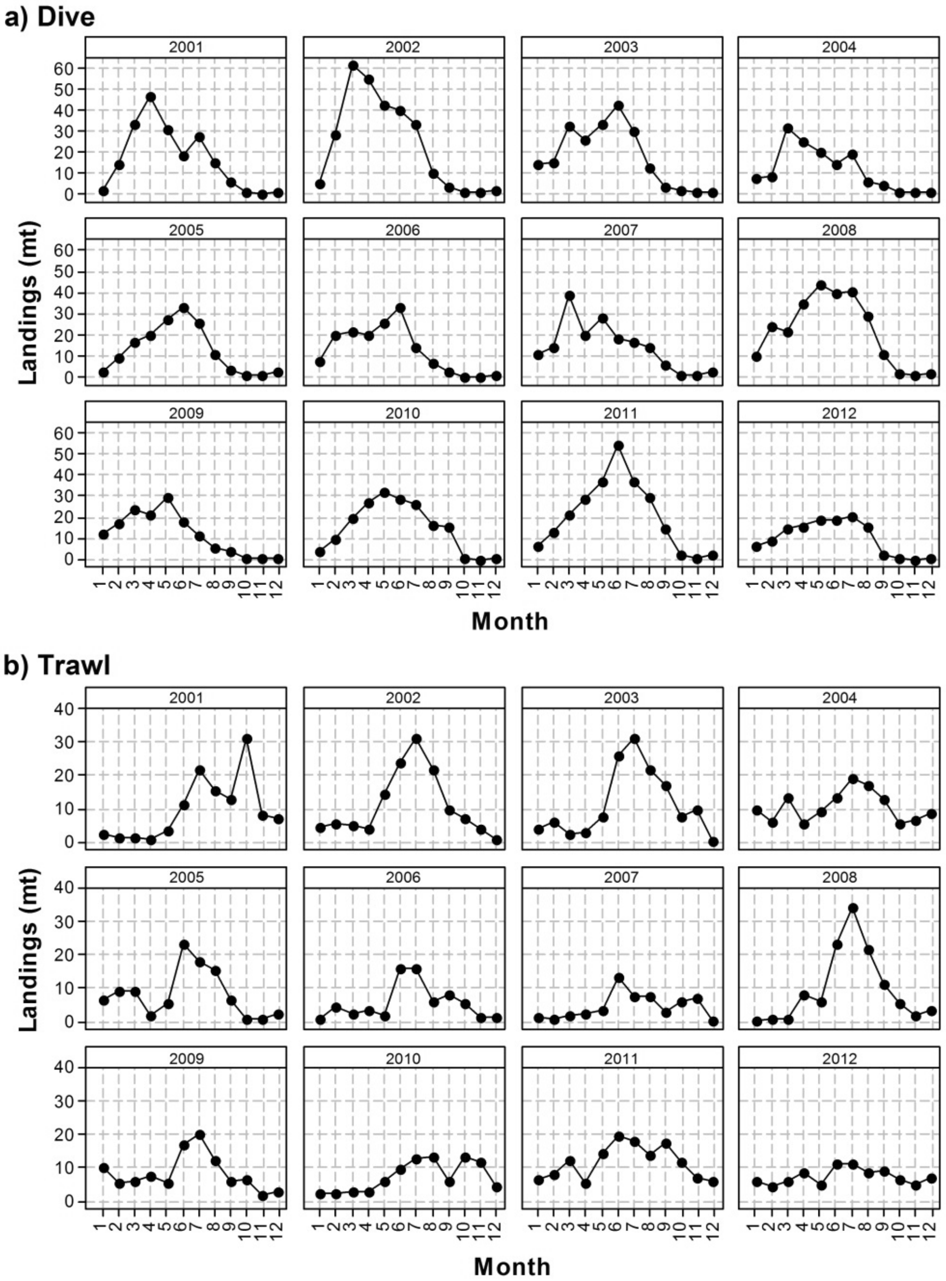

Figure 19. Total monthly commercial sea cucumber landings for a) Dive and b) Trawl fisheries from 2001–2012. Panel headings indicate the year.

summer between the months of April to June (fig. 19). There is a concern that because this is also the spawning period for warty sea cucumber, they may be more vulnerable to overharvesting at this time. Trawl landings for giant red sea cucumber generally peak later in the year between summer and fall, although it is not yet known whether this is the primary spawning period for this species (fig. 19).

In 2012, there were 83 dive and 16 trawl permits issued, with dive landings reaching 123 t with an ex-vessel value worth $1.2 million. This was a 50% reduction in landings when compared to 2011 (247 t), despite the fact that the average price reached a record high of $8.50/kg ($3.85/lb) in 2012. In 2011, the fishery set an all-time record ex-vessel value of $2.2 million. The 2012 dive landings were the lowest since 2005 when most of the fishery began to sell their product in a cut/processed state. Although the dive fishery mostly targets warty sea cucumber, dive landings of giant red sea cucumber reached a record high in 2012 of 23 t, which comprised 19% of all dive landings. In 2012, trawl landings reached 89 t with an ex-vessel value of $728,469, a

37% reduction in landings when compared to the 142 t landed in 2011, valued at a record high of $1.2 million (ex-vessel).

The limited understanding of the basic biology of warty and giant red sea cucumber presents various challenges in managing this growing fishery. The Department is currently concerned that some individuals are being harvested prior to reaching sexual maturity and that sexually mature individuals are being harvested during reproductive periods. In an effort to address these concerns, the Department is conducting seasonal dive surveys to determine how population densities change across seasons. Coupled with these dive surveys, individuals are also being collected to determine sex ratio, reproductive state, and size at first sexual maturity. Findings will inform key gaps in the basic biological understanding of our sea cucumber species while providing valuable information needed to explore potential management options.

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STATE OF THE CALIFORNIA CURRENT 2012–13: NO SUCH THING AS AN "AVERAGE" YEAR

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ABSTRACT

This report reviews the state of the California Current System (CCS) between winter 2012 and spring 2013, and includes observations from Washington State to Baja California. During 2012, large-scale climate modes indicated the CCS remained in a cool, productive phase present since 2007. The upwelling season was delayed north of 42°N, but regions to the south, especially 33° to 36°N, experienced average to above average upwelling that persisted throughout the summer. Contrary to the indication of high production suggested by

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[1] The first four authors represent members of the SWFSC California Current Integrated Ecosystem Assessment group and worked in equal collaboration on preparation of this report.

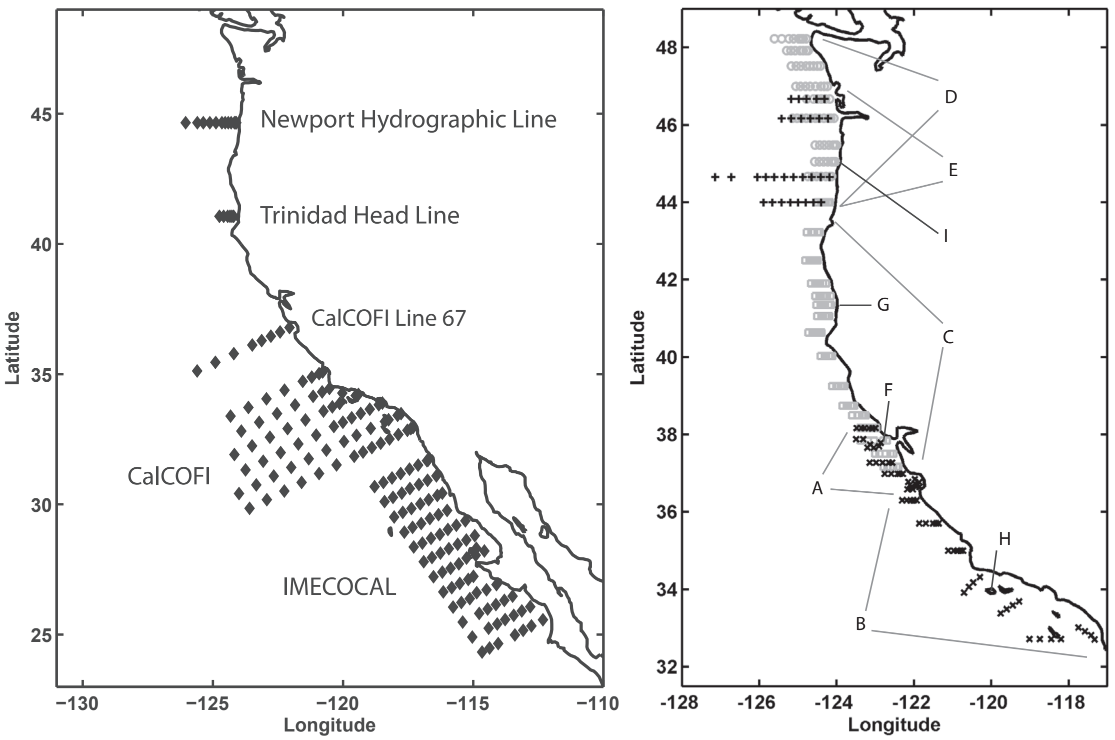

Figure 1. Left: Station maps for surveys that were conducted multiple times per year during different seasons to provide year-round observations in the California Current System. The CalCOFI survey (including CalCOFI Line 67) were occupied quarterly; the spring CalCOFI survey grid extends just north of San Francisco. The IMECOCAL survey is conducted quarterly or semiannually. The Newport Hydrographic Line 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. A. SWFSC FED midwater trawl survey core region (May–June) B. SWFSC FED midwater trawl survey south region (May–June). C. SWFSC FED salmon survey (June and September) (grey squares). D. NWFSC salmon survey (May, June, and September). E. 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.

the climate indices, chlorophyll observed from surveys and remote sensing was below average along much of the coast. As well, some members of the forage assemblages along the coast experienced low abundances in 2012 surveys. Specifically, the concentrations of all life-stages observed directly or from egg densities of Pacific sardine, *Sardinops sagax*, and northern anchovy, *Engraulis mordax*, were less than previous years' survey estimates. However, 2013 surveys and observations indicate an increase in abundance of northern anchovy. During winter 2011/2012, the increased presence of northern copepod species off northern California was consistent with stronger southward transport. Krill and small-fraction zooplankton abundances, where examined, were generally above average. North of 42°N, salps returned to typical abundances in 2012 after greater observed concentrations in 2010 and 2011. In contrast, salp abundance off central and southern California increased after a period of southward transport during winter 2011/2012. Reproductive success of piscivorous Brandt's cormorant, *Phalacrocorax penicillatus*, was reduced while planktivorous Cassin's auklet, *Ptychoramphus aleuticus* was elevated. Differences between the productivity of these two seabirds may be related to the available forage assemblage observed in the surveys. California sea lion pups from San Miguel Island were undernourished resulting in a pup mortality event perhaps in response to changes in forage availability. Limited biological data were available for spring 2013, but strong winter upwelling coastwide indicated an early spring transition, with the strong upwelling persisting into early summer.

INTRODUCTION

This report reviews the oceanographic and ecosystem responses of the California Current System (CCS) between winter 2012 and spring of 2013. 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 a simple figure(s) that might not convey the full complexity of the region being studied. As a consequence, we

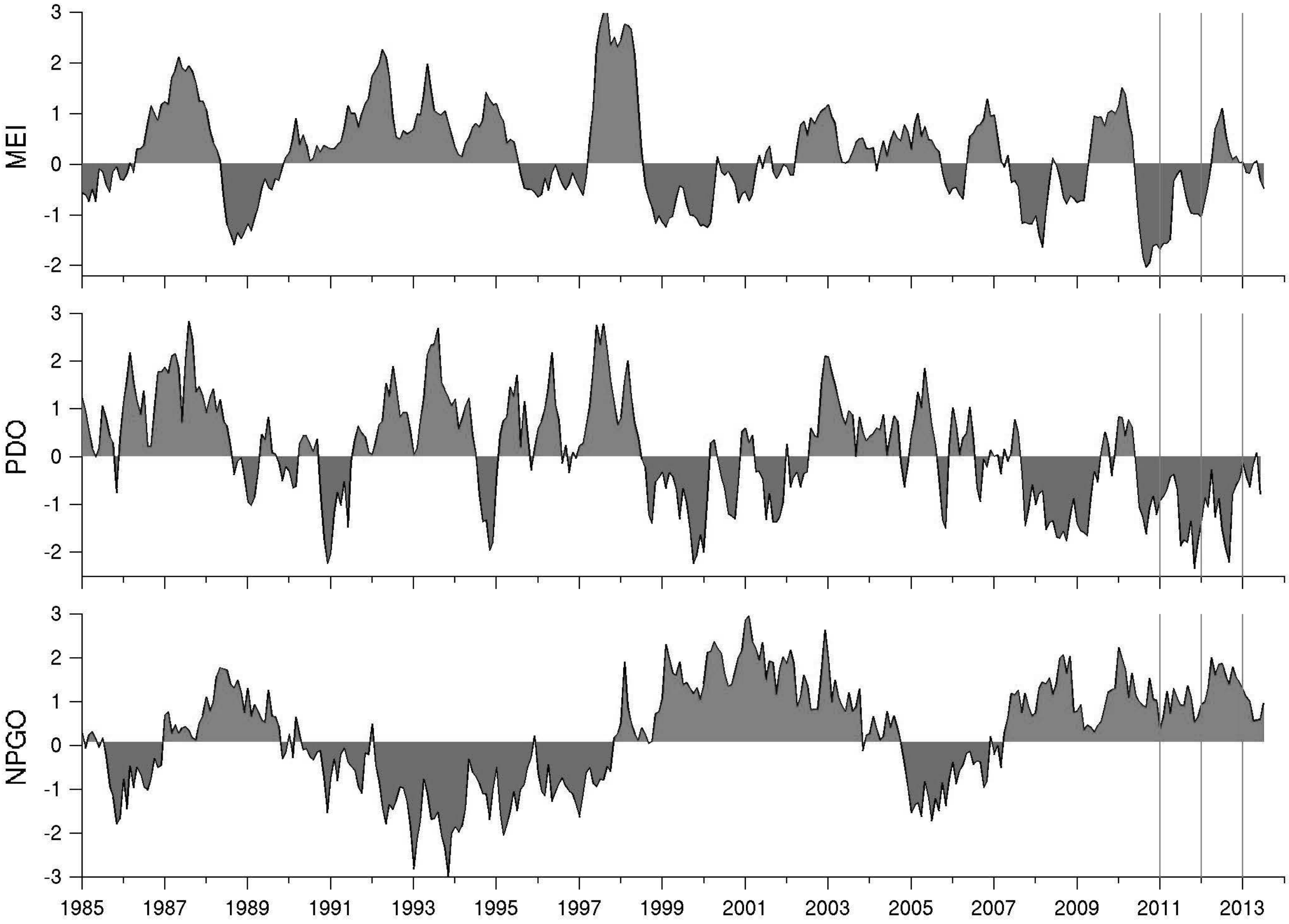

Figure 2. Time series of monthly mean values for three ocean climate indices especially relevant to the California Current: the multivariate ENSO index (MEI), the Pacific Decadal Oscillation (PDO), and the North Pacific Gyre Oscillation (NPGO) for January 1985–June 2013. Vertical lines mark January 2011, 2012, and 2013.

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 in the supplement. Can be found in the supplement (http://calcofi.org/publications/ccreports/568-vol-54-2013.html)

In 1949, the California Cooperative Oceanic Fisheries Investigations program (CalCOFI) was formed to study the environmental causes and ecological consequences of Pacific sardine, *Sardinops sagax*, variability. Consideration of the broader forage communities has been invigorated by recent fluctuations in the abundance of sardine and another important forage fish, the northern anchovy, *Engraulis mordax* (Cury et al. 2011; Pikitch et al. 2012). Specifically, there has been a decline in the observed catches of larval, juvenile, and adult northern anchovy reported by the various sampling programs along the CCS (Bjorkstedt et al. 2012). While not unprecedented, with two similar examples since 1993, the estimated Pacific sardine biomass declined from 1,370,000 MT in 2006 to 659,539 MT in July 2012 (http://www.pcouncil.org/wp-content/uploads/MAIN_DOC_G3b_ASSMNT_RPT2_WEB_ONLY_NOV2012BB.pdf). Here, we return to an initial focus of the CalCOFI program and consider physical and biological signals related to coastal pelagic species. Importantly, the survey designs that we examine are dissimilar and each has unique limitations restricting a common interpretation along the CCLME. Therefore, this report should be considered a first examination for instigating more focused exploration of potential drivers of the forage community's dynamics.

This report will focus on data highlighting variability in the forage community with additional (supporting) data provided in the supplement. Some information in the supplement are data that have been presented in previous reports and are included as a reference to an aspect of the "state of the CCS," which might be of interest beyond the focus here. 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.

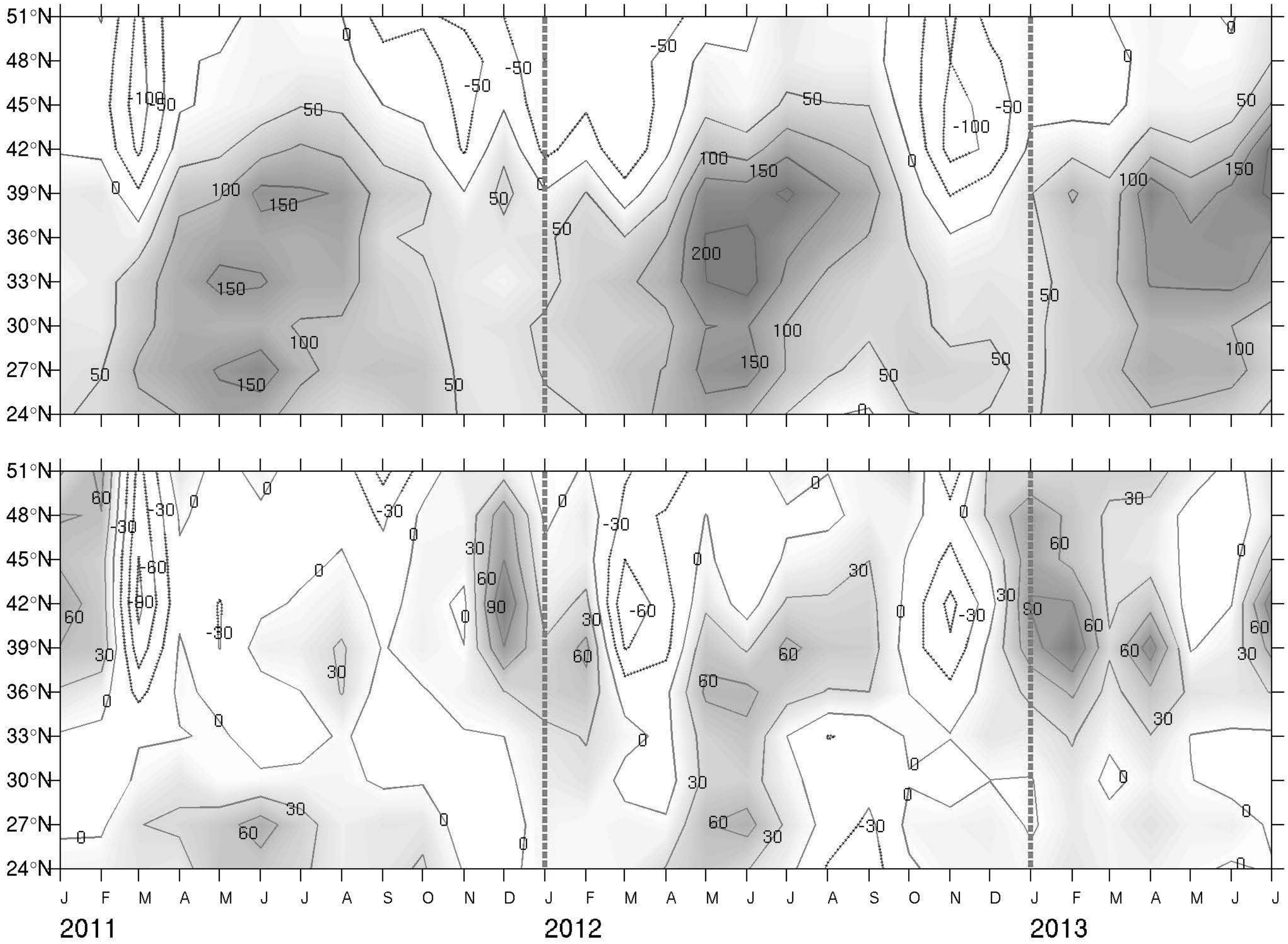

Figure 3. Monthly upwelling index (top) and upwelling index anomaly (bottom) for January 2011–May 2013. Shaded areas denote positive (upwelling-favorable) values in upper panel, and positive anomalies (generally greater than normal upwelling) in lower panel. Anomalies are relative to 1967–2013 monthly means. Units are in m³ s–1 per 100 km of coastline.

NORTH PACIFIC CLIMATE INDICES

The multivariate El Niño Southern Oscillation (ENSO) index (MEI) (Wolter and Timlin 1998) transitioned from La Niña conditions in summer of 2010 through January 2012 (fig. 2). In the summer of 2012, MEI increased but the values were too low and short-lived to be classified as an ENSO event; the values returned to neutral conditions in the spring of 2013. The Pacific Decadal Oscillation index (PDO) (Mantua and Hare 2002) has been negative (cool in the CCS) coinciding with the start of the La Niña in the summer of 2010 (fig. 2). The PDO continued in a negative phase through the summer of 2012, with a minimum in August. After October 2012, the PDO increased to slightly negative values in the winter and spring of 2013. The May 2013 value of the PDO was +0.08 but dropped to a value of –0.78 in June. The North Pacific Gyre Oscillation index (NPGO) (Di Lorenzo et al. 2008) was positive from the summer of 2007 to the spring 2013 with a peak value in July 2012 (fig. 2).

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 indices (fig. 2). In the summer of 2012, predominately negative SST anomalies over the western Pacific coincided with anticyclonic wind anomalies. Warmer than normal SST (+1.0°C) in the central and eastern north Pacific occurred during a period of anomalous eastward winds in October of 2012. For 2013 the northeast Pacific experienced winter SST anomalies that were slightly cooler than normal (< –0.5°C), followed by slightly warmer anomalies (< +0.5°C) in the spring. SST anomalies across the North Pacific in 2013 (January to June) were positive and were simultaneous with a rise in PDO values from the extreme negative values experienced in 2012. However, SST anomalies along the CCS remained slightly negative (< –0.5°C) forced by equatorward meridional wind anomalies (fig. S1).

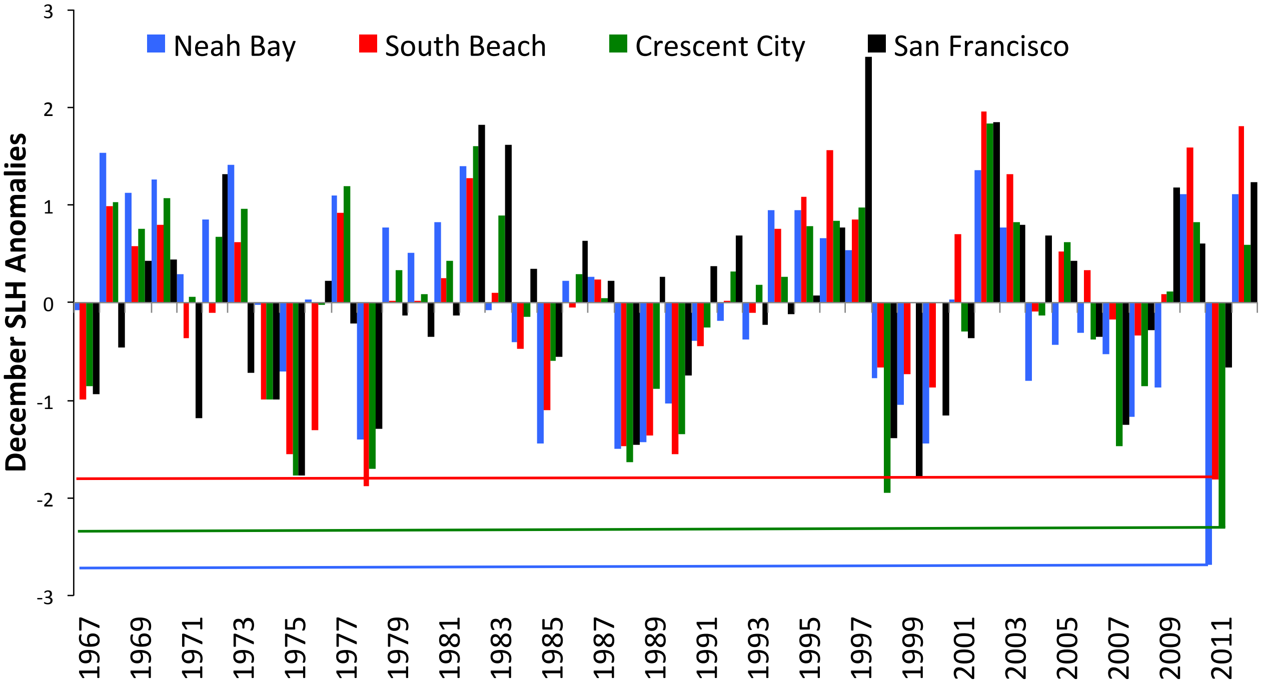

Figure 4. Sea level height anomalies measured by tidal gauges during December for the following four locations along the CCS: Neah Bay, WA, South Beach, OR, Crescent City, CA and San Francisco, CA. Horizontal lines mark the values observed in December 2011.

Upwelling in the California Current

December 2011 was marked by anomalously strong upwelling between 36°N and 45°N and substantially weaker downwelling north of 45°N (fig. 3). This resulted in anomalously low coastal sea levels, as measured by tidal gauges, in December at Neah Bay, WA, South Beach, OR, and Crescent City, CA (fig. 4). Such low coastal sea levels suggests southward transport in winter 2011/2012.

By March 2012, upwelling winds north of 39°N were anomalously low while winds south of 39°N remained near the climatological mean. Upwelling north of 39°N did not resume again until May and for summer and fall remained at close to climatological values. In contrast, south of 39°N average upwelling prevailed from winter 2011 to April 2012, after which it intensified. Strong upwelling continued off central California until fall. North of 36°N, high upwelling persisted through winter 2012 and into January–February 2013 (fig. 3).

The cumulative upwelling index (CUI) gives an indication of how upwelling influences ecosystem structure and productivity over the course of the year (Bograd et al. 2009). In the north from 42° to 48°N, the upwelling season in 2012 began early (fig. S2) resulting in average CUI values from January 1 to the beginning of March, but dropped to below long-term average over the spring and summer. The upwelling season also began early in southern and central California (33°–36°N) during 2012, with highest levels of the CUI at the end of February since record highs experienced in 2007. Strong upwelling continued into the summer off southern California (33°N) with CUI estimates at the end of July being the highest since 1999. At 36°N, the 2012 CUI values at the end of the year were the second highest on record, falling just below the high in 1999. Through mid-2013, CUI values are greater than previously observed records throughout the CCS. While there were significant regional differences in upwelling in 2012, strong upwelling occurred more widely in the CCS in winter and spring of 2013.

Coastal Sea Surface Temperature

In 2011, the daily December values of SST were below average especially at the northern California and Oregon buoys (fig. S3). This is due to upwelling at the start of December; these winds were especially long in duration for the Oregon buoy, with the event lasting over half of the month. Anomalously cool SST values in December 2011 extended into spring of 2012 as measured by all of the buoys. There was very little temperature variation between winter of 2011/2012 through spring of 2012. Periods of northerly winds occurred in January and February for the northern buoys with these winds switching directions to southerly in March and April. SST increased for the northern two buoys but the southern buoys showed average temperatures. Only one buoy (St. George, CA) had a complete record of winds in the summer (June–August) of 2012, and the winds

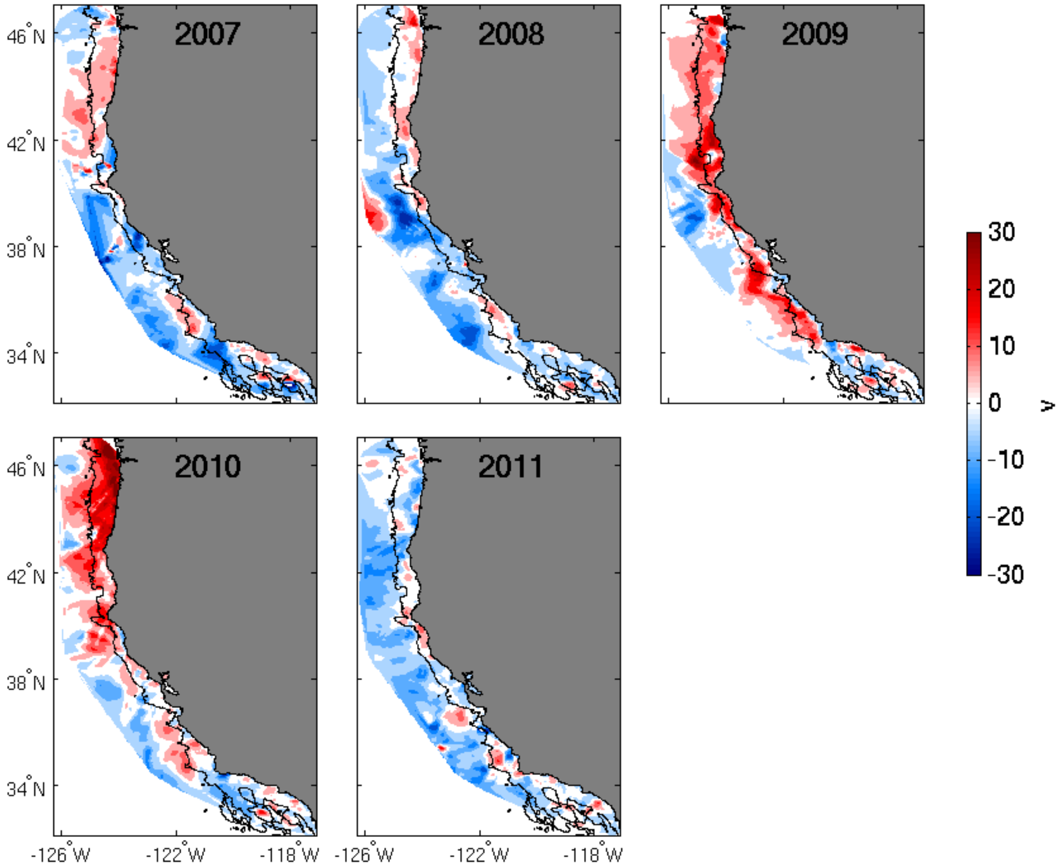

Figure 5. Maps of mean HF radar meridional surface currents observed December 2011 throughout the CCS 2007–11 (December 2012 was not available for this report). Meridional current speed is indicated by color bar (blue shading indicates southward flow) with units of cm/s.

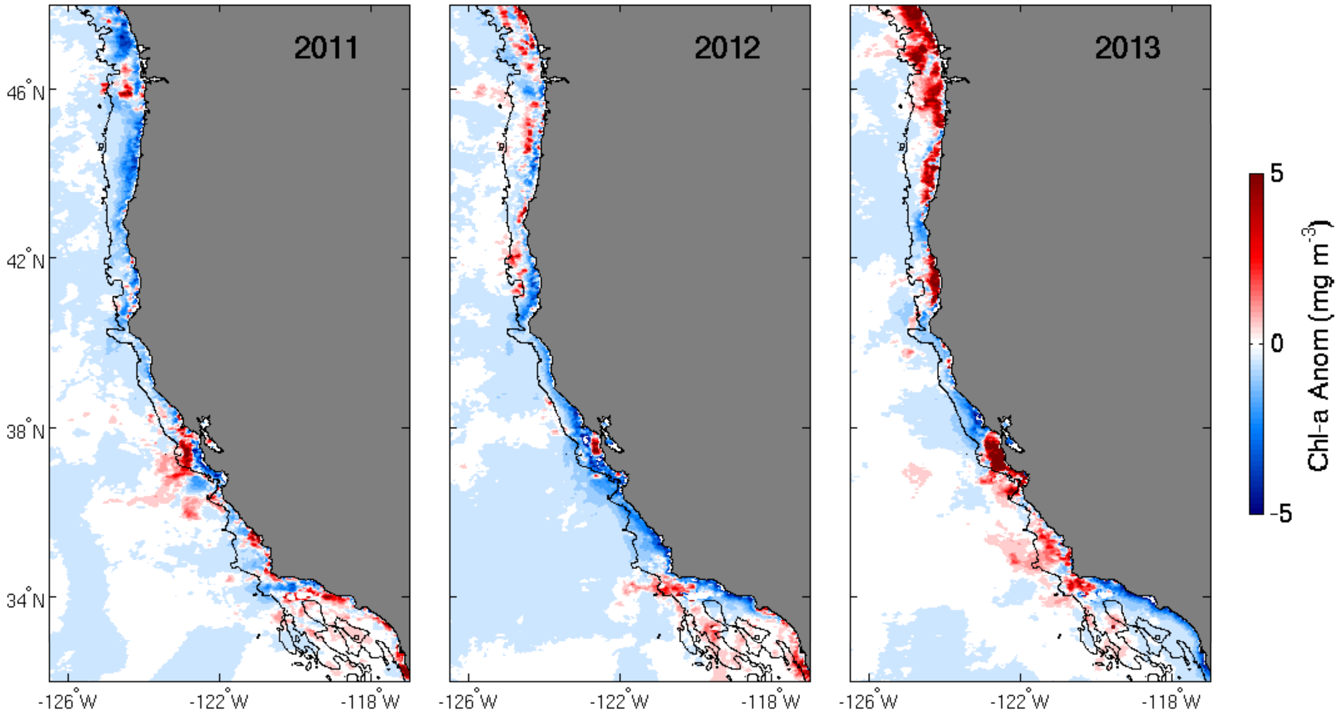

Figure 6. Aqua MODIS satellite measured chlorophyll *a* anomalies for March–May averages. The climatology was based on data for the years 2003–13. The black line is the 1000 m isobath.

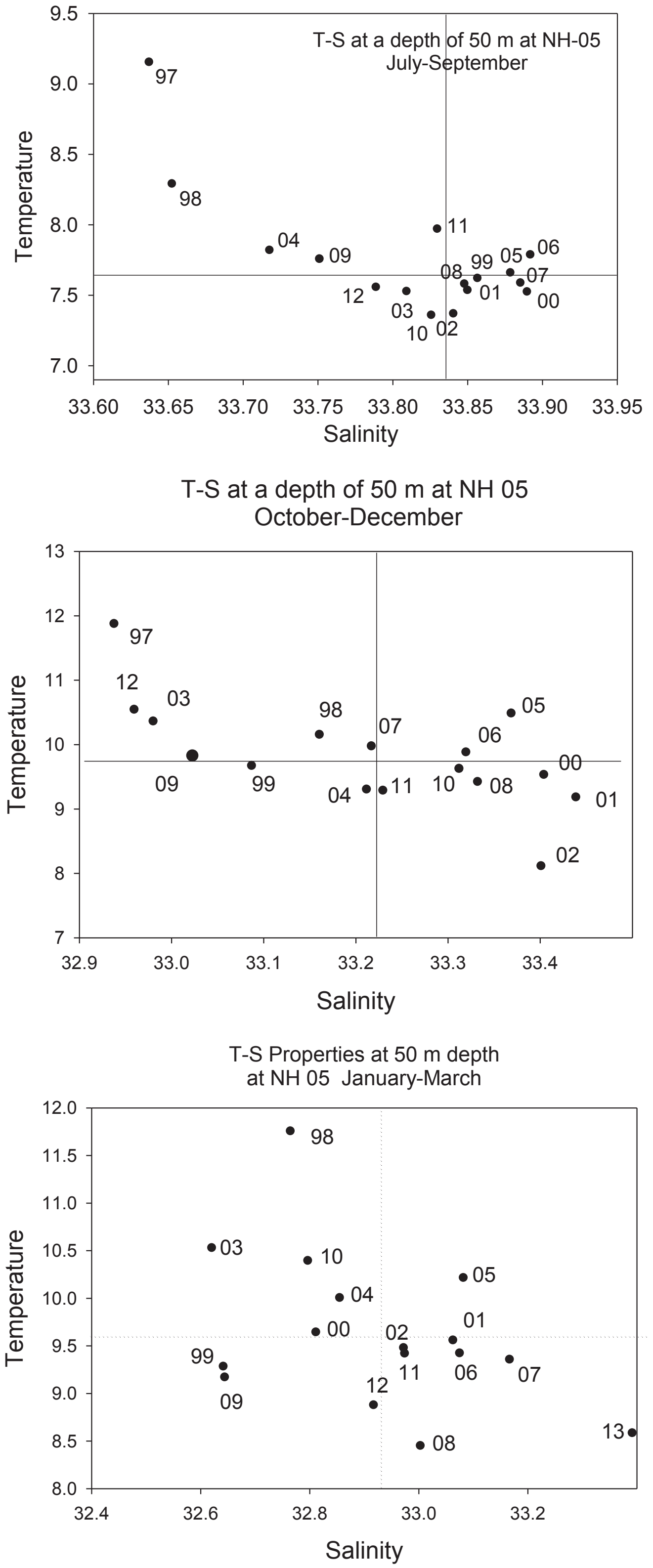

Figure 7. Seasonal mean temperature and salinity at 50 m depth at NH-5 along the Newport Hydrographic Line averaged for summer, fall and winter 2012. Cruises are made biweekly. Numbers adjacent to each data indicate "year."

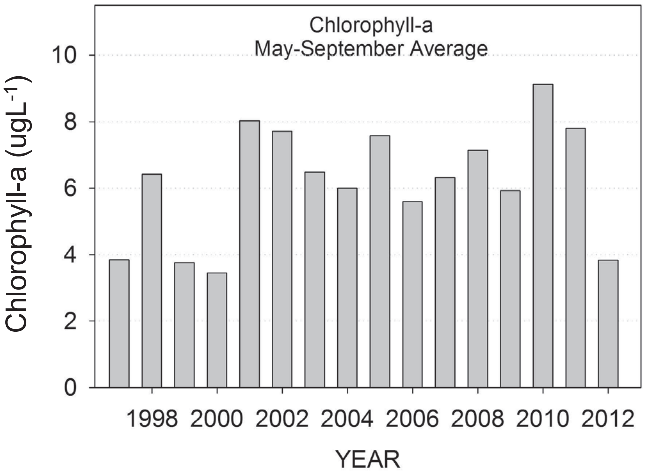

Figure 8. Chlorophyll *a* time series off Newport Oregon at station NH5 showing that chlorophyll *a* averaged over the May–September upwelling season, was unusually low in the year 2012, similar to values not seen since 1999 and 2000.

were predominately downwelling in direction with only a few days of upwelling winds in June. Towards the end of fall (October–November of 2012) above average SSTs occurred for all of the buoys for which we had data. The winds during this time were downwelling-favorable except for a strong upwelling event in the beginning of December. Cool temperatures were evident in early 2013 and persisted until April for all of the buoys. In late April, SSTs dipped due to a strong upwelling event. The winds in January through June of 2013 have mostly been upwelling-favorable except off Oregon where there have been short periods of downwelling.

High Frequency Radar Surface Current Observations

Surface transport was southward in the northern CCS during December 2011, as observed by high frequency (HF) radar (fig. 5) in support of the upwelling (fig. 3) and sea level (fig. 4) data. For the spring of 2012 surface currents observed with HF radar revealed southward currents, developing into marked offshore flow in summer with a general weakening in the fall and a tendency for weak northward flow in winter (see supplement for additional results, fig. S4).

Coast-wide Analysis of Chlorophyll

We used Aqua MODIS satellite measurements to evaluate spring chlorophyll (anomalies; climatology based on 2003–13) in the surface waters of the CCS for 2011–13 (details in supplement). Surface chlorophyll anomalies were generally below average north of San Francisco, CA during the spring of 2011, while the spring values of chlorophyll in 2012 were below average south of Cape Mendocino except for increased production in the Gulf of the Farallones and throughout

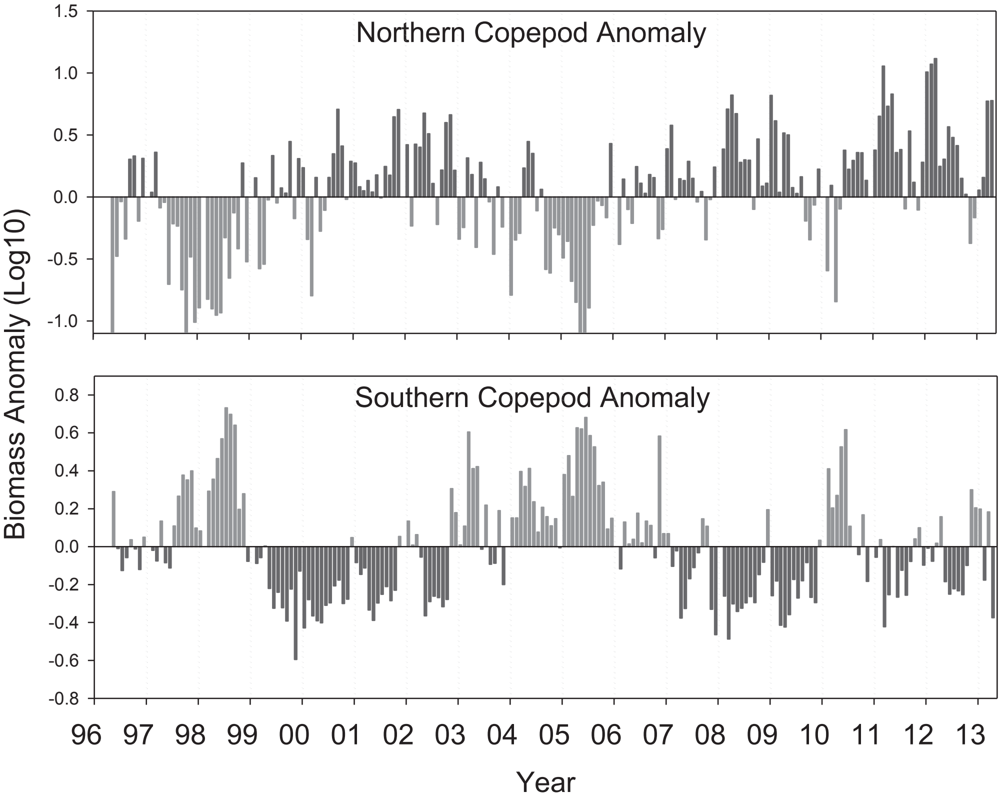

Figure 9. Time series of monthly values of the Northern Copepod Anomaly and Southern Copepod Anomaly. The copepod data are from biweekly sampling at station NH-5 along the Newport Hydrographic Line.

much of the offshore regions south of Point Conception (fig. 6). In spring 2013, chlorophyll was elevated along most of the coast north of Point Conception; south of Point Conception chlorophyll was below average.

REGIONAL SUMMARIES OF HYDROGRAPHIC AND PLANKTONIC DATA

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

Northern California Current: Newport Hydrographic Line

Daily values of SST from the Newport Hydrographic Line showed warm temperature anomalies in June and July 2012, with daily values of temperature anomalies around +3˚C in mid-July. The monthly average anomaly was +1.7˚C for July. SST at hydrographic station NH5 (five miles offshore of Newport) was also above-average over the May–September period with a peak in SST (15.9˚C) observed on 25 June, a value which was the 12th warmest of 450 sampling dates since 1997.

The April–June 2012 data were among the fresher and warmer years; July–September was cool and fresh. By contrast, during the January to March period of 2013, deep water was the most saline of the time series. Concomitant with that, the temperature was also one of the two lowest, 2008 being the lowest (fig. 7). Chlorophyll values at five miles off shore (NH5) averaged over May–September were the lowest they have been since 1999 and 2000 (fig. 8).

Examination of the copepod community can help to determine source waters and provide insights into the productivity of the system (Peterson and Keister 2003). Copepods that arrive from the north are cold-water species that originate from the coastal Gulf of Alaska and include three cold-water species: *Calanus marshallae*, *Pseudocalanus mimus*, and *Acartia longiremis*. Copepods that reside in offshore and southern waters (warm-water species) include *Paracalanus parvus*, *Ctenocalanus vanus*, *Calanus pacificus*, and *Clausocalanus* spp. among others. Copepods are transported to the Oregon coast, either from the north/northwest (northern species) or from the west/south (southern species). The Northern Copepod Index (Peterson and Keister 2003) was positive from autumn 2010 through summer 2012. The January and February 2012 values were the highest ever for the index and occurred after the southern transport anomaly observed in the winter of 2011 (figs. 9 and 4). The

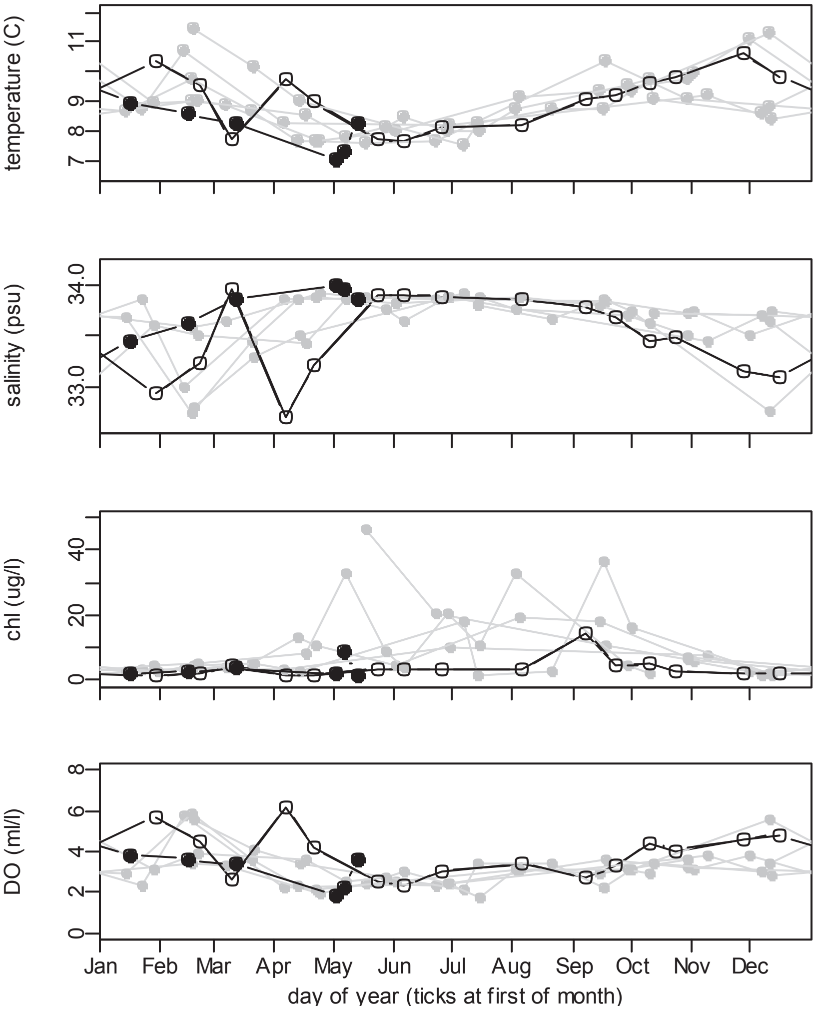

Figure 10. Hydrographic and ecosystem indicators at mid-shelf along the Trinidad Head Line (station TH02, 75 m depth). Panels from top to bottom show near-bottom (60 m) temperature, near-bottom (60 m) salinity, mean chl *a* concentration over the upper 30 meters of the water column, and near-bottom (60 m) dissolved oxygen concentrations. Grey symbols indicate historical observations (2006–11), open circles indicate observations during 2012, and closed symbols indicate observations in 2013.

Southern Copepod Index was predominately negative throughout much of the 2011 to 2013 period (fig. 9).

Northern California Current: Trinidad Head Line

Consistent with the Newport Hydrographic Line, observations along the Trinidad Head Line indicated that coastal waters off northern California were affected by strong downwelling and freshening during a series of storms in spring 2012 (fig. 10). Storm activity continued to affect waters off northern California through the spring and into summer, with northward wind and rain events occurring into July. Chlorophyll concentrations in the upper water column remained very low over the shelf throughout 2012 (figs. 6 and 10), save for a modest bloom that developed in early fall (fig. 10). This trend was apparent along the entire line, out to approximately 50 km offshore. Low chlorophyll concentrations in spring and summer 2012 do not appear to have been a result of low nutrient availability as nutrient concentrations were average.

In contrast to the stormy conditions observed in early 2012, ocean conditions in early 2013 along Trinidad Head Line reflect the effects of a relatively dry winter marked by unusually consistent, extended periods of upwelling favorable winds, and relatively infrequent storms of short duration. Intense upwelling throughout April resulted in the coldest, saltiest water observed on the shelf during the time series; conditions over the shelf remained cold and salty relative to spring 2012 (fig. 10). Since the onset of intense upwelling, average chlorophyll concentrations in the upper water column have remained relatively low (fig. 6).

In 2012 the copepod assemblage over the northern California shelf included relatively few northern neritic species, and high species diversity reflecting the preva-

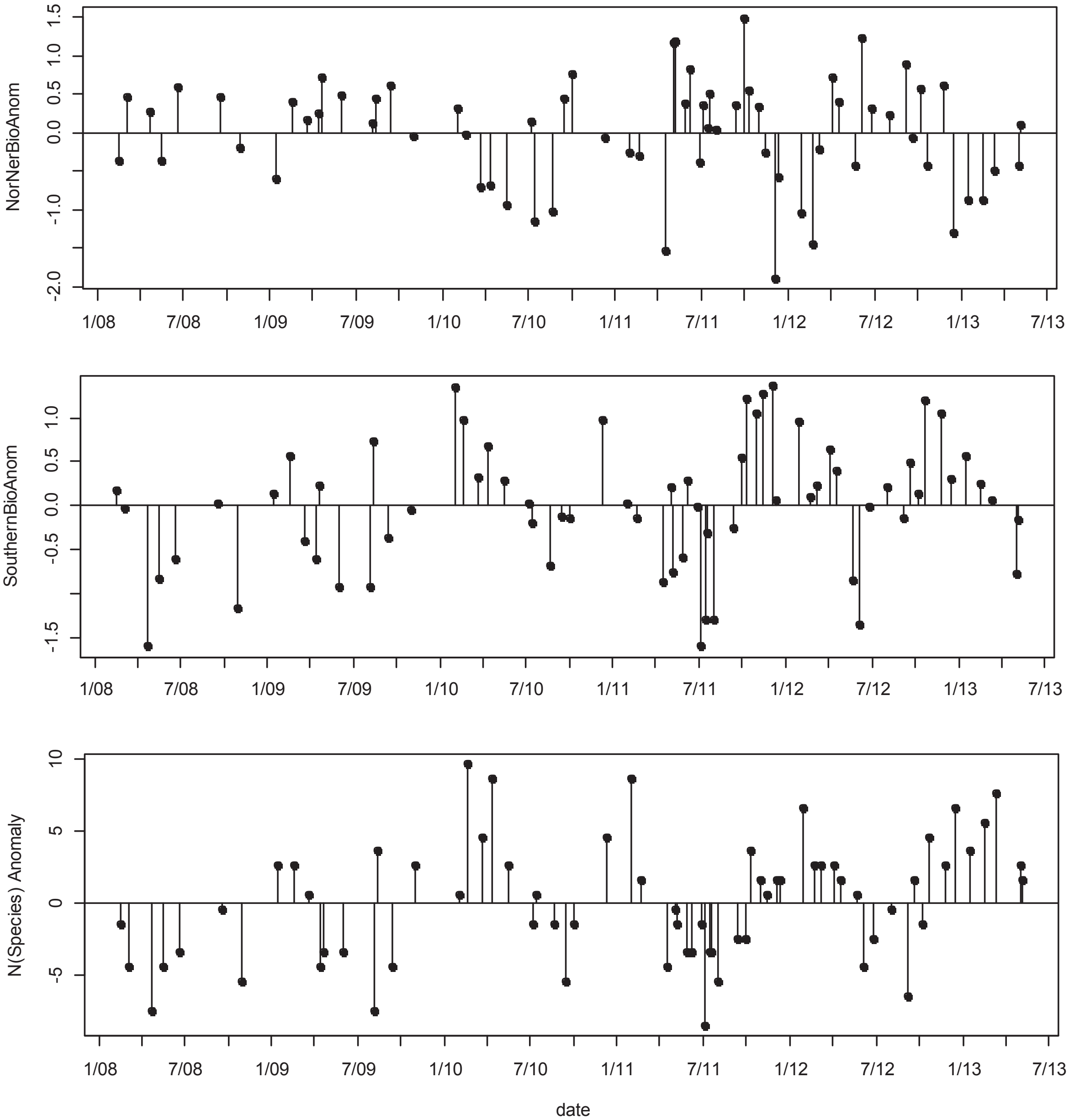

Figure 11. Anomalies (from the 2008–13 mean) in biomass and species richness of the copepod assemblage at mid-shelf on the Trinidad Head Line (station TH02, 75 m depth). Top: Biomass anomaly of dominant northern neritic copepods (dominated by *Pseudocalanus mimus*, *Calanus marshallae*, and *Acartia longiremis*). Middle: 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.). Bottom: species richness anomaly.

lence of "southern" and "offshore" taxa over the shelf (fig. 11). Northern neritic taxa were modestly more abundant in late spring and summer, but southern taxa were displaced from the shelf only for a brief period in summer 2012. Coupled trends in the copepod assemblage (declining biomass of southern and oceanic taxa and increasing biomass of northern neritic species) in early 2013 were consistent with expected effects of physical forcing and patterns observed to the north (Newport Hydrographic Line).

Central California[2]

In January 2012 surface values were colder and saltier due to upwelling winds in late 2011. However, salinity values returned to average by June (fig. 12). Surface temperatures remained lower than average until fall. At 100 m anomalous high salinity and low temperature values persisted from January to May, after which they became average to above average for the remainder of

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[2] See supplement for HF radar data and description of surface current patterns in the Central California region.

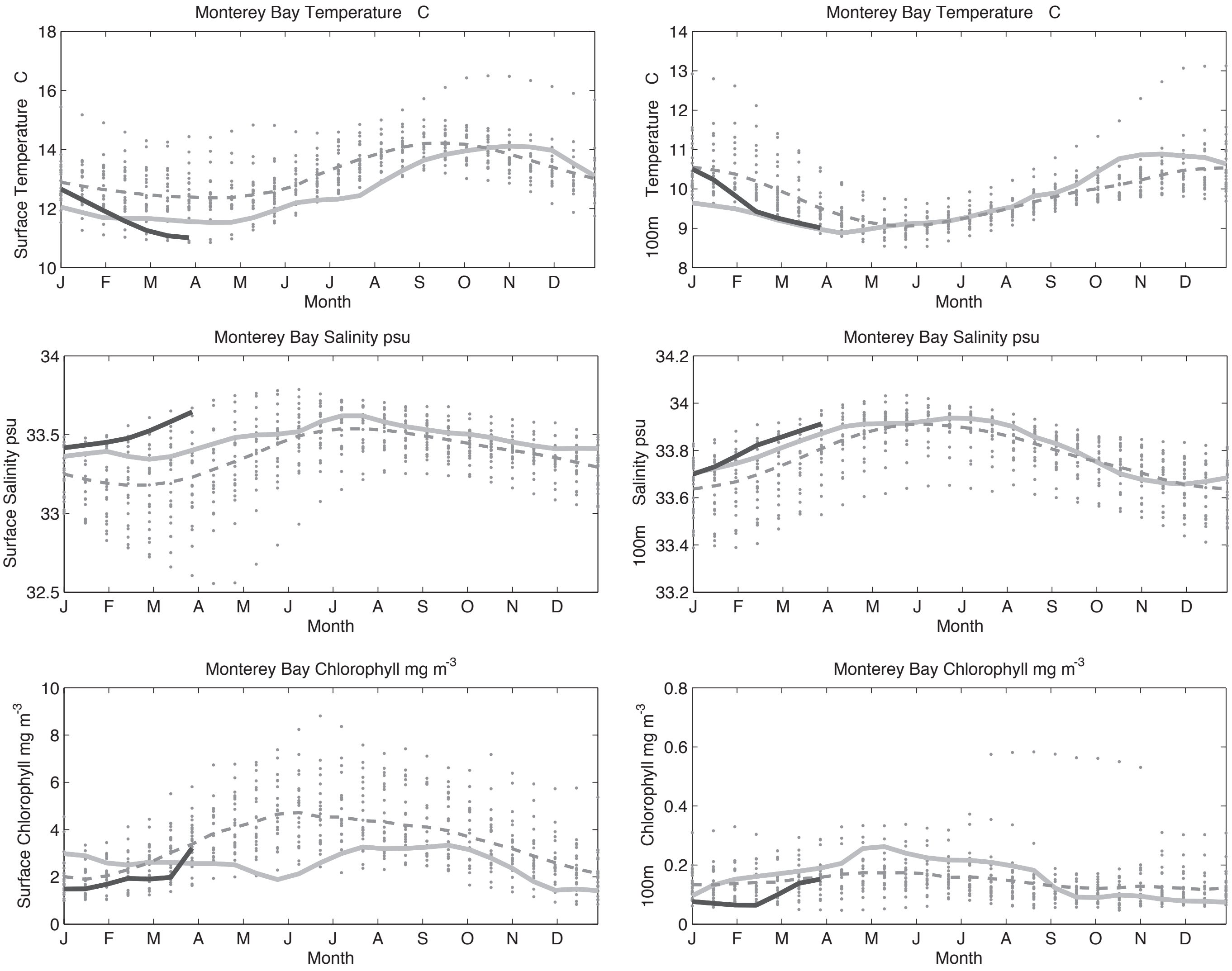

Figure 12. Temperature (top panels), salinity (middle panels) and chlorophyll concentration (bottom panels) at the surface (left hand column) and at 100 m (right hand column) observed at the M1 mooring.

the year. Surface chlorophyll was above average during January–February but was below average in the spring and continued to decrease to the lowest values on record by June (fig. 12). At 100 m chlorophyll was average to above average from January to August.

In early 2013, upwelling was significantly stronger than 2012, with the surface salinity and temperature near their maximum and minimum values respectively by April (fig. 12). Surface chlorophyll values increased from below average values in January to mean values by April. At depth, the relationships were similar to those at the surface (fig. 12).

Southern California

The 2012 mixed-layer temperatures continued to be mostly below long-term averages in southern California (fig. 13), consistent with the trends across much of the northeast Pacific (PDO, fig. 2). Mixed-layer temperatures since the 1998/99 ENSO have been decreasing but not significantly. Mixed-layer salinities have been increasing over the last two years; this increase reflected a similar increase of the NPGO (fig. 2). Areas of the CalCOFI study domain within the California Current and coastal areas affected by it saw the increase in salinity values. The increase in salinity is primarily observed in those areas of the CalCOFI study domain that are affected by the California Current. The salinity signal was not observed in the offshore areas of the CalCOFI domain that represent the edge of the North Pacific Gyre (fig. S6).

Concentrations of nitrate were close to long-term averages, except for above average spring 2013 values (fig. 13). The distinctive increase of nitrate at the σ_t 26.4 kg/m^3 isopycnal from 2009 to 2012 noted in Bjorkstedt et al. 2012 has returned to near-mean values over the last

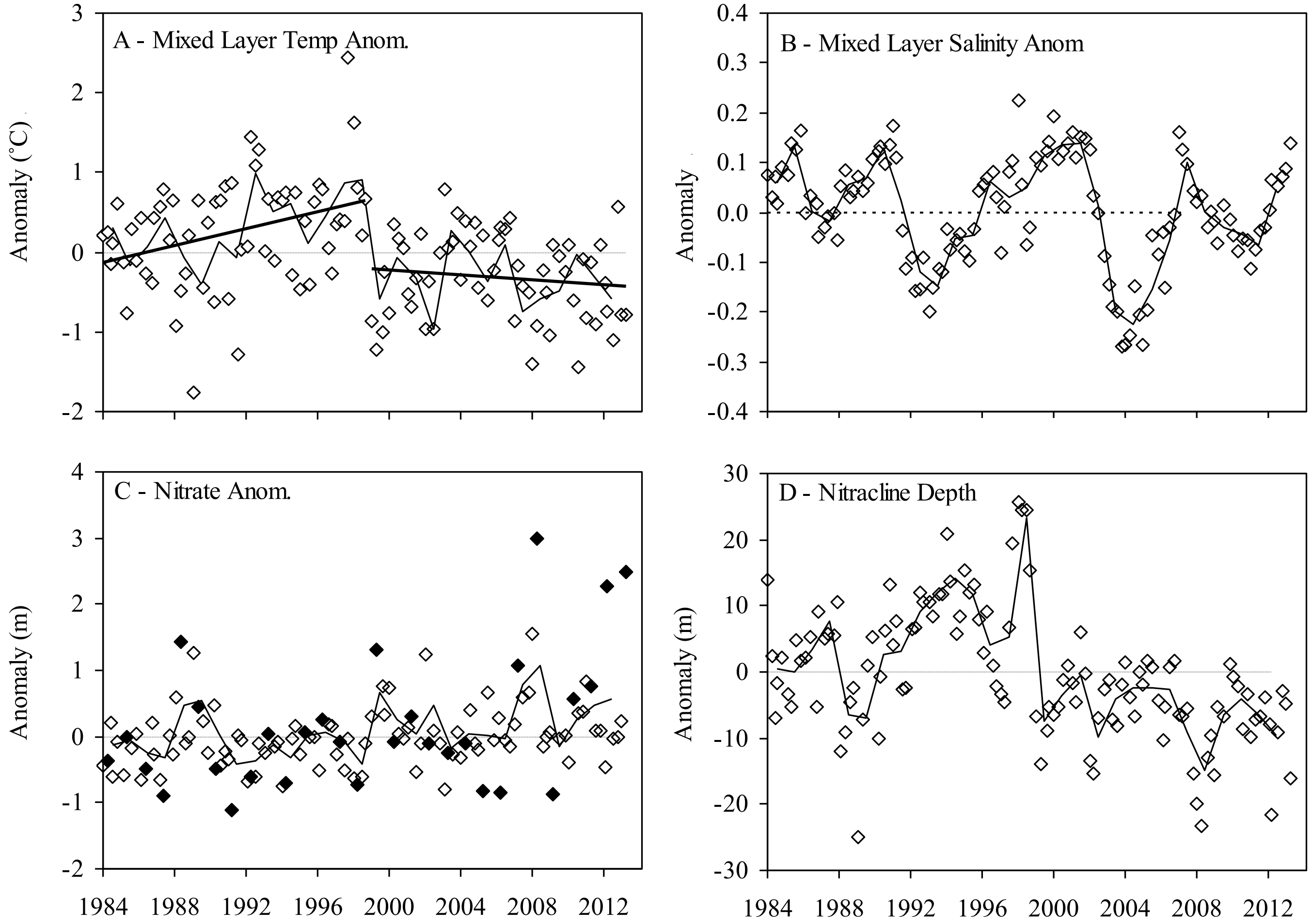

Figure 13. Property anomalies for the mixed layer (ML) of the CalCOFI standard grid: A – ML temperature anomaly, B – ML salinity anomaly, C – ML nitrate concentration anomaly and D – nitracline depth anomalies which are negative when the nitracline is closer than expected to the surface and positive when deeper than long-term averages. Data from individual CalCOFI cruise data are plotted as open diamonds. The thin solid lines represent the annual averages, the dotted lines the climatological mean, which in the case of anomalies is zero and the straight solid lines, when present, long-term linear trends. In panel C, nitrate, solid symbols are spring values.

12 months. Nitrate anomalies at the isopycnal were 1.8 µM during July 2012, the highest value observed over the last 29 years, but dropped to 0.9 µM in the spring of 2013 (data not shown).

In the CalCOFI region (fig. 1) concentrations of chlorophyll were similar to long-term averages (fig. 14) for all four cruises covered by this report. At the edge of the North Pacific Central Gyre, concentrations of chlorophyll were still above long-term averages while the depth of the subsurface chlorophyll maximum dropped from 50 m to 75 m (fig. S7). Similar patterns were observed in the southern California Current region (fig. S7). Concentrations of chlorophyll, however, were at or below long-term averages in the northern California Current region and in the coastal areas (figs. 6 and S7). Values of primary production were below or at long-term averages during the summer and fall of 2012 but substantially above long-term averages during the first half of 2013.

Anomalies of zooplankton displacement volume, a proxy for zooplankton biomass, are only available up to the fall of 2012 (fig. 14, lower panel). Values during 2012 were significantly greater than long-term averages, comparable to values observed during the 1980s and the 1999 La Niña period. These patterns were largely driven by very high abundance of salps and pyrosomes during 2012.

Baja California (Investigaciones Mexicanas de la Corriente de California, IMECOCAL)

Consistent with the observations from 2011–12 (Bjorkstedt et al. 2012), temperatures remained cooler than average in 2012–13. In fact, the three coolest SST values since 1998 occurred in 2011, 2012, and 2013. As well, surface waters continued to be fresher through spring of 2013 but were slightly more saline than that of 2011 (fig. 15). Chlorophyll off Baja California was near average throughout 2011–13, with the exception

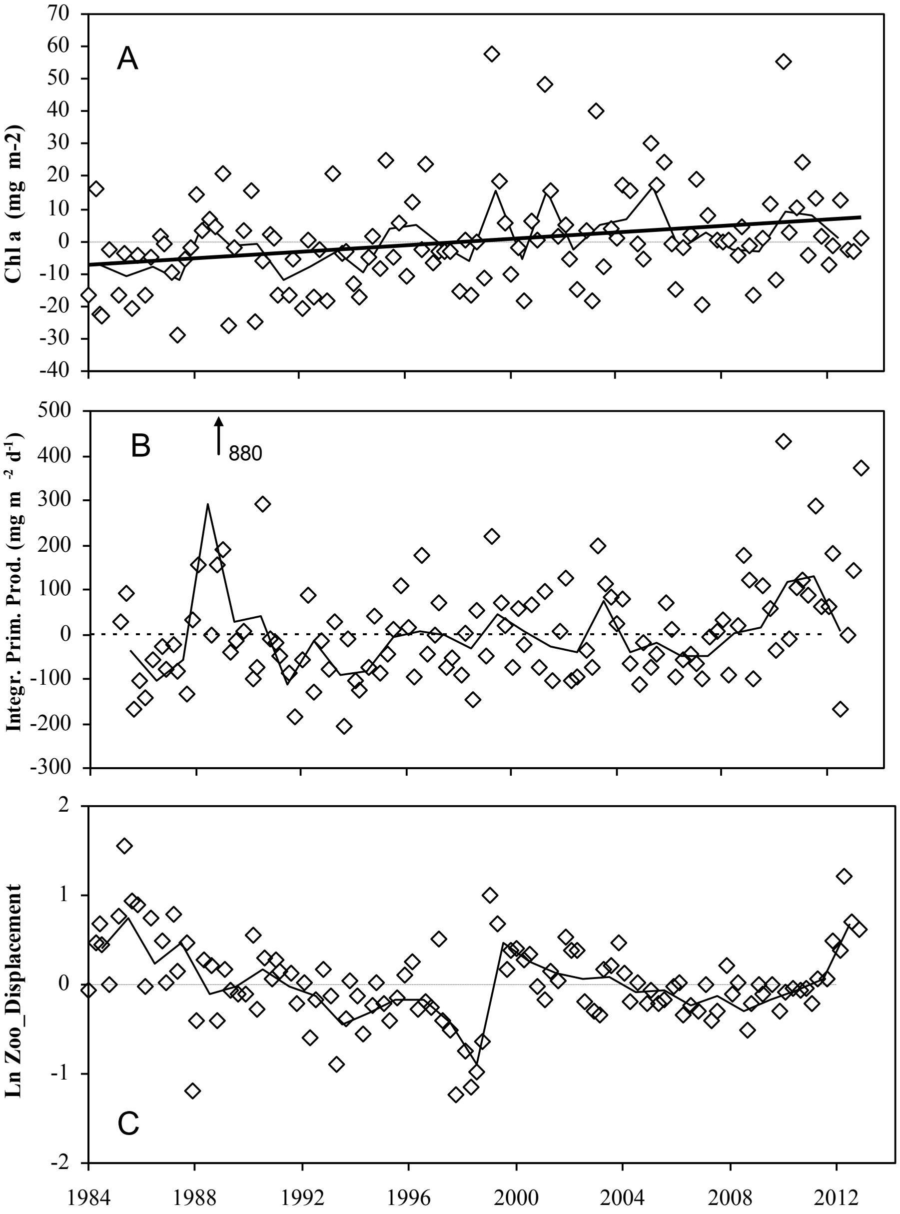

Figure 14. CalCOFI region averages for standing stocks of chlorophyll-*a* (A) and rates of primary production (B) both integrated to the bottom of the euphotic zone and (C) the log of zooplankton displacement volume, all plotted against time.

of a single high and positive anomaly during spring of 2012 (fig. 16).

Zooplankton displacement volume remained high during 2012 through February 2013 continuing an eight-year period of higher than average values (fig. 17). However, euphausiid density was below average between the springs of 2011 and 2012. Copepods have been anomalously abundant since 2010 except for the 2011/2012 winter values.

GELATINOUS ZOOPLANKTON

In this report gelatinous zooplankton are divided into two categories: herbivores and carnivores. Tunicates, the herbivorous filter-feeding forms, include salps, doliolids, pyrosomes, and appendicularians. The carnivorous forms are represented by a variety of taxa, such as jellyfish (e.g., Hydromedusae, Schyphomedusae, siphonophores), pelagic snails (pteropods, heteropods), and arrow worms (chaetognaths).

Northern California

Catches of tunicates in the NWFSC pelagic survey were very low (zero in many cases) from June 2004 until June 2010, after which salp densities spiked over a short period, reaching a maximum of 3400 individuals per 10^6 cubic meters of water sampled by August of

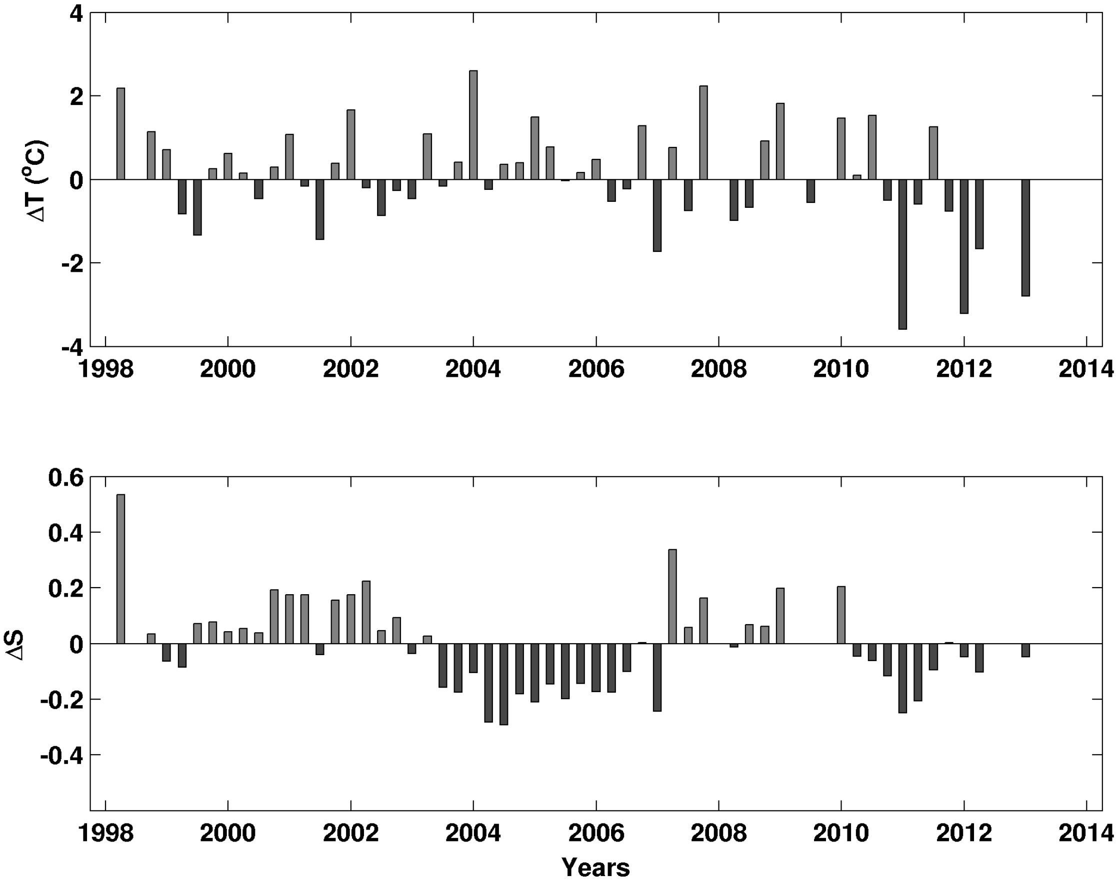

Figure 15. Mixed layer temperature anomaly and mixed layer salinity off Baja California Peninsula (IMECOCAL). Each bar represents each cruise conducted.

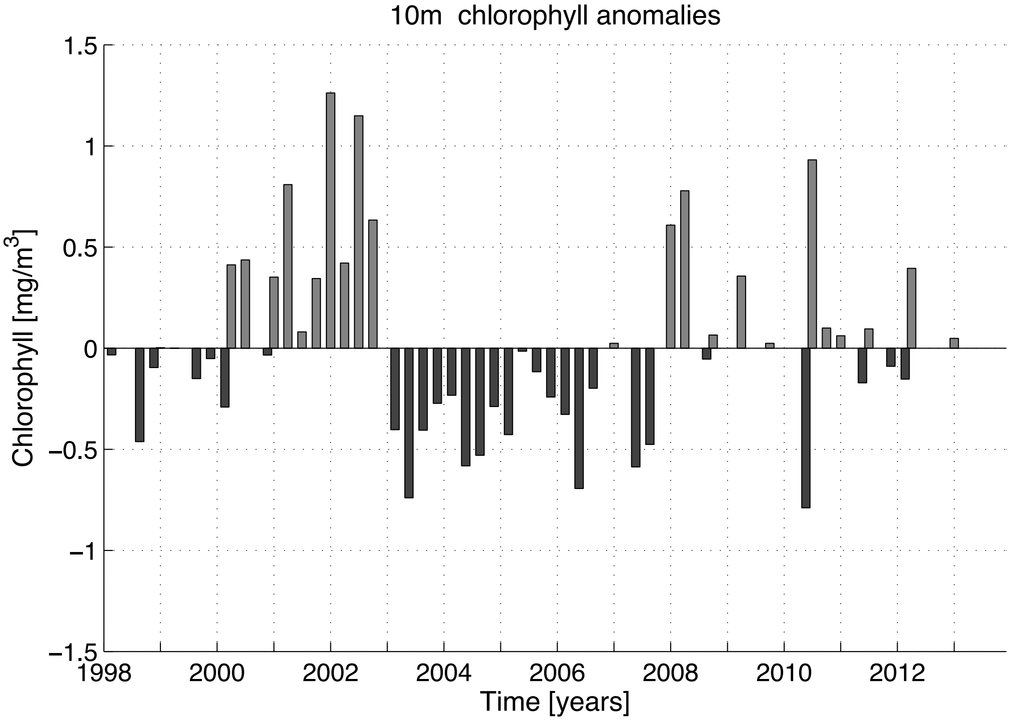

Figure 16. Anomaly time series of 0–100 m integrated chlorophyll *a* off Baja California Peninsula (IMECOCAL). Each bar represents each cruise conducted.

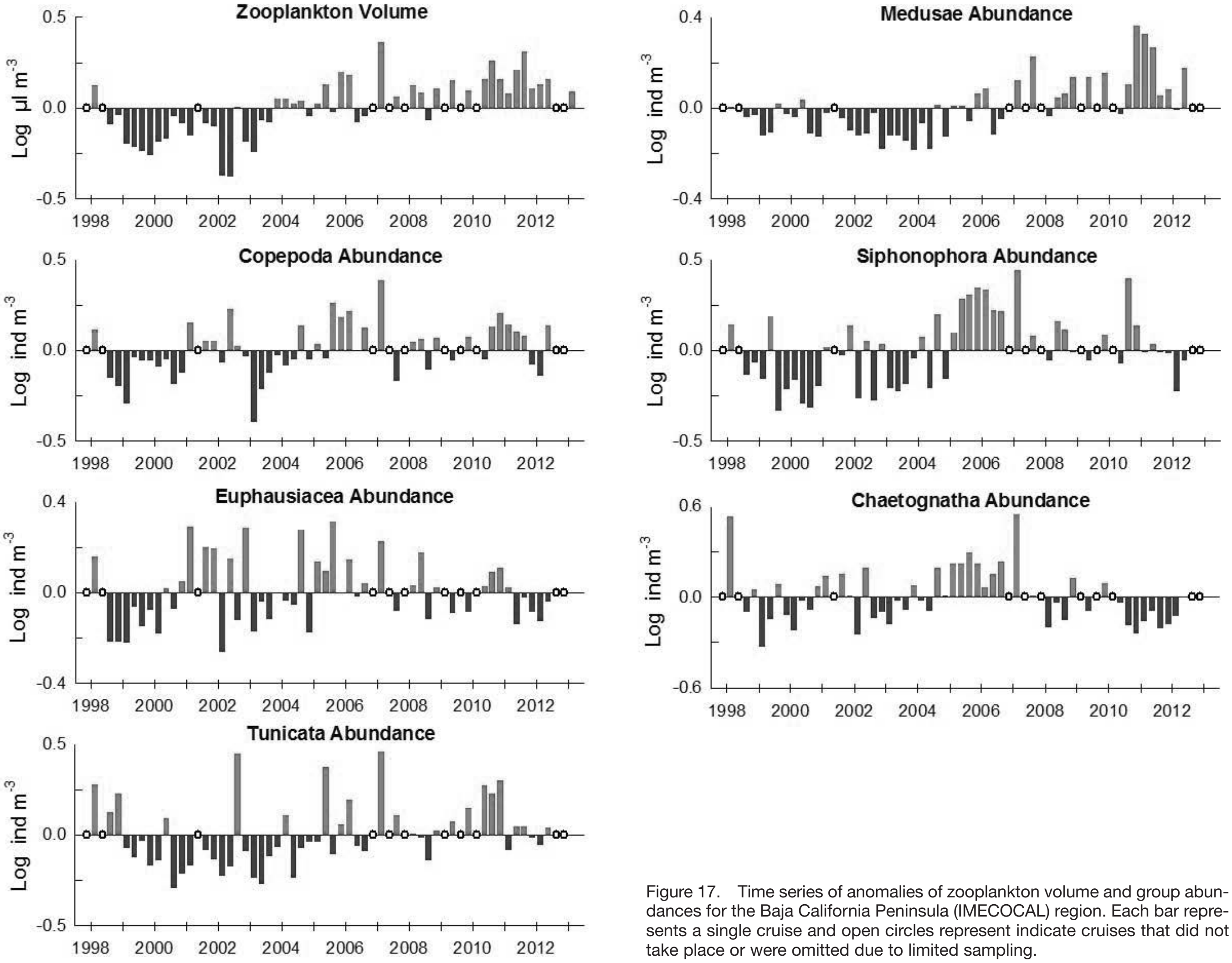

Figure 17. Time series of anomalies of zooplankton volume and group abundances for the Baja California Peninsula (IMECOCAL) region. Each bar represents a single cruise and open circles represent indicate cruises that did not take place or were omitted due to limited sampling.

2010. Densities remained high into early 2011 and then tapered to near normal low catches in 2012 (fig. 18).

Densities of the two dominant larger medusa species in this region, *Chrysaora fuscescens* and *Aequorea* spp., have been monitored as part of a pelagic trawl survey conducted every June and September since 1999 (Suchman et al. 2012)(see supplement for data collection). Catches of both species returned to a more typical level in June 2012, following below-average catches for the last two years (fig. S8). In September 2012, catches of both species were similar to 2011, with densities of *C. fuscescens* being approximately an order of magnitude higher than those of *Aequorea*, similar to that seen earlier by Suchman et al. 2012.

Central California

The major contributors to the herbivorous tunicate catch off Central California were the salps, *Thetys vagina* and *Salpa* spp., as well as pyrosomes, *Pyrosoma* spp. In 2012, the numbers of *S. fusiformis*, other salp species, and pyrosomes in the core region of the SWFSC rockfish recruitment survey (roughly Point Reyes to Point Piños) far exceeded previously recorded values (fig. 19) (Bjorkstedt et al. 2012), although the abundance of *Thetys vagina* remained well within the range of previously observed blooms (fig. 19). The largest salp and pyrosome catches were in the southern region of the expanded coast-wide rockfish recruitment survey (fig. 19). Although there is no baseline data to compare these trawl survey catches, they are consistent with accounts of high salp abundances in this region during 2012 (Bjorkstedt et al. 2012). By spring 2013 salps, pyrosoma, and *Thetys vagina* were near typical values in the core region and reduced in the southern region (fig. 19).

In 2012, within the rockfish recruitment survey's core region, large salp catches mostly occurred at offshore stations, and the magnitude of the catches were substantially larger than the long-term average (fig. 20). Salp

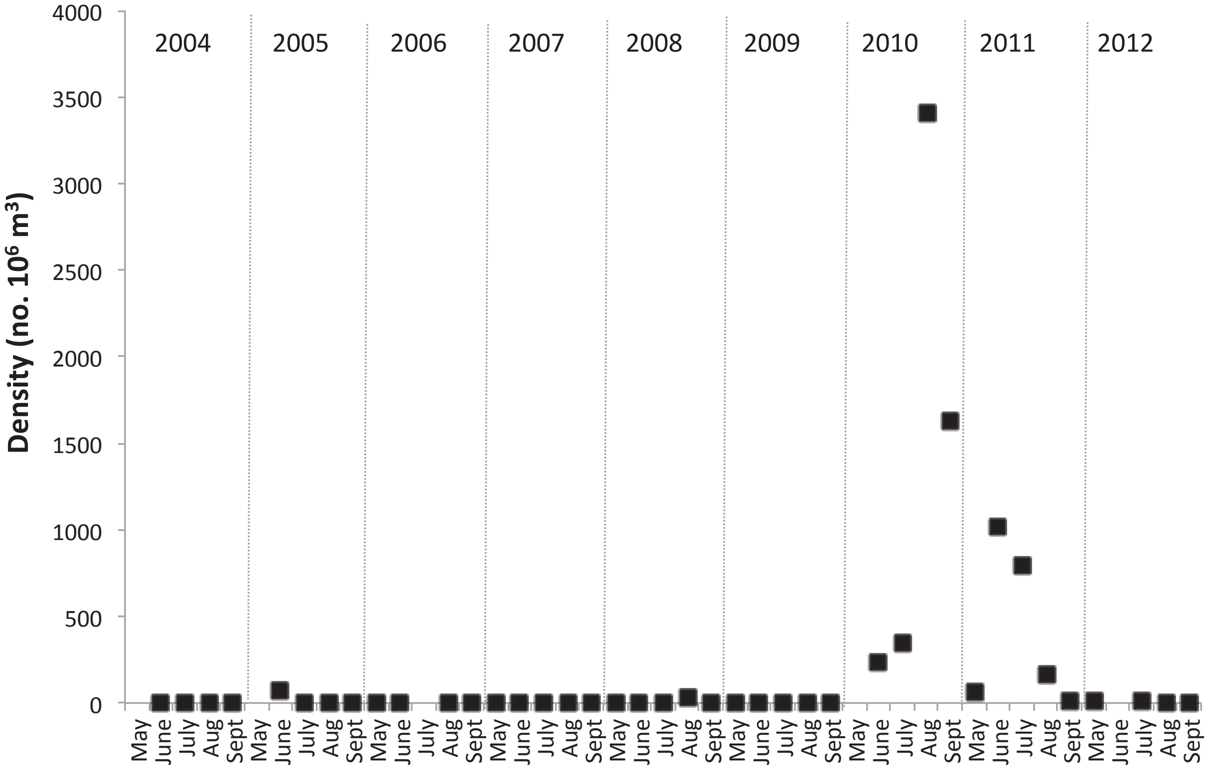

Figure 18. Densities of salps (mostly *Thetys vagina* and *Salpa fusiformis*) observed in the NWFSC pelagic rope trawl surveys off the coast of Oregon and Washington in May–September, from 2004 to 2012.

catches during 2013 have returned to more typical values observed in the survey. The summer salmon survey (fig. 1) that immediately followed the rockfish recruitment survey did not encounter extreme salp concentrations in 2012 and 2013, but this was likely due to the predominantly inshore sampling (data not shown).

The observed abundances of the jellyfish *C. fuscescens* during late spring of 2012 and 2013 were within the range of variability noted since 1990 (fig. 19). As in previous years, the largest catches of *C. fuscescens* occurred within the Gulf of the Farallones while the largest catches of *Aurelia* spp. occurred inside Monterey Bay's upwelling shadow (Graham and Largier 1997).

Southern California

There were large concentrations of gelatinous zooplankton encountered off southern California (predominantly tunicates). A proxy for the abundance of larger, mostly gelatinous, zooplankton is the difference between total zooplankton displacement volume (ZDV) and small fraction ZDV (fig. 21A) leaving the large fraction ZDV (fig. 21B). The latter fraction was substantially increased during 2011 to 2012 compared to the previous decade.

Baja California

At the southern extent of the CCS off Baja, herbivorous tunicates maintained average abundances during the last two years (fig. 17). However high-density patches occurred in discrete locations, such as in Vizcaino Bay. Carnivorous forms were present in similar abundance and composition as the 2011 reported values. Medusae continued to have positive anomalies while chaetognaths maintained negative anomalies. In contrast, the siphonophores shifted from the high positive anomalies in 2010 to a strong negative anomaly in February 2012.

SYNTHESIS OF OBSERVATIONS ON HIGHER TROPHIC LEVELS

Pelagic Fishes off Oregon and Washington

Time series plots of yearly abundance data are presented for each of the five most dominant and consistently collected forage species (jack mackerel, *Trachurus symmetricus*, Pacific sardine, northern anchovy, Pacific herring, *Clupea pallasii*, and whitebait smelt, *Allosmerus elongates*) (fig. 22) measured during the NWFSC-NOAA Bonneville Power Administration (NOAA/BPA) survey surface trawls. The survey also captures Pacific mackerel, *Scomber japonicas*, shown as well. The survey extends from Cape Flattery in northern Washington to Newport in central Oregon from June to September. Although other forage species are caught in these surveys, these five six species represent the bulk of the forage fish catch in surface waters. They include migratory species (Pacific

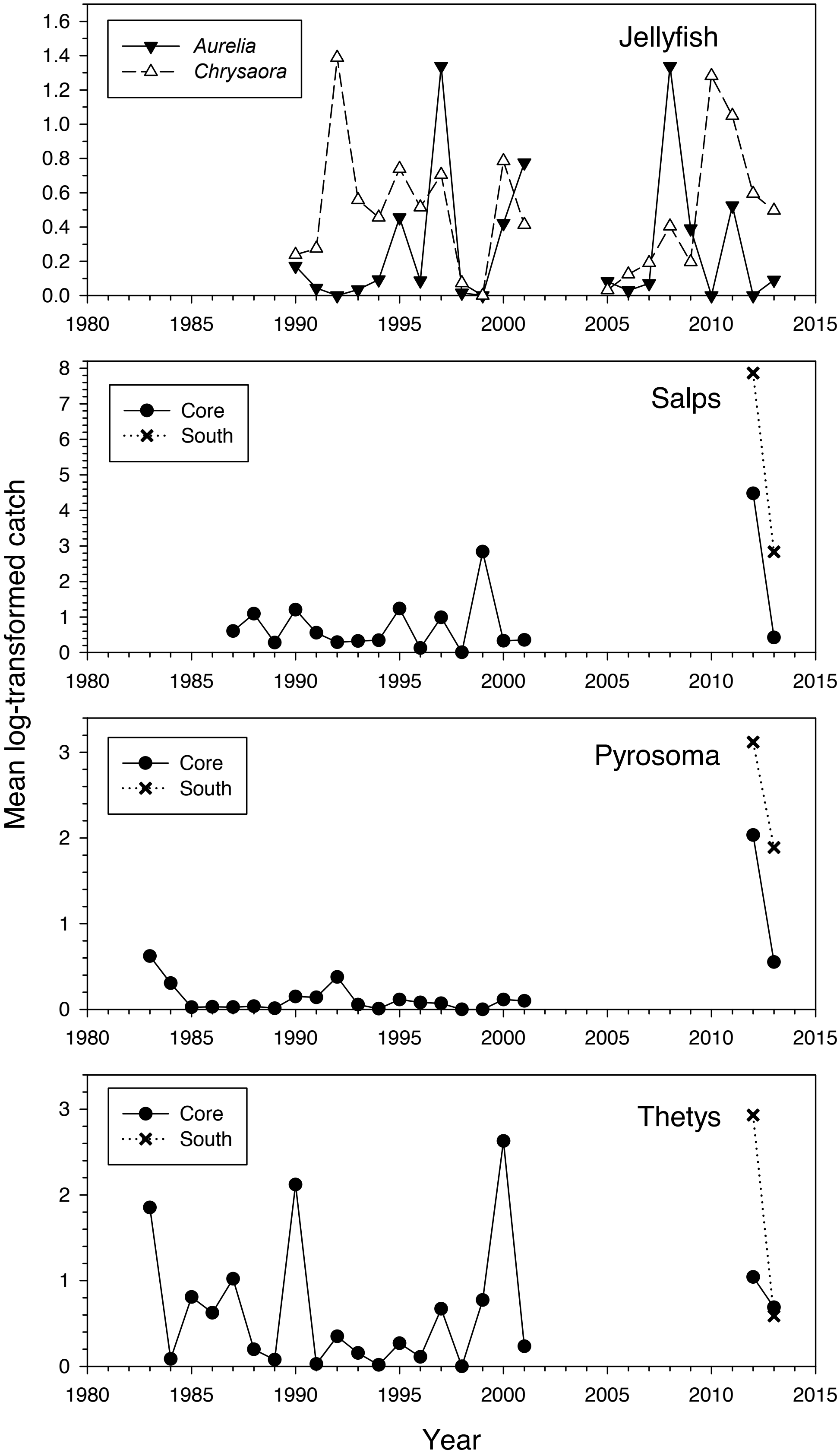

Figure 19. Geometric mean of catches per unit volume of gelatinous zooplankton from the central California rockfish recruitment survey.

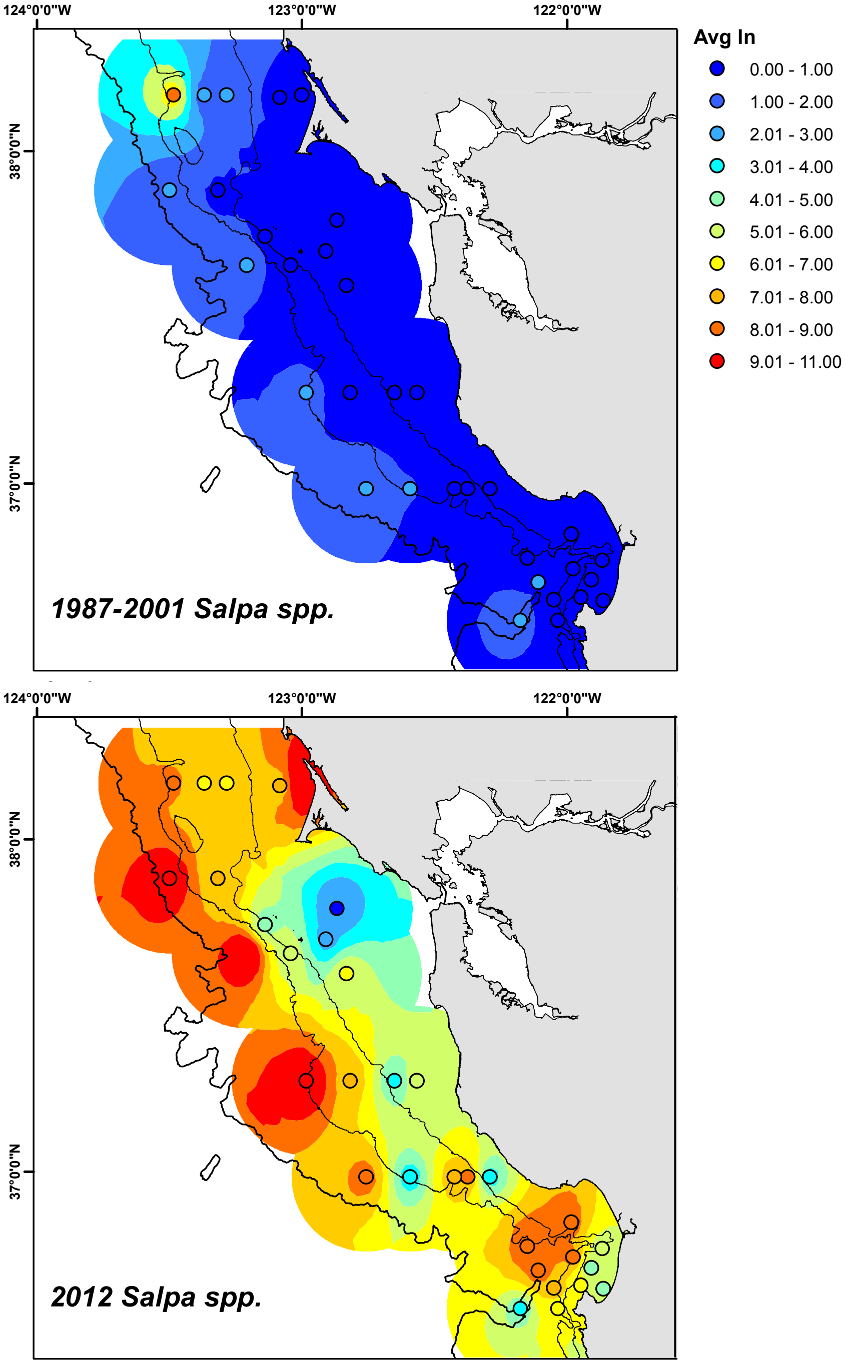

Figure 20. Distribution of the historical geometric mean of catches of salps from central California rockfish recruitment survey, 1987–2011, and those from 2012.

sardines and some northern anchovies) that may spawn off the Pacific Northwest or migrate from California (Emmett et al. 2005; Litz et al. 2008). Jack mackerel serve as a forage fish at younger ages but off Oregon and Washington are too large to be fed upon by most predators such as seabirds or adult rockfishes. Herring and whitebait smelt are likely spawned locally. A number of these species have seasonal trends in abundance (Emmett et al. 2005) so may experience intra-annual variability in abundance that is not captured by sampling two times per year. Ultimately, a number of forage fish are at reduced abundance (fig. 22, survey D, fig. 1). In 2012, Pacific herring, and Pacific sardine were at their lowest observed abundances since the start of the survey in 1998. Northern anchovy abundance was lower than it has been since 2002 (fig. 22).

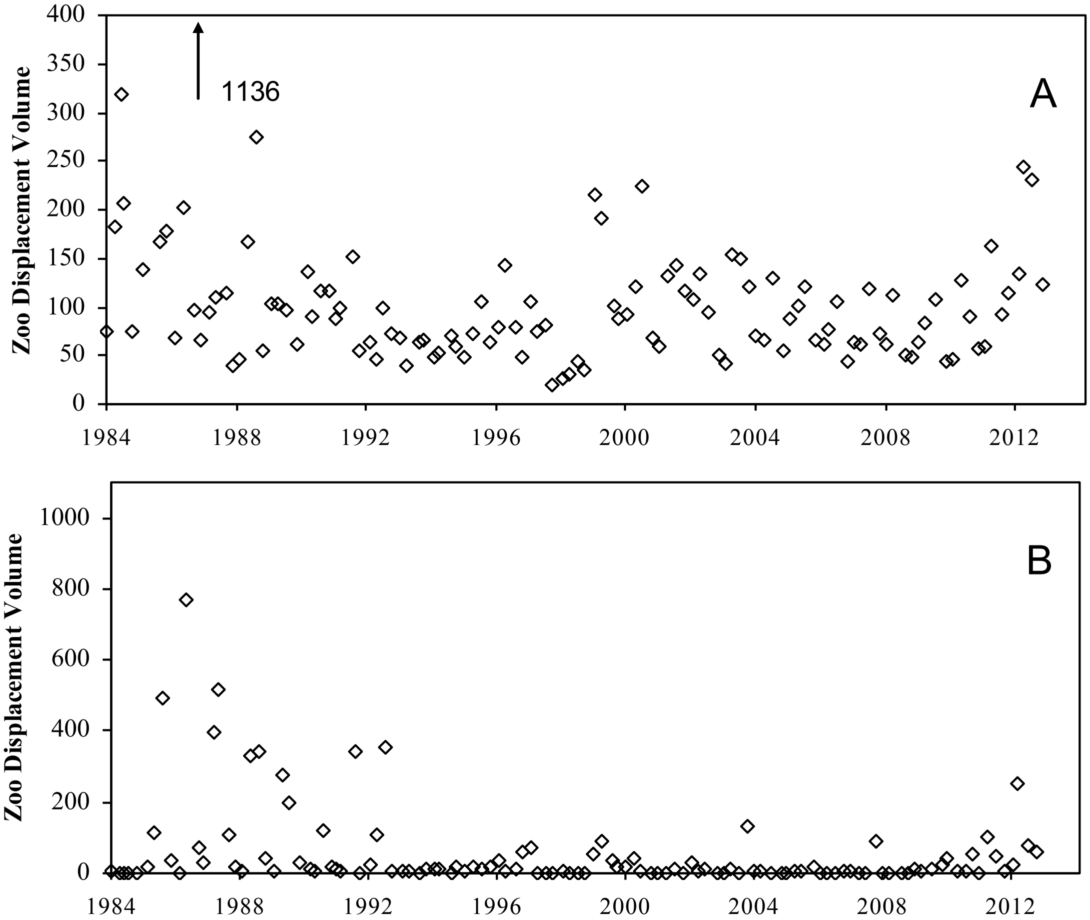

Figure 21. Zooplankton displacement volume (ml per 1000 m^2 seawater) for the small zooplankton fraction (A) and the large fraction (B). The large fraction consists of all organisms whose individual volume is larger than 5 ml. The small fraction is calculated by difference.

The ichthyoplankton and juvenile fish communities along the Newport Hydrographic Line off the coast of Oregon in May 2012 were similar to the average assemblages found in the same area and month during the previous five years both in terms of mean concentrations and relative concentrations of the dominant taxa (fig. 23). However, larval myctophids were found in the highest concentration in July 2012 of the five-year time series, while larval northern anchovy were found in higher concentrations (>3x) in July 2012 than in the same month in 2007–10. In addition, concentrations of the dominant taxa of juvenile fish were higher in July 2012 than in the same month in the previous five years, largely due to the abnormally high concentration of juvenile rockfish found in July 2012 (>10x that of any other year in 2007–11). No juvenile Pacific hake or northern anchovy were collected from the midwater trawl samples in May or July 2012, although age 1 and adult specimens of both species were found. Similarly, the biomass of ichthyoplankton in 2013 from winter collections along the Newport Hydrographic Line were above average (1998–2013), predicting average-to-good feeding conditions for juvenile salmon during the 2013 out migration (see supplemental results, fig. S9).

In the June NOAA/BPA surveys from 2008 and 2009, catches of juvenile spring-run Chinook salmon were high, with record high catches in 2008. Although catches in June 2011 were poor, catches in June 2012 were high, ranking second among the 15 years of surveys (fig. 24) suggesting excellent nearshore forage. However, catches of coho salmon in September 2012 survey were relatively low (fig. 24).

Pelagic Fishes Off Central California

Trends in both 2012 and 2013 showed higher productivity for the species and assemblages that tend to do better with regionally cool, high southward transport conditions, including juvenile rockfish, market squid, and krill (predominantly *Euphausia pacifica* and *Thysanoessa spinifera*) (fig. 25, see supplement for additional results). In 2012, juvenile rockfish catches were above average, as they have been in most years since 2008, and in 2013 the highest catches of juvenile rockfish in the time series of the survey were recorded, with huge numbers of juvenile

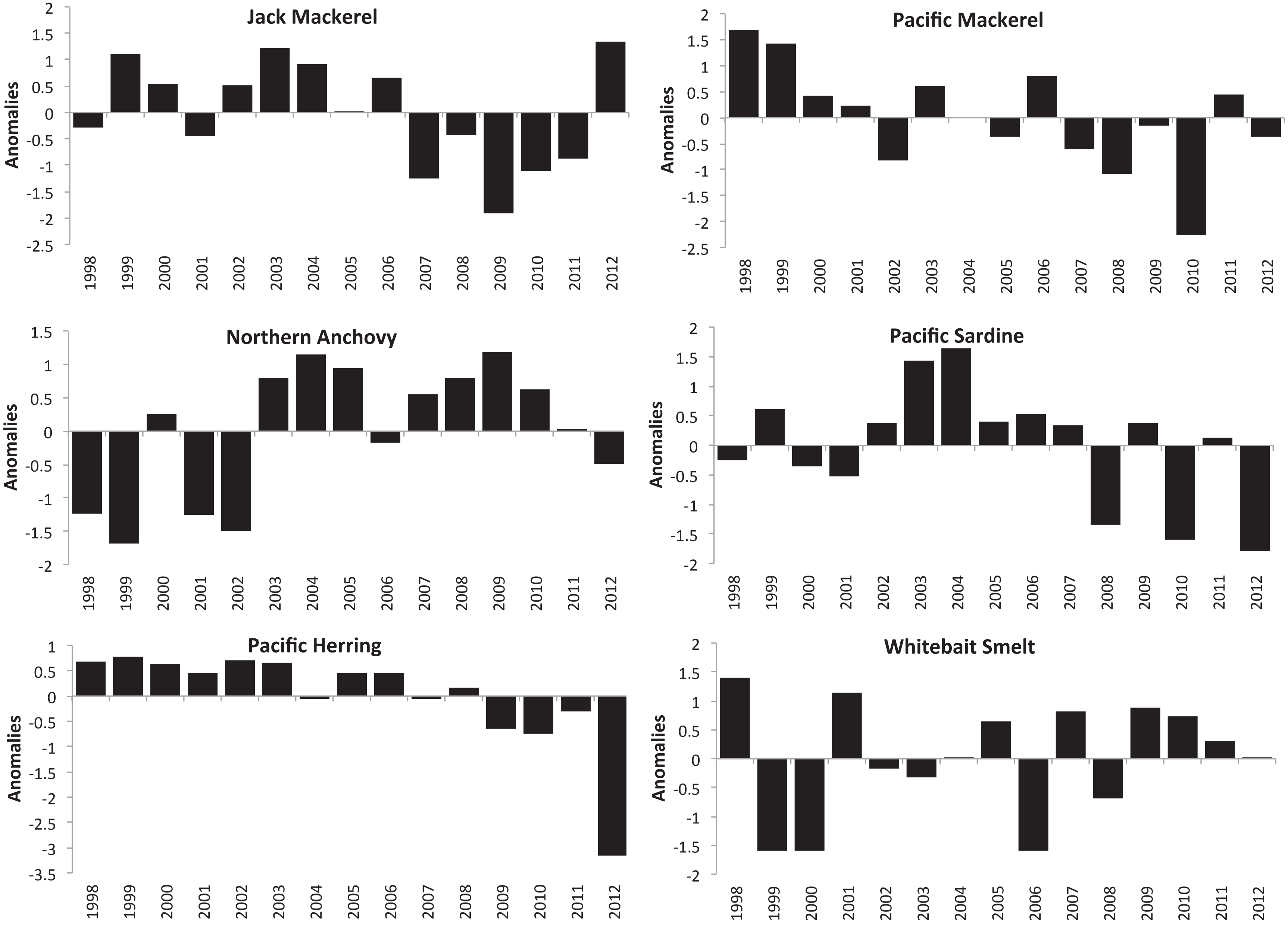

Figure 22. Group anomalies of catches per unit volume for the six most common forage fish collected during the NWFSC pelagic rope trawl survey, 1998–2012.

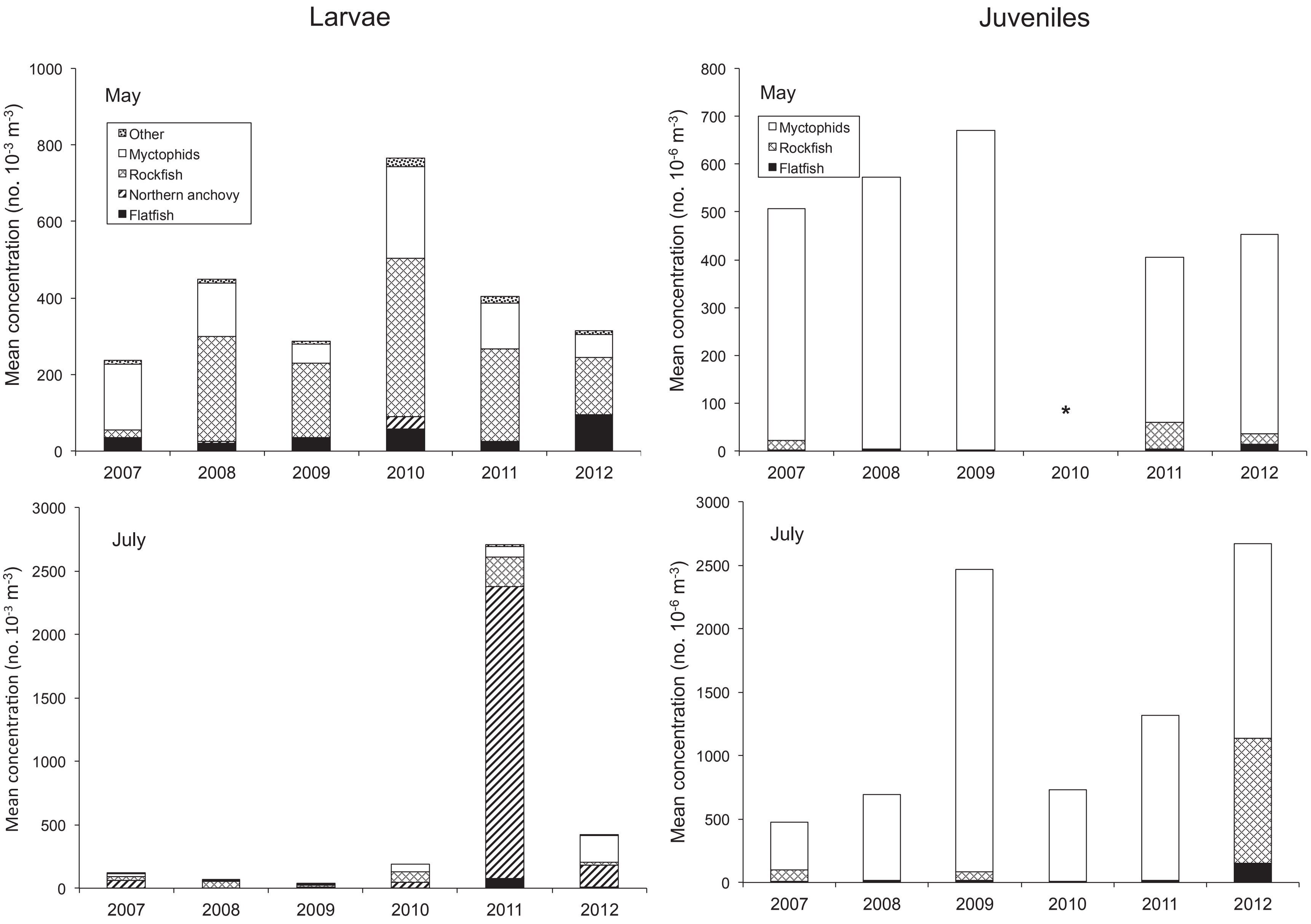

Figure 23. Mean concentrations of the dominant taxa for fish larvae (left) and juveniles (right) collected in May and July in 2007–12 along the Newport Hydrographic (NH) line off the coast of Oregon (44.65°N, 124.41–125.36°W). No midwater trawl samples were collected for juveniles in May 2010.

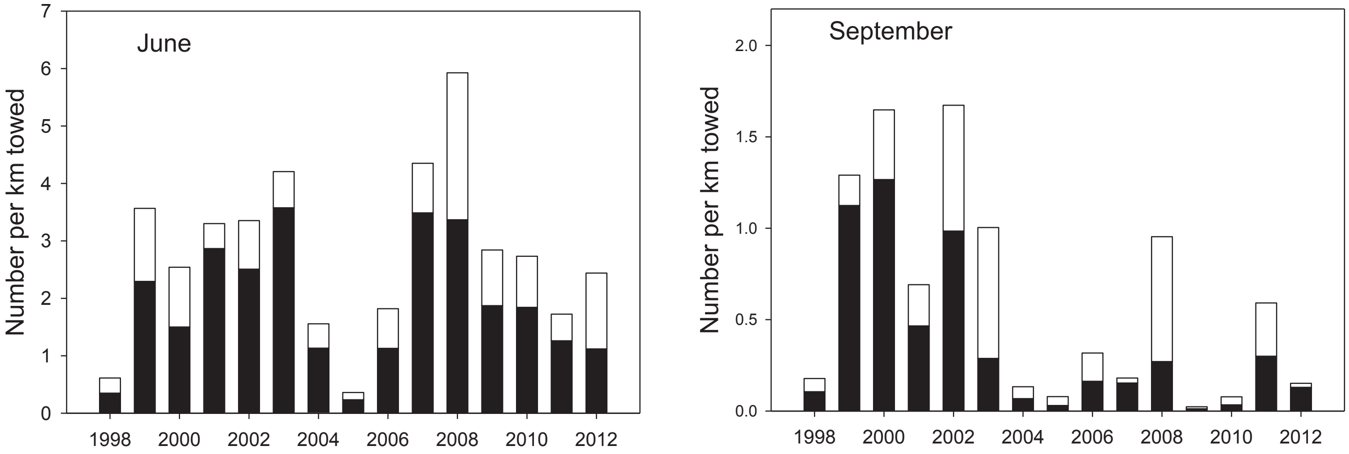

Figure 24. Catches of juvenile coho salmon (black bars) and Chinook salmon (white bars) off the coasts of Washington and Oregon.

rockfish of all species (as well as young-of-year groundfish of other species, such as Pacific hake, flatfishes, and lingcod, *Ophiodon elongates*) encountered throughout both the core and expanded survey areas. Market squid and krill were at very high levels in 2012 and 2013 as well. Although more northern anchovy were encountered in 2013 than in the previous five years, catches of both that species and of Pacific sardine remained well below long-term averages. As with the 2012 results, 2013 continued to indicate a pelagic micronekton community structure dominated by cool-water, high transport, high productivity forage species (juvenile groundfish, krill, and market squid (see Ralston et al. 2013).

Later in the summers of 2010–12 a surface trawl survey was used to characterize juvenile salmon and the micronekton from central California to Newport, Oregon. The summer of 2012 continued a period of extremely low abundance for northern anchovy, Pacific sardine, and Pacific herring. The survey caught no adult northern anchovy in 2011 or 2012 and very few in 2010; no Pacific sardine in 2012 and very few in the two years before that; and very few Pacific herring in all three years, 2010–12. Other important forage fishes such as surf smelt, *Hypomesus pretiosus*, and whitebait smelt were more abundant and were consistently taken in all three years since 2010, but these two osmerid species were primarily encountered in the northern portion of the study area. Market squid was very abundant in all three years and was encountered throughout the study area. Sub-yearling juvenile Chinook salmon (80–250 mm fork length, FL) were less abundant in the catches in 2012 than in the previous two years (fig. 26, see supplement for results concerning additional age classes). Unlike Chinook salmon, the abundance of juvenile coho salmon (100–300 mm FL) was similar in the summer of 2011 and 2012 (fig. 26). Significantly more juvenile coho salmon were caught in either of those two years than in July 2010.

Pelagic Fishes Off Southern California

The spring coastal pelagic species survey showed sardine egg densities were similar in 2012 to those measured in 2011 (methods in supplement, fig. S11). However, densities of sardine eggs and anchovy eggs were lower than those measured in most years since 1997 (fig. 27). Jack mackerel egg densities were similar to those measured during most other years in the time series. In 2013, sardine, anchovy, and jack mackerel egg densities were similar to those measured in the previous two years (fig. 28).

An examination of larval captures from the CalCOFI surveys 1951–2011 demonstrated similar trends (fig. 29). Larval Pacific sardine catches have been relatively stable over recent decades, minus low catches in 2004 and 2010. In general, larval northern anchovy were captured in greater densities than Pacific sardine before the mid-1990s. However, larval northern anchovy catches have declined substantially since the early 1980s (fig. 29). Unfortunately, data on larval catch densities beyond 2011 have not yet been enumerated.

SEABIRDS AND MAMMALS[3]

Breeding Success and Diets of Seabirds at Yaquina Head

Examination of the common murre, *Uria aalge*, diets indicates that smelts were the predominant prey available to the seabirds (fig. S12). When paired with the results from the forage observations in northern CCS, this diet composition was similar to changes in the available proportions in the forage community (fig. 22). The breeding success of common murre remained low relative to 2007–10 (fig. 30, see supplement for data methods). Observations indicate that the reduced

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[3] In addition to seabird and sea lion observations, cetacean density and abundance on the southern CalCOFI lines was quantified. Results are shown in the supplement.

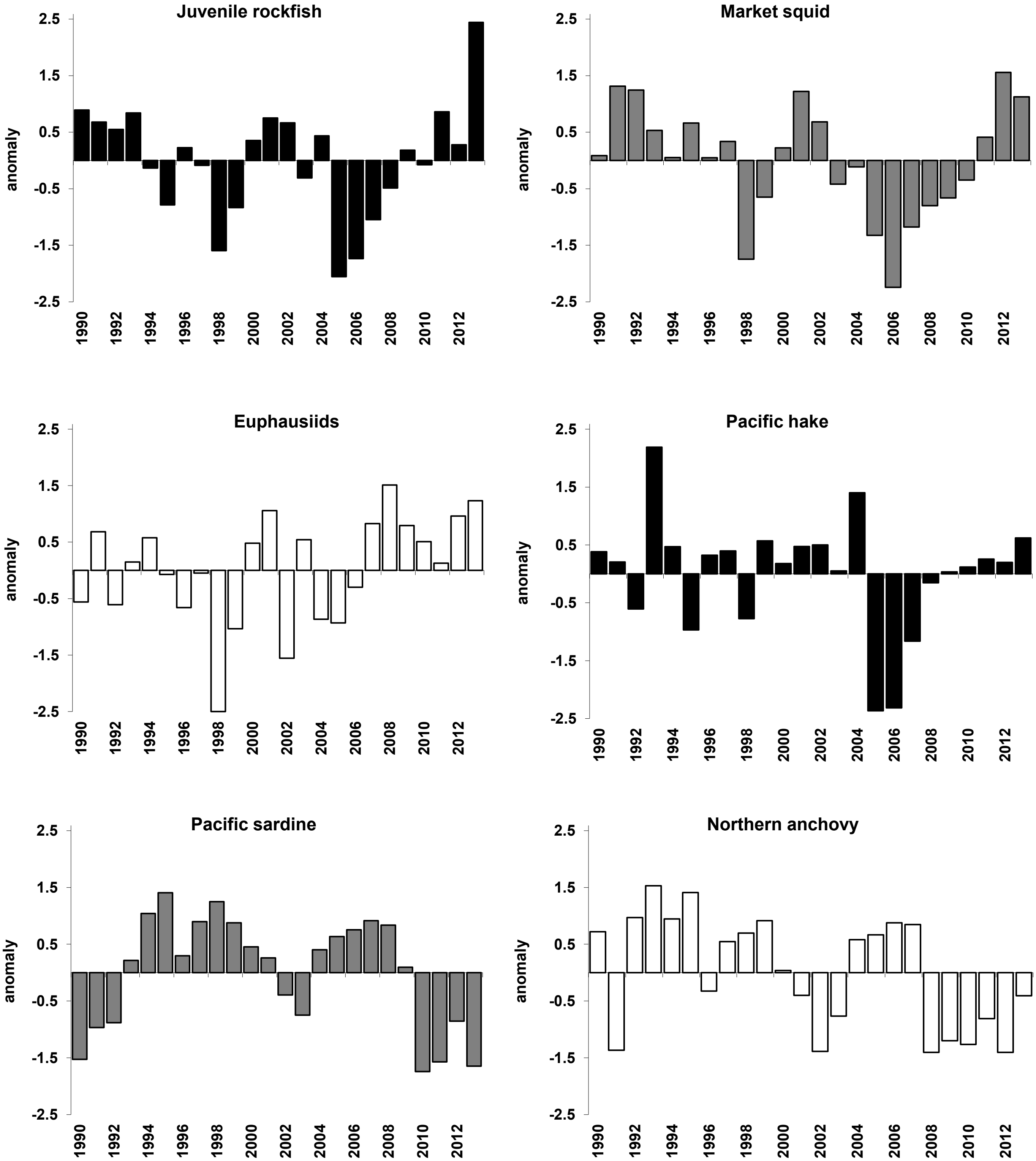

Figure 25. Long-term standardized anomalies of several of the most frequently encountered pelagic forage species from the central California rockfish recruitment survey in the core region (1990–2012).

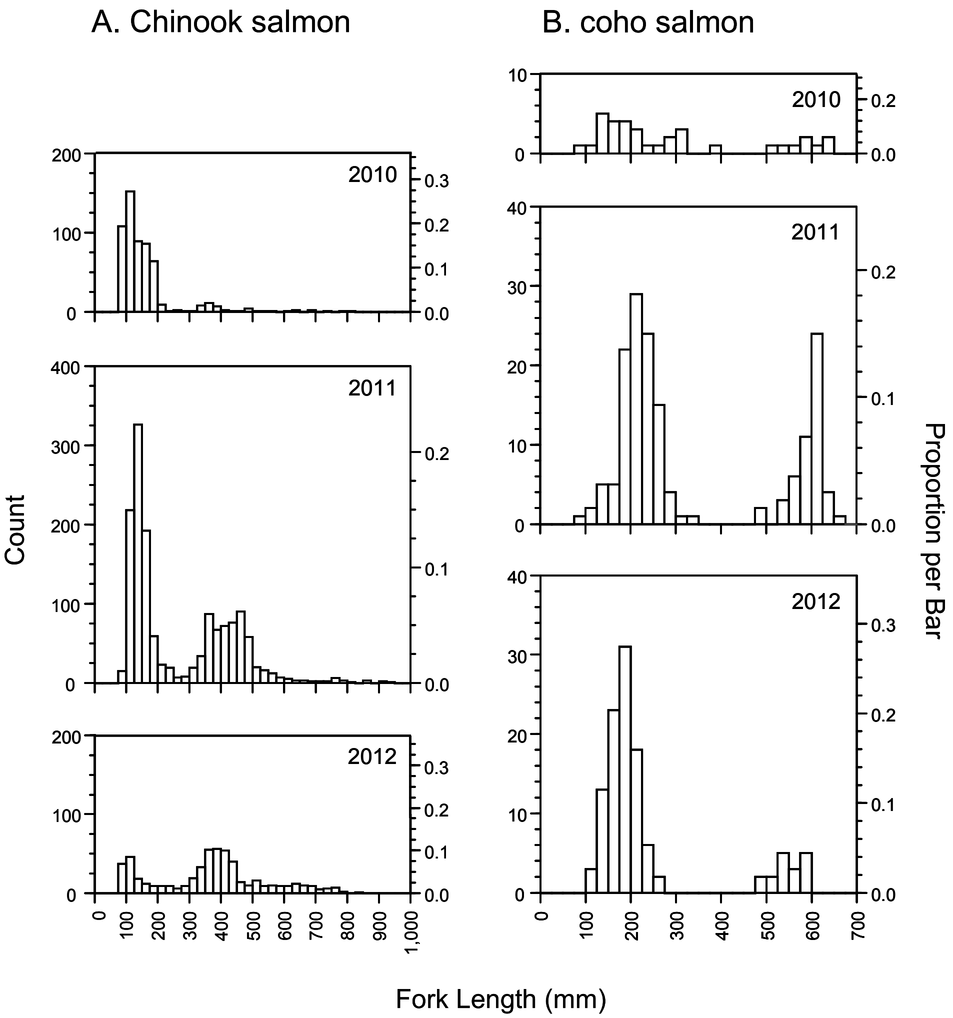

Figure 26. Size frequency distributions of (A) Chinook salmon (*Oncorhynchus tshawytscha*) and (B) coho salmon (*O. kisutch*) captured by rope trawl in the coastal ocean (~1–20 nautical miles offshore) between southern Oregon and central California in June or July of 2010, 2011, and 2012. Counts are total number (not standardized) of fish captured in each year; proportions are fraction of that total count represented by each bar for each year and species. Different scales used for columns A and B.

reproductive success was due to increased predation (e.g., eagles, pelicans, vultures).

Breeding Success of Seabirds at Southeast Farallon Islands

Overall breeding success of seabirds during the 2012 breeding season at Southeast Farallon Island can best be classified as an average year for most species. Cassin's auklets, *Ptychoramphus aleuticus*, which feed primarily on euphausiids, exhibited exceptionally high productivity for the third consecutive year (fig. 31). The average number of chicks fledged per breeding pair was the second highest on record, and reflected both exceptional fledging success and a high rate of successful double brooding. Among the piscivorus seabirds, productivity of common murres was slightly higher than that observed during 2011 while rhinoceros auklets (*Cerorhinca monocerata*) and pigeon guillemots declined to values slightly below the long-term means observed for each species. Pelagic cormorants, *Phalacrocorax pelagicus*, and Brandt's cormorants, *Phalacrocorax penicillatus*, experienced near complete breeding failure in 2012. This is the fifth consecutive year of extremely low reproductive success for Brandt's cormorants but the first breeding failure for the pelagic cormorant since 2005. Productivity of western gulls (*Larus occidentalis*) was slightly higher than during 2011, but continued to be among the poorest years on record, marking the fourth consecutive year of very low reproductive success for this species.

Breeding Success and Diets of Seabirds at Castle Rock

In 2012, the first common murre nest at Castle Rock was initiated on 15 May, between 4 and 32 days later than all other years of study. Although the average nest initiation date could not be determined due to

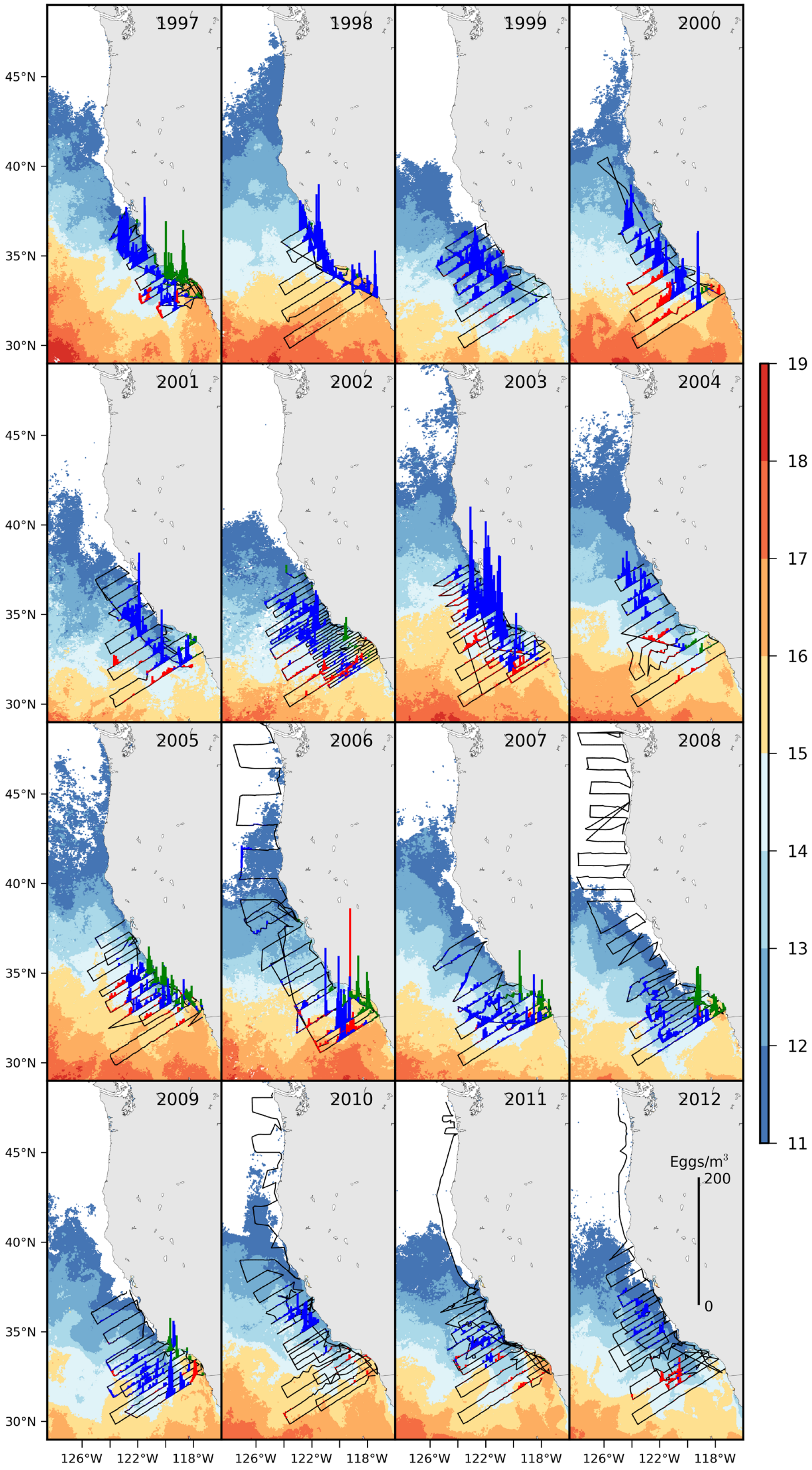

Figure 27. Densities of eggs of Pacific sardine (blue), jack mackerel (red), and northern anchovy (green) collected with the Continuous Underway Fish Egg Sampler (CUFES) along the ship track (black lines) during NOAA spring cruises for 1997 to 2012. The underlying color image shows a monthly composite of satellite AVHRR 1.4 km resolution sea surface temperature (°C) image coincident with the survey period in each year.

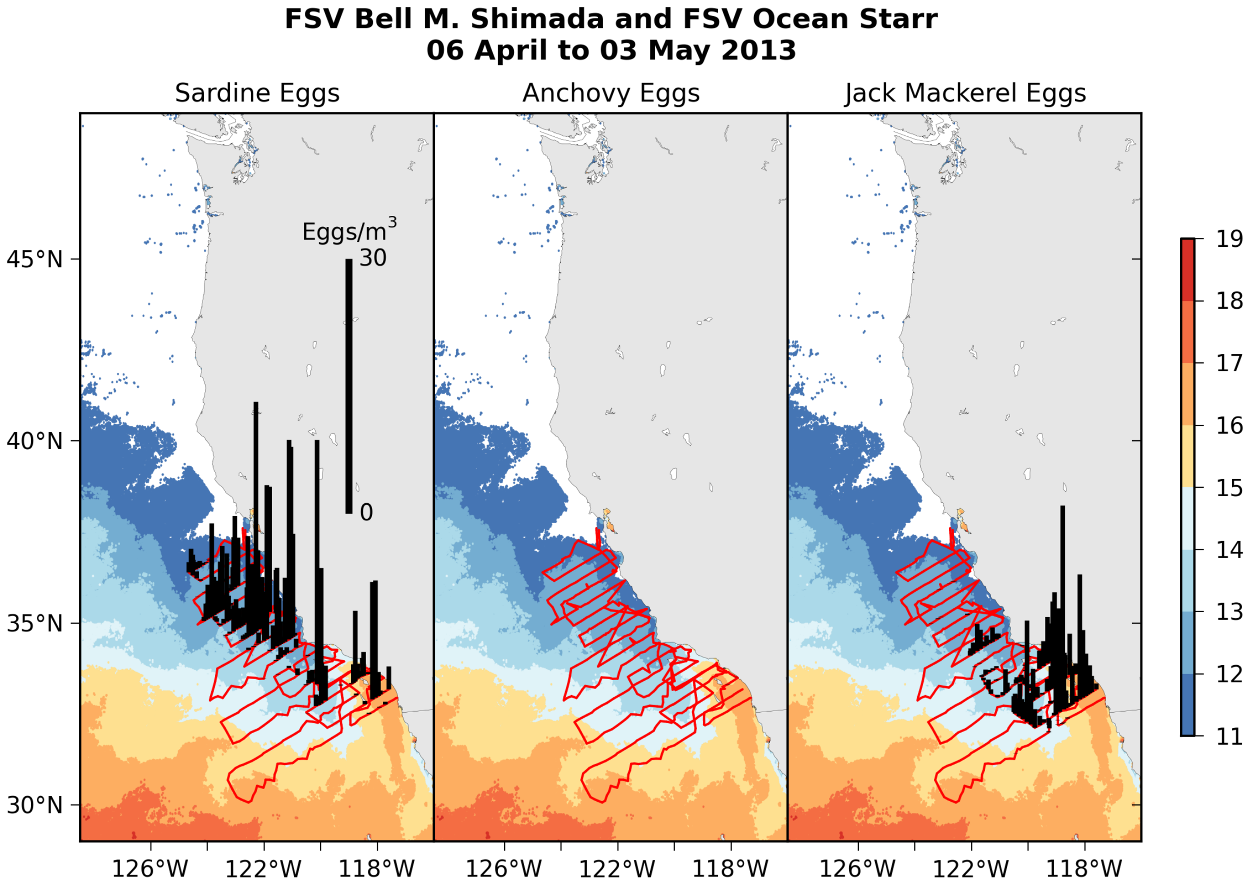

Figure 28. Densities of eggs of Pacific sardine, jack mackerel, and northern anchovy collected with the Continuous Underway Fish Egg Sampler (CUFES) along the ship tracks (red lines) during NOAA coast-wide cruises conducted in spring 2013. The underlying color image shows a monthly composite of satellite AVHRR 1.4 km resolution sea surface temperature (°C) image coincident with the survey period in each year.

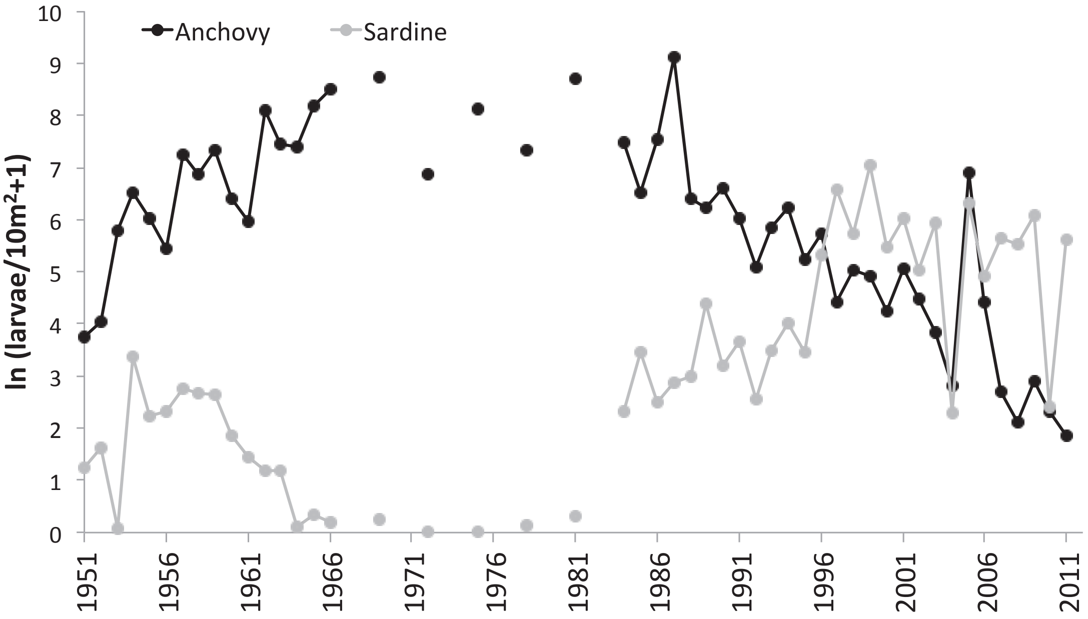

Figure 29. Abundance (ln (number /10 m^2+1)) of northern anchovy and Pacific sardines captured in oblique tows (bongo net) during spring CalCOFI surveys 1951–2011.

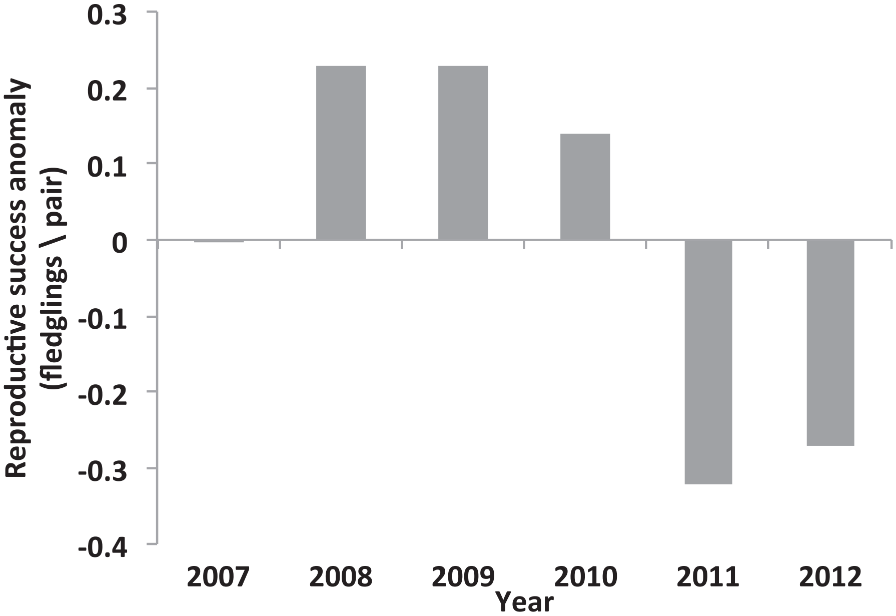

Figure 30. Anomalies of reproductive success (fledglings per breeding pair) of common murre at Yaquina Head.

uncertainties resulting from equipment failure, we concluded that nesting began later than usual in 2012 (see supplement for data collection and additional results, fig. S13).

For Brandt's cormorants, efforts to monitor nest phenology and success began in 2011 and baseline understanding of their reproductive performance is still being developed. Based on nests initiated prior to camera failure in 2012, 71% of first clutches (n = 13) failed during incubation. The failure rate for first clutches was similarly high in 2011, with 68% of first clutches failing during incubation.

At-sea Density of Seabirds off Southern California

Patterns of variability are illustrated in the relative abundance of two species, the sooty shearwater, *Puffinus griseus*, and Cassin's auklet expressed as natural log of density sighted (ln [birds km^{-2} + 1], see supplement for methods). Both species prey upon euphausiid crustaceans, small pelagic fish, and squid. In 2012, there was nothing unusual in the relative abundance of auklets in any season (fig. 32).

In contrast to the resident auklets, shearwaters were most abundant in the study region during the summer (July–August), with lower relative abundance in spring (April–May). During both seasons in 2012, the relative abundance of shearwaters declined (fig. 32). In 2012, numbers were substantially reduced from a recent peak in both spring and summer in 2010. Changes in shearwater abundance may be related to short or long-term changes in food availability. Alternatively, population decreases elsewhere could be affecting our counts; this may be the result of shearwaters declining on some New Zealand islands (Scott et al. 2008).

Productivity and Condition of California Sea Lions at San Miguel Island

California sea lions (*Zalophus californianus*) are permanent residents of the CCS, breeding on 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. 2012). Two indices are particularly sensitive measures of prey availability to California sea lions, pup production, and pup growth through four months of age. Pup production is a result of successful pregnancies and is an indicator of prey availability and nutritional status of adult females from October to the following June. Pup growth from birth to four months of age is an index of the transfer of energy from the mother to the pup through lactation between June and October, which is related to prey availability to adult females during that time and to survival of pups after weaning. The average number of live pups counted at San Miguel Island in July 2012 was 24,993 (fig. 33). The high live pup count in 2012 suggests that pregnant females experienced good foraging conditions from October 2011 to July 2012.

However, the pup growth index for California sea lions at San Miguel Island indicated that dependent pups were in poor condition by the time they reached four months of age. In October 2012, the average predicted

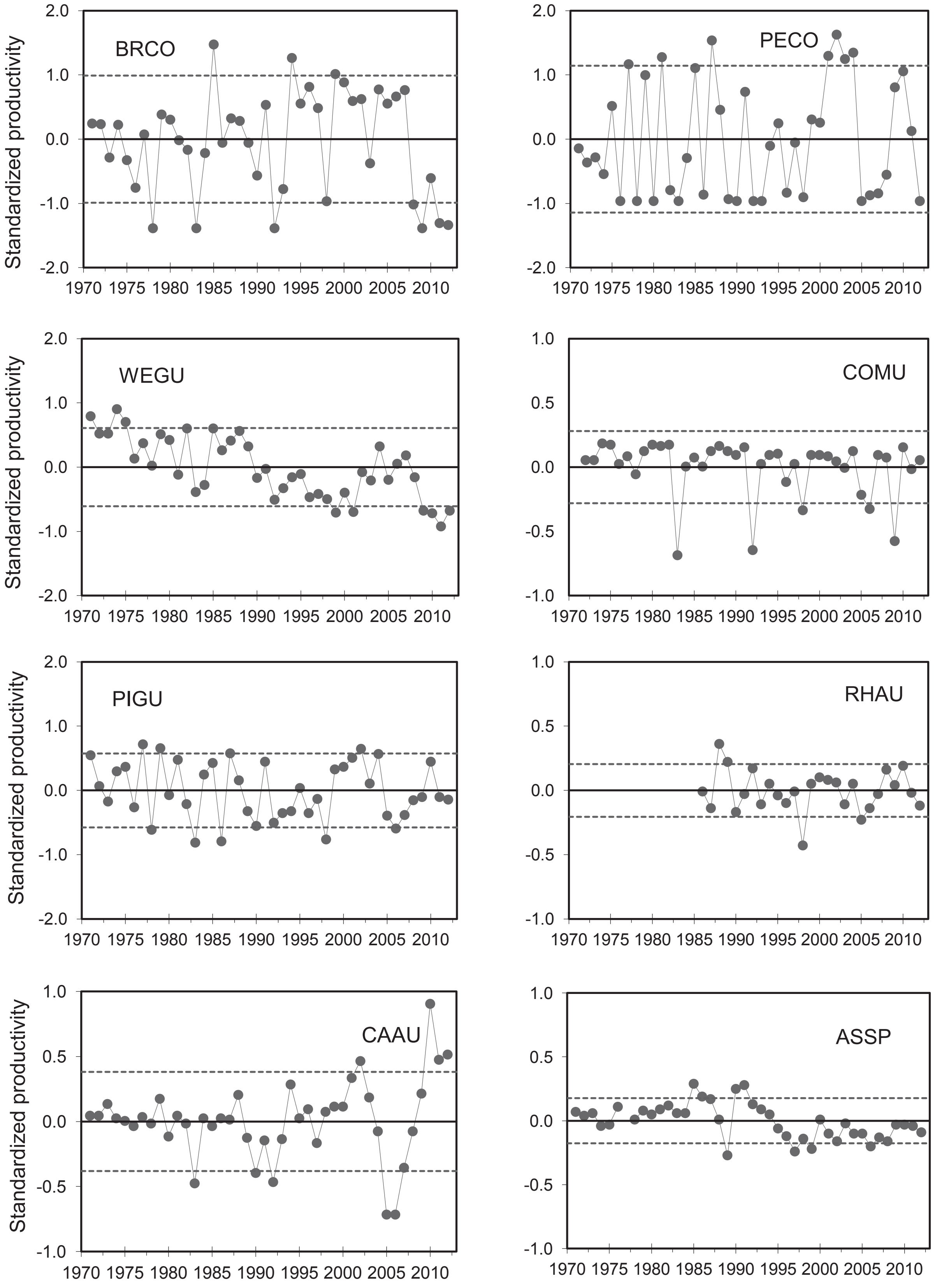

Figure 31. Standardized productivity anomalies (annual production–long term mean) for 8 species of seabirds on Southeast Farallon Island, 1971–2012. The dashed lines represent the 80% confidence interval for the long-term mean. Abbreviations are used fro Brandt's cormorant (BRCO), pelagic cormorant (PECO), western gull (WEGU), common murre (COMU), pigeon guillemot (PIGU), rhinoceros auklet (RHAU), Cassin's auklet (CAAU), and storm petrel (ASSP).

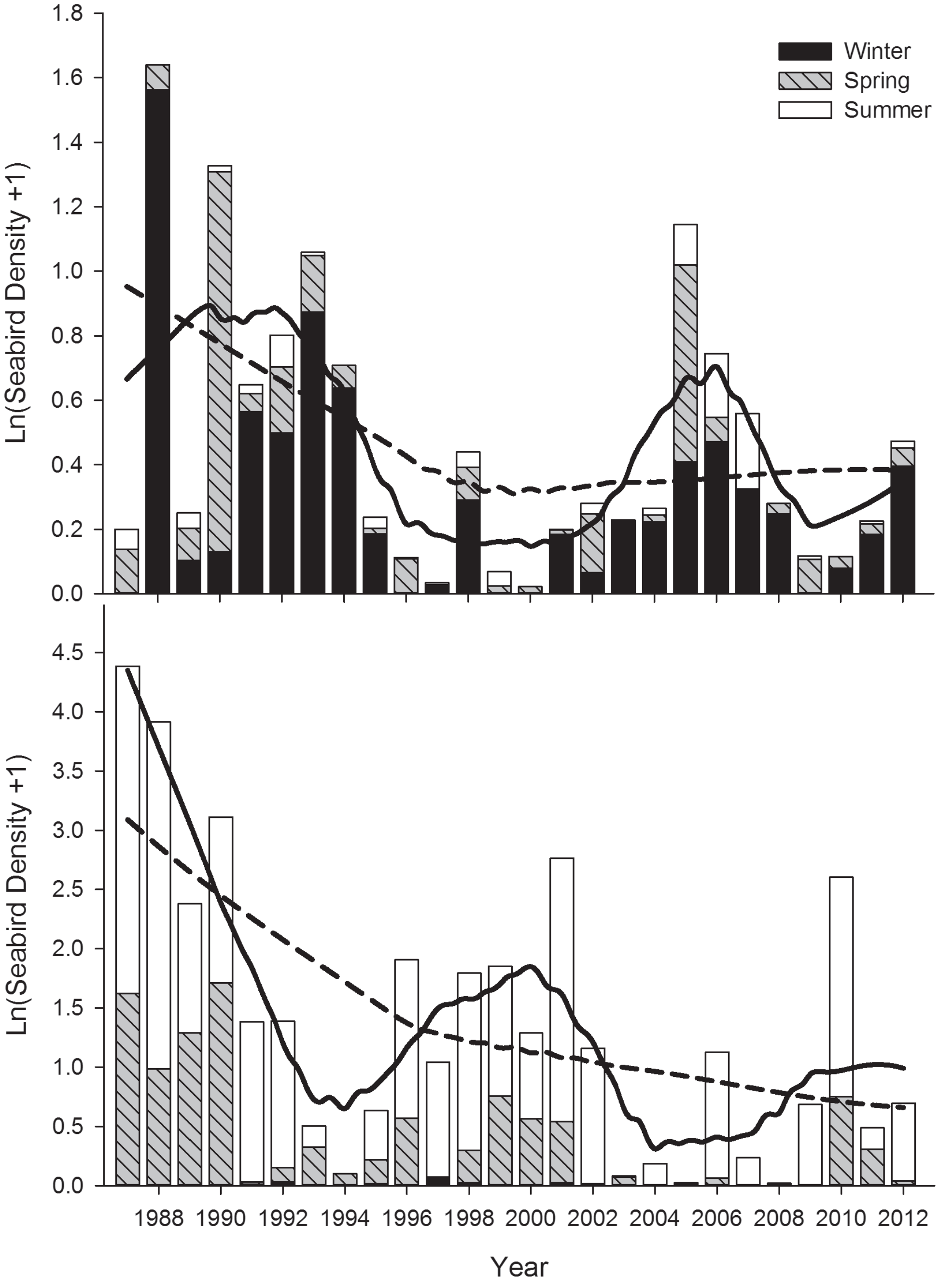

Figure 32. Changes in resident Cassin's auklet (upper panel) and migratory Sooty Shearwater (lower panel) relative abundance (natural log of birds km^{-2}) on 90 CalCOFI/CCE-LTER surveys, May 1987–July 2012. Stacked bars denote seasonal density estimates, with 2 Locally Weighted Regression (LOWESS) smoothing lines on summed annual estimates shown to illustrate short-term (bandwidth = 0.3, solid) and long-term (bandwidth = 0.8, dashed) variability.

weights of four-month-old female (13.0 kg, SE = 0.14) and male (14.5 kg, SE = 0.20) pups were significantly lower compared to the long-term mean for female and male pups (females, mean = 17.4 kg, SE = 0.35; males, mean = 20.2 kg, SE = 0.43) (fig. 34). Average October weights of California sea lion pups have been declining since 2008 but the mean weights for the 2012 cohort were significantly lower than the previous four years. By February 2013, at 7 months of age, pups remained significantly underweight (females, mean = 13.6 kg, SE = 0.55; males, mean = 16.2 kg, SE = 0.69) (fig. 34); an estimated 12 kg and 14.4 kg below the long-term average for females and males, respectively. A longitudinal analysis of pup daily growth rates of branded pups between four and seven months of age showed significantly lower daily growth rates compared to other years for female and male pups (fig. 34). In both October and February, the mean weights for the 2012 cohort were similar to

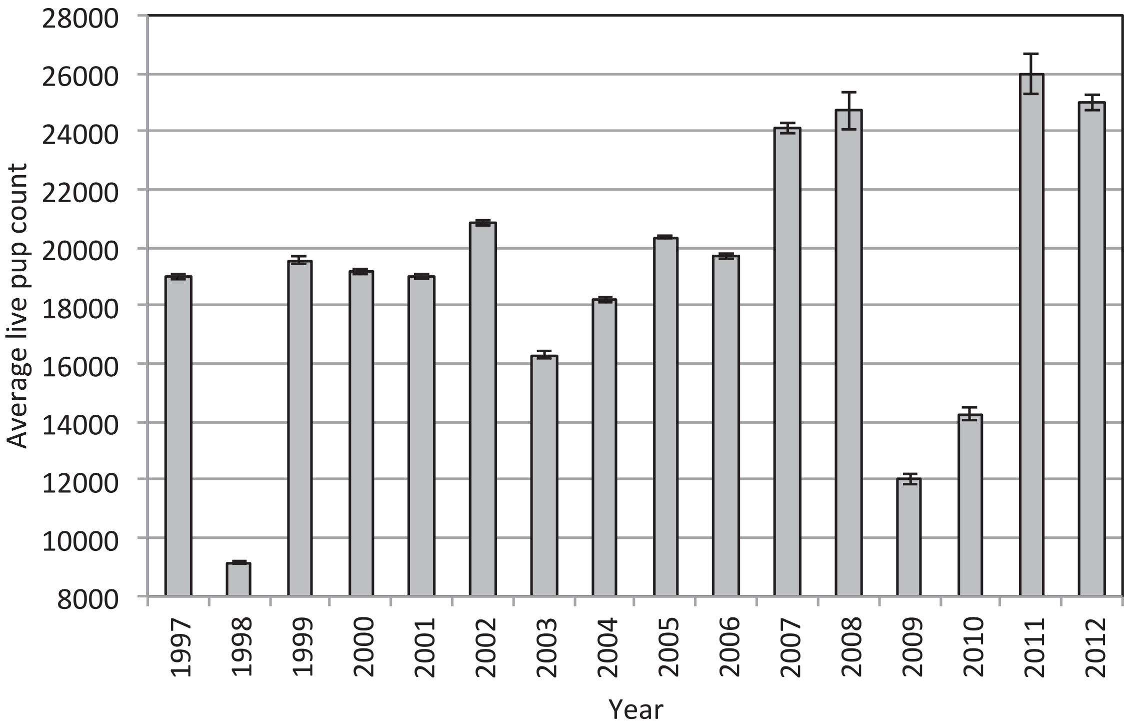

Figure 33. The average number of live California sea lion pups counted at San Miguel Island, California, 1997–2012 in late July when surviving pups were about 6 weeks old. Error bars are ±1 standard deviation.

the 1997 cohort, as were the daily growth rates between October and February. The 1997 cohort was impacted by a strong El Niño event that prevailed in the California Current between May 1997 and May 1998. The oceanographic conditions associated with the El Niño resulted in poor foraging conditions by reducing prey availability for lactating California sea lion females and consequently, their dependent pups were in poor condition (Melin et al. 2012; Melin et al. 2010).

In addition to poor condition of pups on the rookery at San Miguel Island, high numbers of emaciated pups began stranding on southern California beaches in January 2013, indicating that pups were weaning up to three months earlier than normal. High levels of strandings continued into April with three times the normal level of strandings during the four-month period (http://www.nmfs.noaa.gov/pr/health/mmume/californiasealions2013.htm). Although early weaning of pups and emaciated pups at the rookeries could be due to high mortality of adult females, there was no increase in strandings of lactating females during this period and emaciated pups were observed suckling robust females, suggesting that the cause for the poor condition of the pups was not related to mortality of their mothers. In response to the poor condition of pups at the rookeries and the high level of strandings, the National Marine Fisheries Service declared an Unusual Mortality Event of California sea lion pups on March 25, 2013. Two lines of investigation were initiated to explain the Unusual Mortality Event, one focusing on disease in pups or their mothers and the other on a shortage of food available to lactating females (see supplement for comment).

DISCUSSION

In 2012 the basin-scale indices and conditions from regional surveys indicate that oceanographic characteristics of the CCS were similar to recent cool years. The PDO signaled a continued pattern of cool SST and the NPGO was consistent with strong southward transport (fig. 2). The MEI demonstrated a short-lived switch to positive values in the summer of 2012, but was not sufficiently strong to elicit a response in CCS SST. During winter of 2011/2012, upwelling in the northern CCS was substantial, especially north of 39˚N (fig. 3). However, in the north, upwelling winds weakened in midwinter and remained weak until resuming to near-average values in May. In the south, upwelling remained strong. Regional hydrographic studies also demonstrated that conditions were not too dissimilar from conditions observed since 2007 for SST or salinity (figs. 7, 10, 12, 13, and 15).

Winter of 2011/2012 presented an uncharacteristic upwelling period and strong southward transport leading into 2012. Between 36˚N and 45˚N, the winds in December 2011 were unusual because the expected downwelling-producing winds were replaced by moderate upwelling-producing winds, while north of 45°N downwelling winds weakened (fig. 3). The upwelling and weakened downwelling winds resulted in coastal sea levels that suggested transport was more southward than had been observed in the past 45 Decembers (fig. 4). This southward transport was corroborated by HF radar showing anomalous equatorward surface velocities north of Cape Blanco in December 2011 (fig. 5). Consistent with increased southward transport, the northern copepod index calculated for the Newport Hydrographic Line had the largest ever values of northern copepod species during winter 2011/2012 (fig. 9). Interestingly, there was not a similar increase in northern copepods at Trinidad Head, however, an examination of HF radar (fig. 5) suggests that the surface source waters at Trinidad Head during winter 2011 may have been derived from immediately south of Cape Mendocino.

We acknowledge there are limitations and differences between survey designs represented here, but from our available observations, a CCS-wide pattern emerged with reduction of two primary forage fishes, namely northern anchovy and Pacific sardine (as well as Pacific herring where sampled in central and northern California). The abundances of these species along the CCS were near record minima in surveys. In the CalCOFI survey region, egg densities for both northern anchovy and Pacific sardine were low indicating a possible reduction in the spawning stock and/or the spawning stock resided outside the study region (figs. 27 and 28). Similarly, these fishes were caught in reduced numbers in central and northern California (figs. 22 and 25).

Lower observed abundance in northern anchovy in 2012 may have been an extension of a declining trend. Catches of larval anchovy in the southern California waters have declined over the last three decades with the lowest densities recorded in the recent five years ending in 2011 (fig. 29). This pattern indicates either a reduction in spawning stock biomass, early survival, or increased advection from the region (Bakun and Parrish 1982). What made 2012 particularly intriguing relative to forage, was not only that northern anchovy abundance was reduced across the CCS but that Pacific sardine and Pacific herring were at low abundances as well. That 2012 saw a reduction in the clupeiform forage community along the coast suggests that common factors could

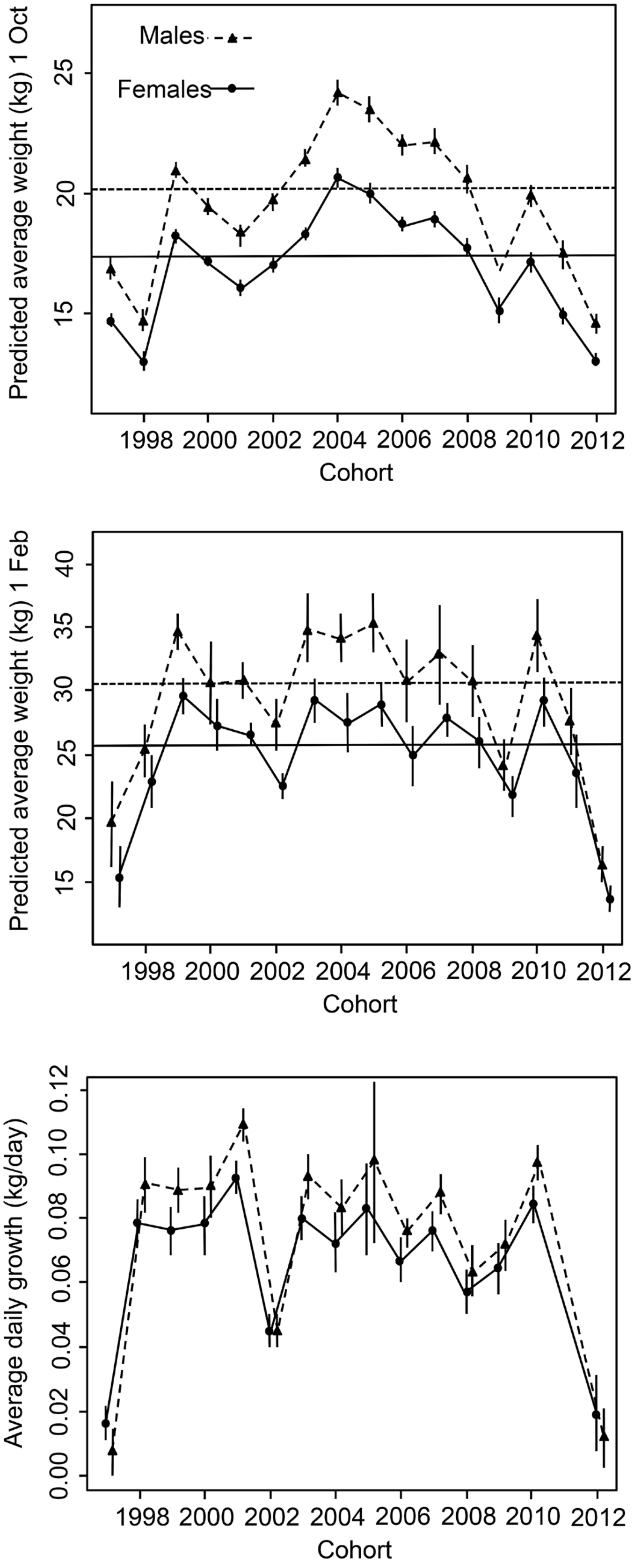

Figure 34. Top panel: Predicted average weights of 4 month old female (circle) and male (triangle) California sea lion pups at San Miguel Island, California, 1997–2012 and long-term average between 1975 and 2012 for females (solid line) and males (dashed line). Error bars are ±1 standard error. Middle panel: Predicted average weights of 7 month old female (circle) and male (triangle) California sea lion pups at San Miguel Island, California, 1997–2012 and long-term average between 1975 and 2012 for females (solid line) and males (dashed line). Error bars are ±1 standard error. Bottom panel: Predicted average daily growth rate of female (circle) and male (triangle) California sea lion pups between 4 and 7 months old at San Miguel Island, California, 1997–2012. Error bars are ±1 standard error.

have led to or exacerbated the reduction in all species, although the data here may be limited for addressing the specific causes.

Strong, early onset of upwelling in the southern CCS region in 2012 had the potential to have distributed forage fishes farther offshore and make them less accessible to the surveys and, possibly, predators (Bakun and Parrish 1982). In fact, at 33°N the cumulative upwelling during the beginning of 2012 was greater than most values on record (fig. S2). However the winds in this southern region relaxed to near climatological means by early spring 2012 (fig. 3). By the time of the 2012 survey, Pacific sardine eggs were distributed in an area narrower than that of 2011, concentrated primarily between CalCOFI line 60–76.7 and reduced numbers were observed between CalCOFI line 85–90 (fig. 27) (Lo et al. 2013). This distribution suggests that fish spawned nearshore, or those offshore did not spawn, or the relaxation of upwelling moved eggs inshore, or something else affected pelagic egg production that is yet to be fully quantified. By contrast, in the north, to where northern anchovy and Pacific sardine migrate, the upwelling winds were more modest and there was not anomalously high offshore advection, therefore, advection would not likely be a primary cause for the reduction in their abundance in those regions (fig. 3). Coming into 2013, a winter and spring of exceptional winds coast-wide, Pacific sardines, northern anchovy, and jack mackerel egg densities in southern California were similar to the previous two years (fig. 28). However, young-of-the-year northern anchovies had increased to near average abundance in the more northern surveys.

Those fishes whose abundance is reliant more on local (typically onshelf) conditions of production (Emmett et al. 2006; Santora et al. 2012) also displayed a CCS-wide signal; in all regions they exhibited improved production/abundance in 2012. For instance, in central California, a micronekton assemblage of rockfish, market squid, euphuasiids (fig. 25), lingcod (not shown), flatfishes (not shown), and octopi (not shown) continued a recent trend of improved production, consistent with increased local upwelling and productive shelf conditions. Similarly, whitebait smelt abundance (Emmett et al. 2006) was at average levels in the north in contrast to the low abundances of northern anchovy and clupeids. It followed that smelt, which sustained an average abundance (fig. 22), comprised a greater proportion of the diets for seabirds located at Yaquina Head than other prey (fig. S12).

The reductions of Pacific sardine and northern anchovy and the improved production of the forage reliant on shelf productivity may point to variability in the quality of the shelf and off-shelf habitats. Namely, over much of the range of northern anchovy, the fish feed, and may even spawn, at and beyond the shelf break (Kramer and Ahlstrom 1968; Smith 1972). In part, the northern anchovy may be held offshore by advection (Bakun and Parrish 1982). This is clear in the central California region where, even during the cool, productive conditions that benefit northern anchovy production (Lindegren et al. 2013), the northern anchovy are not abundant in the survey region (fig. 1). It is only when upwelling subsides, or during relatively unproductive years associated with reduced winds, that northern anchovy become increasingly available to the trawls and the inshore environment. Pacific sardine, as well, reside more offshore at or beyond the shelf break (Kramer 1970). By contrast, the fishes reliant on productive, cool waters inshore have had improved production recently. These fishes, such as rockfish, market squid, lingcod, and others, reside largely in the productive cool nearshore waters during upwelling periods.

While unsubstantiated in the CCS, there is a potential that dense salp concentrations in central and southern California (but not so far south as Baja California) during 2012 could have exacerbated the recent patterns in the forage community (Lavaniegos and Ohman 2003; Loeb et al. 1997). Specifically, research should be considered to examine the negative impacts of massive blooms on feeding rates, growth, reproduction, and survival of fishes in the CCS. The impacts of herbivorous, filter-feeding salps on primary production and food web dynamics can be striking (Alldredge and Madin 1982; Andersen 1998; Madin et al. 2006). These animals are characterized by fast growth rates, short generation times, relatively large body sizes, and very high filtering rates. Their life histories allow them to exist with minimal reproduction during periods of low food supply but also permit rapid, exponential population increases to take immediate advantage of elevated food concentrations. These characteristics underlie episodic population explosions during which time salps can quickly and efficiently remove particulates from large volumes of seawater thereby negatively impacting other herbivores (Alldredge and Madin 1982; Andersen 1998; Madin et al. 2006).

High concentrations of salps occurred in the northern CCS in 2010 and 2011 (fig. 18) and subsequently were anomalously abundant off central and southern California in 2012 (fig. 19), suggesting a spatial-temporal delay in their distribution from north to south. This delay may be due to the advection of seed stocks into, and explosive population growth within, waters offering appropriate conditions. In southern California, there was an increase in the volume of larger zooplankton (mostly salps and pyrosomes) early in 2012 that was about twice as large as values observed in 2011 and larger than any value seen in 20 years (fig. 21). In fact, local abundances were so great that by April 2012 the salps interfered with the coolant system of the Diablo Canyon power plant in south-central California, leading to a shutdown (http://articles.latimes.com/2012/apr/26/local/la-me-0426-jellyfish-nukes-20120426).

Anomalously strong southward transport from northern CCS during December 2011 (figs. 3, 4, and 5) potentially advected abundant seed populations of salps and pyrosomes produced in northern CCS waters during 2010 and 2011, into central and southern California waters as has been demonstrated by Roesler and Chelton 1987. The upwelling event of December 2011 following a downwelling period suggests that any seed populations of salps could have been nearshore when the winds switched, making them particularly vulnerable to southward transport. Once further south, they encountered appropriate primary productivity levels promoting further population increases followed by a reduction in the phytoplankton biomass in the region due to grazing pressure. The regional studies in central and northern California, as well as the remote sensing of the CCS, demonstrated just such a pattern (figs. 6, 10, and 12). In spring of 2011 chlorophyll values in the northern CCS were, indeed, anomalously low but were greater in 2012 (fig. 6). In contrast, central and southern California chlorophyll values were average to above average in spring 2011 but for the most part anomalously low in 2012. The exception in 2012 was a positive anomaly offshore south of Point Conception, near central gyre waters (fig. 6).

Where observed off central California, salps were predominantly at offshore stations (fig. 20; note the log scale). The central California salmon survey, occurring just a month later than the rockfish survey, did not encounter anything so pronounced due to its predominantly inshore stations (fig. 20). Closer inspection of chlorophyll distribution patterns in the spring (fig. 6) suggests higher than typical primary production on the shelf in the Gulf of the Farallones region vitally important to production off central California. By contrast, just south of the Gulf of the Farallones over the Monterey Canyon region, where salps were very abundant (fig. 20), surface chlorophyll values were the lowest on record by June (fig. 12). Off southern California the onshore presence of dense salp aggregations, such as those that shut down the Diablo Canyon nuclear power plant, could have had an impact on coastal ecosystems.

The population dynamics and foraging ecology of seabirds are closely related to ocean conditions and forage abundance, distribution, and composition within the California Current (Ainley and Hyrenbach 2010; Ainley et al. 1995; Santora et al. 2011; Veit et al. 1996). In 2012, seabirds on Southeast Farallon Island had generally average production (few species indicators fell outside of 1 s.d.). However, Cassin's auklet and Brandt's cormorant were notable in the degree to which they had good and poor reproductive success, respectively. These differences may relate to changes in the forage community. Cassin's auklet, who rely on more onshelf (nearer to nesting sites) prey such as *T. spinifera* (Sydeman et al. 2001; Sydeman et al. 1997), had exceptional reproductive success (fig. 31); consider as well the reproductive failures of 2005 and 2006 were associated with reduced prey availability on the shelf. In 2012, Cassin's auklet in southern California also did not demonstrate substantial changes to their foraging behavior that would be indicative of a drastic reduction or redistribution in their forage (fig. 32). Brandt's cormorant rely, in part, on northern anchovy in the neritic environment (Sydeman et al. 1997) and, therefore, reduced availability in northern anchovy inshore is a likely cause of their poor reproductive success.

In the northern CCS at Yaquina Head, common murre did experience reduced fledgling success in contrast to that at Southeast Farallon Island, but this reduction was likely the result of predators at the colony (e.g., brown pelicans, *Pelecanus occidentalis*, and bald eagles, *Haliaeetus leucocephalus*) (fig. 30). The top-down impacts of seabird predators may be related to bottom-up processes affecting prey availability (Hipfner et al. 2012). For example, in 2012 brown pelicans caused dramatic common murre chick mortality at Yaquina Head, more than any previous year recorded. Pelicans were observed grabbing common murre chicks on the colony and consuming some directly, but shaking others until the chicks regurgitated fish, then the pelicans consumed the regurgitated fish. Northern anchovy and Pacific sardine are dominant prey items for pelicans and, with their regional abundance greatly reduced in 2012, the pelicans may have been desperate for alternative prey (Horton and Suryan 2012).

Consistent with a coast-wide change in the forage community was the poor condition and mortality event of California sea lion pups from San Miguel Island. It is suspected that this event was brought on by the inability of mothers to provide sufficient nourishment to their dependent pups through lactation (fig. 34). The population response was very similar to that observed during strong El Niño events when the availability of sea lion prey is diminished in the CCS, and the unusual mortality event in 2012 may be related to the reduced availability of forage fish during 2012. The unusual mortality event is currently under investigation and both forage community dynamics and disease are being considered (see supplement).

Interestingly, the estimated abundances of another predator, juvenile Chinook salmon, in California did not show a pattern of abundance easily attributable to the observed changes in the forage community, as did seabirds and sea lions. This was surprising, as it would be expected that juvenile Chinook salmon, reliant on forage on the shelf (Daly et al. 2009; Wells et al. 2012), would have been universally successful in 2012. Rather, catches of juvenile Chinook salmon in California were observed at lower abundance than the previous two years of the survey. However, what was a reduction in observed abundance of salmon in the California in 2012 may not have been great if a longer time series (more than the current 2010–13) had been available for comparison with the 2012 survey. Consistent with the possibility that 2012 was not as poor a year for California Chinook salmon as the three-year survey may suggest, juvenile Chinook salmon were abundant in the northern CCS during June off Washington and Oregon.

With 2013 came an exceptionally strong winter and spring upwelling period (fig. 3) that acted predictably on the regional hydrography; salinities were greater and surface temperatures lower (figs. 7, 10, and 12). Biological data, for the most part, has yet to be processed, therefore, the biological signal will be discussed in greater detail in the next year's report. However, the May–June juvenile rockfish survey did report record numbers of young-of-the-year pelagic rockfish, and high abundances of many other micronekton forage species as well (other juvenile groundfish, krill, and market squid). While beyond the defined time period of this report, it is also worth noting that by the end of summer and early fall, upwelling relaxed dramatically and, with the associated reduction in advection, anchovy abundance was observed to be very high nearshore in central California leading to impressive feeding aggregations of marine mammals and seabirds (see http://www.santacruzsentinel.com/santacruz/ci_24091445/whale-time-anchovies-bring-record-numbers-humpbacks).

The coming year will offer an opportunity to evaluate the coast-wide effects of strong winds early in the year on the system. Specifically, following on the findings of previous work (e.g., Bakun and Parrish 1982; Cury and Roy 1989; Mackenzie and Leggett 1991; Piatt and Springer 2003) we may observe changes indicative of poor production for a number of the indicators we examine in this report. Namely, increased diffusion of nutrients and phytoplankton away form the coast (i.e., reduced coastal front development due to turbulence) may be noted, forage composition and distribution may be altered, and there may be reductions in seabird production brought on by changes in the seascape. However, 1999 also represented a strong upwelling year and, from that, rockfish, salmon, and seabirds, as well as other taxa, were very productive along much of the CCS. Obviously these species did not experience the hypothesized negative effects of too much upwelling.

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Part II

SYMPOSIUM OF THE CALCOFI CONFERENCE 2012

A SOUTHERN CALIFORNIA PERSPECTIVE ON HARMFUL ALGAL BLOOMS

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EXTENDED ABSTRACT

Understanding the complexity of harmful algal blooms (HABs) and their impacts on marine resources requires collaborations that overlaps a variety of disciplines, agencies, and regions. Ongoing monitoring efforts by California Department of Public Health (CDPH), the Southern California Coastal Ocean Observing System (SCCOOS) and the Central and Northern Coastal Ocean Observing System (CeNCOOS) provide the basis for evaluating and assessing the potential of marine biotoxins within commercially and recreationally important fisheries along the California coastline. These programs focus efforts on a particular marine resource (CDPH, farmed and recreationally harvested bivalves) or on a specific toxin (domoic acid only for SCCOOS) to meet regulatory requirements or funding shortfalls that constrain sample collection and processing. Since 2001, prevalence and persistence of offshore toxic blooms, particularly of domoic acid, has compounded this problem and additional monitoring efforts are needed to assess potential risks to consumers and inform seafood advisories within the state. Finding opportunities to collaborate with the California Cooperative Oceanic Fisheries Investigations Group (CalCOFI) and the Southwest Fisheries Science Center (SWFSC) can help assess the potential risks to our marine resources and seafood consumers, and provide novel opportunities for data collection and sharing. This presentation is focused on three main points: 1) providing an overview on the HAB monitoring efforts in southern California, 2) discussing the potential impact on California fisheries, and 3) providing input on how CalCOFI and SWFSC can be engaged in HAB monitoring.

HAB Monitoring in California

One of the oldest HAB programs in the U.S. started in 1929 along the California coast to monitor for saxitoxins that can cause illness or death in extreme cases from paralytic shellfish poisoning (PSP). In the 1940s, such monitoring was mandated for the sale of commercial shellfish by the National Shellfish Sanitation Program. By the 1960s, routine coastal monitoring for PSP toxins in shellfish began as a means to protect those recreationally harvesting shellfish. The regulatory alert level for saxitoxins in shellfish is ≥ 80 µg 100 g^{-1} (0.8 ppm). Several dinoflagellate species within the genus *Alexandrium* spp. (formerly *Gonyaulax*) produce PSP toxins.

The CDPH monitoring program was expanded in 1991 to include phytoplankton monitoring (net tow samples) along the coast as a means to provide an early warning of toxic blooms and prioritize shellfish samples for toxin analysis. At this time the program also began routine monitoring for a second biotoxin: domoic acid (DA), a naturally occurring and toxic amino acid that can cause amnesic shellfish poisoning (ASP; Bates et al. 1989). Toxin production has been confirmed in 12 of 30 species of the diatom genus *Pseudo-nitzschia* (Horner et al. 1997; Bates and Trainer 2006). ASP was first recognized in 1987 when three people died and 105 cases of acute poisoning were reported after consuming DA-contaminated blue mussels (*Mytilus edulis*) from Prince Edward Island, Canada (Bates et al. 1989). Along the West Coast of the U.S., human illness or death from ASP has not been reported though numerous cases of large-scale deaths and illnesses of marine mammals and wildlife have occurred since 1991 (Fritz et al. 1992; Work et al. 1993; Lefebvre et al. 1999; Scholin et al. 2000; Bejarano et al. 2008; Fire et al. 2010; Bargu et al. 2012). The regulatory alert level for DA in shellfish is ≥ 20 µg g^{-1} (20 ppm).

The CDPH program standards to protect consumers includes weekly monitoring of marine biotoxins in shellfish and the relative abundance of toxigenic phytoplankton along the coast, posting of annual quarantines from May 1 to October 31 each year, issuing special health advisories as needed for recreationally harvested bivalves, and public education and outreach. The program relies on commercial growers (7 sites) to provide weekly shellfish and plankton samples, and a volunteer network to provide weekly to monthly shellfish samples (70 sites) and plankton samples (115) from coastal stations (1–4 per county). The resulting data are used to regulate shellfish growers, as well as to inform state health advisories about safe consumption of recreationally harvested shellfish when HABs are present. These data, maps and advisories are available at http://www.cdph.ca.gov/healthinfo/environhealth/water/Pages/Shellfish.aspx.

Academic and ocean observing research communities interested in understanding the temporal and spatial scales of HABs, factors which promote HABs, as well as improving the detection and prediction of these events began regular, weekly pier-based HAB monitoring efforts in southern California at one site in 2005 (SIO, La Jolla) and an additional four sites in 2008 (SCCOOS, http://www.sccoos.org/data/habs/index.php). These efforts are focused on all HAB species in California that may pose significant impacts to human health, marine life, marine resources, and the economy including both toxin producing (*Pseudo-nitzschia* spp., *Alexandrium* spp., and *Dinophysis* spp.) and bloom forming species (*Lingulodinium polyedrum*, *Akashiwo sanguinea*, *Prorocentrum* spp. *Cochlodinium* spp., *Phaeocystis* spp., and others). Weekly measurements include HAB species abundance estimates, chlorophyll *a* concentration, temperature, salinity, nutrient concentrations (nitrate, nitrite, phosphate, silicate, and ammonia) and particulate DA concentration. These data are posted weekly to the SCCOOS HAB Web site and shared through the California Harmful Algal Bloom Monitoring and Alert Program (CalHABMAP, http://habmap.info) e-mail list serve, which brings together researchers, marine mammal and wildlife rescue groups, managers, and the general public throughout the state of California.

While coastal monitoring efforts and the CDPH program have been effective at protecting and informing consumers of toxic HABs in coastal areas, these efforts have historically focused on nearshore shellfish resources and not on detection of HABs in offshore waters including areas near the Channel Islands. Additional monitoring is now needed for two primary reasons. First, the prevalence, intensity, and duration of these offshore toxic blooms of *Pseudo-nitzschia* have increased in California over the past decade (CDPH data; Lewitus et al. 2012). As a result, there is a need to monitor commercially and recreationally important species more frequently as they are exposed to higher levels of biotoxins more often and for longer periods of time. Second, these blooms have developed and/or continued offshore, especially in the Santa Barbara Channel (SBC) region, often decoupled from coastal blooms—something not commonly seen in the past. This new pattern in the distribution of toxic blooms now requires that monitoring occur in offshore areas, not just along the coast as is presently done.

The California Sea Grant Extension Program, in collaboration with the CDPH and the California Department of Fish and Wildlife (CDFW) recognized that a more focused and organized offshore monitoring program was critically needed given that 1) toxic offshore blooms are persisting, 2) higher levels of biotoxins may pose more risk to consumers, 3) offshore shellfish and fish samples for biotoxin analysis are obtained haphazardly from recreational and commercial fishermen, rendering useful but incomplete data sets, and 4) the value of a more consistent and reliable offshore monitoring program to better manage offshore fisheries and ensure areas not impacted by HABs are not included in health advisories when another offshore area is impacted by a HAB event. This collaborative effort is looking to expand the CDPH biotoxin monitoring program into offshore areas of southern California (Santa Barbara County to the Mexican border) with funding from the Collaborative Fisheries Research West program. They are seeking volunteers to help with one or more of the sampling tiers; Tier 1, phytoplankton; Tier 2, bivalve shellfish (mussels, oysters, scallops, clams) or filter-feeding finfish (anchovies, sardines); Tier 3, crustacean shellfish (crabs, lobster). Several other organizations (e.g., whale watching, dive and island charters, commercial fishermen, National Park Service) and individuals are joining this effort, but coordinating with additional groups that frequent offshore areas, such as CalCOFI and SWFSC, is of great interest.

Impacts on Fisheries

Biotoxins have been detected in a wide variety of species other than bivalve shellfish including but not limited to pelagic filter-feeding species (Pacific sardines and Northern anchovies), California spiny lobster, crab (Dungeness, rock and pelagic red), Humboldt squid, Market squid, and benthic-feeding groundfish including several commercial and recreationally important species (Pacific halibut, Dover sole, and sanddab); (Wekell et al. 1994; Busse et al. 2006; Vigilant and Silver 2007; Mazzillo et al. 2010). Of particular concern has been the high levels of DA found in samples from California over the last 10 years: 1) mussels from an offshore oil platform that contained 610 ppm of DA; 2) anchovies with 2,300 ppm of DA in viscera; 3) lobster viscera with 1,170 ppm of DA, and several samples with 200–400 ppm of DA; and 4) rock crab containing 300–400 ppm (CDPH data). Toxins are typically concentrated in the viscera (internal organs, digestive glands) and not the body tissue (meat), so thorough cleaning and removal of the viscera in larger species (e.g., crab, scallops) can minimize the risk. However many species (e.g., mussels, oysters, sardines, anchovies) are eaten whole and pose the greatest risk to consumers (Mazzillo et al. 2010). Some individuals and ethnicities may also consume the entire rock scallop, rock crab (crab butter) and lobster (lobster tomalley, pâté, bisque) increasing the risk of exposure to biotoxins and other contaminants.

Importantly, even at high DA concentrations, the preliminary data indicates the meat of the larger crustaceans and game fish remains relatively toxin free even though low concentrations of toxins have been detected in the body tissue (meat) of anchovies (*Engraulis mordax*; Work et al. 1993; Altwein et al. 1995; Lefebvre et al. 2002; Mazzillo et al. 2010), coho salmon (*Oncorhynchus kisutch*; Lefebvre et al. 2007), Dungeness crab (*Cancer magister*; Altwein et al. 1995), mantle of Humboldt squid (*Dosidicus gigas*; Mazzillo et al. 2011) and mantle of octopus (*Octopus vulgaris*; Costa et al. 2004). Overall, these findings are based on a relatively limited number of samples and require more comparative data during HAB events to improve our understanding of the risk exposure to biotoxins for all seafood species.

In general, HABs directly impact California fisheries through the closure of shellfish beds, aquaculture facilities, and even the closure of markets and recreational sport fisheries due to toxin accumulation above regulatory limits and die-offs of natural and farmed fish and shellfish. Almost every year since 2001 CDPH has had to extend the time period of the annual shellfish advisory or issue additional warnings to protect consumers about eating seafood (other than bivalves) such as sardines, anchovies, lobster, and crab that have been found to have biotoxins above the regulatory alert level (20 ppm for DA). The health advisories that have resulted from these findings have impacted commercial fishermen, as some distributors will not buy products coming from the areas under advisory. In most cases, the advisories cover a large area due to a lack of data to pinpoint the location of the bloom and associated affected animals.

Currently, shellfish growers are the most highly regulated in terms of biotoxins, providing the best protection for the consumer, but an equivalent level of monitoring and regulatory oversight for commercial and recreationally important wild-caught fisheries in California does not exist. Ultimately, there are several unanswered questions related to human health impacts of HABs on fisheries. How often are toxins found in offshore populations of shellfish, squid, and finfish? Can one indicator species provide adequate protection to consumers if modes of toxin uptake differ and depuration rates vary for impacted species (bivalves, lobster, crab, squid, and finfish)? Do increased amounts of toxin found in seafood pose a greater risk of acute toxicity to the consumer? Are there human health concerns with chronic exposure to algal biotoxins? These are just a few of the complex questions that need greater attention to protect both the consumer and the seafood industry.

Potential Assistance from CalCOFI

The last goal of this presentation is to provide input on how the CalCOFI and SWFSC groups can be engaged in research and monitoring of HABs. One immediate and cost-saving approach for the offshore monitoring of HABs is to have consistent samples collected during the quarterly CalCOFI cruises and SWFSC fish survey cruises. Sample types consist of water samples (30–100 ml), filtered water samples (400 ml on GF/F filters), net tow samples (20 µm mesh vertical tow), or samples of fish or shellfish (whole or viscera only) and would be analyzed by CDPH and SCCOOS HAB researchers. These samples would be quite beneficial to ongoing research and state monitoring efforts by helping determine HAB species abundance and toxin production in the water and food web at offshore locations on regular intervals. This, in turn, would improve early detection of blooms and increase spatial and temporal data needed to inform health advisories.

Additionally, plankton and hydrographic data sets already being collected by CalCOFI could be reanalyzed to help address HAB related questions. For example, phytoplankton abundance estimates (collected by E. Venrick) and nano- and microplankton biomass and abundance estimates (collected by M. Landry) are currently conducted for some stations and lines throughout the CalCOFI sampling grid. These measurements could also be analyzed to look specifically at HAB species such as *Pseudo-nitzschia* spp., thereby providing information on abundance relative to offshore hydrographic conditions and coastal conditions. More broadly, this increased sampling and analysis of data when combined together would ultimately provide a better understanding of the mechanisms and factors associated with offshore HAB blooms, improve understanding of links with coastal blooms, and potentially improve predictions of HAB events.

Conclusions

Adequate offshore HAB-focused sampling is lacking, hindering the states' ability to provide well-informed seafood health advisories and improve our understanding of the factors related to offshore toxic blooms. Engaging CalCOFI and SWFSC in ongoing HAB monitoring efforts could improve the availability of samples both in space and time thereby helping to identify high-risk areas and improving the resolution of information available to researchers, resource managers, and health regulatory agencies. While some coordination is required, the additional sampling appears to be easily integrated with ongoing activities of CalCOFI and SWFSC. The authors encourage such collaboration, as it would not only increase the knowledge about HABs in California, but it would also enhance the states' ability to provide appropriate seafood health advisories.

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Part III

SCIENTIFIC CONTRIBUTIONS

FINESCALE TRIGGERFISH (*BALISTES POLYLEPIS*) AND ROOSTERFISH (*NEMATISTIUS PECTORALIS*) PRESENCE IN TEMPERATE WATERS OFF BAJA CALIFORNIA, MÉXICO: EVIDENCE OF EL NIÑO CONDITIONS

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ABSTRACT

I report here on several unusual catches that may reflect on El Niño conditions off northern Baja California. Eleven finescale triggerfish, *Balistes polylepis*, were captured in waters off San Martin Island on July 30–31, 2011. This island is located (lat 30°29'29.50"N, long 116°6'52.02"W) close to San Quintín Bay in the northern Pacific off Baja California, Mexico, a temperate area influenced by strong upwelling. I also report on the catch of a roosterfish, *Nematistius pectoralis*, at Todos Santos Bay, Ensenada (close to El Sauzal port) (lat 31°53'38.22"N, long 116°41'58.36"W), on September 8, 2012. Both the triggerfish and roosterfish are tropical species, and their presence may be associated with the El Niño of 2009–10 and a weak El Niño in 2012, respectively. These occurrences constitute the first record both for finescale triggerfish in the San Quintín area and for roosterfish at Todos Santos Bay.

INTRODUCTION

The presence of tropical fish species in temperate waters of northern Baja California, México, is uncommon, and when registered are associated with warm years. I report here on unusual catches of two tropical and subtropical fish species, the finescale triggerfish (*Balistes polylepis*) in waters off the coast of San Quintín, and roosterfish (*Nematistius pectoralis*) at Todos Santos Bay. Both species arrived in different years, possibly attributed to warm waters during the recent El Niño conditions in 2009–10 and 2012.

Finescale Triggerfish (*Balistes polylepis* Steindachner, 1876)

The triggerfish was observed during the monthly monitoring (Saturday, 30 July 2011) of the sport fishing catch at San Quintín, Baja California, México (fig. 1). During the surveys, I attempt to identify, measure, and weigh all of the fishes brought in by the sport fishing boat fleet. Information on fishing site, depth, number of anglers, bait used, surface seawater temperature, and boat name were also documented. Temperature data at fishing depth was obtained from the oceanographic cruise of the IMECOCAL Program on July 24, 2011 (http://imecocal.cicese.mx/; last accessed 31 July, 2012), at the closest station from San Martín Island (station 107.32: lat 30°27.49N, long 116°09.79W).

At San Quintín, I monitored seven boats carrying recreational anglers. The catch included kelp bass (*Paralabrax clathratus*), ocean whitefish (*Caulolatilus princeps*), sheephead (*Semicossyphus pulcher*), lingcod (*Ophiodon elongatus*), vermilion rockfish (*Sebastes miniatus*), starry rockfish (*S. constellatus*), and bocaccio (*S. paucispinis*). One of the boats returned with four individuals of the finescale triggerfish (*B. polylepis*) that were taken using hook-and-rod and squid as bait in shallow waters off San Martín Island, Baja California, a volcanic island with central coordinates 30°29'29.50"N, 116°6'52.02"W, situated 5.2 km north of San Quintín Bay (fig. 1). The catch site was at the northeastern part of the island, on a rocky bottom, in 15–20 m depth (lat 31°53'38.22"N, long 116°41'58.36"W). This spot is located at the tip of a small rocky barrier with a light beacon that divides a protected beach from a small lagoon inhabited by sea lions. At the fishing site, the sea surface temperature was 16.1°C; the recorded temperatures at 15 and 20 m-depths were 15.5°C and 14.8°C, respectively. The smallest triggerfish (fig. 2) measured 410 mm total length (TL) (318 mm standard length, SL) and weighed 1,225 g. Lengths and weights of the other three individuals were: 420 mm TL (330 mm SL); 1,067 g; 430 mm TL (355 mm SL), 1,627 g; and 450 mm TL (355 mm SL), 1,487 g. The next day, 31 July 2011, another boat captured eleven triggerfish at the same site. These fish were identified to species by the combination of the following characteristics: a deep and compressed body; olive brown skin color; hard skin with small scales on the deep, first dorsal fin with three spines, followed by a gap; and a second fin with 27 dorsal rays; an anal fin with 24 soft rays and lacking spines; a pectoral fin with 14 soft rays; and a caudal fin concave with prolonged lobes, a small gill slit, and a small mount with incisor-like teeth.

Roosterfish (*Nematistius pectoralis* Gill, 1862)

On 8 September 2012, a roosterfish (fig. 3) was captured by a small panga with a gill net, at Todos Santos Bay, Baja California. Also taken in that catch

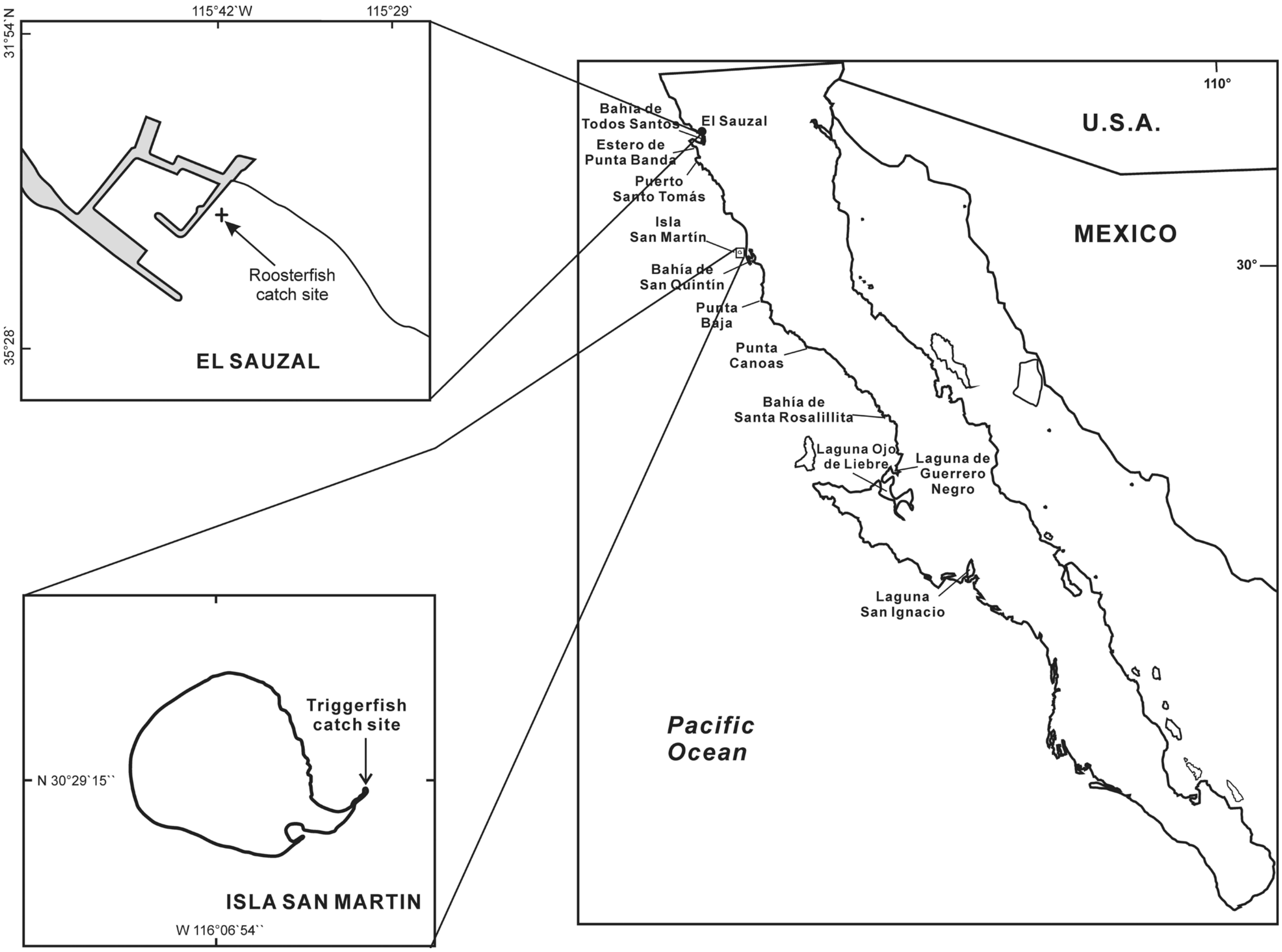

Figure 1. Finescale triggerfish catch site at Isla San Martin, Baja California, México, and roosterfish catch site at Todos Santos Bay.

were California corbina (*Menticirrhus undulatus*), California halibut (*Paralichtys californicus*), spotfin croaker (*Roncador stearnsii*), and white croaker (*Genyonemus lineatus*). The fish was taken near El Sauzal port (8 km north of Ensenada) close to the side east jetty (fig. 1), on a sandy bottom 8 m of water (lat 31°53'38.22"N, long 116°41'58.36"W). The surface seawater temperature at Todos Santos Bay was 23.4°C. This individual measured 215 mm TL, 175 mm SL, weighed 124 g, and was preserved in ethanol. It was identified by the following characteristics: bluish body and silvery below; four black stripes, the first over the eye, the second over the opercle, third and fourth in diagonal along back and sides; 7 long spines on first dorsal fin, dorsal spines black with middle of spines yellow; one spine and 26 rays on second dorsal fin; pectoral rays 16; two spines and 15 rays in anal fin; pectoral fin with 16 rays; and caudal tail forked.

DISCUSSION

The finescale triggerfish is mostly a tropical and subtropical species distributed along the eastern Pacific Coast, from San Francisco, California, to San Antonio (33°35'S), Chile (Miller and Lea 1972; Brito 2003; Love 2011), including the Gulf of California, Hawaii, and Galapagos Islands (Berry and Baldwin 1966). Although usually rare off southern California, large numbers were caught nearshore during the 1982–83 El Niño (Love 2011). The roosterfish is a tropical species with a distribution at the eastern Pacific from southernmost California (one record in San Clemente Island, California) to Peru, including Galapagos Islands and Gulf of California (Miller and Lea 1972).

Triggerfish and roosterfish are fish species found in the artisanal commercial fisheries in the Southern Baja California, and Gulf of California (Bizarro et al. 2007; Smith et al. 2009). Roosterfish is a game fish and is usually for catch and release only.

These catches are particularly noteworthy because neither species has been recorded from northern Baja California, despite a number fish surveys (including rocky reef, sandy seafloor, and sheltered embayment habitats) along this coast [Ensenada region (Díaz-Díaz

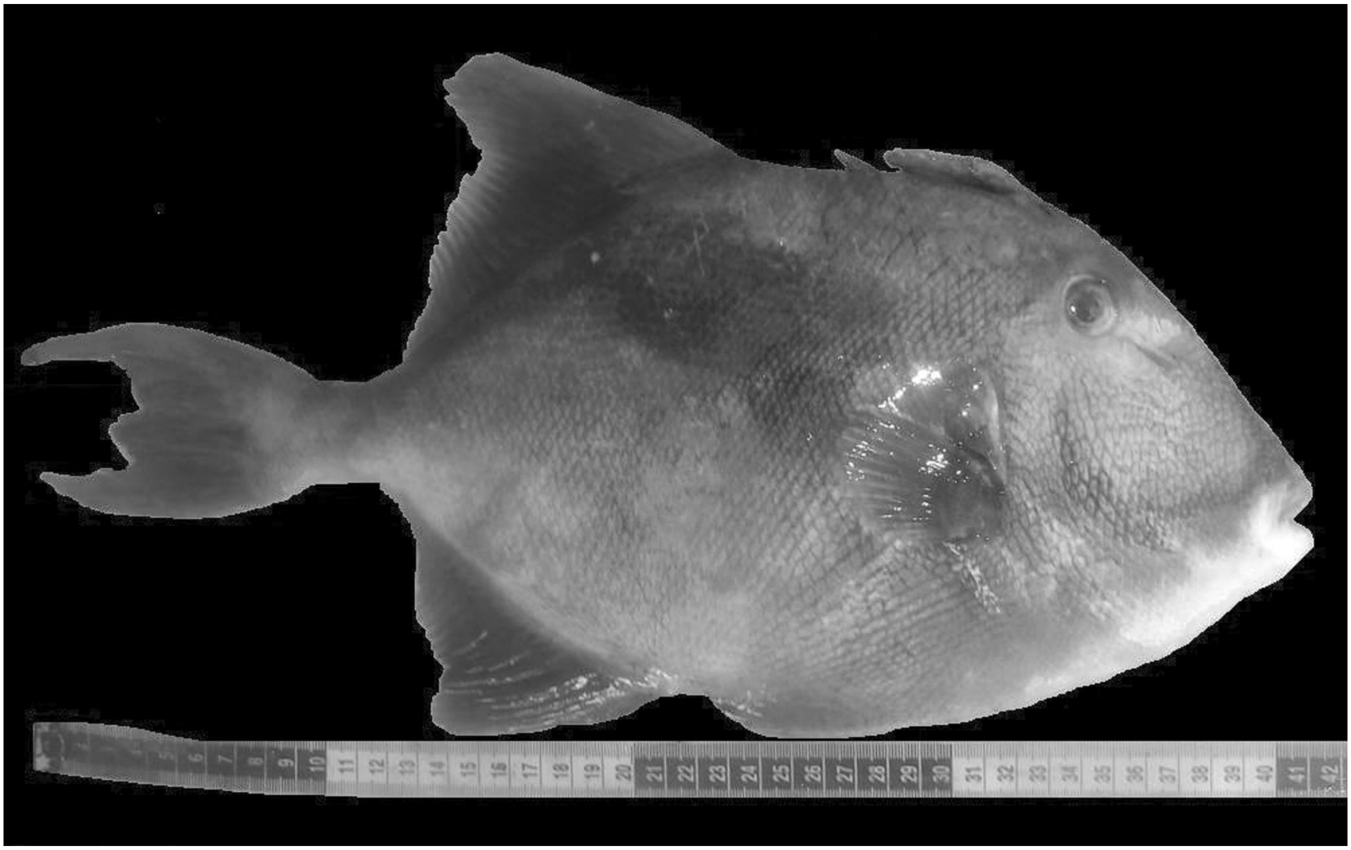

Figure 2. Finescale triggerfish, *Balistes polylepis*, captured on July 30, 2011, at San Martín Island, Baja California, México.

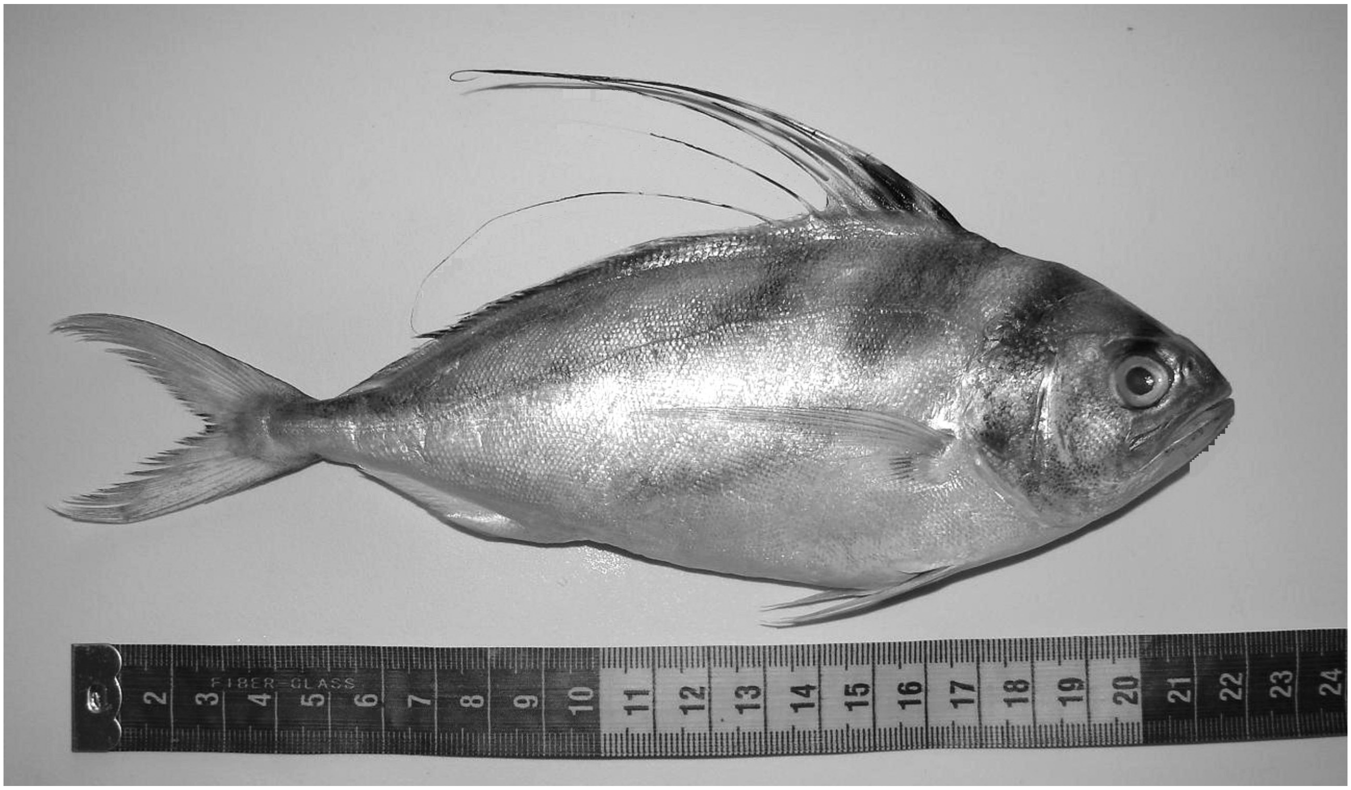

Figure 3. Roosterfish, *Nematistius pectoralis*, captured on September 8, 2012, at Todos Santos Bay, Baja California, México.

and Hammann 1987; Hammann and Rosales-Casián 1990; Rodriguez-Medrano 1993), Punta Banda Estuary, 31°45'N, 116°38'W (Beltrán-Felix et al. 1986); bay and coastal system of San Quintín (Rosales-Casián 1997a,b; Rosales-Casián 2004); El Rosario Bay (Punta Baja) (Rosales-Casián 2011); Santa Rosalillita Bay (unpublished data, 28°40'N, 114°15'W); eight artisanal fishing sites along northwestern coast of Baja California, from the Santo Tomas Port, 31°33'N, 116°40'W, to Canoas Point, 29°25'N, 115°12'W (Rosales-Casián and Gonzalez-Camacho 2003)].

While northern Baja California is normally characterized by cold waters created by strong upwelling (Álvarez-Borrego 2004), during the 1997–98 El Niño some tropical fish species were taken in San Quintín Bay: one juvenile of the burrito or white grunt *Haemulopsis leuciscus* (Rosales-Casián and Ruiz-Campos 1999); the bigscale goatfish (*Pseudupeneus grandisquamis*), bullseye puffer (*Sphoeroides annulatus*), and paloma pompano (*Trachinotus paitensis*); all those species were collected with otter-trawl tows at 5 m-depth, but unrecorded in cold years 1994–95 (Rosales-Casián 2004).

The arrival of the triggerfish at San Martin Island was possibly due to a moderate intensity El Niño during 2009–10, although captures occurred at the end of the La Niña 2011 (NOAA's El Niño page), available at http://www.elnino.noaa.gov/; last accessed 10 August, 2012. The roosterfish presence at Todos Santos Bay, was possibly due to conditions of an undeclared and weak El Niño condition during 2012.

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DO SHIFTS IN OTOLITH MORPHOLOGY OF YOUNG PACIFIC SARDINE (*SARDINOPS SAGAX*) REFLECT CHANGING RECRUITMENT CONTRIBUTIONS FROM NORTHERN AND SOUTHERN STOCKS?

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ABSTRACT

An investigation of otolith morphology of young Pacific sardine (*Sardinops sagax*) caught off San Diego and Monterey, California during 2006–12 revealed an increase in the lighter, more rugose phenotype that predominates in otoliths of sardine captured off Baja California, Mexico. This increase began in July 2008, correlated with decreasing spawning biomass of the northern (cold) stock, and coincided with the decline in growth rates of adult sardine interpreted from otolith weight–fish length relationships. Measurements of habitat temperatures inferred from oxygen stable isotope composition in juvenile otoliths showed morphology and temperature were independent variables, but inferred temperatures were about 2°C higher after July 2008. The shift in otolith morphology did not appear in the adult population in 2009–12. Environmental factors related to a cold phase of the Pacific Decadal Oscillation may have influenced these shifts in juvenile otolith shapes. The results are consistent with a declining contribution of northern stock recruits to the fishery off California.

INTRODUCTION

Pacific sardine (*Sardinops sagax*) is a major pelagic species in the California Current ecosystem. Currently, the range of the commercial sardine fishery extends from Vancouver Island (British Columbia, Canada) to Bahía Magdalena (Baja California Sur, Mexico) (fig. 1). A sardine fishery also occurs in the warm waters of the Gulf of California. Young sardine (age–0 to age–3, <200 mm length) form the basis of a lucrative coastal fishery in southern and central California.

The overall population can be divided into three major subpopulations that differ in preferred temperature, season of spawning, and major areas of spawning (reviewed by Smith 2005): 1) a cold or northern stock that extends from British Columbia to Ensenada (northern Baja California); 2) a temperate or southern stock that extends from southern California to the tip of Baja California; and 3) a warm or Gulf of California stock. Three areas of high spawning activity correspond to these stocks, respectively: one off central and southern California; one off Bahía Magdalena; and a third in the Gulf of California. However, data from decades of California Cooperative Oceanic Fisheries Investigations (CalCOFI) surveys suggest that if conditions are favorable, sardine eggs may be found almost anywhere along the coast (Southwest Fisheries Science Center [SWFSC] data). All three stocks undertake annual seasonal migrations, and they likely have regions of overlap in distribution (Félix-Uraga et al. 2004, 2005; Smith 2005).

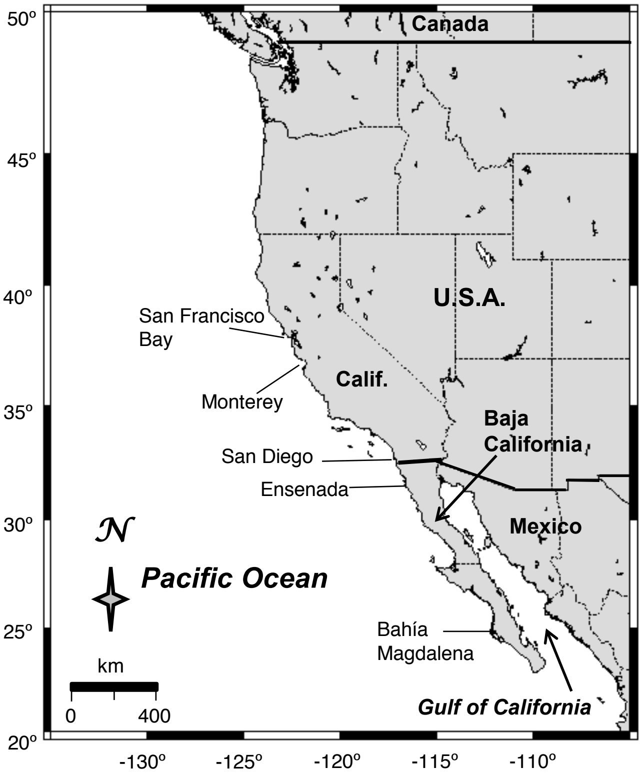

Figure 1. Map of the collection sites of *S. sagax*.

Following the historic collapse of the California sardine fishery in the 1940s and 1950s, and its recovery beginning in the 1980s, fisheries scientists and the CalCOFI program have conducted extensive research into sardine biology and modeling their associated oceanographic conditions in the California Current system (e.g., articles in every volume of CalCOFI Reports; Norton and Mason 2005; Reiss et al. 2008; Rykaczewski and Checkley 2008; McClatchie et al. 2010; Zwolinski et al. 2011; Song et al. 2012; Lindegren and Checkley 2013). However, a number of key factors remain poorly understood, such as the sources of recruitment to the spawning stock; survival of eggs, larvae, and schooling young sardine; and the extent of drift and migratory behavior of young juveniles.

Older juvenile sardine that are targeted by commercial fisheries migrate seasonally within preferred temperature zones that shift north and south (Félix-Uraga et al. 2004, 2005; Zwolinski et al. 2011). The maximum sea surface temperature (SST) associated with potential habitat for the northern stock, 16.4˚C, serves as an indicator to separate southern and northern stocks when temperature-at-catch is monitored (Juan Zwolinski, pers. comm., 29 March 2013). The average monthly SST values near Ensenada and San Pedro, CA (180 km north of San Diego) during 1982–2012 indicated winter temperatures (January–April) were consistently <16.4˚C, and summer temperatures (July–November) were consistently >16.4˚C at both locations.

Besides temperature at catch, other methods have been employed to identify unique characteristics of regional sardine stocks with variable degrees of success, including egg, larval, and adult surveys; fish morphometrics; vertebral counts; tags; parasites; and acoustic-trawl surveys (Smith 2005; Lo et al. 2005, 2010, 2011; Baldwin 2010; Demer et al. 2012). Genetic studies have not yielded regional markers so far (Hedgecock et al. 1989; Grant and Bowen 1998; Pereyra et al. 2004; García-Rodríguez et al. 2011). However, otolith studies show promise for evaluating regional and age characteristics (Félix-Uraga et al. 2004, 2005; Valle and Herzka 2008; Javor et al. 2011; Dorval et al. 2011; Javor and Dorval, submitted).

Spawning seasons of sardine have regional features. The warm (Gulf) stock spawns during the late fall and winter in the Gulf of California while the southern (temperate) stock spawns during the summer in Bahía Magdalena (Smith 2005). The northern stock spawns principally in southern and central California during the early spring (Lo et al. 2005), although migrating adults can spawn in the summer in the Pacific Northwest (Emmett et al. 2005; Lo et al. 2010). Prior to the mid-1990s, the northern stock also regularly spawned near shore in southern California during the summer (SWFSC and CalCOFI data; Andrew Thompson, pers. comm., 29 March 2013).

The spawning off California is probably the source of many of the juveniles commercially caught near San Diego (southern California) and Monterey (central California). It is generally believed sardine recruit to the offshore California stock upon reaching maturity. Although juveniles from both locales are considered members of the same stock, otolith morphology (Javor et al. 2011) and oxygen stable isotope composition (Javor and Dorval, submitted) indicate they have distinct regional characteristics, at least until they reach maturity.

Since Campana and Casselman 1993 showed Atlantic cod (*Gadus morhua*) growth rates significantly correlated with otolith shape, morphometric analysis of otoliths has been widely used as a tool to detect stock structure and interannual variability in fish. Genetic, physiological, and environmental factors control otolith shape. Fast growth rates are associated with smaller otolith sizes relative to fish length in a number of species (Fletcher 1995; Strelcheck et al. 2003; Kristoffersen 2007). Feeding condition may affect both growth and otolith morphology (Gagliano and McCormick 2004; Hüssy 2008). Temperature influenced otolith size in tank-reared fish (Høie et al. 1999), and it likely regulates otolith growth in natural populations of *Merluccius* spp. and *Coelorhynchus* spp. (Lombarte and Lleonart 1993; Bolles and Begg 2000).

A combination of otolith morphology and weight, termed perimeter-weight profiles or PWP, described regional phenotypes in Pacific sardine juveniles (Javor et al. 2011). Otoliths from southern stock captured off Baja California tended to be more rugose and lighter than otoliths of sardine from northern stock caught near Monterey that typically had smoother perimeters and heavier weights. Otoliths from juveniles captured near San Diego generally had an intermediate mixture of PWP features.

Another characteristic of otoliths that indicates regional environmental conditions is oxygen stable isotope content. It provides a proxy for seawater temperature because fish deposit ^{18}O in their calcium carbonate otoliths in or near thermodynamic isotopic equilibrium with their environment (Kalish 1991; Iacumin et al. 1992; Thorrold et al. 1997; Campana 1999). Otolith stable isotope analyses have been used to distinguish stocks of Australian *S. sagax* (Edmonds and Fletcher 1997), and to identify habitat temperatures of fish at different life stages (Gao and Beamish 2003; Gao et al. 2004; Shephard et al. 2007) or seasons (Weidman and Millner 2000; Begg and Weidman 2001; Gao et al. 2001; Høie and Folkvord 2006).

Pacific sardine inhabit a broad temperature range of water, from <10˚C in Oregon and Washington (Emmett et al. 2005) to >25˚C in southern Baja California (Félix-Uraga et al. 2004, 2005). Dorval et al. 2011 experimentally derived a $\delta^{18}O$-temperature calibration model for sardine otoliths in southern California. Javor and Dorval (submitted) applied those equations to a study of young and adult sardine off North America, from Canada to Mexico, that demonstrated: 1) $\delta^{18}O$ values reflected seawater $H_2{}^{18}O$ content and temperature of the region of juvenile capture; and 2) the results depended on the size of the otoliths because young sardine apparently spent progressively more time at depth (i.e., in colder water) as they grew to adulthood.

The overall goal of this survey conducted during 2006–12 was to test methods by which Pacific sardine otoliths could be used to enhance knowledge of the species and aid stock assessment and fishery management. Using otoliths of juveniles collected over 600 km apart off California (San Diego and Monterey), the study focused on significant long-term changes that commenced in mid-2008. The specific research aims were to compare morphological characteristics of otoliths of young and adult sardine using five approaches: 1) Time: seven-year study to evaluate temporal trends in juvenile otolith morphology 2) Temperature: stable oxygen isotope composition to determine the relationships between morphology, temperature, and date of capture 3) Relative abundance of rugose-light and smooth-heavy otoliths among young and mature sardine 4) Relationships to spawning condition, standard length, and growth rates 5) Correlation with an independently-derived population index, spawning stock biomass. Finally, these otoliths were compared with those of sardine landed off Mexico to demonstrate possible shifts in stock parentage of the juveniles caught off California.

MATERIALS AND METHODS

Sardine collections and measurements

Sardine were collected from a live bait receiver in Mission Bay, San Diego, CA (Everingham Brothers), from Monterey Bay, CA (California Department of Fish and Game port samples), and from annual SWFSC surveys during April along the central and southern California coast. During the course of this investigation, the SWFSC also conducted two summer surveys (2008 and 2012) between British Columbia, Canada, and the United States-Mexican border. Sample sizes were 25 fish per haul for the San Diego and Monterey samples, and 25–40 fish per haul for the SWFSC surveys. To compare whole fish attributes (length and condition factor), all fish captured in the survey cruises were evaluated. Otolith collectors, samples, and measurements were previously described for sardine caught off Mexico (Javor et al. 2011). Ages were determined using Yaremko's 1996 method. Condition factor (CF) was calculated by dividing fish weight (g) by the cube of the SL (cm), and multiplying the result by 100. CF, a measure of robustness of a fish, is generally known to be influenced by age, sex, maturation, season, and fat content.

The live bait supplier reported larger adults were sometimes found near shore in shallow water, but the seiners generally avoided catching them for the live bait market. The seiners typically captured sardine within a few km of shore when the fish were easy to find, but they fished as far as 50 km from shore when necessary. The supplier reported extensive bait schools sometimes aggregated in San Diego; for example, 5 km long schools spanning from just outside the surf zone to about 15 m depth water. Such schools were transient, and the site, size, and hour of the aggregations changed. Everingham Brothers has been in business over 60 years, and they have developed fishing logistics predicated by when sardine form near-surface aggregations conducive for day or night seining (Buck Everingham, pers. comm., 13 August 2012).

During 2008–12, the sardine fishery in Monterey Bay was limited to summer months due to quotas. During 2012, sardine were not available for this study. Most of the fishing took place in the bay or close to it.

Fishery-independent SWFSC surveys do not target schools of sardine. Instead of seining, they trawl at night at specific stations using protocols to provide statistically representative catch data that can be incorporated into stock assessment calculations (Hill et al. 2010, 2011, 2012; Lo et al. 2011; www.calcofi.org, accessed 14 February 2013).

During 2004, 65% of the sardine captured in the SWFSC survey measured ≥240 mm, but in the 2005–12 surveys, only 1%–5% of the sardine measured ≥240 mm (Hill et al. 2012; SWFSC unpublished cruise data). Except for age-0 sardine captured in a few trawls, nearly all the sardine caught in spring surveys were in near-spawning or spawning condition (testes scored 2 or 3 on a maturation scale of 3, and ovaries scored 3 or 4 on a maturation scale of 4).

Otolith measurements

Otoliths were cleaned, aged, weighed, photographed, and processed through an image analysis protocol that resulted in a description termed perimeter-weight profile (Javor et al. 2011). Using >2200 *S. sagax* otoliths collected across their North American range, linear regression equations were derived for pairs of otolith measurements that compared perimeter vs. area, perimeter vs. length, and weight vs. length. The PWP calculation for a sample otolith compares the measured feature to that of the average otolith represented on the regression lines, resulting in positive or negative perimeter and weight residuals. The three PWP values are expressed as the percentage of positive residuals in the sample. A score of 50% is average for the population (half the residuals above the line and half below it).

Javor et al. 2011 found sardine otoliths from their southernmost range off Mexico and within the Gulf of California had generally greater perimeters than the population average because they were more rugose (multilobed), and they were typically light in weight. Otoliths from Monterey Bay had generally smaller perimeters (relatively smooth outlines) and were typically heavier than the population average. Because the perimeter and weight features of the PWP together were descriptive of these regional subpopulations, this report also compares sets of otoliths simultaneously by both perimeter (based on length) and weight (based on length) residuals. Type-1 (rugose-light) is defined by positive perimeter and negative weight residuals. Type-2 (smooth-heavy) is defined by negative perimeter and positive weight residuals.

Stable oxygen isotope analysis

Protocols for cleaning otoliths and measurement of $\delta^{18}O$ followed Dorval et al. 2011 and Javor and Dorval (submitted). Briefly, otoliths were cleaned in 2% sodium dodecyl sulfate, washed with Milli-Q® water (MQ-water), treated for 3–5 min in 30% hydrogen peroxide, and washed with multiple rinses of MQ-water. Because $\delta^{18}O$ in juvenile sardine otoliths from a region changes with growth (Javor and Dorval, submitted), the range of weights within each sample set selected for comparison was narrow to mitigate size bias (maximum difference of 0.2 mg). Isotope analyses were conducted on a triple collector gas ratio mass spectrometer (VG Prism) at the University of Southern California. Ultiss reference standards, calibrated to the Vienna Pee Dee Belemnite standard (NBS-19), were run before, between sample blocks, and after each daily set. The average precision was ±0.07‰ (standard deviation, sd) estimated from the Ultiss reference measurements. The raw data were corrected and reported relative to the Pee Dee Belemnite reference standard. Temperature was calculated according to Dorval et al. 2011 based on the composition of seawater near San Diego:

$$\delta^{18}O_{otolith}\ (‰) - \delta^{18}O_{water}\ (‰) = (-0.132 \times \text{Temperature }^{\circ}\text{C}) + 2.455.$$

Calculations and statistics

PWP values were determined from the equations of Javor et al. 2011. Data were compared by linear regressions, two-tailed Student's *t* tests with equal variance, two-way ANOVA, and correlation analysis.

RESULTS

Distributions of type-1 and type-2 otoliths in juveniles

Monthly collections of nearshore sardine captured for the live bait market in San Diego during 2006–12 consisted of immature specimens with a maximum standard length (SL) close to 180 mm (fig. 2). They were mostly age-0 to age-2, with occasional age-3 fish. In some years, evidence of growth in the local population was apparent from the steady month-to-month increase in length. The CF of the juvenile sardine always increased during summer, but the gonads of these young fish were never observed to be close to spawning condition.

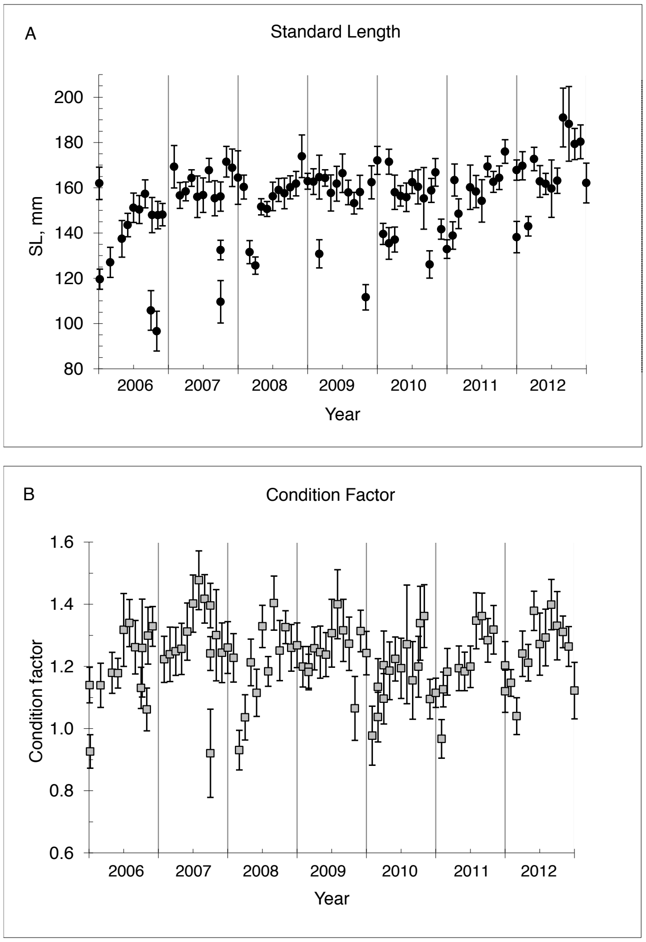

Figure 2. *S. sagax* collected near San Diego, CA, 2006–12. 2A: Standard length ± sd. 2B: Condition factor ± sd.

The average (± sd) SL and CF of sardine captured in Monterey during 2009–11 (170 ± 15 mm and 1.35 ± 0.11, respectively; $n = 548$) were similar to those of live bait caught in San Diego during the same months of capture (160 ± 11 mm and 1.29 ± 0.13, respectively; $n = 175$). For sardine captured in the 2008 summer SWFSC survey, the mean SL was 205 ± 23 mm, and the mean CF was 1.27 ± 0.14 ($n = 901$). This CF value overlapped that of the juveniles captured in the summer near San Diego and Monterey during the course of this study.

During 2006–12, monthly PWP values of otoliths from age-0 to age-2 sardine captured near San Diego showed a distinct change beginning July 2008 (fig. 3A). From 2006 through June 2008, on average there was a nearly equivalent distribution of type-1 (21% of the total) and type-2 (24% of the total) otoliths, with no significant prevalence of one type over the other (two-

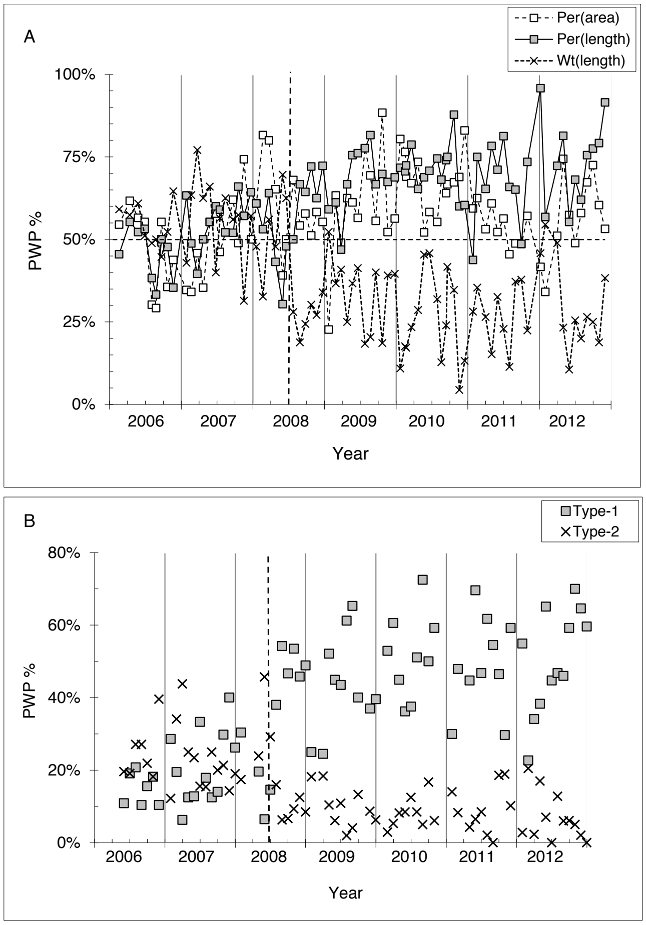

Figure 3. PWPs of *S. sagax* otoliths caught near San Diego. 3A: Monthly perimeter (based on area or length) and weight (based on length) profiles. 3B: Monthly profiles of two features together representing type-1 and type-2 otoliths (described in Materials and Methods).

tailed *t* test, $p = 0.0416$, $n = 23$). From July 2008 through 2012, type-1 otoliths (49% of the total) dominated over type-2 (9% of the total), a significant difference ($p < 0.0000$, $n = 44$) (fig. 3B). There was no significant difference between the two ways to assess the perimeter profile (vs. area or length) before July 2008 ($p = 0.8439$, $n = 27$), but after that date, the PWP values for the two ways to assess the perimeter were not similar ($p = 0.0001$, $n = 48$; data not shown). In other words, more than one geometric dimension of the otoliths changed. Seasonal migration patterns among fish with type-1 and type-2 otoliths were not apparent. A two-way ANOVA test of the ratio of type-1 to type-2 otoliths, sorted by time period (before and after July 2008) and season (January–April and July–November), showed no significant seasonal effects within each time period ($p = 0.4400$, $n = 60$; data not shown).

Comparisons of average annual PWP values of juveniles caught off Monterey showed similar temporal trends (data not shown). The most pronounced shift was the decline in PWP-weight which steadily decreased from 68% in 2007 down to 20% in 2011. During the same period, PWP-perimeter (based on length) increased from 20% to 46%. PWP values for 1996–97 were similar to those for 2006–07.

Relationships of otolith morphology to temperature in juveniles

If the shift in dominant otolith morphologies in immature sardine in 2008 resulted from the immigration of southern stock from Mexico, it might follow that this stock preferred warmer temperatures. The question of whether temperature covaries with otolith morphology in sardine, or whether it might be an indicator of immigrant stock, was tested with our San Diego and Monterey collections of juvenile otoliths by the measurement of oxygen stable isotopes.

The variations in temperatures calculated from $\delta^{18}O$ composition between sample sets of San Diego otoliths of similar weight were compared across survey dates and PWP type. There was no significant difference in temperatures between type-1 and type-2 otoliths for samples collected before July 2008 (fig. 4 and table 1A). Likewise, there was no significant difference between temperatures of the two morphotypes in samples collected after June 2008. However, there was a significant difference in average temperatures for both otolith types between the two time periods, 13.6°–14.6°C and 15.7°–16.0°C, respectively, or about 2°C warmer after mid-2008.

The Monterey collection was tested to compare type-1 and type-2 otoliths in three periods: 1996–97, 2008, and 2009. The otolith weights were similar within each collection period, but different between the sampling years which prevented the interannual comparison of calculated temperatures between sardine of equivalent size. Within each collection period, there were no significant differences in temperatures between otolith types (table 1B). As expected, the small juvenile sardine (2008) recorded warmer temperatures (16.2°–17.4°C) than the older fish (11.0°–12.9°C). These results indicate there likely was no direct effect of temperature on otolith morphology in sardine.

Immature vs. mature sardine

If the post-2008 population of adults recruited predominantly from local juveniles, there should have been an increase in abundance of type-1 otoliths in the mature population if: 1) there was no bias in mortality; and 2) PWP morphology did not change with maturity. No evidence of a shift in type-1 or type-2 otoliths was detected when adult otoliths were compared in five different years between 2004 and 2012, i.e., all the trawls had similar mixes of the two morphological types of otoliths (fig. 5). For this figure, all three PWP criteria were assessed to define type-1 and type-2 otoliths to increase stringency of the evaluation (perimeter based on both area and length, and weight based on length). The *t*-test *p* values of type-1 vs. type-2 abundance ranged within years from 0.905 in 2004, to 0.082 in 2009, and overall for all five years was 0.980. Only one trawl out of the 43 examined in the five years of sampling captured a group of sardine with an otolith PWP resembling a type-1 profile.

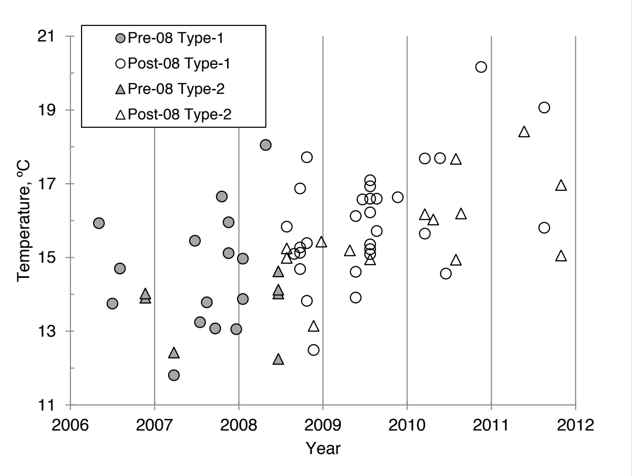

Figure 4. Calculated temperatures of otoliths from juvenile *S. sagax* captured near San Diego before July 2008 (Pre-08) and after June 2008 (Post-08). Otoliths were separated by type-1 and type-2 PWPs as described in the text. Supporting data are in table 1A.

Spawning condition, SL, and growth rates

If type-1 and type-2 otoliths are genetically associated with southern and northern stock, respectively, the season of spawning might be different for the two types. To test this theory, otoliths from the 2012 spring survey (fig. 5) were sorted by fish sex and maturity, and identified as type-1 and type-2 by the three PWP criteria. Among the mature males, 20% and 23% had type-1 and type-2 otoliths, respectively ($n = 156$). Among the mature females, 24% and 28% had type-1 and type-2 otoliths, respectively ($n = 114$). The overall averages were similar for those spring trawls, regardless of sex and maturity: 21% type-1 otoliths, and 26% type-2.

Otoliths continue to accrete calcium carbonate when fish growth slows with maturity, and when environmental conditions inhibit growth. Comparison of the slopes of linear regressions of fish standard length (x) and otolith weight (y) provides a relative estimate of fish growth rate in the population, and the associated coefficients of determination (R^2) describe the relative composition of slow-growing and fast-growing sardine. Juveniles col-

TABLE 1

Comparisons of calculated temperatures and statistical significance of temperature–otolith morphology relationships over time in *S. sagax* captured near San Diego and Monterey. Otoliths were separated as type-1 or type-2 based on PWP parameters. Significance level was determined as $p < 0.01$. 1A: San Diego. Pre-July 2008 (Pre-08) and post-June 2008 (Post-08) data are also depicted in fig. 4. 1B: Monterey. Because of the differences in otolith weight between sample years, interannual comparisons were not calculated.

A. San Diego

Otolith type and date	°C, avg	°C, ± sd	*n*	Wt, mg	Wt, ± sd
Type-1, Pre-08	14.6	1.6	15	1.078	0.062
Type-2, Pre-08	13.6	0.9	7	1.128	0.071
Type-1, Post-08	16.0	1.5	31	1.075	0.068
Type-2, Post-08	15.7	1.3	14	1.129	0.072

2-Tailed *t*-tests	*p*	Significance
Pre-08, Type-1 vs. Type-2	0.147	–
Post-08, Type-1 vs. Type-2	0.608	–
Type-1, Pre-08 vs. Post-08	0.001	+
Type-2, Pre-08 vs. Post-08	0.008	+

B. Monterey

Otolith type and date	°C, avg	°C, ± sd	*n*	Wt, mg	Wt, ± sd
Type-1 1996-97	12.9	1.0	7	1.565	0.075
Type-2 1996-97	12.2	1.6	8	1.570	0.065
Type-1 2008	16.2	1.2	8	0.538	0.043
Type-2 2008	17.4	1.3	10	0.507	0.042
Type-1 2009	11.0	1.1	8	1.423	0.034
Type-2 2009	12.0	1.2	7	1.362	0.090

2-Tailed *t*-tests	*p*	Significance
1996–97, Type-1 vs. Type-2	0.334	–
2008, Type-1 vs. Type-2	0.062	–
2009, Type-1 vs. Type-2	0.122	–

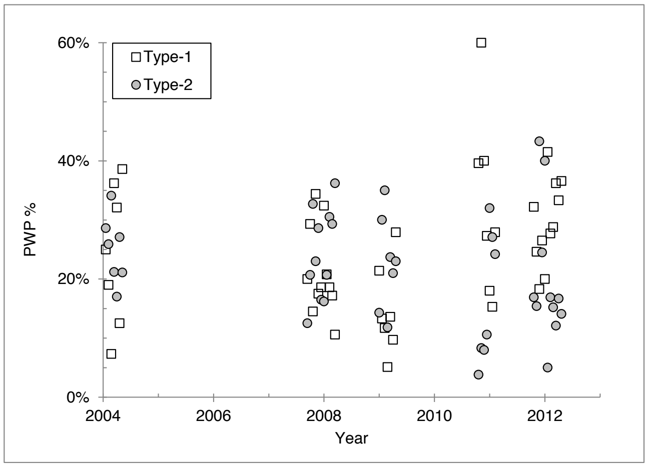

Figure 5. PWPs from annual SWFSC surveys of adult *S. sagax*. Each trawl is depicted with one type-1 and one type-2 point. The points are staggered within each year to facilitate visualization.

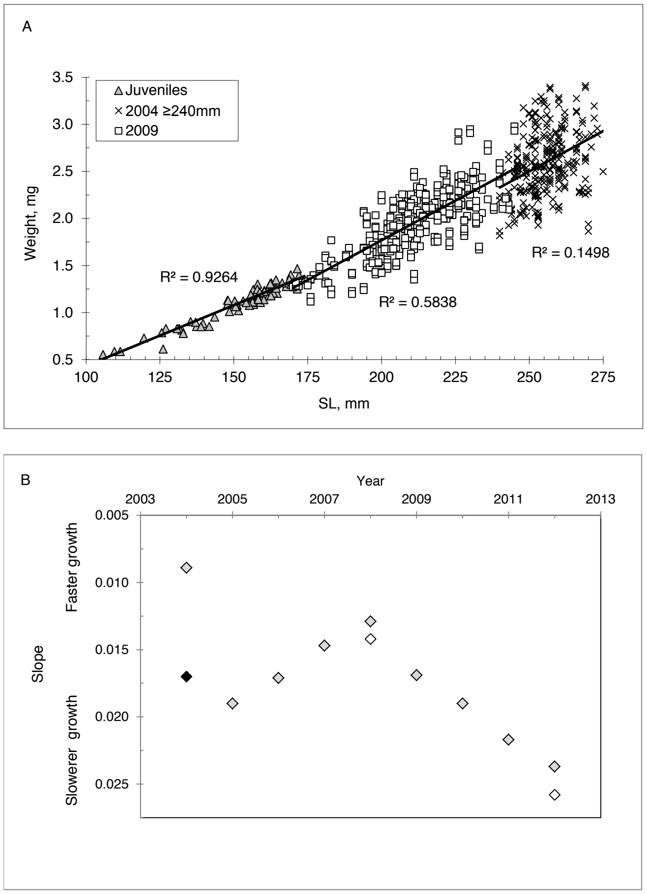

Figure 6. Standard length vs. otolith weight for *S. sagax*. 6A: Relationships for juveniles captured near San Diego in 2006–11, adults ≥240 mm captured in 2004, and sardine from the 2009 survey. R² values are noted on the figure. 6B: Relationships between year of capture and the slope of the linear regression of SL (*x*) vs. otolith weight (*y*). Shaded symbols are from spring surveys and open symbols are from summer surveys. The black symbol represents the slope from sardine ≥240 mm SL. The other slopes were derived from sardine measuring 190–230 mm. Supporting data are in table 2.

TABLE 2

Slopes and R² values derived from the linear regression of SL (mm, *x*) and otolith weight (mg, *y*) for mature *S. sagax* (190–230 mm SL except where noted) captured in spring (2004–12) and in two summer SWFSC surveys where noted. The number of otoliths (*n*) is indicated. The slope data vs. year are depicted in fig. 6.

Year	Slope, m mg/mm	R²	*n*	SL, avg	SL, sd	Notes
2004	0.0170	0.1488	263	255	8	>230 mm
2004	0.0089	0.1441	89	215	11	
2005	0.0190	0.8359	156	200	31	
2006	0.0171	0.6229	297	197	16	
2007	0.0147	0.5088	281	202	15	
2008	0.0129	0.6035	274	207	17	
2008	0.0142	0.6025	265	207	17	summer
2009	0.0169	0.5838	417	211	15	
2010	0.0190	0.5416	329	221	15	
2011	0.0217	0.8647	406	206	27	
2012	0.0237	0.6623	279	221	18	
2012	0.0258	0.6413	430	221	15	summer

lected near San Diego over 75 months (2006–11) and adults captured in the SWFSC surveys shared similar linear regressions with variable goodness of fit (fig. 6A and table 2). Growth of the juveniles was relatively homogeneous (R² = 0.9264) whereas the collection of sardine ≥240 mm in 2004 comprised such a diverse array of otolith weights (R² = 0.1488) that the actual slope of the relationship between otolith weight and SL was of questionable value as an indicator of growth.

To eliminate differences due to variations in fish size, only sardine measuring 190–230 mm SL were compared. When the slopes of the linear regressions for adult sardine were plotted for the 2004–12 surveys, a distinct change in trend occurred in 2008 (fig. 6B). The slope of the linear regression for the 2004 sardine with its correspondingly poor coefficient of determination did not conform to the pattern. From 2005 to 2008, the California population of mature sardine showed a general increase in growth rate that steadily reversed from 2008 to 2012. The linear regressions of the summer survey samples in 2008 and 2012 corresponded to the results of the spring surveys of those years. These results suggest subtle annual changes in growth attributes that have not been detected by other measurements.

Comparisons of juveniles to spawning stock biomass of mature sardine

Comparable trends in the mature parent stock would support the hypothesis of an overall 2008 shift in population composition. One theory is the dominance of type-1 otoliths among the juveniles after mid-2008 resulted from a decrease in the overall mature northern stock in California in conjunction with the immigration of immature sardine from southern stock where

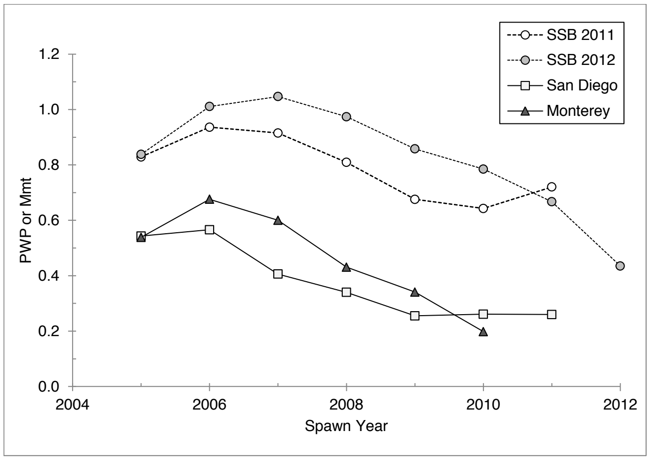

Figure 7. Spawning stock biomass (SSB in million metric tons; Hill et al. 2011, 2012) of *S. sagax* vs. annual average otolith PWP (weight based on length) for age-1 fish captured off San Diego and Monterey. PWP values are plotted for the year the sardine were spawned. Correlation values are in table 3.

TABLE 3

Correlation coefficients for *S. sagax* comparing spawning stock biomass (SSB; Hill et al. 2011) vs. annual average PWP values for otoliths of age-1 sardine captured near San Diego (spawned 2005–11) and Monterey (spawned 2005–10) according to spawn year (fig. 7). Correlation coefficients of the otolith PWP values for the two areas of capture are listed for spawn years 2005–10.

PWP factor	Correlation coefficient San Diego vs. SSB	Monterey vs. SSB
Weight based on length	0.829	0.971
Perimeter based on area	–0.434	–0.384
Perimeter based on length	–0.646	–0.571
	San Diego vs. Monterey	
Weight based on length	0.864	
Perimeter based on area	0.686	
Perimeter based on length	0.795	

type-1 otoliths dominate. This theory was addressed by comparing the average annual PWPs of age-1 sardine captured near San Diego and Monterey with the calculated annual spawning stock biomass of mature sardine in California (Hill et al. 2011, 2012). The trends in otolith morphology correlated with spawning stock biomass for the year the sardine near San Diego and Monterey were born (fig. 7 and table 3). During this survey period, both the biomass and the weight residuals of the otolith PWP measurements generally decreased. The 2011 stock assessment report provided values with excellent correlation coefficients between spawning stock biomass and PWP-weight for San Diego (0.829) and Monterey (0.971) otoliths. PWP perimeter profiles correlated negatively. The 2012 report updated those spawning stock biomass estimates, and correlation coefficients with San Diego (0.542) and Monterey (0.773) otolith PWP-weight were somewhat lower.

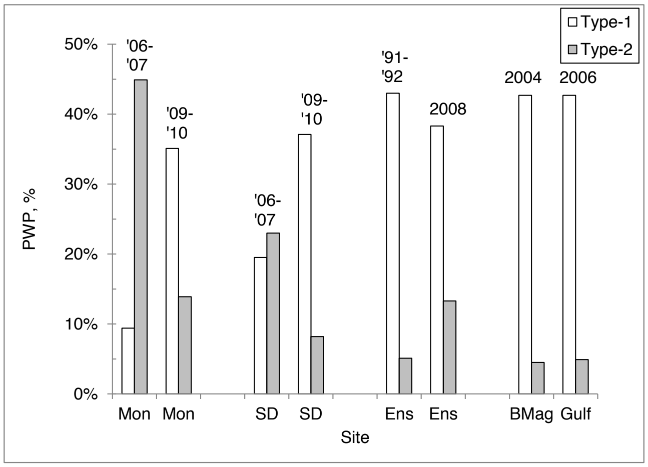

Figure 8. Comparisons of type-1 and type-2 otoliths of *S. sagax* to show the pre- and post-2008 differences in sardine captured near Monterey and San Diego. Number (*n*) of otoliths: Monterey (Mon), 2006–07 (*822*), 2009–10 (*887*); San Diego (SD), 2006–07 (*847*), 2009–10 (*918*); Ensenada (Ens), 1991–92 (*158*), 2008 (*120*); Bahía Magdalena (BMag), 2004 (*89*); and Gulf of California (Gulf), 2006 (*328*). Data for the Mexican otoliths and 2006–07 California otoliths are from Javor et al. 2011.

DISCUSSION

Distributions of type-1 and type-2 otoliths in juveniles

Customary methods of evaluating sardine stock from live bait and port samples (length, weight, condition factor, and age) between 2006 and 2012 revealed only typical annual fluctuations in young sardine captured near San Diego and Monterey. A more detailed assessment of otoliths incorporating weight and morphological measurements using PWP analysis demonstrated long-term shifts in the two California subpopulations, beginning in July 2008. The primary change was the increase and persistent residence of sardine with otolith PWP values similar to those caught in warmer waters off Baja California (fig. 8). At the time this study ended in 2012, the PWP values of San Diego sardine otoliths had not significantly changed since mid-2008, i.e., a large proportion of juveniles with type-1 otoliths remained in the region previously occupied by sardine represented by an approximately equal mixture of type-1 and type-2 otoliths (Javor et al. 2011). The change in ratios of type-1 and type-2 otoliths in juveniles caught near Monterey during the same period was similar to that of San Diego sardine.

Using PWP parameters, there was no evidence of reversing, seasonal north-south migrations of young sardine as previously reported for Baja California and southern California stocks during 1981–2002 that were based on SL, SST temperature at catch, and otolith length and width (Félix-Uraga et al. 2004, 2005; Smith 2005). The finding of the present study does not necessarily contradict the conclusions of the previous investigations, but it does imply the methods of our study may detect different phenomena. The timing of the shift in otolith morphologies between June and July 2008 is consistent with the migration model those authors proposed.

Relationship of otolith morphology to temperature in juveniles

There was no correlation between temperature and otolith morphology in immature sardine as Javor et al. 2011 proposed. In juveniles caught near San Diego after mid-2008, both type-1 and type-2 otoliths recorded $\delta^{18}O$ values that corresponded to water temperatures about 2˚C warmer than in 2006 to early 2008. The most likely explanation for the change in temperatures is the juveniles controlled their thermal environment by the amount of time they spent at depth (Javor and Dorval, submitted). Sardine typically remain at about 15–35 m depth during daylight hours, and at the surface at night to follow and feed on plankton (van der Lingen et al. 2006; Cutter and Demer 2008). In 1995–2003, cohorts of age-1, southern California sardine recorded similar temperatures to those found in the present study, with mean temperature values varying up to 2˚C from year to year (Dorval et al. 2011). They averaged between seawater temperatures at 0 m and 30 m depth in the Southern California Bight.

In the present study, a 2˚C increase was consistent with an increase in the population of juveniles with type-1 otoliths if they came from southern stock migrants. Because sardine school, it is possible the majority of the juveniles with type-1 otoliths preferred warmer waters, and minority northern stock sardine (with a relatively higher proportion of type-2 otoliths) remained schooled with them. The present study also confirmed the correlation between increasing otolith size and cooler temperatures recorded in immature sardine as determined in the juveniles caught near Monterey (Javor and Dorval, submitted).

Immature vs. mature otolith PWPs, and relationships to spawning condition, SL, and growth rates

The lack of a shift in otolith phenotypes among the adult population off California and the Pacific Northwest in 2009–12 poses a problem: Where did the juvenile sardine with type-1 otoliths go after mid-2008? Did they join the offshore spawning stock and reach sexual maturity during the spring? Did their otoliths change morphology?

A comparison of the adult sexual maturity index with otolith PWP values showed no bias against sardine with type-1 otoliths, i.e., nearly all the adults were sexually mature or nearly mature. One theory to explain the lack of increase of sardine with type-1 otoliths among the spawning stock during 2009–12 is greater mortality in cooler northern waters. If they had emigrated from warmer southern waters, this conclusion would be consistent with separation into regional races based on temperature.

Another hypothesis is the otoliths changed morphology with growth. In tank-reared sardine originally collected as juveniles in 2005, otoliths in the fish that survived a year at 13˚C or 21˚C both had relatively smoother and heavier profiles (type-2 morphology) at the end of the experiment (Dorval et al. 2011). Area-based perimeter values decreased from 63% at collection (*n* = 49) to 12%–21% (*n* = 57–109); length-based perimeter values changed from 49% to 14%–44%; and length-based weight values increased from 51% to 73%–91% (the author's unpublished data). Otoliths of the fish that died during the experiment were not monitored to determine whether sardine with type-1 otoliths had higher mortality. Dorval et al. 2011 concluded the changes in morphology were likely to be artifacts of culture conditions. In light of the apparent disappearance of type-1 otoliths from juvenile to mature stages of sardine off California after mid-2008, the changes observed in tank-reared sardine may not have been artifacts. The shift in PWP profiles with maturity may have occurred in nature as well.

The relationship between otolith weight and standard length of mature sardine surveyed off California that shifted in 2008 represents the increasing presence of slower-growing sardine among the adults. The timing of the change was consistent with PWP shifts in regional juveniles.

To our knowledge, otolith weight–SL relationships in long-term population studies of adult fish have not been tracked as proxies for average annual growth rates. Kristofferson 2007 conducted a similar investigation with adult Müeller's pearlside, *Maurolicus muelleri*, comparing relative growth rates of fish from different fjords and the Norwegian Sea, but only within single year collections. A study of Australian pilchards (*Sardinops sagax neopilchardus*) comparing monthly samples over a period of five years focused on assessing otolith weight–age relationships, not relative growth rates (Fletcher 1995). A re-examination of those data for otolith weight–SL relationships would provide corroborating evidence for Pacific sardine (*S. sagax caerulea*), a different subspecies from the West Coast of North America.

Age vs. fish length indices for Pacific sardine have been described, including one for the 2003–04 North American population (Lo et al. 2011). The data have statistical significance because of the large sample size (*n* = 4349 fish), but the regression curve is not very practical as a guide to ageing sardine. The curve becomes asymptotic at three to five years of age, so a 220 mm fish might be three years old or it might be fifteen. Age-1 fish range from less than 100 mm in length to nearly 230 mm, while age-2 fish may reach 240 mm. In addition, aging has a high degree of subjectivity between otolith readers (Hill et al. 2011; Dorval et al. submitted).

By contrast, linear regressions of otolith weight vs. fish length are precise indices that can provide year-to-year assessments of relative growth. Although not evaluated in the present study, otolith weights could be compared to ages as a corroborating factor to describe annual stock characteristics.

Comparisons of juveniles to spawning stock biomass of mature sardine

Did shifts in otolith morphology of immature Pacific sardine captured off California reflect changing parentage from northern and southern stocks? The parallel decrease in PWP-weight of juvenile otoliths and the spawning stock biomass off California during 2006–12 may have been fortuitous. However, the high correlation coefficients support the hypothesis that young sardine with predominantly lighter-weight, type-1 otoliths from southern or temperate stock became proportionately more abundant as the northern population, with a higher proportion of heavier, type-2 otoliths, diminished. In the same period, there was a general decrease in daily egg production and sardine larvae measured during the spring cruises (Lo et al. 2011; SWFSC CalCOFI data). The estimate of the spawning stock biomass incorporates these and other factors into the assessment model which in turn may be updated from year to year (Hill et al. 2010, 2011, 2012). For this reason, the PWP-weight profile correlated with the multiyear spawning stock biomass values presented in the 2011 report better than the estimates presented in the 2012 report. However, no matter which year's assessment model is compared for this period, the overall trend of decreasing northern stock remains.

Why did the juvenile population shift?

Based on maximum landings and SST, Félix-Uraga et al. 2005 presented a model in which the northern stock migrates as far south as northern Baja California in the cooler months where their range overlaps with the southern, temperate stock that largely resides on the Pacific Coast of Baja California. Temperate-stock sardine migrate northward to southern California in the summer months, and as far south as Bahía Magdalena in the cooler months where they overlap with the range of the warm, Gulf stock. Further evidence from environmental modeling (Zwolinski et al. 2011) and acoustic-trawl surveys (Demer et al. 2012) supports this model. The data of the present study suggest the fidelity of the stocks may not be that strict. Instead, northern and southern stocks may intermix off southern and central California with evidence of parentage recorded in juvenile otoliths.

The distance young sardine migrate is not known with certainty. It is linked to fish size and the bioenergetic costs of long-distance swimming (Nøttestad et al. 1999; Lo et al. 2011). Sardine with type-1 otoliths that first appeared in San Diego in July 2008 were relatively mature juveniles (160 mm average SL, and a mixture of age-1 and age-2 fish). If they were spawned in Mexico, how far did they swim and over what period of time? Mature adults in the summer migrations to the Pacific Northwest from southern and central California are greater than 200 mm SL (Lo et al. 2011).

Temperature changes in the California Current could have triggered the juvenile population shift in mid-2008. A warm, El Niño event occurred in 2009–10, between cooler La Niña conditions in 2007–08 and 2010–11 (ggweather.com/enso.oni.htm; accessed 29 May 2013). Therefore an incursion of warm, El Niño seawater did not accompany an initial 2008 northward migration and residence of temperate, southern juvenile stock in California.

Alternatively, the shift in the juvenile population may be coupled with the presently cold oceanographic regime of the Pacific Decadal Oscillation (PDO) cycle in the California Current (Zwolinski and Demer 2012). Since 2008, the PDO index has been negative following warm years from the mid-1970s to mid-1998, a cool phase during 1998–02, and a warm phase during 2002–05 (http://www.nwfsc.noaa.gov/research/divisions/fe/estuarine/oeip/ca-pdo.cfm; accessed 29 May 2013). Coinciding with the shift in the PDO cycle, since 2008 there has been very limited spawning success of sardine off the Pacific Northwest (unpublished proceedings of the Trinational Sardine Forum http://swfsc.noaa.gov/textblock.aspx?Division=FRD&id=18002; accessed 29 May 2013). The success of each annual spawn is dependent on food availability for larval and juvenile sardine. The timing, abundance, and composition of spring phytoplankton blooms in the western North Pacific Ocean during 2001–09 correlated with the springtime PDO index (Chiba et al. 2012) and are probably similarly linked in the California Current ecosystem. Limited or negligible recruitment of northern stock offspring from off northern California and the Pacific Northwest is a likely factor in the diminished representation of juvenile sardine with type-2 otoliths since mid-2008.

The previous decrease in northern stock and collapse of the West Coast sardine fishery in the late 1940s and early 1950s coincided with the latter years of the last major cold PDO cycle (Zwolinski and Demer 2012). Lluch-Belda et al. 1991 theorized that fluctuations of abundance of *S. sagax* along the Pacific Coast follow contraction–expansion patterns: during a cold regime the population contracts toward the south, and during warm periods it expands to the north. The population shifts detected during the 2006–12 study reported here may be a forerunner to further decreases in northern stock if the PDO continues its negative cycle. Commercial exploitation at present levels may also contribute to the decrease in northern stock (Zwolinski and Demer 2012), further opening a niche for immature sardine emigrating from the south.

Alternatively, the shifts in the juvenile population may have occurred in the past independently of PDO cycles (McClatchie 2012) and in the absence of methods such as otolith measurements to recognize the changes. The incursion of southern stock juveniles into California habitat underutilized by diminishing numbers of northern stock juveniles might occur even if the immigrating adults were not fit to reproduce successfully in cooler, northern waters. Data from Mexican surveys would help answer the question of the source of type-1 juvenile otoliths in California sardine, and retrospective analysis of otoliths from previous decades would demonstrate whether the trends noted in this study have a cyclic nature.

SUMMARY

1. During a 2006–12 survey of otoliths from juvenile Pacific sardine caught off California, a long-term shift towards the prevalence of the type-1 phenotype, similar to the phenotype associated with the southern stock off Baja California, began in mid-2008. This finding supports the conclusion that young sardine from Mexico took up residence in a region previously mixed with or dominated by northern stock. A similar geographic shift in otolith phenotypes was not detected in mature adults off California and the Pacific Northwest in 2009–12.
2. Significant differences in temperatures recorded in juvenile otoliths were detected between pre- and post-2008 dates of capture, but not between otolith phenotypes within each time period. After mid-2008, San Diego sardine otoliths of similar size recorded average temperatures about 2°C warmer than those caught before July 2008.
3. Otolith weight–standard length relationships gave a time-course picture of sardine growth rates of mature stock, with a notable shift to slower growth after 2008.
4. The temporal trend of increasing prevalence of type-1 otolith features in immature cohorts in California correlated with generally decreasing annual spawning biomass estimates of the northern stock during 2006–12.
5. Otolith weight and morphological measurements are statistically significant, quantitative means of assessing juvenile and adult sardine population characteristics including relationships to age, standard length, growth rates, stock biomass, and temporal trends in regional perimeter-weight profiles. Measurements of otoliths from immature sardine offer a potentially useful set of variables for forecasting population factors before recruitment to the mature, reproducing population.

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CORRECTED CONVERSION ALGORITHMS FOR THE CALCOFI STATION GRID AND THEIR IMPLEMENTATION IN SEVERAL COMPUTER LANGUAGES

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ABSTRACT

Converting between geographic coordinates in latitude and longitude and the line and station sampling pattern of the California Cooperative Fisheries Investigations (CalCOFI) program is a commonly required task for conducting research on the California Current ecosystem. This note presents several corrections and clarifications to the previously published algorithms for performing these conversions. We include computer code to implement the algorithms in Java™[1], Perl, Python, and R. We note that freely available code to conduct the conversions in Fortran, Matlab®[2], JavaScript™, and Visual Basic®[3] has previously been published, and an online conversion tool is also available. A future version of the PROJ.4 cartographic projections library will also include support for CalCOFI conversions, thereby allowing for convenient conversions using the GRASS GIS, PostGIS, Python, Perl, R, and many other programs and programming languages.

INTRODUCTION

The California Cooperative Fisheries Investigations (CalCOFI) line and station sampling pattern has been used for more than 60 years by the CalCOFI program. The pattern is also currently used by the Investigaciones Mexicanas de la Corriente de California program offshore of Baja California, the California Current Ecosystem Long Term Ecological Research site, and several other research programs in the California Current system. Researchers commonly need to convert between geographic coordinates in latitude and longitude and the CalCOFI line and station sampling pattern to plot their data, merge them with other environmental data, and interpret results. Algorithms for converting from geographic coordinates to CalCOFI line and station grid coordinates, and vice versa, have been published by Eber and Hewitt 1979. However, the article contained a few typographical errors. Some, but not all, of these errors were published as errata by Thombley 2006. Here we list the complete and corrected conversion algorithms for clarity and note changes from Eber and Hewitt 1979. For convenience, we provide computer code that implements these algorithms in Java, Perl, Python, and R. We also list sources of freely available code in Fortran (developed by D. Newton, University of California, Scripps Institution of Oceanography [SIO]), Matlab and JavaScript (developed by R. Thombley, SIO), and Visual Basic (developed by R. Charter, NOAA Southwest Fisheries Science Center). An upcoming release of the PROJ.4 cartographic projection library that will also allow users to easily make CalCOFI conversions in a number of computer programs and languages.

THE CALCOFI STATION SAMPLING PATTERN

The CalCOFI sampling station pattern (fig. 1) consists of a grid rotated –30° off the meridian so that it is approximately normal to the coast offshore of California and Baja California. Cardinal lines are located 120 nm apart and increase in numbering by increments of 10 from northwest to southeast. Ordinal lines are located 40 nm apart along this axis and are numbered by increments of 3.333, which are rounded to the nearest tenth by convention. The station numbering along these lines increases from northeast to southwest (i.e., inshore to offshore) and whole number increments are 4 nm apart. The rotation point is located at 34.15°N, –121.15°W (34°09'N, 121°09'W), which is defined as CalCOFI line 80, station 60. The CalCOFI sampling pattern and its historical evolution are described in greater detail by California Academy of Sciences et al. 1950; i.e., CalCOFI 1950 and Eber and Hewitt 1979. Conversions between the two coordinate systems are accomplished using a Mercator transform and some basic trigonometry. By convention, CalCOFI coordinates are calculated using Clarke's spheroid of 1866.

CONVERSIONS

CalCOFI Line and Station Coordinates to Geographical Coordinates

Conversions are accomplished using the Mercator transform to convert units along the Y-axis from latitude to meridional parts so that positions may be calcu-

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[1] Java™ and JavaScript™ are registered trademarks of Oracle Corporation
[2] Matlab® is a registered trademark of MathWorks, Inc.
[3] Visual Basic® is a registered trademark of Microsoft, Inc.

lated using trigonometry on a plane (cf., Snyder 1987). We follow the notation of Eber and Hewitt 1979 for the Mercator transform and all other equations in this note. The Mercator transform (*MCTR*) is calculated using the following function:

$$(1)\quad MCTR(LA) = \frac{180}{\Pi} * \left(LN\left(tan\left(\frac{\Pi}{\mathbf{180}} * \left(45 + \frac{LA}{2}\right)\right)\right) - \mathbf{0.00676866} * sin\left(\frac{\Pi}{\mathbf{180}} * LA\right)\right),$$

where LA is the latitude to be transformed. This corresponds to the equation on p. 135 of Eber and Hewitt 1979. Differences between the corresponding equations presented by Eber and Hewitt 1979 and in this manuscript are listed in bold type throughout the article. The first change to equation 1 was made because there was a typographical error in the squared eccentricity of the ellipsoid in the original equation, which should read 0.00676866 (Snyder 1987). The second change is a clarification that we have made to all equations. We assume the trigonometric functions (*sin, cos, tan, atan*) operate on units of radians, as they do on most modern computer languages. So we have explicitly added conversions from degrees to radians, and vice versa, where they are needed.

To calculate the geographical coordinates of point *P*, the following algorithm is used corresponding to equations 1–5 at the top of p. 137 of Eber and Hewitt 1987.

$$(2)\quad RLA = \mathbf{34.15} - 0.2 * (PLN - 80) * cos\left(\frac{\Pi}{\mathbf{180}} * 30\right)$$

$$(3)\quad PLA = RLA - \frac{(PSN - 60)}{15} * sin\left(\frac{\Pi}{\mathbf{180}} * 30\right)$$

$$(4)\quad L1 = \left(MCTR(\boldsymbol{PLA}) - MCTR\ (34.15)\right) * tan\left(\frac{\Pi}{\mathbf{180}} * 30\right)$$

$$(5)\quad L2 = \frac{\left(MCTR(RLA) - MCTR\ (PLA)\right)}{\left(cos\left(\frac{\Pi}{\mathbf{180}} * 30\right) * sin\left(\frac{\Pi}{\mathbf{180}} * 30\right)\right)}$$

$$(6)\quad PLO = L1 + L2 + 121.15,$$

where:

PLA = latitude of point *P*, *PLO* = longitude of *P*, *PLN* = line number of *P*, *PSN* = station number of *P*, and *RLA* = latitude of reference point *R* (fig. 1). An assumption of these algorithms is that positions are all located in the northwestern hemisphere. It is usually desirable to express longitude in the western hemisphere either as a negative number or as degrees east of the prime meridian for graphing and analysis, e.g., –121° or 239 rather than 121°W. Thus, equation 6 could be substituted with:

$$(7)\quad PLO = -1 * (L1 + L2 + 121.15),$$

to obtain a negative number or

$$(8)\quad PLO = -1 * (L1 + L2 + 121.15) + 360$$

to obtain a positive number greater than 180°

Geographical Coordinates to CalCOFI Line and Station Coordinates

Converting from geographical coordinates to CalCOFI line and station requires an inverse Mercator transform, which is solved iteratively using the following equation, which corresponds to the algorithm of six steps in the middle of p. 137 of Eber and Hewitt 1979:

$$(9)\quad LA = 2 * \left(atan\left(e^{MCTR\left(\frac{\Pi}{\mathbf{180}} * LA\right) + 0.00676866 * sin\left(\frac{\Pi}{\mathbf{180}} * LA\right)}\right) * \frac{\mathbf{180}}{\mathbf{\Pi}} - 45\right)$$

The initial value of *LA* is set to *MCTR*(*LA*), and three iterations are recommended.

The algorithm for conversion from geographical coordinates to CalCOFI line and station also assumes that longitude is expressed in degrees west of the prime meridian, as described above. If geographical coordinates are expressed as negative numbers or degrees east, the following algorithm should be applied before calculating line and station:

$$(10)\quad \text{If } PLO > 180,\ PLO = (PLO - 360)$$

$$(11)\quad \text{If } PLO < 0,\ PLO = -1 * PLO$$

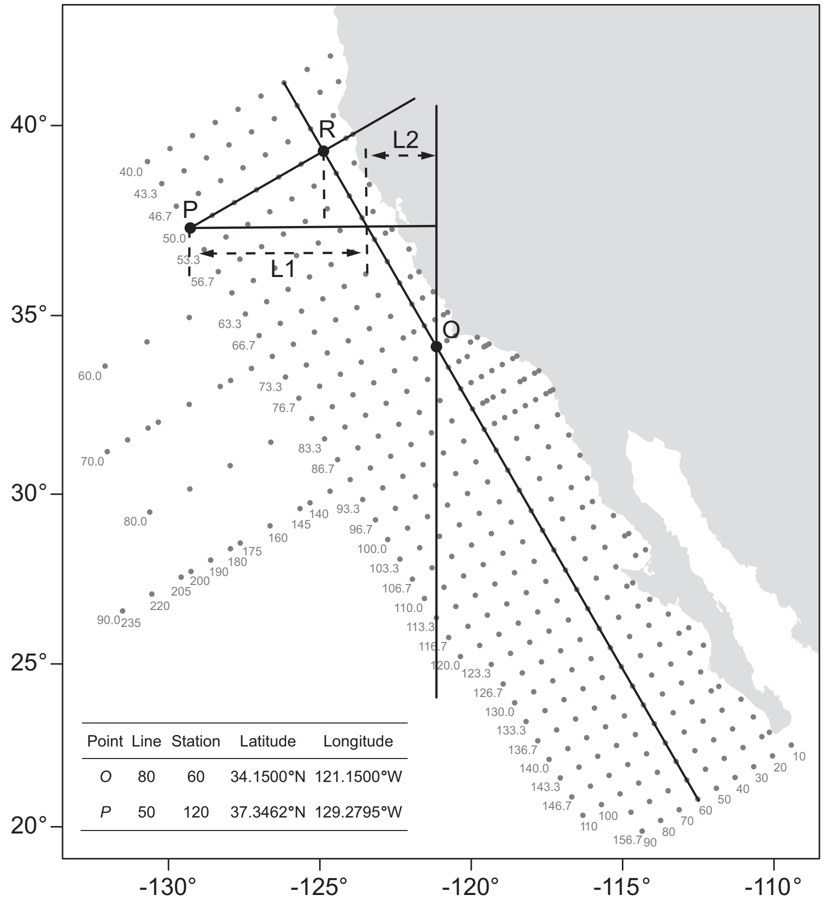
Line and station may then be calculated using the following equations, which correspond to equations 1–6 on lower p. 137 of Eber and Hewitt 1979.

$$(12)\quad L1 = \left(MCTR(PLA) - MCTR\ (34.15)\right) * tan\left(\frac{\Pi}{\mathbf{180}} * 30\right)$$

$$(13)\quad L2 = PLO - L1 - \mathbf{121.15}$$

$$(14)\quad MCTR(RLA) = L2 * cos\left(\frac{\Pi}{\mathbf{180}} * 30\right) * sin\left(\frac{\Pi}{\mathbf{180}} * 30\right) + MCTR(PLA)$$

$$(15)\quad RLA = \text{INVERSE}\left(MCTR(RLA)\right),$$



Point	Line	Station	Latitude	Longitude
O	80	60	34.1500°N	121.1500°W
P	50	120	37.3462°N	129.2795°W

Figure 1. CalCOFI station plan and schematic representation of the geometrical components used for CalCOFI coordinate conversions (after Eber and Hewitt 1979). Point *O* is located at line 80, station 60, 34.15°N, 121.15°W, and is the point about which the CalCOFI sampling grid is rotated –30° off of the meridian. Point *P* is located at line 50, station 120, 129.2795°W, 37.3462°N, and is used as an example for calculations. Reference point *R*, and line segments *L1*, and *L2* are intermediate products used in trigonometric calculations (equations 4–8 and 12–14).

where INVERSE is calculated using three iterations of equation 9.

$$(16)\quad PLN = 80 - (RLA - 34.15) * \frac{5}{cos\left(\frac{\Pi}{\mathbf{180}} * 30\right)}$$

$$(17)\quad PSN = 60 + (RLA - PLA) * \frac{15}{sin\left(\frac{\Pi}{\mathbf{180}} * 30\right)}$$

COMPUTER IMPLEMENTATIONS

We provide the source code for CalCOFI conversions in Java, Perl, Python, and R as appendices I–IV. The code is also available for ftp download from ftp://swfscftp.noaa.gov/users/eweber/calcoficonversions/. These programs are adjusted to accept longitudes *east* of the prime meridian as either positive or negative numbers, e.g., –121° or 239°. Thus, positive numbers less than 180° should not be entered because they would be interpreted as eastern longitudes. For each version, we provide sample conversions from geographic coordinates to CalCOFI coordinates and the inverse conversion at Point *O* (fig. 1), and from CalCOFI coordinates to geographic coordinates and the inverse conversion at point *P*. The conversion algorithm results in small errors, generally in the hundredths of seconds. This is not normally a problem because CalCOFI coordinates are rounded to the nearest tenth of a line and whole station number by convention. However, programmers should be aware that calculating a series of repeated forward and inverse conversions on a point without rounding intermediate results would result in a larger accumulated error. The Python and R code are designed to work with either single-coordinate pairs or arrays of multiple coordinate points. The Java class creates objects that represent a single coordinate, although it could easily be modified to work with arrays.

Java

Objects of the Java class CalcofiCoordConverter hold coordinates as either "longlat" or "calcofi." Coordinates may be retrieved using the "getCoords" method. The current coordinate system may be retrieved using the "getProjection" method. The "reproject" method accepts either "longlat" or "calcofi" as an argument and converts to the appropriate coordinate system. Running the test class with, e.g.,

```
> java TestCalcofiCoordConverter -121.15 34.15 longlat
```

returns:

```
Original coordinates
x -121.15
y 34.15
projection longlat

New coordinates
x 79.99999886102664
y 60.0000059182792
projection calcofi

Backtransformed coordinates
x -121.15000054796204
y 34.15
projection longlat
```

Testing conversion in reverse order at point *P* returns:

```
> java TestCalcofiCoordConverter 50 120 calcofi

Original coordinates
x 50.0
y 120.0
projection calcofi

New coordinates
x -129.2795443042271
y 37.34615242270663
projection longlat

Backtransformed coordinates
x 49.999998777973516
y 120.00000634983587
projection calcofi
```

Perl

The Perl code listed in Appendix II is designed to read input data from a file (coords.in) and write the converted output coordinates (along with the original input coordinate data) to a file (coords.out). The section of the code that begins with "USER-MODIFIED SETTINGS" can be changed to use different filenames and identify the direction of the conversion ("cc2geo" for CalCOFI station grid coordinates to geographic coordinates and "geo2cc" for geographic coordinates to CalCOFI station grid coordinates).

Sample input and output files in comma-separated values format are listed below for conversions in both directions.

Contents for cc2geo_coords.in:

```
LINE,STATION
80.0,60.0
50.0,120.0
```

Contents for cc2geo_coords.out:

```
LINE,STATION,LAT_DD,LON_DD
80.0,60.0,34.1500,-121.1500
50.0,120.0,37.3462,-129.2795
```

Contents for geo2cc_coords.in:

```
LATD,LATM,LATS,LATH,LOND,LONM,LONS,LONH
34,9,0,N,121,9,0,W
34.15,0,0,N,121.15,0,0,W
37,20.7692,0,N,129,16.7727,0,W
```

Contents for geo2cc_coords.out:

```
LATD,LATM,LATS,LATH,LOND,LONM,LONS,LONH,LAT_DD,
LON_DD,LINE,STATION
34,9,0,N,121,9,0,W,34.15,-121.15,80.0000,60.0000
34.15,0,0,N,121.15,0,0,W,34.15,-121.15,80.0000,60.0000
37,20.7692,0,N,129,16.7727,0,W,37.3461533333333,
-129.279545,50.0000,120.0000
```

Python

The Python functions listed in Appendix III perform the conversions on single coordinate pairs as *x* and *y* arguments, or multiple points by entering tuples, lists, or arrays from the numeric python module numpy. The functions always return numpy arrays.

An example of use at point *O*:

```
> line, station = latlontostation(-121.15, 34.15)
> line
79.999998861026384
> station
60.000005918280479
> stationtolatlon(line, station)
array([-121.15000055,   34.15      ])
```

and at point *P*:

```
> lon, lat = stationtolatlon(50, 120)
> lon
-129.27954430422696
> lat
37.346152422706631
>latlontostation(lon, lat)
array([  49.99999878,  120.00000635])
```

Multiple points may be converted equivalently using tuples:

```
> stationtolatlon((80, 50), (60, 120))
```

lists:

```
> stationtolatlon([80, 50], [60, 120])
```

or numpy arrays:

```
> arr = numpy.array((80, 60, 50, 120))
> arr.shape = (2, 2)
> arr
array([[ 80,  60],
       [ 50, 120]])
> stationtolatlon(arr)
```

All three of these examples return:

```
array([[-121.15      ,   34.15      ],
       [-129.2795443 ,   37.34615242]])
```

R

The R functions listed in Appendix IV work similarly:

```
> lineandstation <- latlon.to.station(c(-121.15,
34.15))
> lineandstation
     line  station
[1,]   80 60.00001
> station.to.latlon(lineandstation)
         lon   lat
line -121.15 34.15
```

And:

```
> latlon <- station.to.latlon(c(50, 120))
> latlon
           lon      lat
[1,] -129.2795 37.34615
> latlon.to.station(latlon)
    line station
lon   50     120
```

The R functions will accept matrices of two columns to perform conversions on multiple points at the same time. For example,

```
> mat <- matrix(c(80, 50, 60, 120), 2, 2)
> mat
     [,1] [,2]
[1,]   80   60
[2,]   50  120

> station.to.latlon(mat)
       lon           lat
[1,] -121.1500 34.15000
[2,] -129.2795 37.34615
```

By default, R uses fewer significant digits than Python or Java but this could be adjusted in the R options.

OTHER CODE AND TOOLS TO PERFORM CALCOFI COORDINATE CONVERSIONS

A few other tools and sources of code are freely available to perform CalCOFI coordinate conversions. An online converter tool written in JavaScript by R. Thombley is available from the University of California San Diego, Scripps Institution of Oceanography at http://calcofi.org/field-program/station-information/381-linestaalgorithm.html (accessed 6/5/2013). The page also provides JavaScript code to run the tool locally, and similar Fortran, Matlab, and Visual Basic code to perform CalCOFI coordinate conversions. We note that CalCOFI researchers recognized the typographical errors contained in Eber and Hewitt 1979 shortly after its publication, and corrections were applied to all of the programs mentioned above. However, we are not aware of any other published record of the algorithms with complete corrections.

Another tool that will soon be available for converting to and from the CalCOFI coordinate system is the PROJ.4 cartographic projection library, available at http://trac.osgeo.org/proj/wiki. PROJ.4 is a cross-platform library written in the C language that converts geographic coordinates to and from all commonly used cartographic projections (e.g., Mercator, Robinson, Stereographic, UTM, etc.). The GRASS GIS, PostGIS, MapServer, and many other programs call the PROJ.4 library to handle cartographic projections. It may also be called from the command line, and is used in the geographic libraries of other programming languages such as the pyproj module in Python, the Geo-Proj4 library in Perl, and the rgdal and proj4 packages in R. The senior author has submitted a patch to perform forward and inverse conversions to the CalCOFI coordinate system, which will likely be included in the next release of PROJ.4 (version 4.9). Thus, CalCOFI conversions will be available natively in a number of languages using their existing geographic tools. The PROJ.4 string used to convert to CalCOFI line and station is "**+proj=calcofi +ellps=clrk66**." For the impatient, the patch can be obtained from http://trac.osgeo.org/proj/attachment/ticket/135/calcofi.patch and compiled against the development trunk.

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APPENDIX I. JAVA CLASS FOR CONVERTING CALCOFI COORDINATES AND A TEST CLASS

```
class CalcofiCoordConverter {
   private double[] crds;
   private String proj;

   public CalcofiCoordConverter (double x,
         double y, String projection){
      if (!projection.equals("longlat") &&
         !projection.equals("calcofi")) {
         throw new IllegalArgumentException(
            "projection must be either " +
            "'longlat' or 'calcofi'");
      }
      proj = projection;

      if (proj.equals("longlat") &&
         x > 180.0) x = (x - 360.0) * -1.0;

      crds = new double[2];
      crds[0] = x;
      crds[1] = y;
   }

   public double[] getCoords() {
      return crds;
   }

   public String getProjection() {
      return proj;
   }

   private double toMercator(double lat) {
      double y =
         Math.toDegrees(Math.log(
            Math.tan(Math.toRadians(
            45.0 + lat / 2))) -
            0.00676866 * Math.sin(
            Math.toRadians(lat)));
      return y;
   }

   private double inverseMercator(
         double mercLat) {
      double approxLat = mercLat;
      for (int i = 1; i < 4; i++) {
         approxLat = 2 * (Math.atan(
            Math.exp(Math.toRadians(mercLat) +
            0.00676866 * Math.sin(
            Math.toRadians(approxLat)))) *
            180 / Math.PI - 45);
      }
      return approxLat;
   }

   public void reproject(String projection) {
      if (projection.equals("calcofi") &&
            !proj.equals("calcofi")) {
         double lon = crds[0];
         double lat = crds[1];
         if (lon > 180.0) lon = (
            lon - 360.0) * -1.0;
         // assume pos in the western hemisphere

         if (lon < 0) lon = lon * -1;
         double L1 = (toMercator(lat) -
            toMercator(34.15)) *
            Math.tan(Math.toRadians(30));
         double L2 = lon - L1 - 121.15;
         double mercRefLatitude = L2 *
            Math.cos(Math.toRadians(30)) *
            Math.sin(Math.toRadians(30)) +
            toMercator(lat);
         double refLatitude = inverseMercator(
            mercRefLatitude);
         // line
         crds[0] = 80 - (refLatitude - 34.15) *
            5 / Math.cos(Math.toRadians(30));
         // station
         crds[1] = 60 + (refLatitude - lat) *
            15 / Math.sin(Math.toRadians(30));

      } else if (projection.equals("longlat") &&
            !proj.equals("longlat")) {
         double line = crds[0];
         double station = crds[1];
         double refLatitude = 34.15 - 0.2 *
            (line - 80) * Math.cos(
            Math.toRadians(30));
         double lat = refLatitude -
            (station - 60) * Math.sin(
            Math.toRadians(30)) / 15;
         double L1 = (toMercator(lat) -
            toMercator(34.15)) *
            Math.tan(Math.toRadians(30));
         double L2 = (toMercator(refLatitude) -
            toMercator(lat)) / (Math.cos(
            Math.toRadians(30)) * Math.sin(
            Math.toRadians(30)));
         crds[0] = -1 * (L1 + L2 + 121.15);
         crds[1] = lat;
      }
      proj = projection;
   }
}

public class TestCalcofiCoordConverter {
   public static void main (String[] args) {
      double x = Double.parseDouble(args[0]);
      double y = Double.parseDouble(args[1]);
      String projection = args[2];
      CalcofiCoordConverter crdtest =
         new CalcofiCoordConverter(x, y,
            projection);

      String oldprojection;
      String newprojection;

      // initial projection
      oldprojection = crdtest.getProjection();
      System.out.println("Original coordinates");
      printProjectionInfo(crdtest);

      // do a conversion
      if (oldprojection.equals("calcofi")) {
         newprojection = "longlat";
      } else {
         newprojection = "calcofi";
      }
      crdtest.reproject(newprojection);
      System.out.println("New coordinates");
      printProjectionInfo(crdtest);

      // convert back to original coord. system
      crdtest.reproject(oldprojection);
      System.out.println(
         "Backtransformed coordinates");
      printProjectionInfo(crdtest);
   }

   private static void printProjectionInfo(
         CalcofiCoordConverter crdtest) {
```

```
      double[] coords;
      coords = crdtest.getCoords();
      System.out.println("x " + coords[0]);
      System.out.println("y " + coords[1]);
      System.out.println("projection " +
         crdtest.getProjection());
      System.out.println();
   }
}
```

APPENDIX II. PERL FUNCTIONS FOR CONVERTING CALCOFI COORDINATES

```
#CALCOFI_CONVERSION.PL
#
#This script converts geographic coordinates
#(latitude/longitude) to CalCOFI station grid
#coordinates (line and station numbers) or
#vice versa.
#A conversion flag identifies the direction of
#the conversion.
#
#! /usr/bin/perl -w
#
use strict;

######################## USER-MODIFIED SETTINGS
our $input_fname = "coords.in";
our $output_fname = "coords.out";

#this flag identifies the direction of the
#conversion-a value of "geo2cc" indicates from
#geographic coordinates (latitude/longitude) to
#CalCOFI station grid coordinates;
#-a value of "cc2geo" indicates from CalCOFI
#station grid coordinates to geographic
#coordinates (latitude/longitude).
our $conversion = "geo2cc";
#our $conversion = "cc2geo";
########################

open(INFILE, $input_fname) ||
die "Cannot open INPUT_FILE filehandle: $!\n";
open(OUTFILE, ">" . $output_fname) ||
die "Cannot open OUTPUT_FILE filehandle: $!\n";

if ($conversion eq "geo2cc") {
   print "Converting data in $input_fname from ",
   "geographic coordinates to CalCOFI station ",
   "grid coordinates...\n";
}
if ($conversion eq "cc2geo") {
   print "Converting data in $input_fname from ",
   "CalCOFI station grid coordinates to ",
   "geographic coordinates...\n";
}

print "\nReading data...\n";
our @inputrecs=<INFILE>;
chomp(@inputrecs);
close(INFILE);

#process lat/long data and calculate CalCOFI
#station-line grid coordinates; format other data
#and print all to file
our $m;
our $line;
our $station;
our $latd;
our $latm;
our $lats;
our $lath;
our $lond;
our $lonm;
our $lons;
our $lonh;
our $latdecdeg;
our $londecdeg;

#print header records in output file
if ($conversion eq "geo2cc") {
   print OUTFILE "LATD,LATM,LATS,LATH,LOND,",
   "LONM,LONS,LONH,LAT_DD,LON_DD,LINE,STATION\n";
}
elsif ($conversion eq "cc2geo") {
   print OUTFILE "LINE,STATION,LAT_DD,LON_DD\n";
}
else {
   print "Do not recognize the selected ",
   "conversion! Should be either geo2cc or ",
   "cc2geo. Please correct.\n";
   print "Press any key and program ",
   "will exit...\n";
   our $abort = <STDIN>;
   exit;
}

print "\nProcessing data and writing to output ",
"file...\n";

#skip header record in the input file
for ($m=1; $m<=$#inputrecs; $m++) {
   if ($conversion eq "geo2cc") {
      ($latd,$latm,$lats,$lath,$lond,$lonm,
      $lons,$lonh) = split(/,/, $inputrecs[$m]);

      #get CC line and station numbers
      ($line,$station,$latdecdeg,$londecdeg) =
      &ll2cc($latd,$latm,$lats,$lath,$lond,$lonm,
      $lons,$lonh);

      #round CC line and station numbers to
      #4 decimal places
      $line = sprintf( "%.4f", $line);
      $station = sprintf( "%.4f", $station);

      print OUTFILE "$latd,$latm,$lats,",
      "$lath,$lond,$lonm,$lons,$lonh,",
      "$latdecdeg,$londecdeg,$line,",
      "$station\n";
   }
   if ($conversion eq "cc2geo") {
      ($line,$station) = split(/,/, $inputrecs[$m]);

      #get latitude and longitude values
      ($line,$station,$latdecdeg,$londecdeg) =
      &cc2ll($line,$station);

      #round latitude and longitude to
      #4 decimal places
      $latdecdeg = sprintf( "%.4f", $latdecdeg);
      $londecdeg = sprintf( "%.4f", $londecdeg);

      print OUTFILE "$line,$station,",
      "$latdecdeg,$londecdeg\n";
   }
}

close(OUTFILE);

print "\nConverted data written to $output_fname ...",
"program finished!\n";
```

```
sub ll2cc {
   #Subroutine to implement algorithm that converts
   #lat/long coordinates to CalCOFI grid
   #coordinates (line and station).
   #
   #INPUT: Latitude and longitude values in DMS to
   #be converted to CC grid
   #OUTPUT: A line and station value for CC grid
   #(and signed decimal degrees of latitude and
   #longitude).
   #
   #
   use Math::Trig;

   my $latitude_deg = shift;
   my $latitude_min = shift;
   my $latitude_sec = shift;
   my $latitude_hem = shift;
   my $longitude_deg = shift;
   my $longitude_min = shift;
   my $longitude_sec = shift;
   my $longitude_hem = shift;

   my $latdd = $latitude_deg + ($latitude_min/60.0)
   + ($latitude_sec/3600.0);
   my $londd = $longitude_deg +
   ($longitude_min/60.0) + ($longitude_sec/3600.0);

   if ($latitude_hem eq "S" ||
   $latitude_hem eq "s") {
      $latdd = $latdd*(-1.0);
   }

   if ($longitude_hem eq "W" ||
   $longitude_hem eq "w") {
      $londd = $londd*(-1.0);
   }

   #Note: The following is the reverse of typical
   #conventions for E/W longitude and sign.
   #The CalCOFI grid conversion equations assume
   #longitude is positive value for western
   #hemisphere.
   #
   my $pla = $latdd;
   my $plo = $londd;
   $plo = $plo*(-1.0);

   my $L1 = ( &mctr($pla) - &mctr(34.15) ) *
   tan(deg2rad(30));
   my $L2 = $plo - $L1 - 121.15;
   my $mctr_rla_val = ( $L2 * cos(deg2rad(30)) *
   sin(deg2rad(30)) ) + &mctr($pla);
   my $rla = &invmctr($mctr_rla_val);
   my $pln = 80.0 -
   ((($rla - 34.15) * 5.0)/cos(deg2rad(30)));
   my $psn = 60.0 +
   ((($rla - $pla) * 15.0)/sin(deg2rad(30)));

   return ($pln, $psn, $latdd, $londd);
}

sub cc2ll {
   #Subroutine to implement algorithm that converts
   #CalCOFI grid coordinates (line and station) to
   #lat/long coordinates.
   #
   #INPUT: Line and station value(s) for CC grid to
   #be converted to geographic coordinates
   #OUTPUT: Latitude and longitude values in
   #decimal degrees (signed).
   #
   #
   use Math::Trig;

   my $pln = shift;
   my $psn = shift;

   my $rla = 34.15 -
   (0.2 * ($pln - 80.0) * cos(deg2rad(30)));
   my $pla = $rla - ((1.0/15.0) * ($psn - 60.0) *
   sin(deg2rad(30)));
   my $L1 = ( &mctr($pla) - &mctr(34.15) ) *
   tan(deg2rad(30));
   my $L2 = ( &mctr($rla) - &mctr($pla) )
      / (cos(deg2rad(30)) * sin(deg2rad(30)));
   my $plo = $L1 + $L2 + 121.15;

   #Note: The CalCOFI grid conversion equations
   #assume longitude is positively signed in the
   #western hemisphere.
   #The following changes the sign on the longitude
   #value to be in the convention of negatively
   #signed in the western hemisphere.
   #
   $plo = $plo * (-1.0);

   return ($pln, $psn, $pla, $plo);
}

sub mctr {
   #Subroutine to implement mercator transform
   #function.
   #
   #INPUT: A latitude value in decimal degrees.
   #OUPUT: A value in "mercator meridional units"
   #
   #
   use Math::Trig;
   my $deg = shift;
   my $mctr_val = (180.0/pi) *
   ( log(tan(deg2rad(45.0 + ($deg/2.0)))) -
   (0.00676866 * sin(deg2rad($deg))) );

   return $mctr_val;
}

sub invmctr {
   #Subroutine to implement inverse mercator
   #transform function.
   #Because this function does not have a precise
   #algebraic form, an iterative process is
   #employed.
   #INPUT: A value in "mercator meridional units"
   #OUTPUT: A value in decimal degrees
   #
   #
   my $i;
   my $mctr_rla_val = shift;
   my $rla = $mctr_rla_val;
   my $rla_init = $rla;
   use Math::Trig;
   for ($i=0; $i < 5; $i++) {
      $rla = 2 * ( (180/pi) *
      atan( exp(deg2rad($rla_init) +
      (0.00676866*sin(deg2rad($rla)))) ) - 45);
   }

   return $rla;
}
```

APPENDIX III. PYTHON FUNCTIONS FOR CONVERTING CALCOFI COORDINATES

```
import numpy as np

def invmercator(mercatorLat, iterations=3):
      mercatorLat = np.array(mercatorLat,
                   dtype='float')
      approxLat = mercatorLat
      for i in range(iterations):
         approxLat = 2 * (np.arctan(np.exp(
            np.deg2rad(mercatorLat) +
            0.00676866 * np.sin(np.deg2rad(
               approxLat)))) * 180 / np.pi
            - 45)
      return(approxLat)

def tomercator(latitude):
   latitude = np.array(latitude)
   y = np.rad2deg(
      np.log(np.tan(np.deg2rad(
         45 + latitude / 2))) -
      0.00676866 * np.sin(np.deg2rad(latitude)))
   return(y)

def stationtolatlon(x, y=None):
   """
   x is line, y is station, or x is a matrix
   x and y are numbers, lists, tuples,
   or numpy arrays,
   """
   if y == None:
      line = x[:, 0]
      station = x[:, 1]
   else:
      line = x
      station = y

   line = np.array(line, dtype='float')
   station = np.array(station, dtype='float')

   # need reshape b/c single numbers could
   # be wrapped in arrays
   if len(line.shape) == 0:
      line = line.reshape(1)

   if len(station.shape) == 0:
      station = station.reshape(1)

   refLatitude = (34.15 - 0.2 * (line - 80) *
              np.cos(np.deg2rad(30)))
   latitude = (refLatitude - (station - 60) *
           np.sin(np.deg2rad(30)) / 15)
   L1 = ((tomercator(latitude) -
        tomercator(34.15)) *
        np.tan(np.deg2rad(30)))
   L2 = (((tomercator(refLatitude) -
        tomercator(latitude)) /
        (np.cos(np.deg2rad(30)) *
        np.sin(np.deg2rad(30)))))
   longitude = -1 * (L1 + L2 + 121.15)
   ans = np.vstack((longitude, latitude)).T
   if len(line) == 1:
      ans = ans[0]
   return(ans)


def latlontostation(x, y=None):
   """
   x and y are numbers, lists, tuples,
   or numpy arrays, or
   x can be a matrix with y = None
   """
   if y == None:
      lon = x[:, 0]
      lat = x[:, 1]
   else:
      lon = x
      lat = y
   lon = np.array(lon, dtype='float')
   lat = np.array(lat, dtype='float')
   # need reshape b/c single numbers
   # could be wrapped in arrays
   if len(lon.shape) == 0:
      lon = lon.reshape(1)
   if len(lat.shape) == 0:
      lat = lat.reshape(1)
   # assume we're in the western hemispere
   lon[lon > 180] = -1 * (lon[lon > 180] - 360)
   lon[lon < 0] = lon[lon < 0] * -1
   L1 = ((tomercator(lat) - tomercator(34.15)) *
        np.tan(np.deg2rad(30)))
   L2 = lon - L1 - 121.15
   mercRefLatitude = (L2 * np.cos(np.deg2rad(30)) *
                      np.sin(np.deg2rad(30)) +
                      tomercator(lat))
   refLatitude = invmercator(mercRefLatitude)
   line = (80 - (refLatitude - 34.15) * 5 /
           np.cos(np.deg2rad(30)))
   station = (60 + (refLatitude - lat) * 15 /
              np.sin(np.deg2rad(30)))
   ans = np.vstack((line, station)).T
   if len(line) == 1:
      ans = ans[0]
   return(ans)
```

APPENDIX IV. R FUNCTIONS FOR CONVERTING CALCOFI COORDINATES

```
`.deg2rad` <- function(deg) deg * pi / 180

`.rad2deg` <- function(rad) rad * 180 / pi

`.inverse.mercator` <- function(mercatorlat,
                      iterations = 3)
{
   approxlat <- mercatorlat
   iterlatitude <- function(mercatorlat,
                      approxlat)
   {
      approxlat <- 2 * (atan(exp(.deg2rad(
         mercatorlat) + 0.00676866 *
         sin(.deg2rad(approxlat)))) *
         180 / pi - 45)
      approxlat
   }
   for (i in 1:iterations) approxlat <-
      iterlatitude(mercatorlat, approxlat)
   approxlat
}

`.to.mercator` <- function(latitude)
{
   y <- .rad2deg(log(tan(.deg2rad(45 +
              latitude / 2))) - 0.00676866 *
              sin(.deg2rad(latitude)))
   y
}

`station.to.latlon` <- function(x,
                      roundlines = true)
{
```

```
   if (length(x) == 2 & class(x) != 'matrix'){
      x <- matrix(x, 1, 2)
   }
   line <- x[, 1]
   station <- x[, 2]

   reflatitude <- 34.15 - 0.2 * (line - 80) *
      cos(.deg2rad(30))
   latitude <- reflatitude - (station - 60) *
      sin(.deg2rad(30)) / 15
   l1 <- (.to.mercator(latitude) - .to.mercator(
      34.15)) * tan(.deg2rad(30))
   l2 <- (.to.mercator(reflatitude) -
         .to.mercator(latitude)) /
         (cos(.deg2rad(30)) * sin(.deg2rad(30)))
   longitude <- -1 * (l1 + l2 + 121.15)
   cbind(lon = longitude, lat = latitude)
}

`latlon.to.station` <- function(x)
{
   if (length(x) == 2 & class(x) != 'matrix'){
      x <- matrix(x, 1, 2)
   }
   longitude <- x[, 1]
   latitude <- x[, 2]

   # assume we're in the western hemispere
   longitude[longitude > 180] <- -1 * (
      longitude[longitude > 180] - 360)
   longitude[longitude < 0] <- longitude[
      longitude < 0] * -1

   l1 <- (.to.mercator(latitude) - .to.mercator(
      34.15)) * tan(.deg2rad(30))
   l2 <- longitude - l1 - 121.15

   mercreflatitude <- l2 * cos(.deg2rad(30)) *
      sin(.deg2rad(30)) + .to.mercator(latitude)
   reflatitude <- .inverse.mercator(
      mercreflatitude)
   line <- 80 - (reflatitude - 34.15) * 5 /
      cos(.deg2rad(30))
   station <- 60 + (reflatitude - latitude) *
      15 / sin(.deg2rad(30))

   cbind(line = line, station = station)
}
```

AN OVERVIEW OF ICHTHYOPLANKTON RESEARCH IN THE NORTHERN CALIFORNIA CURRENT REGION: CONTRIBUTIONS TO ECOSYSTEM ASSESSMENTS AND MANAGEMENT

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ABSTRACT

We review the scientific literature based on ichthyoplankton research conducted in the northern California Current (NCC) north of Cape Mendocino, California to northern Washington. A total of 69 papers have been written on ichthyoplankton research in the NCC region from 1940 to 2012, with several more currently in the process of publication. Although there were some extended California Cooperative Fisheries Investigation (CalCOFI) cruises in the 1950s conducted as far north as northern California, the first dedicated larval fish survey in this region was made by Ken Waldron of the Bureau of Commercial Fisheries in 1967. Extensive cruises were conducted starting in 1969 and continuing through the 1970s by William Pearcy at Oregon State University (OSU) and the ichthyoplankton were analyzed by Sally Richardson and her colleagues. Much new information on larval taxonomy, spatial and temporal distributions, and relationships to environmental conditions was generated as part of these studies. Nearshore studies continued in the early 1980s by OSU focusing on the recruitment and connections of mainly flatfish species to the local estuaries. At the same time, there were a series of eight joint U.S.-Soviet large-scale cruises covering the entire region organized by Art Kendall of NMFS, with the data analyzed primarily by Miriam Doyle. After a hiatus in the early to mid-1990s, sampling began anew by NMFS and OSU focusing initially off the central Oregon coast, but by the mid-2000s was expanded over a broader area of the NCC over multiple years and seasons to provide information to managers on the outlook for future recruitment. We discuss current gaps in our knowledge, and give examples of applications of ichthyoplankton data to fisheries management and to improving our understanding of ecosystem processes and their relationships to environmental variability.

INTRODUCTION

Ichthyoplankton research is well-known to be an important tool in understanding trophic dynamics, recruitment processes, and associations between environmental fluctuations and productivity of recreationally, commercially, and ecologically important fish stocks (Hunter and Kimbrell 1980; Houde 1997; Miller and Kendall 2009). A notable example of a long-term (>60 yr) sampling program that has contributed greatly to our understanding of the physical and biological drivers of fish production has been the California Cooperative Fisheries Investigation (CalCOFI) program which has been sampling almost continuously since 1949 in the southern California Current (reviewed by McClatchie 2013). The success of this program inspired similar studies using similar sampling regimes further north into the northern California Current (NCC) region. For this reason, many studies have been conducted in the NCC over the past 70 years to examine the development, spatial and temporal distributions, size distributions, food habits, age and growth, community structure, environmental relationships, and production of fish eggs and larvae. This has resulted in an increasing abundance of information on ichthyoplankton dynamics in the NCC that is widely scattered among a variety of peer-reviewed publications, theses, dissertations, technical reports, and other gray literature that are often part of broader geographic or community studies, may be difficult to access, or are simply overlooked.

The present study is the first to provide a synopsis of the research that has been conducted to date on ichthyoplankton in the NCC. The objectives of this study are to (1) outline in tabular form the purpose, parameters, and implications of each study, (2) provide an historical background for ichthyoplankton research in the NCC, (3) examine temporal trends in this research, (4) identify applications of the research to management, and (5) discuss current and future research needs. In addition, we provide a list of all egg and larval fish taxa that have been collected in the region during recent years (i.e., 1996–2012). The results of this study are intended to provide fisheries researchers with an easily accessible, comprehensive, and tabular reference guide to ichthyoplankton research in the NCC to aid in ongoing research and guide the development of future studies.

METHODS

We used various library and internet search engines, historical and current literature references, and personal communication with leading scientists in the field of ichthyoplankton research in the California Current region to compile our list of studies to include in the present literature review. We only included studies on ichthyoplankton in the coastal and oceanic regions of the NCC from north of Cape Mendocino, California to northern Washington State, excluding estuaries and rivers. For each study that we examined, we provided the following information: author name(s), publication year; title, literature source, and annual and seasonal period; frequency, latitudinal, longitudinal, and depth ranges of sampling; number of transects and stations sampled; number of samples collected; gear types used; taxa examined; and the purpose and scientific, management, and sampling implications of the study. We did not include progress reports, theses, or gray literature that contained information subsequently published in peer-reviewed literature. In addition, we did not include references to ichthyoplankton updates contained in the State of the California Current articles published in the annual CalCOFI Reports, which can be accessed via their Web site (http://www.calcofi.org 2013). References for larval fish identification, distribution, habitat association, and seasonal parturition for the various taxa occurring in the NCC are found in Matarese et al. 1989, although several important or omitted references are also included in the present review. All dates (i.e., years) included in the figures refer to the periods of sampling and not the publication years of the reviewed studies.

RESULTS AND DISCUSSION

Historical background and recent studies

A total of 69 papers have been written on ichthyoplankton research in the NCC region from 1940 to 2012, encompassing sampling conducted as early as 1939 (tables 1, 2). From 1996 to 2012, 116 larval fish taxa representing 40 families and an additional two orders (one of which, Elopomorpha, is a superorder) have been collected in the NCC as part of the most recent pelagic sampling regime (table 3).

Although there were some extended CalCOFI cruises in the 1950s up to at least northern California (Ahlstrom 1956; Ahlstrom and Stevens 1976), the first dedicated larval fish survey in this region was made by Ken Waldron of the Bureau of Commercial Fisheries (predecessor to National Marine Fisheries Service [NMFS]) in 1967 (Waldron 1972). An extensive series of cruises were conducted starting in 1969 and continuing through the 1970s by William Pearcy at Oregon State University (OSU) and the ichthyoplankton were analyzed by Sally Richardson and her colleagues (Richardson 1973, 1981; Laroche 1976; Pearcy et al. 1977; Richardson and Pearcy 1977; Richardson et al. 1980a, b; Laroche et al. 1982). Much original information on larval taxonomy, spatial and temporal distributions, community structure, and relationships to environmental conditions were generated as part of these studies.

Nearshore larval studies continued in the 1980s by OSU focusing on the recruitment and connections of species to the local estuaries (Gadomski and Boehlert 1984; Boehlert et al. 1985; Brodeur et al. 1985; Shenker 1988). At the same time, there were a series of eight joint U.S.-Soviet large-scale surveys covering the entire NCC organized by Art Kendall of NMFS, that led to a series of papers looking mainly at distribution, community structure, and feeding ecology (Grover and Olla 1986, 1987; Dunn and Rugen 1989; Doyle 1992, 1995; Doyle et al. 1993, 2002). After a hiatus in the early to mid-1990s, sampling began anew by NMFS and OSU focusing initially off the central Oregon coast (Auth and Brodeur 2006; Auth et al. 2007; Brodeur et al. 2008), but by the mid-2000s was expanded over a broader area of the NCC over multiple years and seasons (Emmett et al. 1997; Auth 2008, 2009, 2011; Parnel et al. 2008; Takahashi et al. 2012; Auth et al. submitted). Several of these studies were able to provide information to managers on the outlook for future recruitment of commercially-important species in the NCC (Phillips et al. 2007; Brodeur et al. 2011; Daly et al. 2013).

Trends in research

We found disparity in the relative proportion of ichthyoplankton studies conducted in the NCC by decade, month, gear type, purpose, and spatial-temporal distribution. Relatively few studies were conducted prior to 1970 (<20%), with a sharp increase in the 1970s (24%) followed by a gradual decline in the 1980s (20%) and 1990s (14%), before reaching a maximum in the 2000s

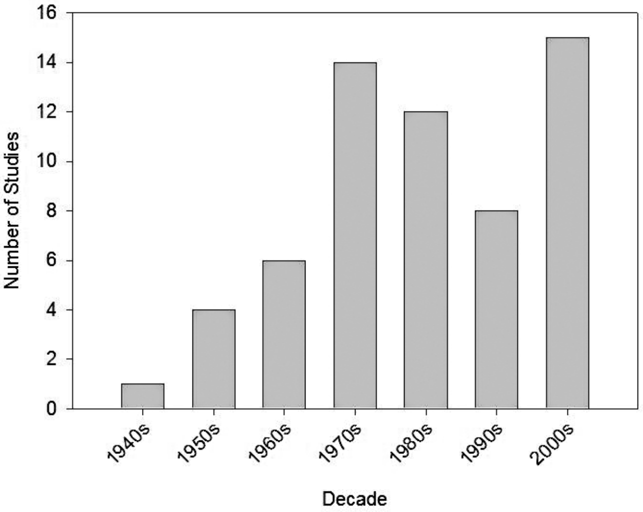

Figure 1. Studies conducted in the northern California Current from 1949 to 2012 by decade of sampling.

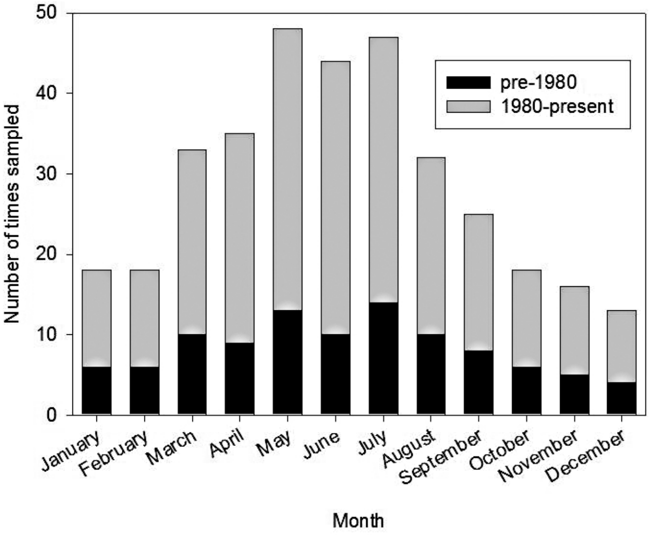

Figure 2. Studies conducted in the northern California Current from 1949 to 2012 by month displayed by sampling period (i.e., pre-1980 and post-1980).

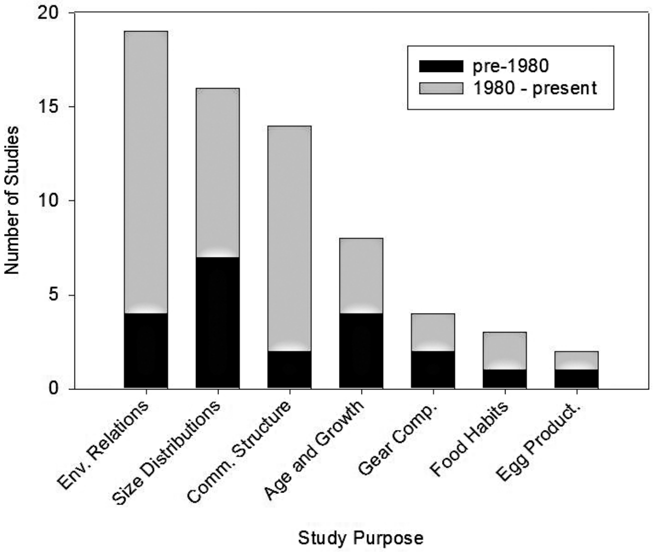

Figure 4. Studies conducted in the northern California Current from 1949 to 2012 by purpose displayed by sampling period (i.e., pre-1980 and post-1980).

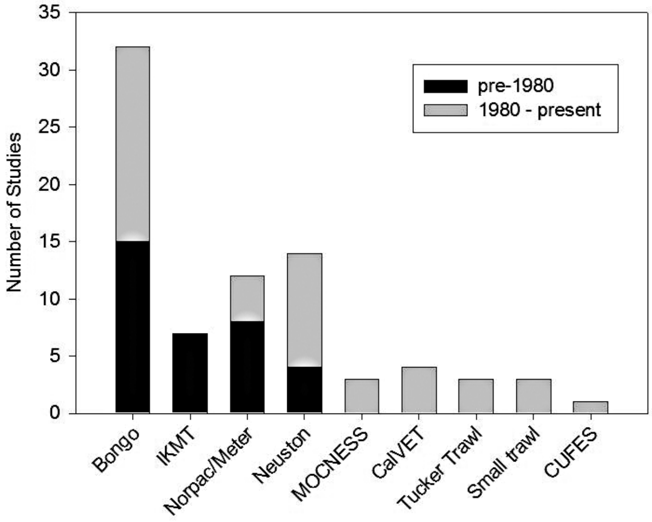

Figure 3. Studies conducted in the northern California Current from 1949 to 2012 by gear type displayed by sampling period (i.e., pre-1980 and post-1980).

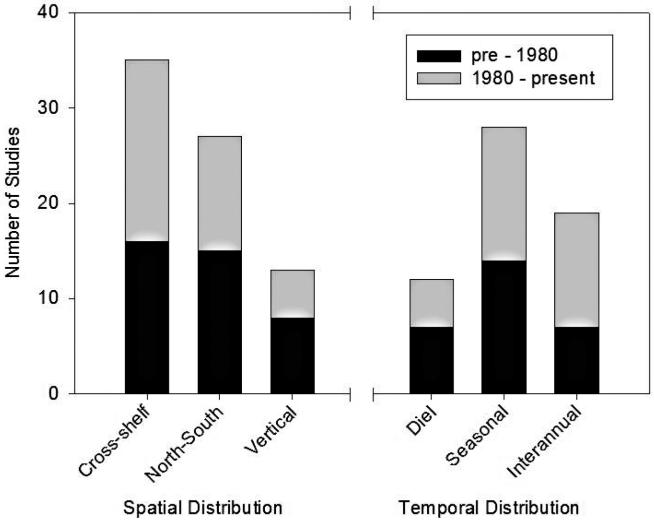

Figure 5. Studies conducted in the northern California Current from 1949 to 2012 by spatial and temporal scale of sampling displayed by sampling period (i.e., pre-1980 and post-1980).

(25%) (fig. 1). Most sampling was conducted from March to September, with peak sampling occurring in May–July, most likely due to the rough weather conditions prevalent in the NCC during fall and winter months that make consistent sampling difficult. The predominant type of gear used to collect samples consisted of bongo, neuston, and ring (North Pacific [NorPac]/meter) nets, with bongos being favored during all periods and employed in more than half of the studies overall (fig. 2). Relatively rarely used gear types included the Isaacs-Kidd midwater trawl (IKMT), which was seldom used after 1980, and the Multiple Opening/Closing Net and Environmental Sampling System (MOCNESS), Californian Vertical Egg Tow (CalVET), Tucker and smaller trawls, and the Continuous Underway Fish Egg Sampler (CUFES), which were used only since 1980 (fig. 2). The primary purposes of the ichthyoplankton studies were investigations of environmental relations to larval ecology and examinations of size distributions and community structure, while age and growth, gear comparison, food habits, and egg production were the focus of smaller proportions of the total number of studies (fig. 3). Interannual and seasonal were the dominant temporal scales examined while longitudinal (inshore-offshore) and latitudinal distributions were the primary spatial scales examined in the ichthyoplankton studies conducted to date, while vertical and diel studies were undertaken much less frequently (fig. 4).

In summary, many of the early studies focused on single species of interest to an investigator, and although there were some studies that attempted to describe the whole larval community (e.g., Waldron 1972; Richardson and Pearcy 1977), there were few that examined community structure in a quantitative sense (Richardson et al. 1980). Knowledge on the taxonomy of early-life stages of marine fishes in the Northeast Pacific was relatively scant in the early years (Kendall and Matarese 1994), but many descriptions done in the 1980s led to a more complete catalogue of egg and larval stages by the end of the decade (Matarese et al. 1989). A shift on a national scale towards informing resource assessments of important species in many of the U.S. Large Marine Ecosystems (Sherman et al. 1983) led to large-scale sampling of this region and shifted the emphasis to gaining a mechanistic understanding of recruitment processes for a variety of species. More recent studies attempted to look more holistically at the role of early-life stages in pelagic ecosystems with a view towards predicting recruitment in fish populations (e.g., Daly et al. 2013).

Applications to management and future studies

Ichthyoplankton research in the NCC has yielded much important information that can be used for fisheries and ecosystem management in the region (table 2), although many unanswered questions still remain which are the subjects of ongoing and future research. As mentioned earlier, the vast majority of studies have provided information on abundance and distribution patterns, early-life history traits, community structure, and environmental relationships, which can be incorporated into single-species and ecosystem-based models to regulate commercially and ecologically important fish stocks (e.g., Kendall and Matarese 1987; Shanks and Eckert 2005; Auth et al. 2011).

As an example of using larval fishes as an indicator of potential ocean changes, the marked variations in abundance and productivity of larval fishes observed during anomalous El Niño years (Brodeur et al. 1985; Doyle 1995; Auth et al. submitted) or other low production years (Brodeur et al. 2006; Takahashi et al. 2012) may be an indicator of future responses under projected climate changes in the California Current. A recent study by Roegner et al. (2013) examined finer-scale variations in the spatial and temporal surface distributions and concentrations of ichthyoplankton relative to the dynamics of the Columbia River plume during a delayed transition from downwelling to upwelling conditions to understand the fate of meroplanktonic organisms under strong advective forcing. Recent work by Thompson et al. (submitted) examines the large-scale and regional responses of ichthyoplankton assemblages to climate variability in the contrasting regions of the California Current of Oregon and southern California. Finally, Johnson et al. (in prep.) has completed a study examining the effects of recent hypoxia events in NCC coastal waters on the larval abundance and distribution of ecologically and commercially important fish taxa. Much of the information summarized in the current review will be the basis for a future study by us to utilize early-life history traits of important fish taxa in conjunction with changing environmental forcing factors in the development of ecosystem-based management policies in the California Current, similar to that proposed by Doyle and Mier 2012 for the Gulf of Alaska region.

Another critical informational gap that exists is the inability to identify to species or species groups samples of larval *Sebastes* spp. (rockfish). Currently, larval *Sebastes* spp., one of the most abundant and commercially important taxa in the ichthyoplankton community, are not identifiable below the generic level based on meristics and pigmentation patterns. However, Gray et al. (2006) have developed a technique to identify most *Sebastes* to species level based on mitochondrial markers, which has already been utilized for larval *Sebastes* in the southern California Current (Thompson et al. 2011) and juvenile *Sebastes* in the NCC (Johansson et al. in prep.). The implementation of this technique to identify *Sebastes* larvae in the NCC would vastly facilitate the utility of ichthyoplankton sampling to make species-specific inferences of larval *Sebastes* spp. survival, ecological and trophic significance, and recruitment in this region.

Although we presently have a good understanding about where and when the early-life stages of most fishes occur in the NCC, and some knowledge about the important physical and biological factors that affect their abundance patterns, there is a general dearth of knowledge about the ecological aspects of their early-life history in this region. For example, there are only a limited number of studies that have examine the diets of larval fish (Gadomski and Boehlert 1984; Grover and Olla 1986, 1987) and no attempts to examine feeding selectivity or food consumption in relation to available food sources. Similarly, although there is one estimate of egg mortality for sardines (Bentley et al. 1996), there have been no attempts to quantify sources of mortality for fish larvae similar to those made off southern California (Hewitt et al. 1985), or to identify important invertebrate and vertebrate predators on early-life stages in this region (Bailey and Houde 1989; Brodeur and Bailey 1996). Larval fish have been documented in the stomachs of at least some gelatinous zooplankton off Oregon (Auth and Brodeur 2006), although quantification of predation rates will require some dedicated process studies which have not been attempted to date.

The trophic interactions of fish larvae can also be important in developing fisheries management plans in the NCC. This is especially true for those involving piscivory by commercially and recreationally important salmonids on early-life stages of pelagic fish prey taxa. Although some previous work has been done to address this interaction (Brodeur 1989; Brodeur et al. 2011b), Daly et al. (2013) found that a significant relationship exists between the biomass of larval fish prey taxa in winter and subsequent *Oncorhynchus kisutch* (coho salmon) and spring and fall *O. tshawytscha* (Chinook salmon) survival. This relationship has been one of the most important among a long list of physical and biological indicators that have been used to explain and predict salmon survival in the ocean (Burke et al. 2013).

Other important applications of ichthyoplankton research to fisheries management are the estimation of spawning stock biomass (SSB), and perhaps above all, prediction of future recruitment success of commercially, recreationally, and ecologically important fish stocks. Several ichthyoplankton studies have been conducted in the NCC to examine the factors influencing SSB, year-class strength, and recruitment in general (Parrish et al. 1981), and for individual taxa such as *Engraulis mordax* (northern anchovy) (Richardson 1981), *Sardinops sagax* (Pacific sardine) (Bentley et al. 2006), *Isopsetta isolepis* (butter sole) and *Parophrys vetulus* (English sole) (Mundy 1984), *Merluccius productus* (Pacific hake) (Phillips et al. 2007), *Sebastes* spp. (Brodeur et al. 2011a), and *Anoplopoma fimbria* (sablefish) (Kendall and Matarese 1987; Sogard 2011). Although some recruitment models do exist which include physical factors and their effects on early-life stages (e.g., Kruse and Tyler 1989), the contribution of early-life ecology and survival to variation in recruitment of adults remains poorly understood among most fish species. Another study that is currently underway (Auth et al. in prep.) aims to utilize environmental and larval and juvenile fish data collected as part of the 2004–12 Stock Assessment Improvement Plan (SAIP, see Auth 2011 for sampling details) in conjunction with adult fish data from the Pacific West Coast bottom trawl survey of groundfish to determine if and to what degree a relationship exists between environmental factors, SSB, ichthyoplankton production, survival into the juvenile stage, and future adult recruitment. Studies such as this, in conjunction with continued research into areas of early-life fishery dynamics such as trophic interactions, mortality, growth, and environmental connectivity, could bring us closer to solving the recruitment problem, which has been referred to as "the holy grail of fisheries science" (Houde 2008).

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TABLE 1

Summary of sampling protocols, sampling effort, and taxa examined for all ichthyoplankton studies conducted in the northern California Current (NCC) region (1940–2012).

Study	Period	Frequency	Latitudinal range	Longitudinal range	Depth range (m)	Transects (no.)	Stations (no.)	Samples (no.)	Gear type (mouth diameter/ area and mesh size)	Taxon
Brock (1940)	1939 (May)	Annual	44.77–44.90°N	126.33–128.37°W	Surface	1	2	4 (individuals)	Dip net (unspecified mesh)	*Anoplopoma fimbria*
Ahlstrom (1956)	1949 and 1955 (July–September)	Unspecified	20–48°N	110–150°W	0–>123	Unspecified	Unspecified	Unspecified	Unspecified	*Trachurus symmetricus*
Aron (1959)	1957 (July–September)	Continuous	48–59°N	122°W–174°E	20–250	Unspecified	149	143	0.5 m Isaacs-Kidd midwater trawl (IKMT) (3.2 mm)	Community
Aron (1962)	1957 (summer) and 1958 (summer and fall)	Seasonal	32–56°N	122°W–174°E	0–400	Unspecified	90	564	0.5 m IKMT (3.2 mm)	Community
Pearcy (1962)	1961 (March–May) and 1962 (April)	Monthly	43.34–44.65°N	124.72–125.26°W	Surface	Unspecified	4	4	Dip net (unspecified mesh)	*Sebastolobus* spp.
LeBrasseur (1970)	1956–59 (unspecified months)	Unspecified	42–59°N	124–160°W	0–150	Unspecified	Unspecified	~3000	Norpac net (2 mm) and IKMT (unspecified mesh)	Community
Day (1971)	1963 (May and November)	Monthly	46.8–50.0°N	124.3–128.5°W	0–150	4 (May), 9 (November)	18 (May), 44 (November)	139	0.9 m IKMT (3 mm)	Community; featured taxa: Agonidae, Cottidae, Hexagrammidae, Liparidae, Pleuronectidae, and Scorpaenidae
Waldron (1972)	1967 (April and May)	Monthly	42–51°N	122.4–136.5°W	1–200	10	103	103	1 m ring (500–600 µm)	Community; featured taxa: Ammodytidae, Gadidae, Pleuronectidae, Myctophidae, and Scorpaenidae
Richardson (1973)	1969 (May–October)	Monthly	42.00–46.50°N	124.00–129.50°W	1–200	Unspecified	Unspecified	354	IKMT, 70 cm bongo, and 1 m ring (all 571 µm)	Community; featured taxa: Bothidae, *Engraulis mordax*, Osmeridae, Pleuronectidae, Myctophidae (esp. *Stenobrachius leucopsarus* and *Tarletonbeania crenularis*), and Scorpaenidae (esp. *Sebastes* spp.)
Ahlstrom and Stevens (1976)	1972 (May)	Monthly	20–48°N	107–148°W	Surface (neuston), 0–200 (ring)	24	148	148 (neuston), 148 (ring)	0.3 m^2 neuston and 1 m ring (505 µm)	Community; featured taxa: *Anoplopoma fimbria, Engraulis mordax, Cololabis saira, Macrorhamphosus gracilis,* Myctophidae, *Sebastes* spp., and *Trachurus symetricus*
Laroche (1976)	1975 (January–October)	Monthly	46.1°N	124.1°W	Entire water column	1	6 (January and March), 2 (July–October)	48 (January and March), 228 (July–October)	1 m ring (571 µm)	Community; featured taxon: Osmeridae
Pearcy et al. (1977)	January 1971–August 1972, 1972–73 (March and April), 1974–75 (March)	Monthly	42.0–46.2°N	124.0–128.2°W	1–200 (IKMT), 1–150 (bongo), 1–1000 (opening-closing midwater trawl)	36 (IKMT), 89 (bongo), unspecified number (opening-closing midwater trawl)	36 (IKMT), 89 (bongo), unspecified number (opening-closing midwater trawl)	>2200 (IKMT), 593 (bongo), unspecified number (opening-closing midwater trawl)	0.5 m IKMT (571 µm), opening-closing midwater trawl (unspecified mesh), and 70 cm bongo (571 µm)	*Eopsetta jordani, Glyptocephalus zachirus*, and *Microstomus pacificus*
Richardson and Pearcy (1977)	January 1971–August 1972	Biweekly	44.65°N	124.1–125.5°W	1–150	1	12	287	20 and 70 cm bongo (233–571 µm)	Community
Laroche and Richardson (1979)	1972–73 (March and April), 1974–75 (March)	Monthly	42.7–46.3°N	124.0–125.2°W	Surface (neuston), 0–200 (bongo)	12	84	16 (neuston), 320 (bongo)	0.35 m^2 neuston (505 µm) and 70 cm bongo (571 µm)	*Isopsetta isolepis, Parophrys vetulus* (primary), *Platichthys stellatus*, and *Psettichthys melanostictus*

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[1] Additional live individuals for spawning and rearing were collected in fall–winter 1978 at 44.17°N, 124.30°W at 68–77 m water depth using a 12 m otter trawl.

[2] Only the west coast sampling protocal is listed.

(continued)

TABLE 1, cont'd.

Summary of sampling protocols, sampling effort, and taxa examined for all ichthyoplankton studies conducted in the northern California Current (NCC) region (1940–2012).

Study	Period	Frequency	Latitudinal range	Longitudinal range	Depth range (m)	Transects (no.)	Stations (no.)	Samples (no.)	Gear type (mouth diameter/ area and mesh size)	Taxon
Richardson and Laroche (1979)	1961–76 (unspecified months)	Unspecified	42.6–46.3°N	124–128°W	Unspecified	Unspecified	Unspecified	>12000 (individuals)	70 cm bongo, neuston, and 1 m ring, and IKMT, beam, and otter trawls (unspecified mesh)	*Sebastes crameri, S. helvomaculatus,* and *S. pinniger*
Laroche and Richardson (1980)	1961–76 (January–December)	Unspecified	42.6–46.3°N	124–128°W	Unspecified	Unspecified	Unspecified	556 (individual *Sebastes flavidus*), 365 (individual *S. melanops*)	70 cm bongo, neuston, 1 m ring, dip net, beach seines, and IKMT, beam, and otter trawls (unspecified mesh)	*S. flavidus* and *S. melanops*
Richardson et al. (1980a)	January 1971–August 1972	Biweekly	44.65°N	124.1–125.5°W	1–150	1	12	407 (individuals)	20 and 70 cm bongo (233–571 µm)	*Isopsetta isolepis*
Richardson et al. (1980b)	1972–73 (March and April), 1974–75 (March)	Monthly	42.7–46.3°N	124.0–125.2°W	0–150	12	84	306	70 cm bongo (571 µm)	Community
Kendall (1981)	Unspecified	Unspecified	Unspecified	Unspecified	Unspecified	Unspecified	Unspecified	Unspecified	Unspecified	Community
Laroche and Richardson (1981)	1961–76 (unspecified months)	Unspecified	42.6–46.3°N	124–128°W	Unspecified	Unspecified	Unspecified	Unspecified	70 cm bongo, neuston, and 1 m ring, purse seines, and IKMT and commercial midwater, beam, and otter trawls (unspecified mesh)	*Sebastes entomelas* and *S. zacentrus*
Methot (1981)	1977 (July)	Monthly	42.3–47.0°N	124.1–126.6°W	0–70	7	25	367 (individual *E. mordax*), 141 (individual *S. leucopsarus*)	60 cm bongo (333 µm)	*E.mordax* and *S. leucopsarus*
Parrish et al. (1981)	Unspecified	Unspecified	20–51°N	111–136°W	Unspecified	Unspecified	Unspecified	Unspecified	Unspecified	Community
Richardson (1981)	1975–76 (July)	Annual	43–47°N	124.1–127.8°W	0–150	7	70	140	70 cm bongo (333 µm)	*Engraulis mordax*
Laroche et al. (1982)[1]	November 1977–June 1978	Monthly	44.62°N	124.08°W	Entire water column	1	1	331 (individuals)	70 cm bongo (505 µm)	*Parophrys vetulus*
Rosenberg and Laroche (1982)	November 1977–June 1978	Monthly	44.62°N	124.08°W	Entire water column	1	1	127 (individuals)	70 cm bongo (505 µm)	*Parophrys vetulus*
Gadomski and Boehlert (1984)	January 1971–August 1972, 1972–73 (March and April), 1974–75 (March)	Monthly	42.7–46.3°N	124.0–125.2°W	0–150	12	84	438 (individual *Isopsetta isolepis*), 563 (individual *Parophrys vetulus*)	70 cm bongo (571 µm)	*I. isolepis* and *P. vetulus*
Mundy (1984)	June 1969–August 1972	Biweekly	44.65°N	124.1–124.3°W	Entire water column	1	4	277	20 and 70 cm bongo (233–571 µm)	Community; featured taxa: *Ammodytes hexapterus, Artedius fenestralis, A. harringtoni, A. meanyi, Isopsetta isolepis, Liparis* spp., *Lyopsetta exilis, Microgadus proximus,* Osmeridae, *Parophrys vetulus, Psettichthys melanostictus, Platichthys stellatus,* and *Sebastes* spp.
Young (1984)	Unspecified	Unspecified	Unspecified	Unspecified	Unspecified	Unspecified	Unspecified	Unspecified	Unspecified	Osmeridae
Boehlert et al. (1985)	1982 (May–July)	Biweekly	44.65°N	124.17–124.29°W	Entire water column	1	2	75 depth-stratified samples from 6 hauls (4 day, 2 night)	1 m^2 Tucker trawl (505 µm)	Community
Brodeur et al. (1985)	1983 (April–September)	Biweekly	44.65°N	124.07–124.29°W	Entire water column	2	4	38	70 cm gimballed, bridleless frame and bongo (333 µm)	Community; featured taxon: *Engraulis mordax*

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[2] Only the west coast sampling protocal is listed.

(continued)

TABLE 1, cont'd.

Summary of sampling protocols, sampling effort, and taxa examined for all ichthyoplankton studies conducted in the northern California Current (NCC) region (1940–2012).

Study	Period	Frequency	Latitudinal range	Longitudinal range	Depth range (m)	Transects (no.)	Stations (no.)	Samples (no.)	Gear type (mouth diameter/ area and mesh size)	Taxon
Grover and Olla (1986)	1980 (April–May)	Annual	43.6–47.0°N	124–129°W	Surface	6	9	143 (individuals)	0.5 m neuston (505 µm)	*Anoplopoma fimbria*
Grover and Olla (1987)	1980 and 1983 (April–May)	Annual	43.3–47.3°N	124–129°W	Surface	8	10 (1980), 6 (1983)	267 (individuals, 1980), 136 (individuals, 1983)	0.5 m neuston (505 µm)	*Anoplopoma fimbria*
Kendall and Matarese (1987)	1939–1985	Unspecified	40–60°N	124°W–170°E	0–400	Unspecified	Unspecified	Unspecified	50–70 cm bongo, neuston, and dipnet (unspecified mesh)	*Anoplopoma fimbria*
Shenker (1988)	1984 (April–July)	Biweekly	44.65°N	124.08–125.25°W	Surface	1	12	107	0.7 m² Manta neuston (333 µm)	Community
Brodeur (1989)	1985 (June, July, and September)	Monthly	41–59°N	124–139°W	Surface	35	106	228	0.35 m² neuston (505 µm)	Community
Dunn and Rugen (1989)	1965–88 (unspecified months)	Unspecified	32–61°N	118–179°W	Unspecified	Unspecified	Unspecified	Unspecified	Unspecified	Community
Matarese et al. (1989)	1966–86 (January–December)	Unspecified	38–66°N	120–180°W	Unspecified	Unspecified	Unspecified	Unspecified	60 and 70 cm bongo, neuston, 1.2 m² MOCNESS, 1 m ring, and 1 m² Tucker trawl, and midwater trawls (unspecified mesh)	Community
Brodeur (1990)	1981 (May–August)	Monthly	43.2–46.6°N	124–125°W	0–150	12	48	Unspecified	70 cm bongo (571 µm)	Community
Ureña (1990)	1980–83 (April–November)	Semiannual–annual	40–48°N	124–129°W	Surface (neuston), 0–200 (bongo)	25	125	825 (neuston), 749 (bongo)	0.15 m² neuston and 60 cm bongo (505 µm)	*Citharichthys sordidus, C. stigmaeus, Glyptocephalus zachirus, Isopsetta isolepis, Lyopsetta exilis, Microstomus pacificus, Parophrys vetulus,* and *Psettichthys melanostictus*
Doyle (1992)	1980–87 (April–November)	Semiannual–annual	40–48°N	124–129°W	Surface (neuston), 0–200 (bongo)	25	125	1161 (neuston), 1086 (bongo)	0.15 m² neuston and 60 cm bongo (505 µm)	Community; featured taxa: *Ammodytes hexapterus, Anoplopoma fimbria, Cololabis saira, Cryptacanthodes aleutensis, Engraulis mordax, Hemilepidotus hemilepidotus, H. spinosus, Hexagrammos decagrammus, H. lagocephalus, Ophiodon elongatus, Ronquilus jordani, Scorpaenichthys marmoratus, Sebastes* spp., and *Tarletonbeania crenularis*
Markle et al. (1992)	1961–82 (unspecified months)	Unspecified	32–61°N	118–179°W	0–600	Unspecified	425	796 (individuals)	IKMT, Cobb, rectangular, and commercial midwater trawls, Tucker trawl, and 1 m² multiple plankton sampler (unspecified mesh)	*Microstomus pacificus*
Doyle et al. (1993)[2]	1980–87 (April–November)	Semiannual–annual	40–48°N	124–129°W	Surface (neuston), 0–200 (bongo)	25	125	1161 (neuston), 1086 (bongo)	0.15 m² neuston and 60 cm bongo (505 µm)	Community
Doyle (1995)	1980–87 (April–November)	Semiannual–annual	40–48°N	124–129°W	Surface (neuston), 0–200 (bongo)	25	125	1161 (neuston), 1086 (bongo)	0.15 m² neuston and 60 cm bongo (505 µm)	Community
Bentley et al. (1996)	1994 (July)	Monthly	43.2–46.3°N	124.1–126.8°W	0–70	12	234	234	0.05 m² CalVET (150 µm)	*Sardinops sagax*
Emmett et al. (1997)	1994–95 (July)	Annual	43–47°N	124–127°W	0–70	12	234	355	0.05 m² CalVET (150 µm)	*Engraulis mordax*

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Study	Period	Frequency	Latitudinal range	Longitudinal range	Depth range (m)	Transects (no.)	Stations (no.)	Samples (no.)	Gear type (mouth diameter/area and mesh size)	Taxon
Doyle et al. (2002)	1980–81, 1984–85, and 1994–95 (April–June)	Annual	40–57°N	124–168°W	0–200	Unspecified	Unspecified	950	60 cm bongo (333–505 µm)	Community
Matarese et al. (2003)	1972–96 (January–December)	Unspecified	38–66°N	120–180°W	Unspecified	Unspecified	Unspecified	11,379	60 and 70 cm bongo, neuston, 1.2 m^2 MOCNESS, 1 m ring, 1 m^2 Tucker trawl, and midwater trawls (unspecified mesh)	Community
Emmett et al. (2005)	1994–98 (July; June in 1996)	Annual	42.6–47.0°N	124.1–126.8°W	0–70	17	340	1086	0.05 m^2 CalVET (150 µm)	*Sardinops sagax*
Shanks and Eckert (2005)	Unspecified	Unspecified	30–47°N	Unspecified	Unspecified	Unspecified	Unspecified	Unspecified	Unspecified	Community
Auth and Brodeur (2006)	2000 and 2002 (April–September)	Monthly	44.65°N	124.17–125.12°W	0–350	1	5	281 depth-stratified samples from 43 hauls	1.2 m^2 MOCNESS (333 µm)	Community; featured taxa: *Engraulis mordax, Lyopsetta exilis, Sebastes* spp., *Stenobrachius leucopsarus,* and *Tarletonbeania crenularis*
Brodeur et al. (2006)	2000, 02, 04, and 05 (April–September)	Monthly	44.00–46.67°N	124.22–125.36°W	0–350	4	20	195	60 cm bongo and 1.2 m^2 MOCNESS (333 µm)	Community; featured taxa: *Engraulis mordax, Merluccius productus,* and *Trachurus symmetricus*
Charter et al. (2006)	2001 (August–December)	Annual	30–48°N	118–131°W	0–200	Unspecified	71	71	70 cm bongo (505 µm)	Community
Pool and Brodeur (2006)	2000 and 2002 (June and August)	Monthly	41.9–44.7°N	124.1–126.0°W	Surface	6	98	347	0.3 m^2 neuston (333 µm)	Community
Auth et al. (2007)	2000 and 2002 (August)	Diel	44.00°N	125.00°W	0–350	1	1	74 depth-stratified samples from 9 hauls (5 day, 4 night)	1.2 m^2 MOCNESS (333 µm)	Community; featured taxa: *Lyopsetta exilis, Sebastes* spp., *Stenobrachius leucopsarus,* and *Tarletonbeania crenularis*
Phillips et al. (2007)	1996–2004 (January–December), 2004–06 (May–November)	Biweekly (1996–2004), monthly (2004–06)	44.65°N (1996–2004), 38.48–47.00°N (2004–06)	124.17–124.29°W (1996–2004), 123.35–126.00°W (2004–06)	0–20 (1996–2004), 0–100 (2004–06)	1 (1996–2004), 16 (2004–06)	2 (1996–2004), 75 (2004–06)	85 (1996–2004), 320 (2004–06)	60 cm bongo and 1 m ring (1996–2004), 60 and 70 cm bongo (333 µm) and 1 m^2 Tucker trawl (2004–06) (335 µm)	*Merluccius productus*
Auth (2008)	2004–06 (May)	Annual	38.48–47.00°N	123.35–126.00°W	0–100	15	60	170 depth-stratified samples from 106 hauls	1 m^2 Tucker trawl (335 µm)	Community; featured taxa: *Citharichthys* spp., *Engraulis mordax, Sebastes* spp., and *Stenobrachius leucopsarus*
Brodeur et al. (2008)	1996–2005 (January–December)	Biweekly	44.65°N	124.17–124.29°W	0–20	1	2	258	60 cm bongo and 1 m ring (200 and 333 µm)	Community; featured taxa: *Ammodytes hexapterus, Artedius harringtoni, Citharichthys* spp., *Engraulis mordax, Isopsetta isolepis, Liparis* spp., Osmeridae, *Parophrys vetulus, Psettichthys melanostictus,* and *Sebastes* spp.
Parnel et al. (2008)	1999–2004 (April–July), 1999–2001 (sporadically other months)	Biweekly	46.05°N	124.05–124.25°W	0–40	1	2	85	1 m ring (335 µm)	Community; featured taxon: *Engraulis mordax*

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[1] Additional live individuals for spawning and rearing were collected in fall–winter 1978 at 44.17°N, 124.30°W at 68–77 m water depth using a 12 m otter trawl.

[2] Only the west coast sampling protocal is listed.

(continued)

TABLE 1, cont'd.

Summary of sampling protocols, sampling effort, and taxa examined for all ichthyoplankton studies conducted in the northern California Current (NCC) region (1940–2012).

Study	Period	Frequency	Latitudinal range	Longitudinal range	Depth range (m)	Transects (no.)	Stations (no.)	Samples (no.)	Gear type (mouth diameter/ area and mesh size)	Taxon
Auth (2009)	2007 (March, April, and October) and 2008 (March, June, and July)	Monthly	41.90–44.65°N	124.10–128.73°W	0–45 (0–100 in June and July 2008)	2	30	72	70 cm bongo (60 cm in June and July 2008) (335 µm)	Community; featured taxa: *Engraulis mordax, Sebastes* spp., *Stenobrachius leucopsarus*, and *Tarletonbeania crenularis*
McClatchie (2009)	2008 (April and July/August)	Monthly	30–49°N	118–128°W	3	Unspecified	Continuous	Continuous	CUFES	*Engraulis mordax* and *Sardinops sagax*
Bystydzieńska et al. (2010)	2009 (June–July)	Monthly	44.00–46.16°N	125.12–125.28°W	0–100	3	5	13 (individuals)	60 cm bongo (333 µm)	*Tarletonbeania crenularis*
Lo et al. (2010)	2003 (July), 2004 (March and July), and 2005 (March)	Annual	42–48°N	124.5–128.0°W	18–20 (surface trawl), unspecified (CalVET), 3 (CUFES)	7	42	214 (surface trawl), 151 (CalVET), continuous (CUFES)	Surface trawl (7 mm), 0.05–m^2 CalVET (150 µm), and CUFES (July only)	*Sardinops sagax*
Auth (2011)	2004–09 (May–October/ November)	Monthly	44.00–46.67°N	124.18–127.14°W	0–100	4	30	489	60 and 70 cm bongo and 1 m^2 Tucker trawl (June 2004) (335 µm)	Community; featured taxa: *Engraulis mordax, Lyopsetta exilis, Sebastes* spp., *Stenobrachius leucopsarus*, and *Tarletonbeania crenularis*
Auth et al. (2011)	January 1971–August 1972, November 1977–June 1978, April–September 1983, and December 1996–December 2005	Biweekly–monthly	44.65°N	124.17–124.29°W	Entire water column (0–20 in 1996–2005)	1	2	350	60 and 70 cm bongo and 1 m ring (200–571 µm)	Community; featured taxa: *Ammodytes hexapterus, Citharichthys* spp., *Engraulis mordax, Isopsetta isolepis,* Osmeridae, *Parophrys vetulus, Psettichthys melanostictus*, and *Sebastes* spp.
Brodeur et al. (2011a)	1998–2010 (January–March)	Biweekly	44.65°N	124.10–124.65°W	0–20	1	6	179	60 cm bongo (200–333 µm) and 1 m ring (333-µm)	*Sebastes* spp.
Brodeur et al. (2011b)	2008 (May–June)	Monthly	46–47°N	124.2–124.5°W	0–10 (herring and Marinovich trawls), 0–20 (Methot trawl), 0–30 (bongo)	Unspecified	Unspecified	21 (each gear type)	37.2 m^2 herring (10 mm), 27.0 m^2 Marinovich (6 mm), and 5 m^2 Methot (1 mm) trawls, and 60 cm bongo (335 µm)	Community
Sogard (2011)	1993–2001 (April–May); too few samples in 1996 for analysis	Annual	44.8°N	124.6°W	Surface	1	1	295 (individuals)	0.7 m^2 Manta (1 mm) and 3.7 m^2 neuston (4.8 mm)	*Anoplopoma fimbria*
Watson and Manion (2011)	2008 (April and July/August)	Monthly	34.1–48.4°N	121–128°W	Surface (Manta), 0–212 (bongo)	20	99	186 (Manta), 188 (bongo)	0.13 m^2 Manta and 70 cm bongo (both 505 µm)	Community
Takahashi et al. (2012)	2005 (August–October) and 2006 (August–September)	Monthly	44.0–48.3°N	124.17–124.29°W	0–40 (2005), 0–12 (2006)	13	113 (2005), 101 (2006)	175 (individuals, 2005), 203 (individuals, 2006)	Midwater (3 mm, 2005) and surface trawls (8 mm, 2006)	*Engraulis mordax*

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[1] Additional live individuals for spawning and rearing were collected in fall–winter 1978 at 44.17°N, 124.30°W at 68–77 m water depth using a 12 m otter trawl.

[2] Only the west coast sampling protocal is listed.

TABLE 2
Study purpose and primary results and management implications of studies listed in Table 1.

Study	Purpose	Scientific, management, and sampling implications
Brock (1940)	Examine development and longitudinal distributions.	Development and spatial distribution of early-life stages of a commercially important species.
Ahlstrom (1956)	Examine development and latitudinal, longitudinal, and vertical distributions.	Development and spatial distribution of early-life stages of a commercially important species.
Aron (1959)	Examine seasonal, latitudinal, longitudinal, vertical, and diel distributions and relative abundances of late-larval taxa and their relation to environmental factors (i.e., temperature and bathymetry).	Variability in the seasonal, spatial, and diel distributions and relative abundances of early-life stages of important commercial and forage taxa. Study is limited to larger, late-larval stage individuals due to the large mesh size employed in sampling, and no flow data are provided to calculate actual abundances.
Aron (1962)	Examine seasonal, latitudinal, longitudinal, vertical, and diel distributions and relative abundances of late-larval taxa and their relation to environmental factors (i.e., temperature, salinity, and bathymetry).	Variability in the seasonal, spatial, and diel distributions and abundances of early-life stages of important commercial and forage taxa, and their relation to environmental factors. Study is limited to larger, late-larval stage individuals due to the large mesh size employed in sampling.
Pearcy (1962)	Examine development and seasonal, latitudinal, and longitudinal distributions.	Development and spatial and temporal distribution of early-life stages of a commercially important species.
LeBrasseur (1970)	Examine annual, seasonal, latitudinal, and longitudinal occurrences and distributions.	Qualitative early description of the temporal and spatial occurrences of larvae in the northeastern Pacific Ocean. Concludes that, in view of the low incidence of larvae, both in terms of numbers and species in the oceanic waters off western Canada, it is unlikely that any major stocks of unexploited or unknown fish species are resident in the mid-ocean area. Gear comparison.
Day (1971)	Examine seasonal, latitudinal, longitudinal, and vertical distributions and abundances of late-larval taxa.	Variability in the seasonal and spatial distributions and abundances of early-life stages of important commercial and forage taxa. Study is limited to larger, late-larval stage individuals due to the large mesh size employed in sampling.
Waldron (1972)	Examine latitudinal and longitudinal distributions and abundances of larvae in the northeastern Pacific Ocean and Puget Sound.	Variability in the spatial distributions and abundances of larvae of important commercial and ecological taxa.
Richardson (1973)	Examine seasonal, latitudinal, longitudinal, and vertical distributions, abundances, and length frequencies of larvae. Compare gear types.	Variability in the seasonal and spatial distributions, abundances, and length frequencies of larvae of commercially and ecologically important taxa. Larval *Engraulis mordax* were concentrated in Columbia River plume waters from June to August. Isaacs-Kidd midwater trawl (IKMT) caught the greatest number and had the greatest frequency of occurrence of major taxa, whereas the bongo caught the most larvae per volume filtered.
Ahlstrom and Stevens (1976)	Examine latitudinal and longitudinal distributions, abundances, and length frequencies. Compare gear types.	Identification and spatial distribution of early-life stages of all taxa with pelagic larvae. Discern the advantages and disadvantages of sampling with different gear types.
Laroche (1976)	Examine taxonomic composition, relative abundance, seasonal occurrence, and diel depth distribution of early-life stages of fish collected off the mouth of the Columbia River.	No conclusive diel or tidal depth differences in abundance. The important forage taxon Osmeridae was dominant, followed by *Engraulis mordax*. Most early-life stage taxa were collected in January-June.
Pearcy et al. (1977)	Examine annual, seasonal, latitudinal, longitudinal, vertical, and diel distributions, abundances, length frequencies, and stage duration of larvae. Estimate age and duration of pelagic life.	Variability in the annual, seasonal, spatial, and diel distributions, abundances, and length-frequencies of early-life stages of important commercial taxa. Duration of the pelagic larval stage for *Glyptocephalus zachirus* and *Microstomus pacificus* estimated to be 1 year, while that for *Eopsetta jordani* is estimated at 6 months.
Richardson and Pearcy (1977)	Examine annual, seasonal, latitudinal, longitudinal, vertical, and diel distributions, abundances, and assemblages of larvae. Compare distribution patterns of larvae off the mid-Oregon coast with those found in nearby Yaquina Bay, elsewhere in the northeast Pacific Ocean, and with other planktonic components.	Variability in the annual, seasonal, spatial, and diel distributions, abundances, and assemblages of larvae of commercially and ecologically important taxa. Coastal and offshore assemblages were identified. Peak abundance in both assemblages occurred between February and July. The larval taxa present in the coastal assemblage were similar to those in Yaquina Bay, but dominant taxa were very different. The coastal zone is an important spawning area for the commercially important species *Parophrys vetulus*, which utilizes Yaquina Bay estuary during part of its early life. Larval fish and zooplankton trends do not always correspond with each other.
Laroche and Richardson (1979)	Examine annual, seasonal, latitudinal, longitudinal, vertical, and diel distributions, abundances, and length frequencies of larvae and their relation to environmental factors (i.e., coastal winds, surface water transport, upwelling, coastal precipitation, temperature, and salinity). Compare gear and tow types. Estimate age and duration of pelagic life.	Variability in the annual, seasonal, spatial, and diel distributions, abundances, and length-frequencies of early-life stages of important commercial taxa, and their relation to environmental factors. Development of an indirect method to obtain rough estimates of age from size composition for *Parophrys vetulus* larvae. Duration of the pelagic larval stage for *P. vetulus* estimated to be 18–22 weeks.
Richardson and Laroche (1979)	Document developmental characteristics to aid in taxonomic identification, and seasonal, latitudinal, and longitudinal distributions and length frequencies.	Identification and seasonal and spatial distribution of early-life stages of commercially important taxa.

(continued)

TABLE 2, cont'd.
Study purpose and primary results and management implications of studies listed in Table 1.

Study	Purpose	Scientific, management, and sampling implications
Laroche and Richardson (1980)	Document developmental characteristics to aid in taxonomic identification, and seasonal, latitudinal, and longitudinal distributions and length frequencies.	Identification and seasonal and spatial distribution of early-life stages of commercially important taxa.
Richardson et al. (1980a)	Document developmental characteristics to from egg through benthic juvenile to aid in taxonomic identification, and seasonal, latitudinal, and longitudinal distributions and length frequencies.	Identification and seasonal and spatial distribution of early-life stages of commercially important taxa.
Richardson et al. (1980b)	Examine annual, seasonal, latitudinal, longitudinal, and diel distributions, abundances, length frequencies, and assemblages of larvae and their relation to environmental factors (i.e., coastal winds, surface water transport, upwelling, coastal precipitation, temperature, and salinity).	Variability in the annual, seasonal, spatial, and diel distributions, abundances, length-frequencies, and assemblages of larvae of important commercial and ecological taxa, and their relation to environmental factors. Coastal, transitional, and offshore assemblages persisted along the coast and from year to year. Differences in the extent off offshore distribution of the coastal assemblages among years reflected differences in local coastal wind patterns. These consistencies suggests that transport may not be a major cause of larval mortality and recruitment failure in the northern California Current (NCC).
Kendall (1981)	Describe the life-history patterns of North Pacific fishes, the constraints on fisheries investigations imposed by these patterns, and offer some suggestions for further studies.	Broad, theoretical discussion of the importance of early-life history stages and studies to fisheries research in the northeastern Pacific Ocean.
Laroche and Richardson (1981)	Document developmental characteristics to aid in taxonomic identification, and seasonal, latitudinal, and longitudinal distributions and length frequencies.	Identification and seasonal and spatial distribution of early-life stages of commercially important taxa.
Methot (1981)	Determine and compare the larval growth rates of two co-occurring, dominant species. Examine covariance in growth rate between the species among samples for clues to relationships between larval fish and their environment.	Larval growth of important forage species. No correlation found between *Engraulis mordax* and *Stenobrachius leucopsarus* growth rates. Based on ambient water temperatures, growth of *E. mordax* larvae appears to be similar in the laboratory and in the sea.
Parrish et al. (1981)	Present a simplified, but unified and consistent, description of broad time and space scale characteristics of ocean surface flow in the California Current region (CCR), and point out a gross pattern of correspondence to these features among the reproductive strategies of the most successful coastal fish stocks.	Insights into the factors regulating recruitment. Anomalies in surface drift patterns could be a major cause of the observed wide variation in spawning success of the major fishery species of the CCR. In the northwest Pacific, coastal fish taxa having pelagic larvae tend to spawn during winter when surface wind drift is generally directed toward the coast, rather than during the more productive upwelling season.
Richardson (1981)	Examine annual, latitudinal, and longitudinal distributions of eggs and larvae of an ecologically important species, and their relation to environmental factors (i.e., temperature, salinity, chlorophyll *a*, and surface currents). Define spawning centers and provide estimates of spawning stock biomass (SSB). Examine ecological data on the early-life stages of *Engraulis mordax*.	Variability in the annual and spatial distributions and abundances of eggs and larvae of an ecologically important species, and their relation to environmental factors. A major spawning center for the northern subpopulation of *E. mordax* is documented off the Oregon-Washington coast beyond the continental shelf, associated with waters of the Columbia River plume. Biomass, SSB, and potential yield estimates are provided.
Laroche et al. (1982)	Examine stage duration, age, and growth.	Spawning season and early-life stage growth of an important commercial species. Duration of the pelagic larval stage for *Parophrys vetulus* estimated to be 8–10 weeks.
Rosenberg and Laroche (1982)	Document developmental characteristics to aid in taxonomic identification, and examine stage duration, age, and growth.	Early-life stage growth of an important commercial species. Duration of the pelagic larval stage for *Parophrys vetulus* estimated to be 120 d (17 weeks).
Gadomski and Boehlert (1984)	Describe annual differences in the feeding ecology of larvae of the commercially important species *Isopsetta isolepis* and *Parophrys vetulus* in order to improve understanding of the causes of variability in year-class strength.	Larval *I. isolepis* have a varied diet. Larval *P. vetulus* are dependent upon a specific prey (i.e., the appendicularian *Oikopleura* spp.). A mismatch of *P. vetulus* and appendicularian abundance peaks may result in significant food-related mortality.
Mundy (1984)	Examine annual, seasonal, and longitudinal distributions, abundances, length frequencies, and community structure of larvae and their relation to environmental factors (i.e., temperature, salinity, wind speed and direction, wind stress curl, upwelling intensity, percipitation, zooplankton, and relative year-class strength estimates for *Isopsetta isolepis* and *Parophrys vetulus*). Determine spawning seasons, transport mechanisms, and early-life histories of coastal northeastern Pacific fishes.	Variability in the annual, seasonal, and spatial distributions, abundances, and length frequencies of early-life stages of commercially and ecologically important taxa, and their relation to environmental factors. Identification of spawning seasons and mechanisms of larval retention. Identified three seasonal spawning groups: winter, spring-summer, and continuous. Abundances of *I. isolepis* and *P. vetulus* larvae are not good predictors of year-class strength in the fishery. Gear comparison.
Young (1984)	Document developmental characteristics to aid in taxonomic identification.	Identification of early-life stages of commercially, recreationally, and ecologically important taxa.

(continued)

TABLE 2, cont'd.
Study purpose and primary results and management implications of studies listed in Table 1.

Study	Purpose	Scientific, management, and sampling implications
Boehlert et al. (1985)	Examine seasonal, longitudinal, diel, and vertical distributions, abundances, and community structure of fish larvae.	Variability in the seasonal, longitudinal, diel, and vertical distributions, abundances, and community structure of early-life stages of important commercial and forage taxa. Identification of longitudinal assemblages. Highest abundances near seasonal thermocline. Evidence for type I and II diel vertical migration.
Brodeur et al. (1985)	Examine seasonal and longitudinal distributions, abundances, length frequencies, and community structure, and their relation to environmental factors, of a nearshore assemblage during anomalous El Niño conditions.	Shoreward displacement and increased abundance of offshore taxa, especially the commercially ecologically important species *Engraulis mordax*, and reduced abundance of nearshore taxa during El Niño conditions.
Grover and Olla (1986)	Detect the possible occurrence of starvation in larval *Anoplopoma fimbria* in the NCC using selected morphological measurements to determine variability in larval condition. Analyze prey size-selection and diet to examine the relationship between larval condition and feeding requirements.	Occurrence of starving larvae at a single station appears to reflect a paucity of copepod nauplii. Definitive shifts in prey size occur at ~12.5 and 20.5 mm standard length (SL). The diet of larger larvae is more diverse than that of smaller larvae. Smaller larvae appear limited in the size of prey they can exploit. This limitation, combined with larvae ≤12.5 mm SL being associated with an unsuitable prey patch, may have been responsible for the high incidence of empty guts and starvation at a single station.
Grover and Olla (1987)	Examine the effect of an El Niño event on the feeding habits of larval *Anoplopoma fimbria*, through a comparison of their diet in the NCC during the 1983 El Niño event and 1980, a year in which oceanographic conditions were not anomalous. Examine ontogenetic differences in diet.	Differential utilization of appendicularians, pteropods, and amphipods was seen in the two years. Small copepods contributed significantly more to the diet in the El Niño year of 1983 than in 1980. Dietary data for 1983 were generally supported by independent plankton observations, especially with respect to the predominance of *Paracalanus parvus,* a small calanoid copepod species. Because adult *A. fimbria* live and spawn in deep water, changes in the food habits of neustonic larvae may represent one of the principal effects of the El Niño conditions on this species.
Kendall and Matarese (1987)	Review studies to describe spawning season, egg and larval morphology, developmental rates, and annual, seasonal, latitudinal, longitudinal, and vertical distributions, larval feeding, and determination of year-class size.	Determination of spawning season and early-life stage morphology, developmental rates, distribution, feeding, and year-class size of an important commercial species. *Anoplopoma fimbria* spawn pelagic eggs in winter near the continental shelf. The eggs float deeper than 200 m and probably require 2–3 weeks to develop. Shortly after hatching, larvae appear to swim to the surface and grow quickly (up to 2 mm per day) as part of the neuston during the spring. There is no transition from larvae to juvenile, but by summer the young-of-the-year fish are found at the surface in inshore waters. Evaluation of how early-life history information might be used to improve fisheries management.
Shenker (1988)	Examine seasonal, longitudinal, and diel distributions, abundances, length-frequencies, and assemblages of larvae and their relation to environmental factors (i.e., upwelling, temperature, salinity, and chlorophyll *a*).	Variability in the seasonal, spatial, and diel distributions, abundances, length-frequencies, and assemblages of larvae of important commercial and ecological taxa, and their relation to environmental factors. Identification of pre-upwelling (i.e., *Anoplopoma fimbria*, *Hemilepidotus spinosus*, *Hexagrammos* spp., *Parophrys vetulus*, and *Scorpaenichthys marmoratus*) and post-upwelling (i.e., *Engraulis mordax* and *Sebastes* spp.) assemblages. These taxa had distinct zonal (east-west) distribution patterns and were generally associated with, or affected by, hydrographic characteristics such as convergences, upwelling, and the Columbia River plume.
Brodeur (1989)	Examine the seasonal, latitudinal, and longitudinal distributions and abundances of all neustonic organisms >5 mm, and compare the taxonomic composition and relative abundance with those found in the stomachs of juvenile salmon collected from the same stations at approximately the same times.	Variability in the seasonal and spatial distributions and abundances of early-life stages of important forage taxa. Study assesses the importance of the neustonic fauna to the diets of juvenile coho and Chinook salmon.
Dunn and Rugen (1989)	Document all ichthyoplankton cruises conducted by the Northwest and Alaska Fisheries Center (NWAFC) during 1965–88.	For each cruise, the report explains areas of sampling, cruise purposes, number of stations sampled, sampling methodology, and associated measurements made, along with a brief assessment of catch composition. Provides a good overview/reference for NWAFC sampling during 1965-88.
Matarese et al. (1989)	Document developmental characteristics to aid in taxonomic identification, and seasonal, latitudinal, and longitudinal distributions.	Identification and seasonal and spatial distribution of early-life stages of all taxa with pelagic, coastal larvae.
Brodeur (1990)	Examine seasonal, latitudinal, longitudinal, and diel occurrence of early-life stage taxa.	Variability in the seasonal and spatial occurrences of early-life stages of important commercial and forage taxa. Study is mostly qualitative.
Ureña (1990)	Examine annual, seasonal, latitudinal, and longitudinal distributions, abundances, and length frequencies of eggs and larvae and their relation to environmental factors (i.e., temperature, salinity, density, and upwelling intensity). Develop standard criteria to stage larval specimens of the eight pleuronectiformes and use that classification with standard length as an indicator of a chronological order of development.	Variability in the annual, seasonal, and spatial distributions, abundances, and length frequencies of early-life stages of eight important commercial flatfish taxa, and their relation to environmental factors. Identification of spawning seasons and mechanisms of larval retention. Increased poleward advection of eggs and larvae from regions south of the study area during the 1983 El Niño event. Gear (depth) comparison.
Doyle (1992)	Examine annual, seasonal, latitudinal, longitudinal, diel, and vertical distributions, abundances, and community structure of eggs and larvae. Gear comparison.	Variability in the temporal and spatial distributions, abundances, and community structure of early-life stages of important commercial and forage taxa, and their relationship to variable environmental factors and seasonal currents. The ecological significance of a neustonic existence. Gear (depth) comparison.

(continued)

TABLE 2, cont'd.
Study purpose and primary results and management implications of studies listed in Table 1.

Study	Purpose	Scientific, management, and sampling implications
Markle et al. (1992)	Document developmental characteristics to aid in taxonomic and stage identification, and examine stage duration, age, and growth.	Spawning season and early-life stage growth of an important commercial species. Duration of the pelagic larval stage for *Microstomus pacificus* estimated to be 18–24 months. Metamorphosis is protracted, seasonally-triggered, and may involve a significant period during which larvae switch between midwater and bottom habitats.
Doyle et al. (1993)	Examine broad-scale spatial patterns in the ichthyoplankton off the west and east coasts of the U.S.	Multispecies spatial patterns imply the existence of persistant and geographically distinct larval fish assemblages, possibly related to specific hydrographic features, off both coasts. On the West Coast, four assemblages were identified: coastal/shelf, slope/transition, Columbia River plume, and oceanic, for which northern and southern components were apparent during winter and spring. Gear (depth) comparison.
Doyle (1995)	Identify anomalies in the seasonal, latitudinal, and longitudinal distribution and abundance patterns of larval taxa during the El Niño event in 1983 with those in other years during the 1980s.	Provides insight into the effects of El Niño events on the spawning patterns and early-life history of ecologically and commercially important fish in the NCC region. Anomalies observed during the El Niño event in 1983 include temporal shifts in peak abundance of some ichthyoplankton, reduced abundance of others, the occurrence of rare southern species, and changes in distribution patterns. These anomalies are attributed to changes in spawning patterns and advection of ichthyoplankton in response to the physical oceanographic anomalies (i.e., water temperature and transport) resulting from El Niño. A high level of stability in the spawning and early-life history patterns of taxa is implied, since only a small portion of the dominant taxa were affected by the sttrong 1983 El Niño event. Gear (depth) comparison.
Bentley et al. (1996)	Examine latitudinal and longitudinal distributions of eggs and larvae, and estimates of egg production and mortality and SSB.	First documented occurrence of early-life stages of *Sardinops sagax* north of California since the 1940s. Early-life stage spatial distribution, egg production and mortality, and SSB estimates for a commercially important taxa. Identification of an association between geographic distribution of *S. sagax* eggs and the 14°C isotherm derived from the 1–10 m depth zone. The isotherm of 14°C may form a distinct boundary for spawning *S. sagax* off Oregon and may prove useful for determining boundaries for future spawning surveys.
Emmett et al. (1997)	Examine annual, latitudinal, and longitudinal distributions of eggs and larvae of an ecologically important species.	Abundance and distribution of *Engraulis mordax* eggs and larvae were extremely limited when compared to those observed in the mid-1970s. Eggs, and thus spawning, occurred nearshore on the continental slope. Larvae occurred offshore in the Columbia River plume.
Doyle et al. (2002)	Identify dominant taxa and taxonomic assemblages in the ichthyoplankton of the Gulf of Alaska, eastern Bering Sea, and U.S. West Coast. Describe latitudinal and longitudinal distributions of these assemblages, and relate them to the prevailing oceanographic conditions in the three regions.	Occurrence of geographically distinct assemblages of larvae in each region. For all three regions, assemblage structure is primarily related to bathymetry, and shelf, slope, and deep-water assemblages are described. This shallow to deep-water gradient in taxon occurrence and abundance reflects the habitat preference and spawning location of the adult fish. Another degree of complexity is superimposed on this primary assemblage structure and appears to be related to local topography and the prevailing current patterns.
Matarese et al. (2003)	Create a regional atlas to summarize and illustrate the annual, seasonal, latitudinal, and longitudinal distribution, abundance, and length-frequency patterns of fish eggs and larvae of 102 taxa within 34 families found in the northeast Pacific Ocean.	Summary of general life-history data for each taxon. Variability in the annual, seasonal, and spatial distributions, abundances, and length frequencies of egg and larval stages of numerically dominant taxa. Framework for future studies to define assemblages of larvae and how their occurrences reflect spatial and temporal patterns.
Emmett et al. (2005)	Examine annual, latitudinal, and longitudinal distributions and abundances of eggs and larvae, and relate them to ecological factors.	Variability in the annual, seasonal, and spatial distributions and abundances of early-life stages of an important commercial and forage species, and their relationship to environmental variables. Identification of an association between geographic distribution of *Sardinops sagax* eggs and surface temperatures between 14° and 15°C.
Shanks and Eckert (2005)	Investigate the effects of life-history traits on alongshore larval transport in the CCR, specifically whether combinations of life-history traits (timing of propagule release, planktonic duration, etc.) might "move" larvae against the dominant southward flow of the California Current. Because oceanographic variables controlling flow change dramatically between nearshore (<30 m deep) and deeper waters, the study compares life-history traits of nearshore fishes to taxa from the continental slope.	Pelagic larval durations of shelf/slope taxa (as are found in the NCC) are long (~136 d). Offspring are pelagic winter through summer and are found at depth below the mixed layer offshore. Offspring experience northward flow in winter and southward flow in spring/summer, perhaps minimizing alongshore drift. Adults are both long-lived and highly fecund. The pelagic phase, rather than being dispersive, may be selected to achieve a migration between larval pelagic and adult benthic habitats. Summaries of data on life-history traits and cross-shelf and vertical distributions of fish larvae.
Auth and Brodeur (2006)	Identify, quantify, and compare distributions, abundances, diversity, evenness, and assemblages across annual, seasonal, longitudinal, and vertical scales, and relate them to temperature and salinity.	Variability in the annual, seasonal, and spatial distributions, abundances, and community structure of early-life stages of important commercial and forage taxa, and their relationship to environmental variables. Community is similar to that reported in previous studies. Trophic interaction between fish larvae and ctenophores and salps. Occurrence of *Sardinops sagax* larvae in the NCC. Identification of longitudinal (coastal, offshore, and Columbia River plume [consisting of *Engraulis mordax* and *S. sagax* larvae]) and seasonal (spring, summer, and fall) assemblages. Cross-shelf location most important factor to community structure. Sampling in the upper 100 m of the water column is sufficient to characterize the larval community. Larvae generally positivelty correlated with in situ temperature, and negatively correlated with salinity.

(continued)

TABLE 2, cont'd.
Study purpose and primary results and management implications of studies listed in Table 1.

Study	Purpose	Scientific, management, and sampling implications
Brodeur et al. (2006)	Examine changes in the ichthyoplankton community resulting from the aomalous late upwelling in 2005, which was unrelated to ENSO.	Early-life stages of the commercially important species *Merluccius productus* and *Trachurus symmetricus* were collected in unprecedented numbers during 2004–05, suggesting that their spawning area had shifted north by ~1000 km. *E. mordax* larvae were found at many stations outside of their normal Columbia River plume habitat. These anomalous occurrences were related to the unusual ocean conditions in 2004–05, similar to El Niño conditions.
Charter et al. (2006)	Document latitudinal and longitudinal abundances and distributions of ichthyoplankton and paralarval cephalopods throughout the CCR in 2006.	This report provides ichthyoplankton and associated station and tow data from the Oregon, California, and Washington Line-Transect Expedition (ORCAWALE) survey during 2006 and makes these data available to all investigators.
Pool and Brodeur (2006)	Examine annual, seasonal, latitudinal, longitudinal, and diel distributions, abundances, and community structure of early-life stages and their relation to environmental factors.	Variability in the annual, seasonal, diel, and spatial distributions and abundances of early-life stages of important salmonid forage taxa, and their relationship to environmental variables.
Auth et al. (2007)	Examine diel and vertical distributions, abundances, diversity, evenness, and community structure of fish eggs and larvae, and their relation to temperature and salinity.	Variability in the diel and vertical distributions, abundances, and community structure of early-life stages of important commercial and forage taxa, and their relationship to environmental variables. Community is similar to that reported in previous studies. Occurrence of *Sardinops sagax* and *Trachurus symmetricus* larvae and eggs in the NCC. Identification of depth-stratified (<100 m and >100 m) assemblages. Depth most important factor to community structure. Sampling in the upper 100 m of the water column is sufficient to characterize the ichthyoplankton community. More larvae collected at night than during the day, so sampling should be conducted at night to minimize effects of net avoidance. Evidence for type I and II diel vertical migration. Eggs and larvae generally possitivelty correlated with in situ temperature, and negatively correlated with salinity.
Phillips et al. (2007)	Document relatively high occurrence of early-life stage *Merluccius productus* in the NCC in 2003–06.	Spawning and recruitment of commercially important *M. productus* has expanded northward from its historical spawning region off southern California, which will likely have major economic and ecological consequences in the NCC.
Auth (2008)	Analyze distribution, abundance, and community structure from the central and NCC region to investigate interannual, latitudinal, longitudinal, and vertical variability during the transitional month (with respect to larval community structure) of May in three consecutive years, each representing periods of highly variable climate-induced oceanic conditions.	The ichthyoplankton community changed swiftly and dramatically in response to the variable environmental conditions of 2004–06. Larvae were found in higher abundances in norther (>43°N) than southern (<43°N) stations. Latitude, station depth, and sea-surface temperature were the most important factors explaining variability in larval abundances of important commercial and forage taxa. Occurrence of commercially important *Merluccius productus* and *Sardinops sagax* larvae throughout the study area. Taxa clustered into two latitudinal and three longitudinal groups suggesting that limited, but representative, sampling within each group could adequately describe the community structure of each region.
Brodeur et al. (2008)	Identify and compare abundance, diversity, and community structure from two nearshore stations off the central Oregon coast to test for annual, seasonal, and monthly differences. Relate the larval communities to fluctuating marine environmental conditions in this dynamic upwelling region using a long time-series of data.	Identified two seasonal assemblages: winter/spring (January–May) and summer/fall (June–December), with the winter/spring assemblage having the highest diversity and abundance. Diversity and abundance of important commercial and forage taxa were positively related to the Pacific Decadal Oscillation (PDO). During cool years (1999–2002; negative PDO), the assemblage was dominated by northern or coastal taxa such as *Ammodytes hexapterus, Citharichthys* spp., and Osmeridae, whereas in warm years (2003–05; possitive PDO), southern or offshore taxa such as *Parophrys vetulus*, *Engraulis mordax*, and *Sebastes* spp. were more important. These changes were related to concurrent shifts in the zooplankton biomass and composition off Oregon during cold and warm environmental regimes. Identified a small subset of fish whose larvae can be monitored as indicators of warm and cold phases in the NCC. Occurrence of commercially important *Merluccius productus* and *Sardinops sagax* larvae collected in the study area.
Parnel et al. (2008)	Examine annual, seasonal, and longitudinal distributions, abundances, and community structure of eggs and larvae, and their relation to environmental factors (i.e., temperature, salinity, chlorophyll *a*, Columbia River flow, and day of spring upwelling transition), near the mouth of the Columbia River.	Variability in the annual and seasonal distributions, abundances, and community structure of early-life stages of commercially and ecologically important taxa, and their relation to environmental factors. Identified strong taxonomic associations based primarily on season (before or after the spring upwelling transition date). Egg and larval abundances were most correlated with temperature. Occurrence of *Trachurus symetricus* eggs denotes spawning of this normally southern commercially important taxa in northern waters.
Auth (2009)	Compare the ichthyoplankton in the heavily-sampled coastal and shelf region to those in the under-sampled far-offshore region in the NCC. Relate these abundance data to local and basin-scale environmental variables and indices.	Abundances of all dominant commercially and ecologically important larvae were significantly greater in the normally unsampled, far-offshore (>2000 m depth) region than in the normally sampled, coastal and shelf (<2000 m depth) region. *Engraulis mordax* were exclusively found in the warmer Columbia River plume waters in the far-offshore region in June and July 2008. *Sardinops sagax* eggs and larvae were exclusively found at the furthest offshore stations. Abundances were generally positively correlated with temperature and negatively correlated with salinity. Sampling designs should incorporate far-offshore stations at least 100 km beyond the continental slope if they are to truely capture the entire community structure of the important commercial and forage species in the NCC.
McClatchie (2009)	Document seasonal, latitudinal, and longitudinal abundances and distributions of *Engraulis mordax* and *Sardinops sagax* eggs throughout the CCR in 2008.	This report provides *E. mordax* and *S. sagax* egg data from the California Current Ecosystem Survey (CCES) cruises during 2008 to aid in estimation of spawning locations, success, and SSB.

(continued)

TABLE 2, cont'd.
Study purpose and primary results and management implications of studies listed in Table 1.

Study	Purpose	Scientific, management, and sampling implications
Bystydzieńska et al. (2010)	Examine stage duration, age, and growth.	Spawning season and early-life stage growth of an important forage species. Back-calculated hatch dates suggest a prolonged spawning season without any distinct peak.
Lo et al. (2010)	Examine annual, seasonal, latitudinal, and longitudinal distributions of eggs and early-life stages, estimate egg production and SSB, and identify spawning habitat of a commercially and ecologically important species.	Spawning habitat in 2003–04 was located in the southeastern area of the Pacific northwest coast (PNC), a shift from the northwest area off the PNC in the 1990s. Egg production off the PNC for 2003–04 was lower than that off California and that in the 1990s. Because the biomass of *Sardinops sagax* off the PNC appears to be supported heavily by migratory fish from California, the sustainability of the local PNC population relies on the stability of the population off California, and on local oceanographic conditions for local residence.
Auth (2011)	Investigate annual, seasonal, latitudinal, and longitudinal distributions, abundances, diversity, and community structure. Identify and describe the variability within taxonomic, annual, seasonal, latitudinal, and longitudinal ichthyoplankton assemblages within the NCC. Identify taxa indicative of each temporal and spatial assemblage. Identify the local and larger-scale environmental factors that influence variability in ichthyoplankton abundance and diversity.	Several seasonal and cross-shelf assemblages were identified, and annual, seasonal, latitudinal, and longitudinal gradients of taxonomic associations with significant indicator taxa were found. Community is similar to that reported in previous studies. Sampling can be reduced to four seasonal collections and fewer stations within each of three cross-shelf regions, and still adequately describe the spring-fall larval community. The larval community is influenced by variable local and larger-scale environmental conditions. Distance from shore, salinity, and temperature were the local environmental factors explaining the most variability in larval abundance. Indices such as Columbia River outflow and SST can help predict the spawning success of several dominant ecologically and commercially important taxa 2–4 months in advance. Researchers and managers may be able to incorporate the temporal and spatial distributions and abundances, along with in situ environmental statistics, into fisheries models.
Auth et al. (2011)	Examine seasonal and pseudo-decadal changes in abundance, community structure, diversity, and evenness using a long time-series of data from several studies. Incorporate readily available regional and basin-scale environmental data into generalized additive models (GAMs) to determine the most important environmental factors relating to the trends in larval fish data. Support informing fisheries management of the influence of climate on stock structure by affecting recruitment success of larval life-history stages.	The most abundant taxa from 1996–2005 differ from those of earlier decades. Abundances were generally greater in winter/spring (January-May) than summer/fall (June–December). Using GAMs, variations in taxa presence-absence and abundance were compared to climate indices such as the PDO, Northern Oscillation Index (NOI), and the Multivariate ENSO Index (MEI) and local environmental factors, such as upwelling, Ekman transport, and wind stress curl. Significant relationships were found for various combinations of environmental variables with lag periods ranging from zero to seven months. Large-scale climate indices explained more of the variance in abundance and diversity than did the more local factors. Readily-available oceanographic and climate indices can explain and possibly predict variations in the dominant, commercially and ecologically important ichthyoplankton taxa in the NCC. Different indices explain more variability in abundances of different taxa possibly due to variability in life-history strategies.
Brodeur et al. (2011a)	Identify the early-life stage at which recruitment may be set and provide indicators of year-class strength. Relate environmental indices to larval abundance, predation by salmonids, and future recruitment of *Sebastes* spp.	Multiple indicators used to identify upcoming strong year classes in *Sebastes* spp. suggest that 2004 and 2010 were above average for their recruitment. Continued monitoring of larval abundance may be used to predict future strong and weak year classes of this commercially important taxon.
Brodeur et al. (2011b)	Examine seasonal, latitudinal, and longitudinal abundances, distributions, length frequencies, and community structure of early-life stages of important salmonid prey taxa. Compare the taxonomic and size composition of potential salmonid prey organisms caught in a range of plankton/micronekton sampling gears with those found in juvenile *Oncorhynchus kisutch* and *O. tshawytscha* stomachs collected concurrently in the same locations in coastal marine waters, with a goal of evaluating factors related to prey estimation using different gears.	Gear comparison. Overlap between prey fields and salmonid diets was moderate for samples from the larger gear types but low for those from bongo nets towed in the same area.
Sogard (2011)	Examine variability in interannual growth rates and their relation to environmental factors and recruitment.	Growth rates were related to fish size and water temperature. Interannual differences in growth corresponded to large scale (e.g., PDO) oceanographic indices of productivity and transport in the NCC. Growth during the early neustonic stage was generally correlated with subsequent recruitment to the adult stock. The results are consistent with longer-term observations of strong environmental drivers of recruitment in West Coast *Anoplopoma fimbria* and suggest that bottom-up processes during the early-life stages are important determinants of year class success.
Watson and Manion (2011)	Document seasonal, latitudinal, longitudinal, and depth-stratified (surface versus entire water column) abundances and distributions of ichthyoplankton and paralarval cephalopods throughout the CCR in 2008.	This report provides ichthyoplankton and associated station and tow data from the California Cooperative Oceanic Fisheries Investigations (CalCOFI) and CCES cruises during 2008, makes these data available to all investigators, and serves as a guide to the computer data base.
Takahashi et al. (2012)	Examine seasonal variability in growth rate of early-life stages of *Engraulis mordax* in response to physical and biological factors (i.e., upwelling intensity, temperature, chlorophyll *a*, and copepod community) in the anomalously late upwelling year of 2005, and compare these results to the more normal upwelling year of 2006.	Identification of variable spawning timing, location, and success. Delayed upwelling in 2005 resulted in low food availability and consequently reduced *E. mordax* growth rate in early summer, but once upwelling began in July, high food availability enhanced larval growth rate to that typical of a normal upwelling year (e.g., 2006) in the NCC.

TABLE 3

Summary of ichthyoplankton taxa collected in the northern California Current (NCC) region during recent years (1996–2012). Occurrence = rare (frequency occurrence <0.05), common (frequency occurrence >0.05), abundant (mean concentration >5 1000 m^{-3}) as defined by Brodeur et al. 2008 and Auth 2011.

Taxa	Common Name	Occurrence
Elopomorpha		
Undetermined spp.	Leptocephalus larval eels	Rare
Clupeiformes		
Undetermined spp.	Herrings, Anchovies	Rare
Clupeidae		
Sardinops sagax	Pacific sardine	Rare
Engraulidae		
Engraulis mordax	Northern anchovy	Abundant
Bathylagidae		
Bathylagus pacificus	Pacific blacksmelt	Rare
Leuroglossus schmidti	Northern smoothtongue	Rare
Lipolagus ochotensis	Eared blacksmelt	Common
Pseudobathylagus milleri	Stout blacksmelt	Rare
Undetermined spp.	Blacksmelts	Rare
Microstomatidae		
Microstoma microstoma	Slender argentine	Rare
Nansenia candida	Bluethroat argentine	Rare
Osmeridae		
Undetermined spp.	Smelts	Abundant
Phosichthyidae		
Cyclothone signata	Showy bristlemouth	Rare
Sternoptychidae		
Undetermined spp.	Hatchetfishes	Rare
Stomiidae		
Chauliodus macouni	Pacific viperfish	Rare
Tactostoma macropus	Longfin dragonfish	Rare
Aristostomias scintillans	Shiny loosejaw	Rare
Notosudidae		
Scopelosaurus spp.	Paperbones/Waryfish	Rare
Paralepididae		
Lestidiops ringens	Slender barracudina	Rare
Myctophidae		
Electrona rissoi	Chubby flashlightfish	Rare
Protomyctophum crockeri	California flashlightfish	Rare
Protomyctophum thompsoni	Bigeye lanternfish	Common
Tarletonbeania crenularis	Blue lanternfish	Abundant
Nannobrachium regale	Pinpoint lampfish	Common
Nannobrachium ritteri	Broadfin lampfish	Rare
Stenobrachius leucopsarus	Northern lampfish	Abundant
Diaphus theta	California headlightfish	Rare
Notoscopelus resplendens	Patchwork lampfish	Rare
Merlucciidae		
Merluccius productus	Pacific hake	Rare
Gadidae		
Microgadus proximus	Pacific tomcod	Common
Theragra chalcogramma	Walleye pollock	Rare
Ophidiidae		
Spectrunculus grandis	Pudgy cuskeel	Rare
Bythitidae		
Brosmophycis marginata	Red brotula	Rare
Cataetyx rubrirostris	Rubynose brotula	Rare
Gobiesocidae		
Gobiesox maeandricus	Northern clingfish	Rare
Lampridae		
Lampris guttatus	Opah	Rare
Trachipteridae		
Trachipterus altivelis	King-of-the-salmon	Rare
Melamphaidae		
Melamphaes lugubris	Highsnout bigscale	Rare
Scorpaenidae		
Sebastes spp.	Rockfishes	Abundant
Sebastolobus spp.	Thornyheads	Common
Anoplopomatidae		
Anoplopoma fimbria	Sablefish	Rare
Hexagrammidae		
Oxylebius pictus	Painted greenling	Rare
Ophiodon elongatus	Lingcod	Rare
Hexagrammos decagrammus	Kelp greenling	Rare
Hexagrammos lagocephalus	Rock greenling	Rare
Hexagrammos octogrammus	Masked greenling	Rare
Cottidae		
Hemilepidotus hemilepidotus	Red Irish lord	Rare
Hemilepidotus jordani	Yellow Irish lord	Rare
Hemilepidotus spinosus	Brown Irish lord	Rare
Hemilepidotus spp.	Irish lords	Rare
Scorpaenichthys marmoratus	Cabezon	Rare
Myoxocephalus polyacanthocephalus	Great sculpin	Rare
Ascelichthys rhodorus	Rosylip sculpin	Rare
Chitonotus pugetensis	Roughback sculpin	Rare
Enophrys bison	Buffalo sculpin	Rare
Paricelinus hopliticus	Thornback sculpin	Rare
Radulinus asprellus	Slim sculpin	Rare
Radulinus boleoides	Darter sculpin	Rare
Synchirus gilli	Manacled sculpin	Rare
Ruscarius meanyi	Puget Sound sculpin	Rare
Artedius fenestralis	Padded sculpin	Rare
Artedius harringtoni	Scalyhead sculpin	Common
Artedius lateralis	Smoothhead sculpin	Rare
Artedius corallinus or *notospilotus*	Coralline or Bonyhead sculpin	Rare
Clinocottus acuticeps	Sharpnose sculpin	Rare
Clinocottus embryum	Calico sculpin	Rare
Clinocottus globiceps	Mosshead sculpin	Rare
Oligocottus maculosus	Tidepool sculpin	Rare
Oligocottus snyderi	Fluffy sculpin	Rare
Cottus asper	Prickly sculpin	Rare
Leptocottus armatus	Pacific staghorn sculpin	Common
Hemitripteridae		
Blepsias cirrhosus	Silverspotted sculpin	Rare
Agonidae		
Stellerina xyosterna	Pricklebreast poacher	Rare
Bothragonus swani	Rockhead	Rare
Xeneretmus latifrons	Blacktip poacher	Rare
Bathyagonus pentacanthus	Bigeye poacher	Rare
Psychrolutidae		
Malacocottus zonurus	Darkfin sculpin	Rare
Undetermined spp.	Fathead sculpins	Rare
Liparidae		
Liparis fucensis	Slipskin snailfish	Common
Liparis gibbus	Variegated snailfish	Rare
Liparis mucosus	Slimy snailfish	Rare
Liparis pulchellus	Showy snailfish	Rare
Liparis spp.	Snailfishes	Abundant
Carangidae		
Trachurus symmetricus	Jack mackerel	Rare
Bathymasteridae		
Ronquilus jordani	Northern ronquil	Rare
Stichaeidae		
Poroclinus rothrocki	Whitebarred prickleback	Rare
Plectobranchus evides	Bluebarred prickleback	Rare
Anoplarchus purpurescens	High cockscomb	Rare
Xiphister atropurpureus	Black prickleback	Rare
Cryptacanthodidae		
Cryptacanthodes aleutensis	Dwarf wrymouth	Rare
Pholidae		
Pholis spp.	Gunnels	Rare
Ptilichthyidae		

(continued)

TABLE 3, cont'd.
Summary of ichthyoplankton taxa collected in the northern California Current (NCC) region during recent years (1996–2012). Occurrence = rare (frequency occurrence <0.05), common (frequency occurrence >0.05), abundant (mean concentration >5 1000 m^{-3}) as defined by Brodeur et al. (2008) and Auth (2011).

Taxa	Common Name	Occurrence
Ptilichthys goodei	Quillfish	Rare
Ammodytidae		
Ammodytes hexapterus or *personatus*	Pacific sand lance	Abundant
Icosteidae		
Icosteus aenigmaticus	Ragfish	Rare
Gobiidae		
Clevelandia ios	Arrow goby	Rare
Lepidogobius lepidus	Bay goby	Rare
Rhinogobiops nicholsii	Blackeye goby	Rare
Centrolophidae		
Icichthys lockingtoni	Medusafish	Rare
Tetragonuridae		
Tetragonurus cuvieri	Smalleye squaretail	Rare
Paralichthyidae		
Citharichthys sordidus	Pacific sanddab	Abundant
Citharichthys stigmaeus	Speckled sanddab	Rare
Pleuronectidae		
Atheresthes stomias	Arrowtooth flounder	Rare
Embassichthys bathybius	Deepsea sole	Rare
Eopsetta jordani	Petrale sole	Rare
Glyptocephalus zachirus	Rex sole	Common
Hippoglossoides elassodon	Flathead sole	Rare
Isopsetta isolepis	Butter sole	Abundant
Lepidopsetta bilineata	Rock sole	Rare
Lepidopsetta 2	Sole	Rare
Lyopsetta exilis	Slender sole	Abundant
Microstomus pacificus	Dover sole	Common
Parophrys vetulus	English sole	Abundant
Platichthys stellatus	Starry flounder	Rare
Pleuronichthys coenosus	C-O turbot	Rare
Pleuronichthys decurrens	Curlfin sole	Rare
Psettichthys melanostictus	Sand sole	Abundant

ESTIMATING FISH POPULATIONS FROM REEF CITIZEN SCIENCE VOLUNTEER DIVER ORDER-OF-MAGNITUDE SURVEYS

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ABSTRACT

We describe several models to convert order-of-magnitude count data to a numeric mean and demonstrate that with a sufficient number of surveys, estimates of the mean with a reasonably small confidence interval can be attained. The method is applied to fish survey data collected as part of the Reef Environmental Education Foundation (REEF) Volunteer Survey Project, a citizen science program that has accumulated a database of over 172,000 surveys by recreational divers using the Roving Diver Technique (RDT). We compare three models to convert RDT order-of-magnitude counts to expected arithmetic means. For each model, parameter estimates and associated confidence intervals were derived from 292 RDT surveys where precise counts were also made. Models were compared using the small sample Akaike Information Criteria (AICc). The best-fitting model uses disaggregated bin-count data and considers the relative proportion of counts in adjacent bins.

INTRODUCTION

There is growing interest by scientists, resource managers, and decision makers in the potential role of data collected by citizen scientists as another source for tracking fish populations. Such data sets may be applied to stock assessments, the evaluation of California's network of Marine Protected Areas (MPAs), and how marine fishes respond to changing ocean conditions. Moreover, the species of nearshore rocky reef fishes addressed in this study play an important role in commercial and recreational fisheries, as well as dive tourism. This paper proposes a method to quantitatively analyze data like that generated by the Reef Environmental Education Foundation (REEF) Fish Survey Project, a citizen science data collection program conducted by recreational divers.

Because biological populations tend to grow and decline exponentially, population densities often vary across both time and space by orders of magnitude (May 1975; Engen and Lande 1996). One of the most efficient methods of surveying such populations is with order-of-magnitude counting methods. REEF developed the Roving Diver Technique (RDT) to enlist SCUBA divers to conduct fish surveys (Semmens et al. 2000; Schmitt et al. 2002). The surveyors roam across a dive site and record order-of-magnitude counts of fish species they observe and can positively identify, with the following counting bins: **S**ingle = 1, **F**ew = 2–10, **M**any = 11–100, and **A**bundant >100 (hereafter termed SFMA data). As of July 2013, over 172,000 surveys have been made worldwide, with the results made publicly available on REEF's website, www.REEF.org. In the Monterey Peninsula area of the California coast, 3,157 surveys were conducted over fifteen years, from 1997 through 2011. These data, collected by volunteer citizen science divers, have great potential to augment and strengthen regional scientific, conservation, and management efforts (Wolfe and Pattengill 2013; Holt et al. 2013). This paper identifies computational techniques to convert REEF categorical data to arithmetic means, thereby enhancing its statistical usefulness.

Our results presented here show that, with a sufficient number of surveys, order-of-magnitude count data can be converted to numeric means with reasonably small confidence intervals. Because RDT dives have mean durations covering mean distances, the average number of fish seen per dive can be used to approximate relative fish density. We base our analysis on 292 RDT surveys where exact counts were made instead of order-of-magnitude SFMA counts. The exact count data were converted to SFMA data for 36 species, and then three different models were compared to determine which most accurately converts SFMA data back to arithmetic means. Akaike Information Criterion for small samples (AICc) was used to determine the model that gave the best, most parsimonious fit. While all three estimation models were compared using the same SFMA data, the first model aggregated the SFMA data into a single log-density score *DEN*, while the second and third models were based on the disaggregated SFMA bin data. The latter two models proved to be more precise, with significantly tighter confidence intervals around the estimated mean. We then quantified the confidence interval associated with the best estimation method and examined other sources of uncertainty.

TABLE 1
SFMA counts and numeric mean for 36 fish species based on 292 exact-count surveys. Values under columns S, F, M, and A are the number of dives for which that species was recorded in that $\log_{10}$ counting bin.

			1	2–10	11–100	101+		
	Species Name		S	F	M	A	Total	Obs. Mean
1	Striped Seaperch	*Embiotoca lateralis*	6	90	167	1	264	17.1
2	Blue Rockfish	*Sebastes mystinus*	5	41	121	91	258	114.6
3	Kelp Rockfish	*Sebastes atrovirens*	12	133	106	0	251	12.7
4	Kelp Greenling	*Hexagrammos decagrammus*	56	171	4	0	231	3.3
5	Pile Perch	*Damalichthys vacca*	30	148	41	1	220	8.0
6	Painted Greenling	*Oxylebius pictus*	36	140	31	0	207	6.3
7	Black Perch	*Embiotoca jacksoni*	40	133	20	0	193	4.6
8	Black & Yellow Rockfish	*Sebastes chrysomelas*	47	138	6	0	191	3.4
9	Blackeye Goby	*Coryphopterus nicholsi*	28	116	24	1	169	6.6
10	Black Rockfish	*Sebastes melanops*	41	107	21	0	169	5.6
11	Senorita	*Oxyjulis californica*	13	29	89	35	166	67.1
12	Lingcod	*Ophiodon elongatus*	72	83	0	0	155	2.0
13	YOY Rockfish	*Sebastes* spp. (<5 cm)	12	30	62	49	153	125.7
14	Tubesnout	*Aulorhychus flavidus*	19	22	50	52	143	143.4
15	Olive Rockfish	*Sebastes serranoides*	41	84	13	0	138	4.1
16	Gopher Rockfish	*Sebastes carnatus*	47	82	3	0	132	3.2
17	Cabezon	*Scorpaenichthys marmoratus*	84	43	0	0	127	1.6
18	Kelp Perch	*Brachyistius frenatus*	36	54	26	2	118	10.3
19	Rubberlip Surfperch	*Rhacochilus toxotes*	26	63	16	0	105	5.6
20	Reef Surfperch	*Micrometrus aurora*	4	25	34	0	63	15.8
21	Rainbow Surfperch	*Hypsurus caryi*	16	25	18	0	59	10.4
22	Copper Rockfish	*Sebastes caurinus*	25	24	2	0	51	2.5
23	Snubnose Sculpin	*Orthonopias triacis*	31	20	0	0	51	1.7
24	Speckled Sanddab	*Citharichthys stigmaeus*	12	32	5	0	49	4.0
25	Yellowtail Rockfish	*Sebastes flavidus*	18	25	4	0	47	3.4
26	Gibbonsia Kelpfish	*Gibbonsia* spp.	39	6	0	0	45	1.2
27	Treefish	*Sebastes serriceps*	28	10	0	0	38	1.4
28	Monkeyface Prickleback Eel	*Cebidichthys violaceus*	27	10	0	0	37	1.4
29	Vermillion Rockfish	*Sebastes miniatus*	32	4	0	0	36	1.1
30	Opaleye	*Girella nigricans*	14	19	2	0	35	2.8
31	California Sheephead	*Semicossyphus pulcher*	14	21	0	0	35	2.2
32	Blacksmith	*Chromis punctipinnis*	10	11	4	8	33	68.0
33	Scalyhead Sculpin	*Artedius harringtoni*	24	9	0	0	33	1.4
34	Grass Rockfish	*Sebastes rastrelliger*	26	6	0	0	32	1.3
35	Kelp/Calico Bass	*Paralabrax clathratus*	22	6	0	0	28	1.3
36	Coralline Sculpin	*Artedius corallinus*	18	5	0	0	23	1.3

Fish species shown in Tables 1 and 2 are listed in descending order of total sightings over 292 surveys.

METHODS

Exact Count Database: To correlate SFMA data with precise counts of fish seen, exact counts of all observed fish species were recorded while concurrently conducting a REEF RDT survey. 292 such dives were made by lead author JW between 2002 and 2012 on nearshore reefs of south Monterey Bay and Carmel Bay, the area identified by the REEF geozone code prefix 4114. Most dives were from shore at traditionally recognized dive sites extending from Del Monte Beach and the Breakwater in south Monterey Bay to Point Lobos State Marine Reserve in south Carmel Bay. Thirty-six fish species were observed on over 8% of the dives, and these formed the basis of the exact count data set used to derive methods of converting SFMA data to arithmetic means (table 1). Observed numeric means were calculated for each species. The data were also categorized by the lower resolution SFMA $\log_{10}$ counting bins, enumerating how many dives a single fish was seen, or a Few (2–10), Many (11–100), or Abundant (over 100).

Verify Underlying Log-Normal Distribution: To formulate reasonable estimation methodologies, the exact count data were examined to determine the underlying distribution of fish sightings. As expected (Limpert et al. 2001), sightings generally followed a log-normal distribution (figs. 1 and 2). The numeric mean $\bar{x}$ of a log-normal distribution with mean μ and standard deviation σ is:

$$\bar{x} = e^{(\mu + \sigma^2/2)} \tag{1}$$

To determine closeness of fit of species' sightings to a perfect log-normal distribution, the ratios of expected to observed numeric means were plotted against the log-transformed mean abundances for the 36 species. The log-normal distribution assumption fit well for most species, but tended to overestimate the numeric mean for abundant schooling fish species (fig. 3).

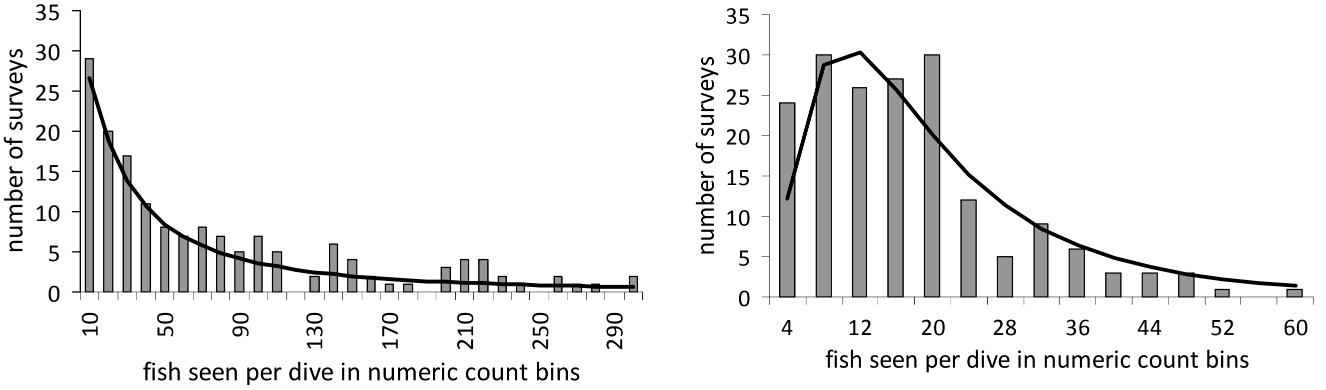

Figure 1a. blue rockfish, numeric x-axis

Figure 2a. striped seaperch, numeric x-axis

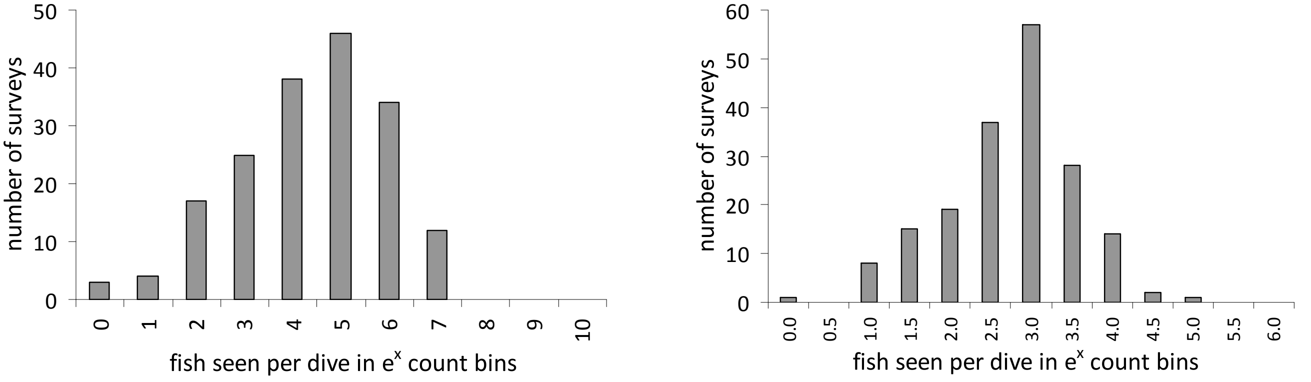

Figure 1b. blue rockfish, logn x-axis

Figure 2b. striped seaperch, logn x-axis

Figures 1 and 2. Figures 1 and 2 refer to blue rockfish and striped seaperch species (left and right graphs), respectively. Figures 1a and 2a (upper graphs) are histograms of the number of surveys (vertical axis) plotted against arithmetic counting bins of fish seen per dive (horizontal axis), with a fitted lognormal distribution (solid line) drawn on top. Figures 1b and 2b (lower graphs) are histograms of the same surveys plotted against natural log counting bins of fish seen per dive.

Because fish counts fit log-normal distributions more closely than normal distributions, Δ used in the least squares regression below were based on proportional rather than arithmetic differences. Likewise, confidence intervals were calculated as "times/divide" $^x/$ proportions rather than "plus/minus" $^+/_-$ arithmetic intervals (Limpert et al. 2001). A times/divide factor of $^x/30\%$ (shorthand for x1.30, /1.30) corresponds to plus/minus factors of +30%, –23%.

Application of Least Squares Regression: Three estimation models for converting SFMA data were examined. Optimal parameters for each model were deduced using least squares regression applied to all 36 fish species by calculating the proportional difference, Δ, of the ratio of the expected to observed numeric mean for each species as:

$$\Delta = \ln(ExpectedMean/ObservedMean) \qquad (2)$$

For each species, Δ was squared, and the residual sum of the squares (RSS) was calculated by summing Δ^2 for all 36 species, giving each species equal weight in the regression. For each model, optimal parameters to minimize RSS were determined using the Solver Add-On Tool of Microsoft Excel.

Aggregate Log-Density Score, DEN: The REEF Web site reports summaries for groups of surveys for any requested period of time and geographic area within the REEF database. Counts for each species are summarized by sighting frequency (*SF*) and log-density score (*DEN*). The value *DEN* is a single number that aggregates nonzero sightings into a log average:

$$DEN = \frac{S + 2F + 3M + 4A}{S + F + M + A} \qquad (3)$$

where:

S = *number of dives reporting a Single individual of a given species*

F = *number of dives reporting a Few (2–10) individuals of that species*

M = *number of dives reporting Many (11–100) individuals of that species*

A = *number of dives reporting Abundant (over 100) individuals of that species*

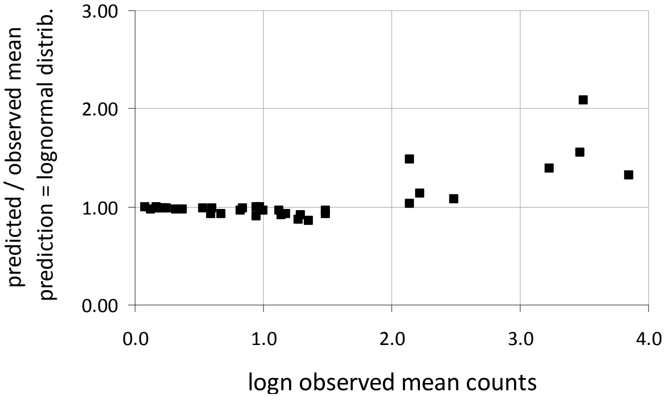

Figure 3. The log-normal distribution's predicted / observed numeric mean ratio plotted as a function of the logn-transformed observed mean counts for a given species; each point represents one of the 36 species observed. Given a perfect log-normal distribution with mean μ and standard deviation σ, predicted numeric mean = exp(μ + σ²/2). The graph suggests that counts of most species closely follow a log-normal distribution, but stray from perfectly log-normal for the most abundant species, where a perfect log-normal distribution predicts higher counts than are actually observed.

Model Descriptions

Models were formulated to predict expected mean from SFMA data. The optimized parameters for these models are intended to apply to all fish species studied, based on best overall fit to 36 fish species reported in the 292 exact count dives. The first model was based on the aggregate log-density score *DEN*, while the second and third models were based on disaggregated SFMA bin counts.

Model 1. The first model used an exponentiation formulation:

$$ExpectedMean_1 = A^{(DEN-1)^B} \tag{4}$$

where A = *a base coefficient* and
B = *an exponent coefficient.*

Model 2. A second model can be devised where a single theoretical average value is sought for each count category, with no consideration of the relative proportion of adjacent count categories. This leads to a simple formulation:

$$ExpectedMean_2 = \frac{S + f_2 F + m_2 M + a_2 A}{S + F + M + A} \tag{5}$$

The parameters f_2, m_2 and a_2 can be regarded as the average number of fish that are seen on dives where 2–10, 11–100, and over 100 fish are seen, respectively.

Model 3. With disaggregated SFMA data, the proportion of sightings in an adjacent category may provide information on the probable average value for the category in question. For instance, for 20 dives with a distribution of 16 Single counts, 4 Few counts, and zero Many and Abundant counts ($S = 16$, $F = 4$, $M = 0$, $A = 0$), it is reasonable to expect the average number of individuals seen in the Few category to be at the lower end of the range of 2 to 10, perhaps between 2 and 3 (fig. 4a). On the other hand, for 20 dives with a distribution of $S = 1$, $F = 3$, $M = 12$, $A = 4$, one would expect a higher average number of individuals seen in the Few category, closer to the upper end of the range 2 to 10 (fig. 4b).

In the hypothetical distributions described, the average number of observed individuals in the "Few" category shifts from 2.4 to 8.4 as the expected mean from all categories increases. An "Average of Few" variable based on the proportion of adjacent count categories can be formulated, as well as similar variables for the Many and Abundant categories. These variables, *AvgF, AvgM* and *AvgA*, are bound by the limits that define their ranges, and are formulated as follows:

$$AvgF = \frac{2S + f_f F + 10M}{S + F + M}$$

$$AvgM = \frac{11F + m_m M + 100A}{F + M + A} \tag{6}$$

$$AvgA = \frac{a_m M + a_a A}{M + A}$$

f_f = *contribution of Few component to AvgF*
m_m = *contribution of Many component to AvgM*
a_m = *contribution of Many component to AvgA*
a_a = *contribution of Abundant component to AvgA*

The variables *AvgF*, *AvgM* and *AvgA*, multiplied by their corresponding category counts *F*, *M* and *A*, can then be summed and divided by the total nonzero counts to give the expected average sightings per dive:

$$ExpectedMean_3 = \frac{S + F \cdot AvgF + M \cdot AvgM + A \cdot AvgA}{S + F + M + A} \tag{7}$$

Incorporation of Zero Counts

In all the models described above, the expected mean represents the mean for nonzero surveys. This nonzero mean is multiplied by the sighting frequency (fraction of nonzero sightings) to calculate an overall average number of fish of a given species seen per dive.

$$ExpectedMean\ (AllSurveys) = SightingFrequency \cdot ExpectedMean(NonZeroSurveys) \tag{8}$$

Akaike Information Criterion (AICc)

To determine best fit while avoiding the pitfalls of either underfitting or overfitting the data, models were

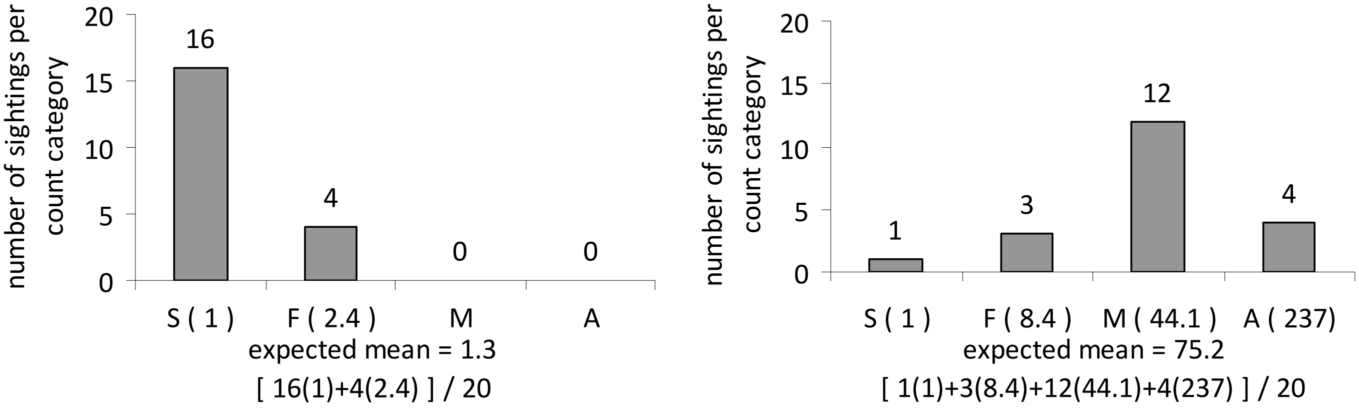

Figure 4: Distributions with a low expected mean (fig. 4a) and high expected mean (fig. 4b). Note that the expected value for "Few", *AvgF*, is 2.4 in the first distribution due to the preponderance of "Single" counts, and 8.4 in the second distribution due to the preponderance of "Many" counts.

compared using the small sample Akaike Information Criterion (AICc; Burnham and Anderson 2002), given by:

$$AICc = -n \cdot \ln(RSS/n) + 2k + \frac{2k(k+1)}{n-k-1} \qquad (9)$$

k = number of estimable parameters in the model
n = number of samples

For least squares regression, *k* is the number of parameters being fitted in the model, plus one. The added one represents RSS, the target parameter to minimize (Burnham and Anderson 2002). The sample size is $n = 36$, the number of fish species that each model was applied to and checked against. The model with the minimum AICc score has the best fit of all the models considered. Where AICc scores are very close (within 2 points), AIC relative weights can be applied.

Confidence Intervals

Confidence intervals around the expected numeric mean were calculated and combined to capture two separate sources of uncertainty: (1) SFMA translational error, and (2) observational variance. Both confidence intervals narrowed with increasing number of dive surveys.

Translational Imprecision Confidence Interval: The data upon which the estimate coefficients are based are not truly statistically independent of the data used to calculate the observed mean fish seen per survey, and therefore the regression method described above may underestimate the coefficient of variation. Furthermore, the associated coefficient of variation and confidence interval reflects an amalgamation of 36 species with behaviors that range from solitary to schooling. A bootstrap procedure was used to address issues of statistical independence, as well as determine estimate error as a function of nonzero sightings. This bootstrap procedure also avoids the issues associated with the alternative of deducing confidence intervals from log-normal distribution properties (Singh et al. 1997; Zhou and Gao 1997; Parkin et al. 1990).

The nonzero count data for the eleven most frequently seen species were broken into small segments. Fifty different segments, each *n* sightings long, were taken sequentially from a given species' string of nonzero sightings. For each segment, the prediction method (model 3) was applied and the resulting expected mean was compared to the observed mean. Each segment is so small that for all practical purposes it is statistically independent of the larger data set from which the optimal estimate coefficients were determined. This process was repeated fifty times, and the standard error was determined for this species for a given *n* sightings. The process was repeated for $n = 3$ to 150 sightings, so that a given confidence interval could be plotted against the number of nonzero sightings for each species.

To use a specific example, to determine the uncertainty associated with $n = 4$ surveys, the first four counts for 258 blue rockfish nonzero sightings were 35, 4, 6, 255. This was converted to order of magnitude counts: M, F, F, A and represents the first $n = 4$ segment of fifty segments. This segment's SFMA count is: $S = 0$, $F = 2$, $M = 1$, $A = 1$. The observed mean for the first segment was calculated (75.0) and Model 3 was applied to calculate expected mean (81.3), as well as the expected/observed ratio (81.3/75.0 = 1.084). This process was repeated for the next 49 segments of $n = 4$ length (using 200 of the 258 blue rockfish sightings), and the standard error was calculated from the fifty ratios of expected to observed means. For larger *n* values where $50n$ exceeds the total number of nonzero sightings for a species, the segments wrapped around to the beginning of the string.

The standard errors for the eleven species clustered into two main groups, "typical" species with less than

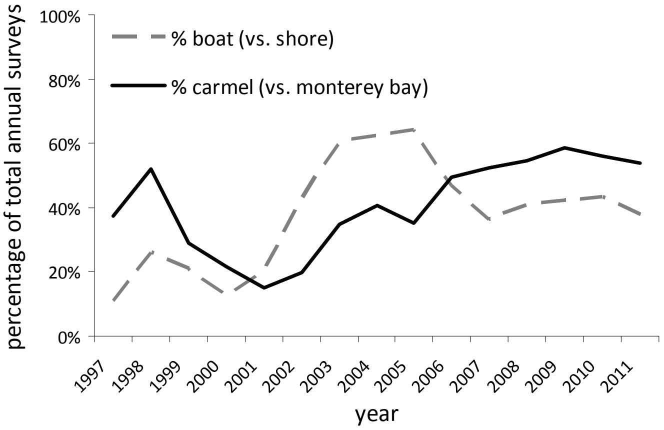

Figure 5: Year-to-year variation in dive platform (boat vs. shore) and geographic location (Carmel Bay versus South Monterey Bay) for fifteen years of REEF surveys around the Monterey Peninsula. Percentages shown are the fraction of boat dives per year (grey dashed line) and fraction of Carmel Bay dives per year (black solid line), as a fraction of total dives per year.

10% of dives reporting Abundant counts, and "abundant" or "schooling" species with a higher proportion of Abundant counts. The "abundant" species counts had less precision, both because they do not fit a log-normal distribution as well (fig. 3), and because they are not bounded by a "Super-abundant" category (over 1,000 individuals). The seven "typical" species were lingcod (*Ophiodon elongatus*), kelp greenling (*Hexagrammos decagrammus*), painted greenling (*Oxylebius pictus*), striped seaperch (*Embiotoca lateralis*), black seaperch (*Embiotoca jacksoni*), pile seaperch (*Damalichthys vacca*), and kelp rockfish (*Sebastes atrovirens*). All "typical" species reported less than 2% Abundant counts. The four "abundant" species were blue rockfish (*Sebastes mystinus*), senorita (*Oxyjulis californica*), tubesnout (*Aulorhychus flavidus*), and juvenile/young-of-year (YOY) rockfish (*Sebastes* spp). For the "abundant" species, the proportion of Abundant counts ranged from 21% to 41%.

Observational Variance Confidence Intervals: Three sources of variance in observational consistency were quantified:

1. *Variability from different divers surveying the same dive site with uneven fish distribution.* At the same dive site under the same conditions, divers will observe different numbers of fish. Part of this is due to the uneven distribution of fish across the site, and part of this is due to variation between divers in survey preferences and diving styles (e.g. path taken, swimming speed, preferred habitats). To quantify this aspect of observational variability, a study was conducted in May 2012 during a REEF Field Survey in the Monterey area where 18 experienced divers made exact counts of three common fish species (kelp greenling, striped seaperch, and blue rockfish) at two boat dive sites in Carmel Bay on one day (Outer Butterfly House and Dali's Wall), while conducting a standard REEF survey for all other species. Six coefficients of variation were calculated (2 sites x 3 species), weighted by relative proportion of nonzero sightings, and pooled by SRSS (described below in "orthogonal combination of variability").
2. *Variability from the same diver surveying the same site at different times of the year under differing conditions.* To quantify the variability from the same diver surveying the same site at different times of the year under differing conditions, the exact count data were mined for years when the same site was surveyed multiple times. Six dives in 2004 and 7 dives in 2009 were conducted at the same site in Carmel Bay (Butterfly House shore dive). Coefficients of variation were calculated for the same three common fish species as used in the variability in divers analysis. This calculated coefficient of variation was multiplied by a reduction factor to remove the effects of taking different routes across the site (quantified as described previously), and from variation caused by underlying year-to-year population trends.
3. *Variability from differing mix of dive sites.* The mix of dive sites in an area surveyed by REEF divers varies from year to year. This variability can be controlled for in three ways. First, the sites included for study can be pared down to a consistent year-to-year data set. Second, the mix of dive sites can instead be normalized for one or more characteristics to take advantage of the data for most or all sites. Third, rather than pruning or normalizing the data, the variability can also be recognized by increasing the confidence interval. This confidence interval can be estimated by taking a subset of normalized data and comparing it to the raw data. For the Monterey Peninsula area, the largest proportional variation among years was in dive platform (boat dives vs. shore dives) and geographic area (Carmel Bay vs. south Monterey Bay). For the 15-year study period, the fraction of boat dives varied among years from 11% to 64%, and the fraction of dives occurring in Carmel Bay ranged from 15% to 59% (fig. 5). For a given species, the mean number of fish sighted per year were adjusted or "normalized" to remove the variation caused by differing proportions of boat dives or Carmel Bay dives from year to year. The proportion of boat dives were normalized around the fifteen year average of 44%, while the proportion of Carmel Bay dives were normalized around the fifteen year average of 42%. The coefficient of variation between the unaltered raw data and the normalized data were calculated for three commonly seen species. The pooled three-species COV was used to increase the confidence interval to account for dive site variation.

Orthogonal Combination of Variability: The three separate sources of observational variability described above are independent of each other. Likewise, conversional imprecision and observational variability are independent of each other. Such independent sources of variability are mathematically orthogonal to each other, and are therefore combined or "pooled" by the square root of the sum of the squares (SRSS) method (Taylor 1997; Hogan 2006; NASA 2010), weighted by the relative number of observations where appropriate. The Coefficient of Variation (COV), defined in this case as standard error divided by the mean, for observational variability was then calculated as $COV/\sqrt{n-1}$ where n is the number of nonzero sightings.

RESULTS

Optimized Parameters for the Three Models

Based on minimizing the sum of Δ^2 for all 36 fish species, the best parametric fit was found for each of the three models. The optimized parameters, and resulting standard deviation and coefficient of variation of the expected-to-observed mean ratios, were as follows:

Model 1:

$$ExpectedMean_1 = 5.73^{(DEN-1)^{1.28}} \tag{10}$$

$$Std.Dev.(ExpMean_1/ObsMean) = 0.369$$

$$COV\big(SD/avg(ExpMean_1/ObsMean)\big) = 0.282$$

Model 2:

$$ExpectedMean_2 = \frac{S + 2.80F + 24.5M + 300A}{S + F + M + A}$$

$$Std.Dev.(ExpMean_2/ObsMean) = 0.105 \tag{11}$$

$$COV\big(SD/avg(ExpMean_2/ObsMean)\big) = 0.104$$

Model 3:

$$AvgF = \frac{2S + 4.16F + 10M}{S + F + M}$$

$$AvgM = \frac{11F + 33.8M + 100A}{F + M + A} \tag{12}$$

$$AvgA = \frac{200M + 348A}{M + A}$$

$$ExpectedMean_3 = \frac{S+F \bullet AvgF+M \bullet AvgM+A \bullet AvgA}{S + F + M + A}$$

$$Std.Dev.(ExpMean_3/ObsMean) = 0.085$$

$$COV\big(SD/avg(ExpMean_3/ObsMean)\big) = 0.085$$

Each of the three models, using their respective best-fit parameters, define expected/observed mean ratios for each of the 36 species, as well as summary statistics for all 36 species together (table 2).

AICc Model Comparison

The models based on disaggregated SFMA bin data (models 2 and 3) had substantially better AICc scores than the model based on an aggregate log-density index derived from the same SFMA data (model 1) (table 3). Of the two disaggregated bin data models, Model 3 scored better than Model 2 by a significant margin, with an associated AICc relative weight (probability) of 99.6% (table 3) for the models considered.

Translational Imprecision Confidence Interval

As the best model determined from AICc, Model 3 was examined in more detail. Plotting the expected mean against observed numeric mean for each of the 36 species resulted in almost a straight 1:1 line, giving a qualitative sense of the preciseness of this data conversion (figs. 6a and 6b).

From the bootstrap method, the translational confidence interval can be described as a function of n, the number of nonzero sightings, as follows:

$$Species\ Category\ Confidence\ Interval_{90\%\ or\ 95\%} = a + \frac{b}{(n-1)^c} \tag{13}$$

The coefficients a, b, and c are defined according to species category (typical vs. abundant) and confidence interval (90% vs. 95% interval, that is, 5% vs. 2.5% low and high tail exclusions). Table 4 lists the coefficients used in Equation 13.

The predicted 90% confidence intervals for typical species were ^{x}/41% for 10 surveys, ^{x}/29% for 20 surveys, ^{x}/25% for 30 surveys, ^{x}/20% for 50 surveys, and ^{x}/17% for 80 surveys.

At very high numbers of nonzero sightings, where the estimate error asymptotically approaches a minimum value (fig. 7), the error for the typical species category was greater than that for abundant species. Therefore, at large n sightings (more than about 130 nonzero surveys), the confidence interval for abundant species should be the maximum of either the typical or abundant species confidence interval equations.

Observational Variability Confidence Interval

Variability Between Divers: For the May 2012 study with 18 divers making exact counts of three species at two dive sites on a single day, the pooled coefficient of variation was found to be 1.11 (two dives x three species, weighted by relative number of nonzero sightings). This

TABLE 2
Comparison of models for 36 fish species based on 292 exact-count surveys.

			Expected Mean per Model			Expected/Observed Ratio per Model		
	Species Name	Observed Mean	1	2	3	1	2	3
1	Striped Seaperch	17.1	37.1	17.6	20.0	1.78	1.03	1.17
2	Blue Rockfish	114.6	123.3	117.8	119.5	0.83	1.02	1.04
3	Kelp Rockfish	12.7	21.6	11.9	12.4	1.44	0.94	0.98
4	Kelp Greenling	3.3	5.6	2.7	3.2	1.54	0.82	0.96
5	Pile Perch	8.0	10.7	8.0	7.5	1.18	1.00	0.94
6	Painted Greenling	6.3	8.8	5.7	5.6	1.25	0.91	0.89
7	Black Perch	4.6	7.4	4.7	4.6	1.45	1.02	1.01
8	Black & Yellow Rockfish	3.4	5.8	3.0	3.4	1.54	0.89	0.99
9	Blackeye Goby	6.6	9.1	7.4	6.8	1.22	1.11	1.02
10	Black Rockfish	5.6	7.2	5.1	4.8	1.16	0.91	0.87
11	Senorita	67.1	66.6	77.0	76.3	0.79	1.14	1.14
12	Lingcod	2.0	3.3	2.0	2.2	1.54	0.97	1.07
13	YOY Rockfish	125.7	81.0	106.7	107.5	0.51	0.84	0.86
14	Tubesnout	143.4	76.9	118.3	121.4	0.42	0.82	0.85
15	Olive Rockfish	4.1	5.9	4.3	4.1	1.32	1.06	1.00
16	Gopher Rockfish	3.2	4.4	2.7	2.8	1.29	0.84	0.89
17	Cabezon	1.6	2.1	1.6	1.6	1.27	1.00	0.99
18	Kelp Perch	10.3	8.3	12.1	10.6	0.72	1.17	1.03
19	Rubberlip Surfperch	5.6	7.5	5.7	5.3	1.22	1.02	0.96
20	Reef Surfperch	15.8	27.1	14.4	15.9	1.43	0.91	1.01
21	Rainbow Surfperch	10.4	10.1	8.9	8.8	0.85	0.86	0.85
22	Copper Rockfish	2.5	3.4	2.8	2.6	1.27	1.10	1.02
23	Snubnose Sculpin	1.7	2.4	1.7	1.7	1.36	1.01	1.02
24	Speckled Sanddab	4.0	6.8	4.6	4.4	1.54	1.15	1.12
25	Yellowtail Rockfish	3.4	4.8	4.0	3.6	1.31	1.18	1.08
26	Gibbonsia Kelpfish	1.2	1.3	1.2	1.2	1.07	1.00	0.94
27	Treefish	1.4	1.8	1.5	1.4	1.23	1.04	0.99
28	Monkeyface Prickleback Eel	1.4	1.8	1.5	1.4	1.31	1.10	1.06
29	Vermillion Rockfish	1.1	1.3	1.2	1.1	1.14	1.08	1.02
30	Opaleye	2.8	4.3	3.3	3.1	1.43	1.19	1.12
31	California Sheephead	2.2	3.8	2.1	2.4	1.62	0.94	1.08
32	Blacksmith	68.0	18.4	77.0	79.6	0.23	1.13	1.17
33	Scalyhead Sculpin	1.4	1.8	1.5	1.4	1.25	1.04	1.01
34	Grass Rockfish	1.3	1.5	1.3	1.3	1.13	1.02	0.96
35	Kelp/Calico Bass	1.3	1.6	1.4	1.3	1.19	1.05	0.99
36	Coralline Sculpin	1.3	1.6	1.4	1.3	1.26	1.10	1.05
	Standard Deviation of (Expected Mean / Observed Mean)					0.338	0.105	0.085
	Coefficient of Variation [SD / mean(Expected Mean / Observed Mean)]					0.282	0.104	0.085
	RSS/n					0.1746	0.0110	0.0071

Note: RSS = sum of ln (Expected Mean / Observed Mean) squared

TABLE 3
Akaike Information Criterion (AICc) comparison of Models. The model with the lowest AICc value indicates the best balance between under- and over-fitting, with best relative likelihood (probability).

Model	RSS/n	k	AICc	AIC Weight, w_i (probability)
Model 1	0.1746	3	–54.3	0.000
Model 2	0.0110	4	–153.1	0.001
Model 3★	0.0069	9★	–154.2	0.003
Model 3	**0.0071**	**5**	**–161.1**	**0.996**

★ A variation of Model 3 where the *a priori* constants 2, 10, 11, and 100 are allowed to vary to more closely fit observed data. Per AICc, this approach, which increases the number of fitting parameters to minimize RSS, overfits the data.

captures the variability from divers with different surveying habits, preferences and swimming speeds, taking different routes across the same dive site, and counting fish that move about and are found in patches across the site.

Variability From Differing Conditions Over a Year: Looking at three common fish species, the pooled coefficient of variation for differing conditions over the year was found to be 0.79. However, part of this variation was not random, but instead reflected real population trends. Another part of this variation, surveying different areas at the same site, overlaps and repeats the variation measured in the May 2012 study. Assuming that 40% of this variation is due to differing conditions over the year at the same site, this coefficient of unique variation is estimated to be 0.32.

Variability From a Changing Mix of Dive Sites: Year-to-year fluctuations in fish populations, normalized for Monterey Bay versus Carmel Bay dives (fig. 5), and shore versus boat dives (fig. 5), were compared against the raw data (fig. 8). Calculating the coefficient of variation for each of the three species, and pooling appropri-

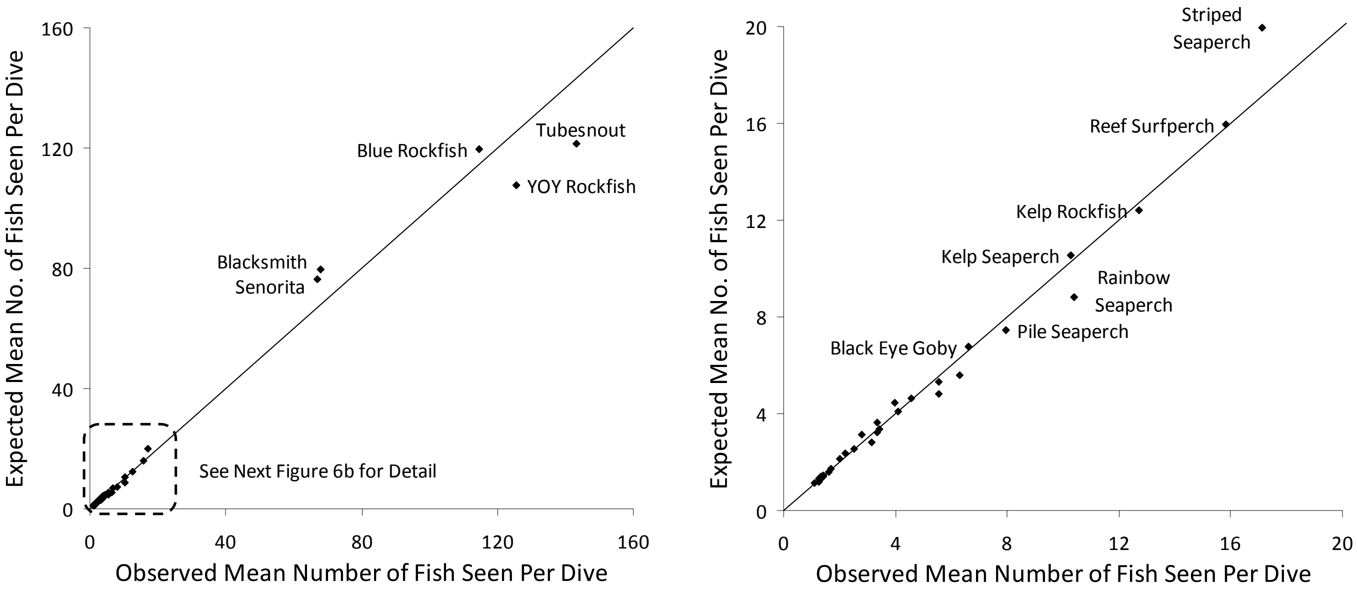

Figure 6: Model 3's expected versus observed mean number of fish sighted per dive for various species (each data point represents an observed fish species). Data from a perfect predictive model would fall on a 1:1 line. Figure 6a (left graph) shows the full range of species' predicted and observed counts (0–160). Figure 6b (right graph) shows that most species cluster in the region of 20 or fewer average sightings per dive.

TABLE 4

Coefficients for Calculating Confidence Interval, $C.I. = a+b/(n-1)^c$ for Model 3, where n = number of nonzero fish sightings for a given species, area, and time period.

Species Category:	Typical Species		Abundant Species	
Proportion of Abundant Counts:	Less than 10%		More than 10%	
	TRANSLATIONAL ERROR			
Confidence Interval:	90%	95%	90%	95%
Coefficients:				
a	0.05	0.06	−1.80	−2.16
b	1.07	1.28	3.53	4.22
c	0.50	0.50	0.12	0.12
	TRANSLATIONAL + OBSERVATIONAL ERROR			
Confidence Interval:	90%	95%	90%	95%
Coefficients:				
a	0.02	0.03	−0.26	−0.27
b	2.03	2.42	3.20	3.88
c	0.48	0.48	0.38	0.39

Translational Error = Uncertainty from converting SFMA $\log_{10}$-bin count data to expected arithmetic mean.

Observational Error = Uncertainty from stochastic distribution of fish across a dive site, and variability between divers, diving conditions, and dive sites.

ately, leads to a coefficient of variation of 0.15.

Observational Variability Pooled Across Sources: The pooled coefficient of variation for the three sources of observational error is therefore estimated to be

$$\sqrt{1.11^2 + 0.32^2 + 0.15^2} = 1.16.$$

Observational standard error (normalized to one) as a function of n surveys is $\pm 1.16/\sqrt{n-1}$. Because this is a log-normal distribution, it is more accurate to express the standard deviation relative to the mean as the mean multiplied or divided by $\upsilon + \sqrt{1 + \upsilon^2}$ where $\upsilon = 1.16/\sqrt{n-1}$

Combined Translational and Observational Confidence Intervals

The observational error can be combined with the SFMA translational error using SRSS to express the combined error as a function of the number of nonzero sightings in a year for two fish species categories, typical and abundant (fig. 9). The same combined error is also expressed as coefficients of Equation 13 in Table 4. For typical fish species, the 90% confidence interval drops below $^x/30\%$ at 60 sightings per year, and the 95% confidence interval drops below $^x/30\%$ at 90 sightings per year.

DISCUSSION

Models for Estimating Abundances: The methods described in this paper convert order-of-magnitude counts to an aggregate arithmetic mean with a reasonably small confidence interval, given a sufficient number of surveys. Parameters for each model were optimized for best fit to 36 fish species common to the Monterey Peninsula in California. The distributions of exact counts from 292 surveys for these 36 fish species were essentially log-normal. Because these distributions were generated by roving diver "random walks" across patchy distributions of fish on nearshore reefs, the optimized estimation parameters, based on underlying stochastic distributions, are likely to also apply to other species and geographic regions.

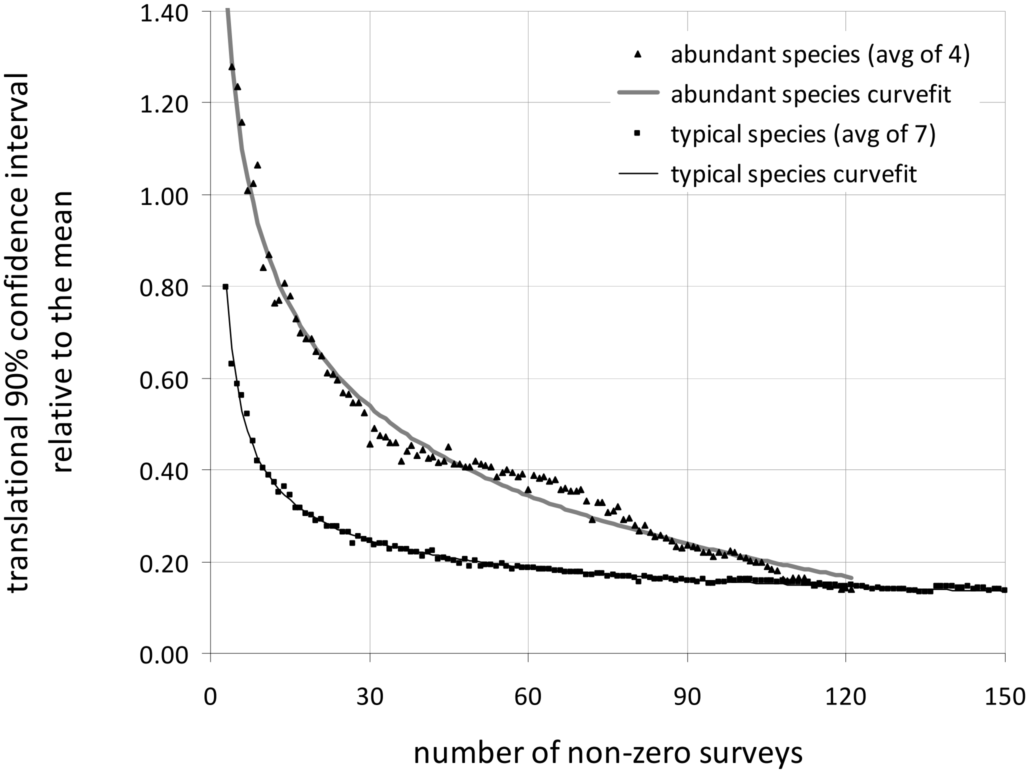

Figure 7: Translational 90% confidence interval relative to the mean (vertical axis), as a function of number of non-zero surveys (horizontal axis). Translational error is that associated with converting SFMA data to expected arithmetic means. A confidence interval value of 30% indicates the upper end of the interval is mean times 1.30, and the lower end is mean divided by 1.30. "Typical" species are those where Abundant sightings comprise less than 10% of all nonzero sightings. "Typical" species error is based on the average of 7 typical species. "Abundant" species are those where Abundant sightings comprise more than 10% of all nonzero sightings. "Abundant" species error is based on the average of 4 abundant species.

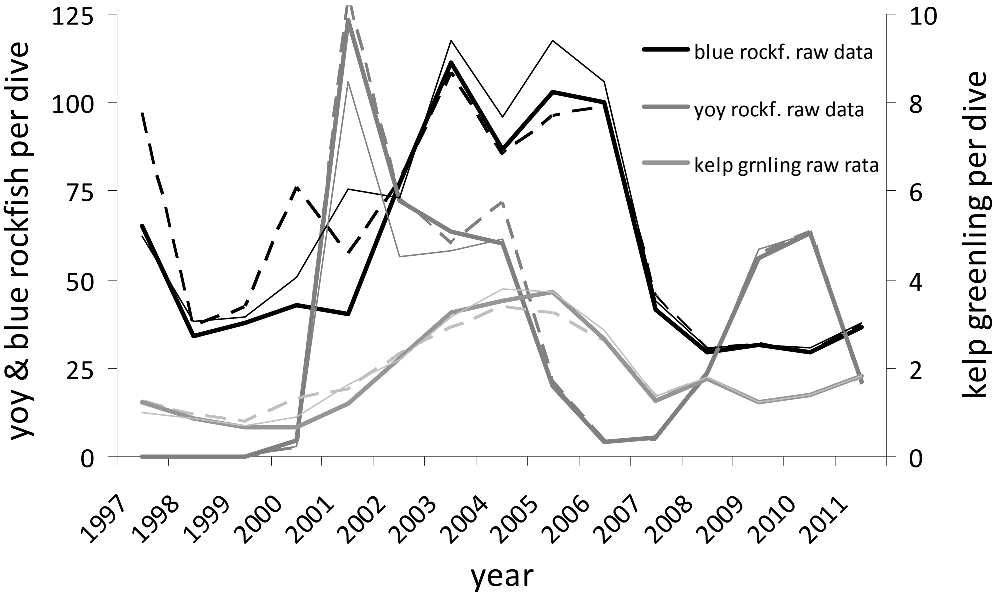

Figure 8: Fish population estimates for three species (YOY rockfish < 5 cm, blue rockfish > 5 cm, and kelp greenling) are plotted over 15 years, based on REEF surveys around the Monterey Peninsula, California. For purposes of comparison, raw data estimates are plotted alongside data normalized for consistent year-to-year boat/shore and Carmel/Monterey ratios. Solid lines are raw data, dashed lines are normalized for boat versus shore dive sites, and thin lines are normalized for Carmel versus Monterey bay dive sites. Refer back to Figure 5 for the year-to-year variations in mix of dive sites that create the differences between raw and normalized data.

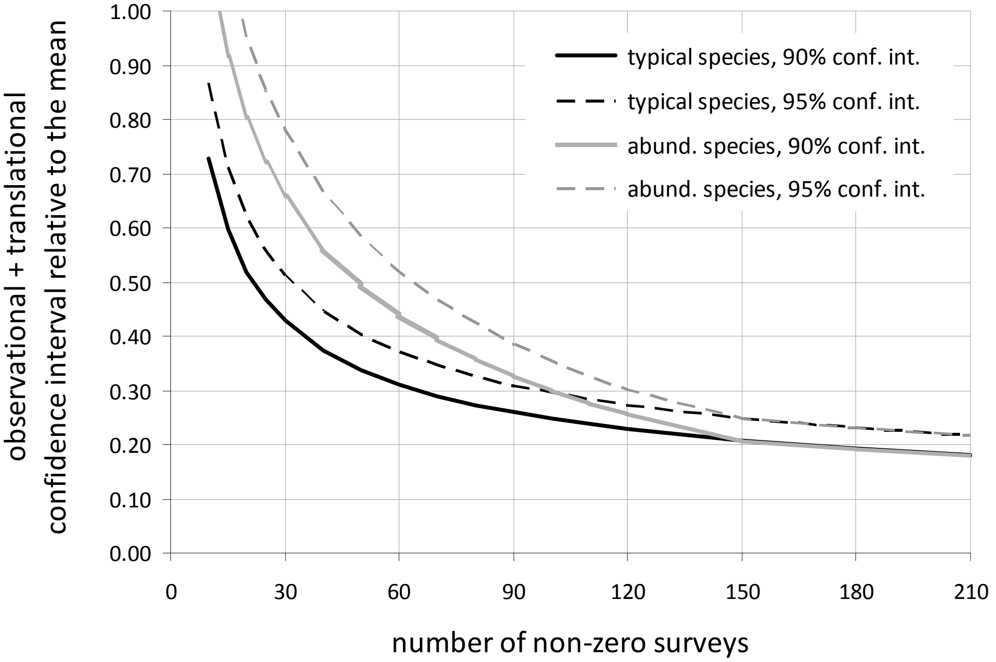

Figure 9: The combined observational and translational confidence interval (vertical axis) as a function of the number of nonzero dive surveys (horizontal axis. Translational error is that associated with converting SFMA data to expected arithmetic means, while observational error is from uneven fish distributions and variations between divers, dive conditions and dive sites. 90% and 95% confidence intervals corresponds to 5% and 2.5% high and low tails, respectively. A confidence interval value of 30% indicates the upper end of the interval is mean times 1.30, and the lower end is mean divided by 1.30. “Typical” species are those where Abundant sightings comprise less than 10% of all nonzero sightings. “Typical” species error is based on the average of 7 typical species. “Abundant” species are those where Abundant sightings comprise more than 10% of all nonzero sightings. “Abundant” species error is based on the average of 4 abundant species.

Both the coefficient of variation of the predicted/observed ratios and AICc scoring suggests that Model 3 is the most accurate in converting SFMA data to numeric means. Model 3 appears to be the most effective because it (a) considers the relative proportion of adjacent count bins, and (b) reflects the underlying log-normal distribution of fish sightings. In fact, the exact count data indicate that the f_f and m_m coefficients are close to (within 5% of) the mean of the log-transformed bounds for their respective ranges. That is:

$$f_f = 4.16 \approx e^{(\ln(1.5)\,+\,\ln(10.5))/2} = 3.97 \qquad (14)$$

$$m_m = 33.8 \approx e^{(\ln(10.5)\,+\,\ln(100.5))/2} = 32.5 \qquad (15)$$

The values for these coefficients make intuitive sense because the sightings in the integer sub-bins (e.g., 2, 3…9, 10) within each range (e.g., Few) decline exponentially. Because the Abundant category is the highest order of magnitude counted, the a_m and a_a coefficients do not follow the same pattern.

Per the AICc selection criterion, Model 3 prevails over Model 2 given the assumed values for k, the number of parameters, of 5 and 4, respectively. Some may argue that the constants 2, 10, 11, and 100 found in Estimate 3 are actually AIC parameters and should be accounted for in k when calculating AICc scores. The authors considered these *a priori* constant properties based on the definition of Few (2–10) and Many (11–100). In fact, a slightly smaller apparent confidence interval can be attained if these constants are allowed to vary as fitting parameters. However, AICc analysis revealed that allowing these constants to vary ($k = 9$) is inappropriate overfitting.

Even though Model 2 does not prevail according to AICc scoring, it may nevertheless be attractive to some researchers because of its simple formation and reasonable accuracy, with a sacrifice of only about 22% in increased confidence interval compared to Model 3.

Model 1, with a confidence interval roughly three times larger than Models 2 and 3, can still be useful in making rough estimates and discerning global trends, when the only data available are the sighting frequency (*SF*) and log-density index (*DEN*) information available to the public on the www.REEF.org Web site. Disaggregated SFMA data, upon which Models 2 and 3 rely, are available to researchers through special request.

Some researchers may propose ordered logit regression as an alternative estimation method. A preliminary investigation suggests that this approach will achieve AICc scores better than Model 1, but worse than Models 2 and 3. This might be expected, because the method is

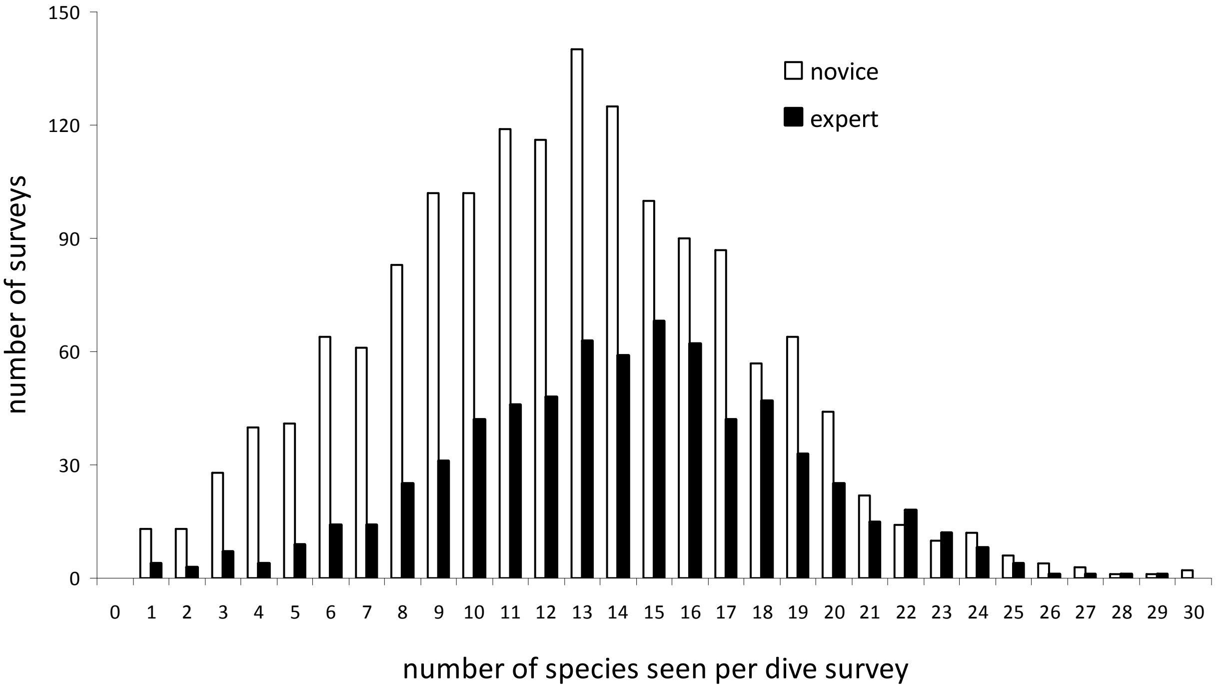

Figure 10: Histogram of number of surveys (vertical axis) as a function of number of fish species seen per dive (horizontal axis), for novice surveyors (white bars) and expert surveyors (black bars). The mean number of fish species seen on a dive by novices is 12.4, compared to 14.1 species for experts.

designed for analyzing qualitative ranges such as opinions that range from "strongly disagree" to "strongly agree." Because the logit function is based on the premise of evenly distributed categories, other ordinal regression (cumulative probability) approaches may prove more fruitful, such as negative log-log, based on the more accurate assumption that lower categories are more probable (Norusis 2011).

Dive Site Mix Normalizing Versus Increased Confidence Interval: The reported observational error to take into account a varying mix of dive sites (COV = 0.15) is specific to the Monterey Peninsula data, to the dive site characteristics considered, and to the three species considered. As such, it only represents what may be a "typical" value for this kind of variability in REEF surveys. It is always preferable to instead control the dive site mix, by either culling dive site data to maintain a consistent mix, or to normalize a varying mix of dive sites. When the dive site mix is not controlled or normalized, it is preferable to use COV = 0.15 rather than ignore this contribution to variability altogether.

Bias Towards Undercounting. The REEF RDT survey method may have a consistent tendency to undercount fish populations, leading to conservative estimates of absolute fish densities if this tendency is not accounted for in analyses. However, because this bias is consistent over time, underlying population dynamics should be discernable even if the bias is not corrected. The undercount bias is due to several factors:

1. Strict instructions to surveyors to not count any fish seen whose species cannot be positively identified (Pattengil-Semmens and Semmens 2003a). Novice surveyors therefore undercount less readily identified species (fig. 10). However, previous research suggests that novices count the number of individuals of species that they can identify as accurately as experts (Pattengill-Semmens and Semmens 1998).
2. Tendency to overlook cryptic bottom dwelling species as well as fish sheltering in concealed unobservable crevices.
3. Tendency to not notice pelagic fish swimming overhead or those quickly swimming in and out of view.
4. Inability to see sufficient distance in low visibility conditions.
5. Inability to thoroughly examine the bottom in high surge conditions.
6. Tendency of divers to not count the same fish twice on the return leg of their route (affects density estimates that are based on estimated length of dive route).
7. Tendency of divers to undercount schools of fish. Harrison Stubbs (pers. comm. June 2012) has observed that most people consistently underestimate the number of fish in a still photo of schooling fish,. Even greater bias may occur in situ where a school is constantly moving. This could explain the truncated lognormal distribution at higher fish counts shown in Figure 1b, as well as the higher deviations at higher counts shown in Figure 3.

Sightings Per Dive as an Estimate of Population Density: An underlying premise of this paper is that the mean number of fish seen per dive can be used as a proxy for nearshore fish species relative abundance. This is reasonable, given that dives have an average duration and route length. While this creates internally consistent data for comparisons between areas and between time periods, it is also useful to make estimates of absolute density to compare to other data sets. Wolfe and Pattengill-Semmens 2013 evaluated REEF data collected between 1997–2011 for the Monterey Peninsula area, and compared year-to-year fluctuations with exact-count transect data collected by the Partnership for Interdisciplinary Studies of Coastal Oceans (PISCO). The two data sets correlated well. Furthermore, REEF data could be calibrated with the transect data. For most fish species, a rough estimate of density can be determined from REEF count data by dividing the average number of fish seen per dive by 300 m^2. Because a REEF diver typically surveys a larger area than this on a given dive (approximately 50 minute average dive x 5 m/min average swim speed x 2 m minimum wide swath = approximately 500 m^2), the comparison of PISCO and REEF data provided indirect evidence that the RDT method has some bias toward undercounting compared to transect surveys.

Conclusion: The methods described in this paper convert order-of-magnitude counts to an aggregate arithmetic mean with a reasonably small confidence interval if the number of surveys is sufficiently large. These methods hold particular potential for application to REEF fish surveys. Researchers using RDT data have typically used Abundance Score indices, which is sighting frequency (*SF*) multiplied by the log density index (*DEN*), sometimes calibrated to transect surveys (Green et al. 2012; Pattengill-Semmens and Semmens 2003b). The model proposed in this paper offers two significant advantages: (a) fish seen per dive can be reported in arithmetic units that are easier to compare to other data sets, and (b) confidence intervals are much tighter. For instance, Green et al. 2012, plotting fish seen per dive on a log scale, reported a 95% confidence interval for lionfish in 2008 based on 21 surveys of about $^{x}/3.55$, with similarly broad intervals in other years. Model 1 in this paper would have similar SFMA translational confidence intervals. However, using Model 3, the 95% confidence interval would be $^{x}/1.35$ considering only SFMA translation error, and $^{x}/1.61$ if both translational and observational error were considered—a dramatic tightening of confidence interval in either case.

REEF data for the Monterey Peninsula area of the California coast were used as an example, with results described in a companion paper (Wolfe and Pattengill-Semmens 2013). Both the conversion error and observation error appeared to be reasonably small. For the Monterey data, with annual number of surveys ranging from 50 to 353, it appeared that 90% confidence intervals (5% high and low tails) of combined SFMA conversion and observation error were typically less than $^{x}/30\%$ relative to the mean. For fish population estimates, where confidence intervals are often very broad, this demonstrates that fish population estimates with reasonable error bars can be attained at remarkably low cost with citizen science volunteer efforts supported by a small professional staff.

The authors believe that the methodology of converting SFMA data to numeric means described in this paper can be applied to other coastal ocean areas where large numbers of REEF surveys have been conducted. In addition to the Monterey area of central California, REEF maintains a long-term database of surveys for many areas of the coastal United States and Caribbean, including the Pacific Northwest, Southern California, Hawaii, the South Pacific, and the tropical western Atlantic. The estimation method described in this paper should also prove useful in analyzing data from other order-of-magnitude population survey efforts.

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Paul Humann and Ned DeLoach founded REEF in 1990, and Lad Akins served as its executive director for many years—fostering the efforts of thousands of recreational divers to conduct fish and invertebrate surveys. Brice Semmens was instrumental in developing REEF's Roving Diver Technique and has served as a valuable scientific advisor. Lynn Waterhouse, Tom Laidig, Robert VanBuskirk, Nathan Hunt, and Katie Coughlin provided insightful statistical comments. Hundreds of volunteer divers have contributed to the REEF database for Monterey Peninsula. We especially thank the 18 members of the Advanced Assessment Team who assisted us with the Variability Between Divers study in May 2012.

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FISH POPULATION FLUCTUATION ESTIMATES BASED ON FIFTEEN YEARS OF REEF VOLUNTEER DIVER DATA FOR THE MONTEREY PENINSULA, CALIFORNIA

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ABSTRACT

A database of fish surveys conducted by volunteer recreational divers trained by Reef Environmental Education Foundation (REEF) was used to examine fish populations in Monterey Peninsula, California, between 1997 and 2011. Over 3,000 surveys were conducted as part of this ongoing citizen science effort. Variations in relative density over time are reported for 18 fish species, including several fisheries-targeted species. Two recruitment pulses of young-of-the-year rockfish (*Sebastes* spp.) were observed over the study period, with subsequent increases in older rockfish. Several predator species increased and subsequently declined, peaking two years after prey populations. Strong concordance was found between REEF data and those collected by Partnership for Interdisciplinary Studies of Coastal Oceans (PISCO), a consortium of academic institutions. Results show that data collected by REEF has great potential to augment and strengthen professional research data and serve as a valuable baseline to evaluate marine reserves.

INTRODUCTION

Citizen science data collection efforts have proven to be a cost-efficient way to collect much needed information for conservation and management efforts (Pattengill-Semmens and Semmens 2003; Dickinson et al. 2012; Holt et al. 2013). Citizen science efforts marshaled by Reef Environmental Education Foundation (REEF) have accumulated a rich, long-term database of marine life surveys using volunteer divers trained and supported by a small professional staff (Pattengill-Semmens and Semmens 2003; REEF 2013). Since 1993, REEF has engaged over 14,000 recreational SCUBA divers across North and Central America, Hawaii, and the South Pacific to conduct fish surveys. As of July 2013, over 172,000 surveys had been conducted worldwide, with the results made publicly available on REEF's Web site, www.REEF.org. These data have proven key to providing fisheries-independent data in stock assessments, documenting change in populations due to management zones, evaluating regional patterns in biodiversity, and tracking invasive lionfish range expansion in the Caribbean. A complete list of publications that include REEF data can be found on www.REEF.org.

Using a numerical conversion method to calculate population estimates from REEF log-scale data (Wolfe and Pattengill-Semmens 2013), fifteen years of fish data for the nearshore reefs of the Monterey Peninsula, California, were examined. The study area encompasses south Monterey Bay and Carmel Bay, and extends northeast to the Monterey shale beds and southwest to Point Lobos (fig. 1). REEF survey results were also compared to transect surveys conducted by the Partnership for Interdisciplinary Studies of Coastal Oceans (PISCO), a consortium of scientists from universities along the U.S. West Coast.

The primary objectives of this study were: (1) to determine if fish population trends are evident in this time series data, (2) to compare those trends with another data set using a different methodology (PISCO), (3) to determine if REEF data can be calibrated to a common density index, and (4) to evaluate whether the REEF data offer unique and/or complementary information that can be used by researchers, agencies, and policy makers.

METHODS

REEF Volunteer Survey Project Roving Diver Technique: The REEF Volunteer Survey Project started collecting data in the marine waters of California in 1997. REEF volunteers conduct fish surveys using the Roving Diver Technique (RDT; Schmitt and Sullivan 1996). The RDT is a visual survey method designed to generate a comprehensive species list, along with sighting frequency and relative abundance estimates. During RDT surveys, divers swim freely throughout a dive site and record every observed identifiable fish species. Divers are encouraged to explore not only reef structure, but also scan for pelagic species overhead and investigate crevices, ledges, and rock/sand interfaces. During a survey, divers assign each recorded species to one of four $\log_{10}$ abundance categories. Surveyors enter species data along with survey time and environmental information into an online data entry interface (optical scanforms used prior to 2007). REEF staff carefully review the survey reports before transferring the information into the per-

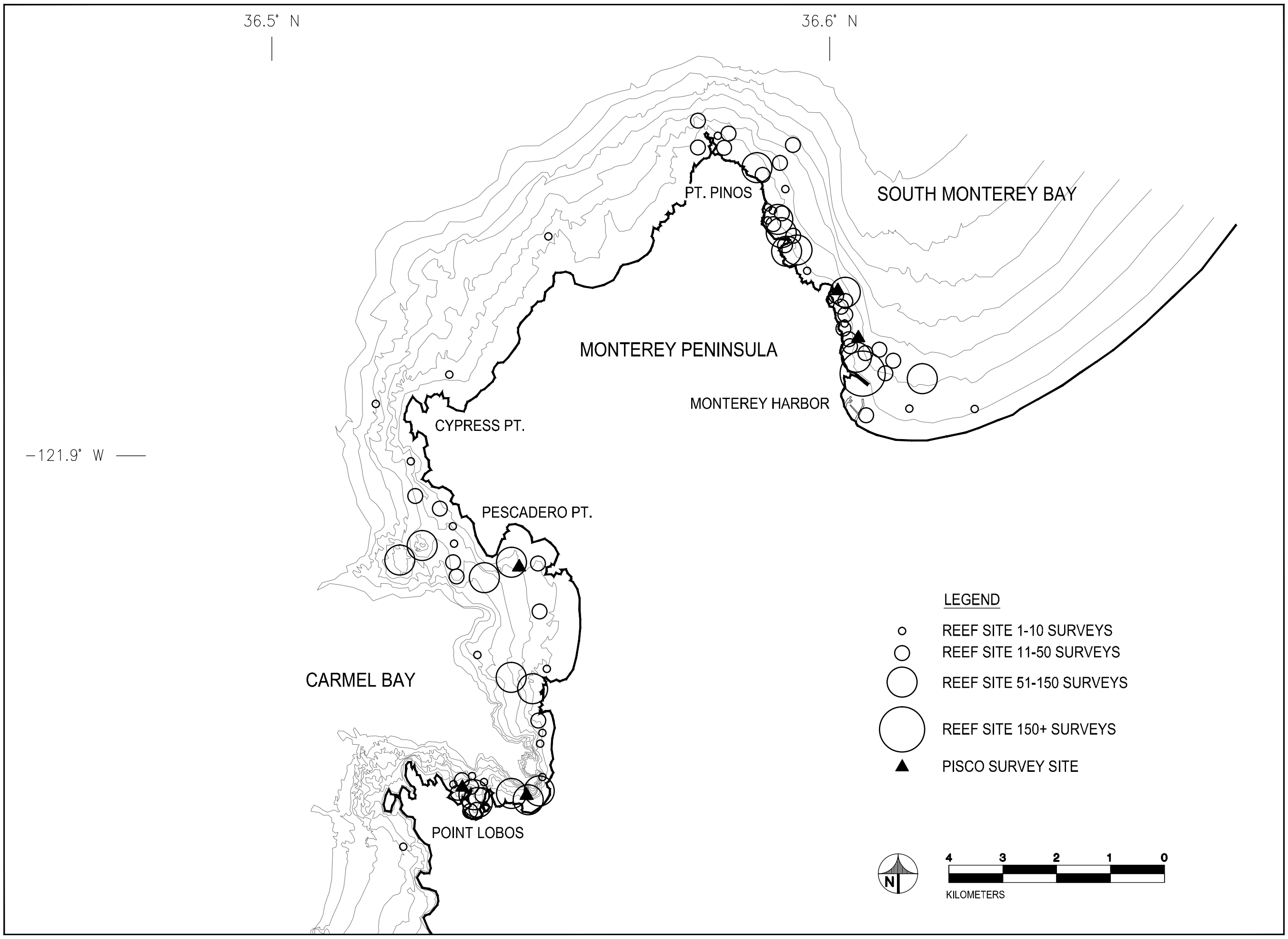


Figure 1. Rocky reefs surround much of the Monterey Peninsula, California (bathymetric contours from Seafloor Mapping Lab, CSUMB) . Circle symbols indicate REEF fish survey sites; triangle symbols indicate sites surveyed by both REEF and PISCO.

manent database, culling or correcting obvious errors and contacting divers if anomalous or unusual sightings are reported. Summary data can then be accessed by the public at REEF's webpage (http://www.REEF.org) by geographic location. REEF staff generate raw data files on request for scientists and resource agencies.

Identification and methodology training is made available to REEF volunteers through classroom sessions, webinars, and self-teaching materials (Pattengill-Semmens and Semmens 1998; Semmens et al. 2000). Field identification of Pacific coast fishes is based on regional field guides (Eschemeyer et al. 1983; Gotshall 2001; Love et al. 2002; Humann and DeLoach 2008). Divers are instructed to only report species they can positively identify. REEF surveyors advance through five experience levels (Novice: 1–3 and Expert: 4–5), based on the number of surveys completed and passing scores on comprehensive identification exams.

REEF surveys are conducted throughout the West Coast. The area studied here is identified as REEF Geographic Zone Code 4114 (South Davenport–Point Lobos Reserve), and more specifically the area extending west and south from the south Monterey Bay shale beds through Point Lobos (fig. 1). REEF surveys are conducted year round, with more surveys reported for summer months than winter. The months with the highest number of surveys in the study region are May, when REEF Advanced Assessment Team members conduct an annual Monterey Field Survey over four days; and July, when Great Annual Fish Count organized events take place.

REEF summarizes count results by reporting sighting frequency, *SF*, defined as the fraction of dives when a given species is seen; and log-density index, *DEN*, defined as:

$$DEN = \frac{S + 2F + 3M + 4A}{S + F + M + A} \qquad (1)$$

where, for a given species, area, and period,

S = *number of dives reporting Single (1),*
F = *number of dives reporting Few (2–10),*
M = *number of dives reporting Many (11–100), and*
A = *the number dives reporting Abundant (over 100).*

Converting SFMA data to Expected Arithmetic Mean: Wolfe and Pattengill-Semmens 2013 documented a novel approach to calculating estimates of mean numbers of fish from REEF order-of-magnitude count data, using disaggregated SFMA data rather than the aggregate log-density index *DEN*. The alternative method yielded a threefold tighter confidence interval over *DEN* (Wolfe and Pattengill-Semmens 2013). A brief description of the calculation is given here.

An "Average of Few" variable is formulated, based on the proportion of adjacent count categories Single and Many. Similar variables are calculated for the Many and Abundant categories, as follows:

$$AvgF = \frac{2S + 4.16F + 10M}{S + F + M}$$

$$AvgM = \frac{11F + 33.8M + 100A}{F + M + A} \qquad (2)$$

$$AvgA = \frac{200M + 348A}{M + A}$$

Parameters 2, 10, 11, and 100 are *a priori* constants based on the Few category being defined as 2 to10 and Many being defined as 11 to 100. The other parameters (4.16, 33.8, 200, and 348) are best-fit parameters based on least squares regression.

The variables *AvgF, AvgM,* and *AvgA*, multiplied by their corresponding category counts *F, M* and *A*, are then summed and divided by the total nonzero counts to give the average sightings per dive:

$$ExpectedMean(NonZeroSurveys) = \frac{S + F \cdot AvgF + M \cdot AvgM + A \cdot AvgA}{S + F + M + A} \qquad (3)$$

Finally, the expected mean for nonzero surveys is multiplied by the sighting frequency (fraction of nonzero sightings) to calculate an overall average number of fish of a given species seen per dive.

$$ExpectedMean(AllSurveys) = SightingFrequency \cdot ExpectedMean(NonZeroSurveys) \qquad (4)$$

The average fish seen per dive was normalized for slight variations in year-to-year bottom time, under the assumption that fish sightings are essentially proportional to bottom dive time, with longer dives covering more distance to encounter more fish. Wolfe and Pattengill-Semmens 2013 quantified the confidence interval as a function of the number of nonzero surveys, based on several sources of error, including:

1. Conversion or Translational Error: Converting SFMA data to Arithmetic Mean
2. Observational Error, including the following components:
   a. Variation between divers at the same dive site, swimming different routes across the same site,
   b. Variation between dives at the same site over the year,
   c. Variation in the mix of dive sites surveyed from year to year (boat vs. shore, Carmel vs. Monterey Bays).

The *combined* translational and observational 90% confidence interval (5% high and low tails) can be expressed as a function of the number of nonzero sightings, *n*, per year:

$$Confidence\ Interval\ Typical\ Species_{90\%} = 0.02 + \frac{2.03}{(n-1)^{0.48}} \qquad (5a)$$

$$Confidence\ Interval\ Abundant\ Species_{90\%} = -0.26 + \frac{3.20}{(n-1)^{0.38}} \qquad (5b)$$

In the confidence intervals above, "abundant species" are those where the proportion of Abundant counts to total nonzero sightings, $A/(S + F + M + A)$ exceeds 10%, while all other species are designated "typical." Because the underlying count distribution is log-normal, skewing to zero, the error bars above and below the mean are not equal. Therefore, the error bars are expressed as multipliers and divisors of the expected mean (example: a 90% confidence interval of $^{x}/30\%$ is the mean multiplied and divided by 1.30 instead of $^{+}/_{-}$ 30%; see Limpert et al. 2001).

Fish species populations trends: Using the calculated estimates derived from the method described above (and more fully in Wolfe and Pattengill-Semmens 2013), variations in relative density over time are reported for 18 fish species, including fisheries-targeted species such as blue rockfish (*Sebastes mystinus*), cabezon (*Scorpaenichthys marmoratus*), kelp greenling (*Hexagrammos decagrammus*), and lingcod (*Ophiodon elongatus*).

PISCO survey comparison: REEF data for eight species were compared with those collected through the PISCO program, using data collected in the Monterey Peninsula area between 1999 and 2008. PISCO is a large-scale visual survey effort by academic research divers (PISCO 2012). PISCO collects data on fish populations and trends using 30m x 2m x 2m transects.

TABLE 1
Comparison of REEF and PISCO surveys methods for the years 1999–2008

	REEF	PISCO
Number of Survey Sites	85	5
Number of Surveys	1860 Dives	960 Transects
Survey Extent	Dive Site	Transect
Distance Per Survey	250 m (est.)	30 m
Total Distance Surveyed	470 km (est.)	29 km
Width of Survey	Limited by Visibility	2 meters
Type of Count	Order of Magnitude	Exact
Size of Fish Recorded?	No*	Yes
Type of Surveyor	Non-scientist Volunteer	Scientific Researcher

*Exception: Rockfish less than or equal to 5 cm recorded as YOY rockfish (*Sebastes* spp.).

Fish species, abundance, size, and gender (for species with readily apparent sexual dimorphism) are recorded. PISCO has conducted regular underwater transect surveys at five dive sites in Monterey and Carmel Bays since 1999. PISCO fish surveys take place from approximately mid-August through October, a time of year that captures both early and late season young-of-the-year (YOY) rockfish recruits. Three portions of the water column are sampled: bottom, midwater, and upper kelp canopy. PISCO bottom data were used in comparisons presented here.

Table 1 compares the general characteristics of the two survey methods. Assuming a REEF survey average swimming speed of approximately 5 m per minute (unpublished data) and an average dive duration of 50 minutes, the average distance covered in a REEF survey is about 250 m. Therefore the total distance surveyed by REEF between 1999 and 2007 in 1860 surveys is about 470 km. This is approximately 16 times the distance surveyed by PISCO (960 transects x 30 m/transect) for the same period. Note that because the width of a PISCO transect is limited to 2 m, while the width of a REEF survey is limited by visibility (typically farther than 1 m to each side), the ratio of benthic area surveyed is probably greater than distance surveyed.

To quantify extent of covariance between the two data sets, Pearson's correlation coefficient (r) was calculated from year-to-year data pairs for each species. YOY rockfish were identified as a special case. Because the standard deviation of the REEF/PISCO ratio increased in proportion to individuals counted, the seven non-YOY species were combined into an aggregate analysis, comparing logn of PISCO counts against logn of REEF counts. For this aggregate data set, Pearson's r and corresponding p-value were calculated, along with mean REEF/PISCO multiplier and associated standard error and 90% confidence interval.

Young-of-the-year (YOY) trends: In addition to evaluating trends in several fish species, trends in YOY rockfish (*Sebastes* spp.) were also evaluated. While the RDT protocol does not typically differentiate life history stages or size classes, starting in 2000, REEF surveyors began reporting YOY rockfish separately. The REEF protocol defines YOY rockfish as individuals with total length less than or equal to 5 cm. For surveys between 1997 and 1999, zero counts cannot be misconstrued as an absolute absence of YOY rockfish, although anecdotal information and other data sets suggest YOY rockfish populations were quite low.

YOY data sets from two other diver visual surveys are also included: PISCO transect data and 3-minute timed swim count data within a 3 m area from NOAA researcher Tom Laidig (Laidig et al. 2007 for northern California data; Laidig per.comm. for central California data). There are a few differences in the data sets worth noting. PISCO defines YOY as less than 15 cm in total length and Laidig defines YOY as 8 cm and less (compared with <5 cm in the REEF program). For purposes of comparison here, PISCO staff provided the authors with data for YOY rockfish limited to the 5 cm cohort. The time frames of the data sets also varied: Laidig reported data from 1983–2011; PISCO reported data from 1999–2008; REEF reported YOY data 2000–11.

RESULTS

REEF Data Population Trends, 1997 to 2011

During the 15-year period evaluated here (1997–2011), 3,158 REEF surveys were conducted at 85 sites in the study region (figs. 1, 2). A total of 344 volunteers contributed to this data set. A small subset of these volunteers (25) contributed the majority (68%) of the surveys. Approximately one-third of the surveys (1,080) were by Expert-rated surveyors. Survey effort was consistently above 150 surveys per year since 2002, except in 2007 (fig. 2). During the study period, REEF surveyors reported a total of 166 fish species (REEF 2013). Table 2 lists the sighting frequency (%*SF*) and log-density index (*DEN*), for the 35 most common species seen at dive sites around the Monterey Peninsula. The rocky reefs of this study are dominated by several species of rockfish, seaperch, greenlings, midwater planktivores, and several cryptic benthic dwellers.

A positive correlation between YOY rockfish (*Sebastes* spp.) and visibility (a proxy for plankton density) was documented, based on the number of YOY documented compared with the percentage of dives with visibility less than three meters (fig. 3). Both the YOY rockfish and percentage of low visibility dives peaked in 2001, with a lower pulse in 2010.

The pattern in YOY recruitment and subsequent peaks in post-YOY blue rockfish reveals a two year lag (fig. 4), with high YOY peaks in 2001–02 and 2009–10.

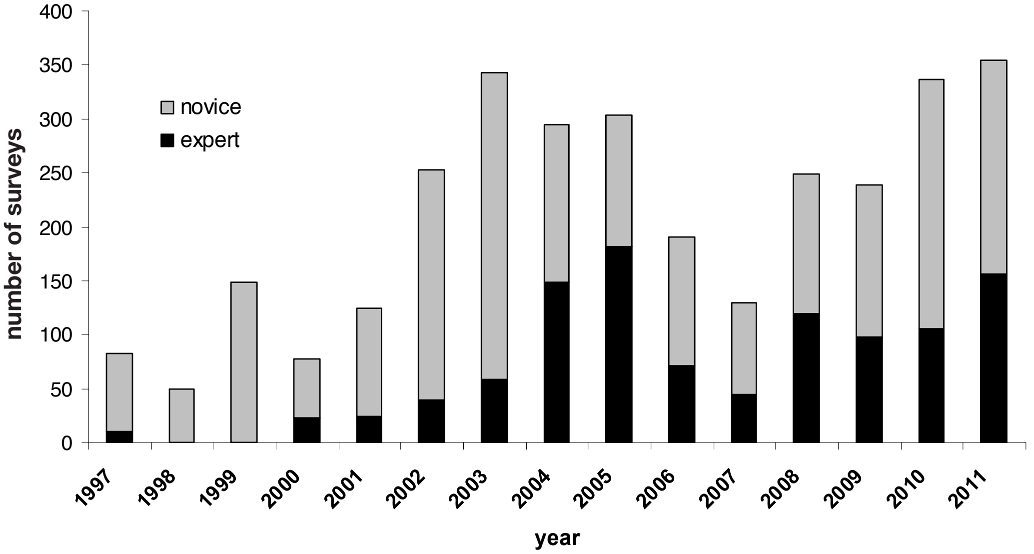


Figure 2. Number of REEF surveys per year in the Monterey Peninsula area ranged from a low of 50 in 1998 to a high of 353 in 2011.

TABLE 2

REEF Survey Data Summary: Most frequently observed fish species in south Monterey Bay and Carmel Bay (REEF geocode 4114–0000), 1997 through 2011. *SF* = Sighting Frequency (percentage of all dives). *DEN* is a log-density index defined as $(S + 2F + 3M + 4A)/(S + F + M + A)$.

Rank	Common Name	Scientific Name	SF%	DEN
1	Blue Rockfish	*Sebastes mystinus*	75.8	2.9
2	Painted Greenling	*Oxylebius pictus*	71.6	2.2
3	Blackeye Goby	*Rhinogobiops nicholsii*	68.2	2.3
4	Kelp Rockfish	*Sebastes atrovirens*	67.9	2.2
5	Kelp Greenling	*Hexagrammos decagrammus*	61.3	1.8
6	Striped Seaperch	*Embiotoca lateralis*	59.5	2.1
7	Pile Perch	*Rhacochilus vacca*	59.5	2.0
8	Black Perch	*Embiotoca jacksoni*	50.3	2.0
9	Gopher Rockfish	*Sebastes carnatus*	50.1	2.0
10	YOY Rockfish	*Sebastes* spp.	44.8	2.9
11	Lingcod	*Ophiodon elongatus*	42.4	1.5
12	Black-And-Yellow Rockfish	*Sebastes chrysomelas*	37.2	1.7
13	Black Rockfish	*Sebastes melanops*	35.7	1.9
14	Senorita	*Oxyjulis californica*	35.4	2.8
15	Olive/Yellowtail Rockfish*	*Sebastes serranoides/flavidus*	34.0	2.0
16	Speckled Sanddab	*Citharicthys stigmaeus*	30.4	2.4
17	Cabezon	*Scorpaenichthys marmoratus*	28.5	1.3
18	Copper Rockfish	*Sebastes caurinus*	28.4	1.7
19	Kelp Perch	*Brachyistius frenatus*	24.3	2.0
20	Rubberlip Seaperch	*Rhacochilus toxotes*	22.0	1.8
21	Snubnose Sculpin	*Orthonopias triacis*	18.3	1.5
22	Tubesnout	*Aulorhynchus flavidus*	17.4	2.5
23	Rainbow Seaperch	*Hypsurus caryi*	16.5	2.1
24	Vermilion Rockfish	*Sebastes miniatus*	14.4	1.4
25	Coralline Sculpin	*Artedius corallinus*	11.0	1.4
26	Treefish	*Sebastes serriceps*	10.7	1.3
27	California Sheephead	*Semicossyphus pulcher*	10.2	1.6
28	Scalyhead Sculpin	*Artedius harringtoni*	9.9	1.6
29	Blacksmith	*Chromis punctipinnis*	9.7	2.2
30	Brown Rockfish	*Sebastes auriculatus*	6.9	1.8
31	Grass Rockfish	*Sebastes rastrelliger*	6.3	1.4
32	China Rockfish	*Sebastes nebulosus*	5.9	1.3
33	Opaleye	*Girella nigricans*	5.5	1.6
34	Kelp Bass	*Paralabrax clathratus*	5.0	1.5
35	Wolf Eel	*Anarrhichthys ocellatus*	4.8	1.1

* Combined into a single category, since many experts believe these two species cannot be distinguished reliably by divers underwater.

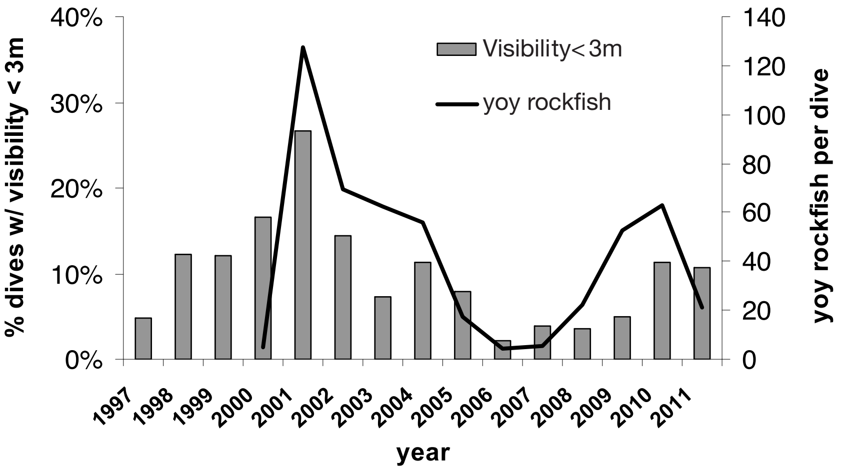


Figure 3. Year-to-year variation in percentage of dives with visibility less than three meters (grey bars) compared to fluctuations in YOY rockfish (*Sebastes* spp.) seen per dive (heavy black line).

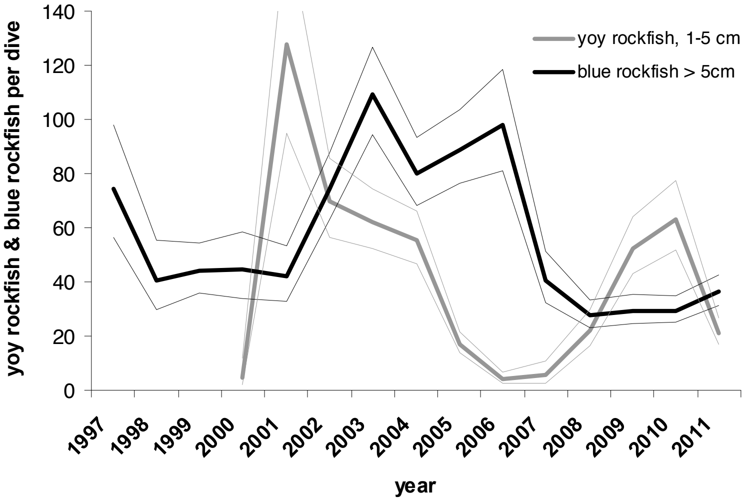


Figure 4. YOY rockfish (*Sebastes* spp., 1–5 cm) and blue rockfish (*Sebastes mystinus* >5 cm) annual average seen per REEF dive for the years 1997 to 2011, normalized for bottom time. The fine lines above and below each thick line indicate the 90% confidence interval (5% high and low tails).

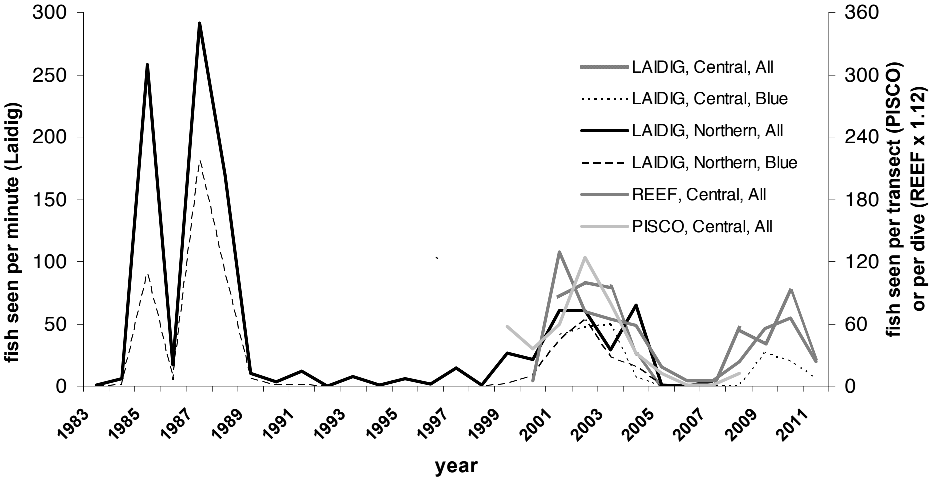


Figure 5. Comparison of Laidig data (Laidig et al. 2007) for blue and total rockfish YOY for northern California (Mendocino County, 1983–2007) and central California (Monterey, 2001–11), PISCO (1999–2008) for all rockfish YOY and REEF (2000–11) for all rockfish YOY. PISCO counts are fish seen per 30 m transect, REEF counts are fish seen per dive, and Laidig counts are fish seen in one minute intervals.

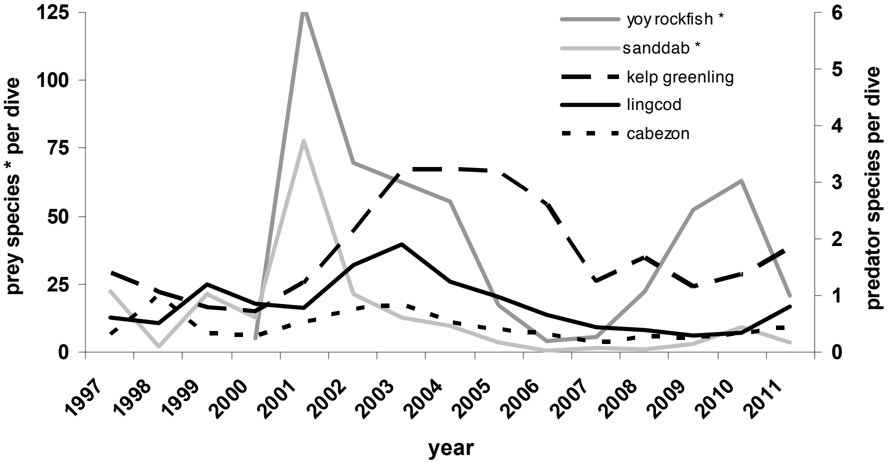


Figure 6. Selected prey and predator fish species annual average seen per REEF dive for the years 1997 to 2011, normalized for bottom time. Prey species (*) are YOY rockfish (*Sebastes* spp.), and speckled sanddab (*Citharicthys stigmaeus*). Predator species are lingcod (*Ophiodon elongatus*), cabezon (*Scorpaenichthys marmoratus*), and kelp greenling (*Hexagrammos decagrammus*).

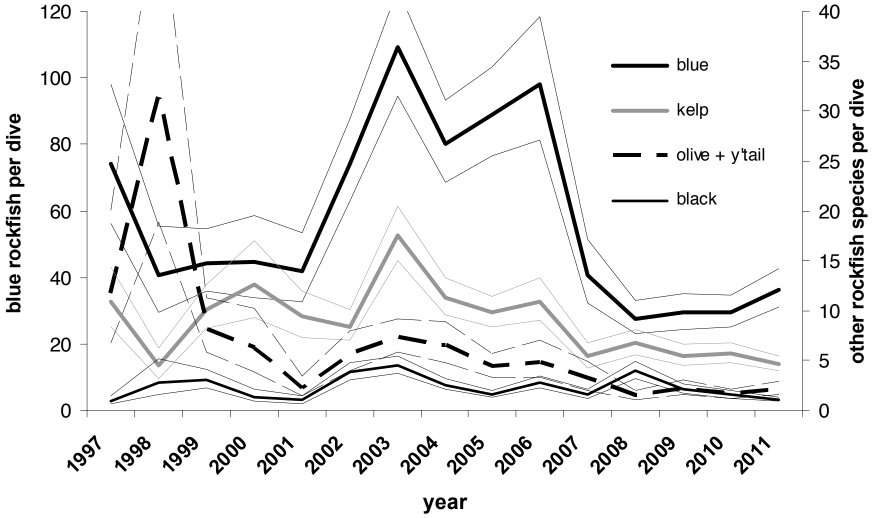


Figure 7. Four species of midwater rockfish annual average seen per REEF dive for the years 1997 to 2011, normalized for bottom time. Midwater rockfish species are blue (*Sebastes mystinus*), black (*S. melanops*), kelp (*S. atrovirens*), and a combined category of olive (*S. serranoides*) and yellowtail rockfish (*S. flavidus*). The fine lines above and below each thick line indicate the 90% confidence interval (5% high and low tails).

While REEF surveyors did not differentiate between rockfish species in YOY counts until 2008, unpublished observations by the authors indicate that blue rockfish were the predominant YOY *Sebastes* observed in the 2001–02 peak years.

Data from three sources (REEF, PISCO, T. Laidig) are combined to further evaluate rockfish recruitment patterns (fig. 5). All three data sets revealed similar patterns in rockfish recruitment. The Pearson correlation coefficients are 0.69 between the REEF and PISCO 2000–08 data, 0.78 between the REEF and Laidig 2001–11 data, and 0.88 between the PISCO and Laidig 2001–08 data. Years of major recruitment of YOY rockfish to nearshore reefs were seen in 1987–88, 2001–02, and 2009–10 (fig. 5). Every subsequent peak is significantly less than its predecessor.

Fluctuations of two prey population cohorts, YOY rockfish and speckled sanddab (*Citharicthys stigmaeus*), are compared to three predator species (fig. 6): kelp greenling, cabezon, and lingcod. The prey species peaked in 2001, while the predator species peaked in 2003 and declined thereafter. In relative terms, the kelp greenling population appears to maintain peak numbers following 2003 longer than either cabezon or lingcod.

Population trends for several groups of species were evaluated, including midwater rockfish, schooling midwater species, seaperch, and warm water species (figs. 7–10). Following the influx of YOY rockfish in 2001

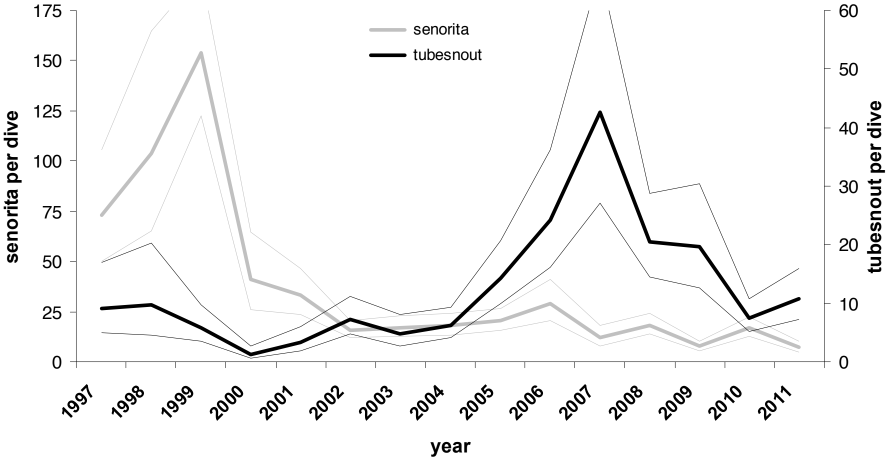


Figure 8. Senorita (*Oxyjulis californica*) and tubesnout (*Aulorhynchus flavidus*) annual average seen per REEF dive over the period 1999 to 2009, normalized for bottom time. The fine lines above and below each thick line indicate the 90% confidence interval (5% high and low tails).

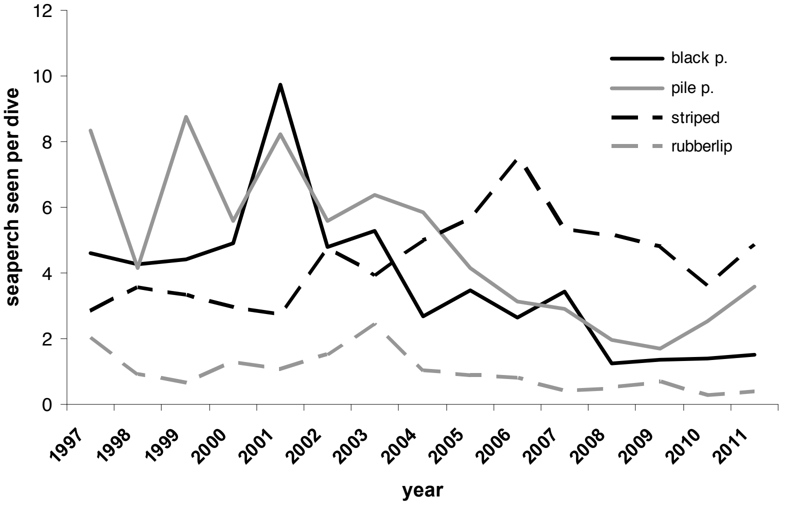


Figure 9. Four species of seaperch population density variation as indicated by annual average fish seen per REEF dive, over the period 1999 to 2009, normalized for bottom time. The seaperch species are: black (*Embiotoca jacksoni*), striped (*E. lateralis*), pile (*Rhacochilus vacca*), and rubberlip (*R. toxotes*).

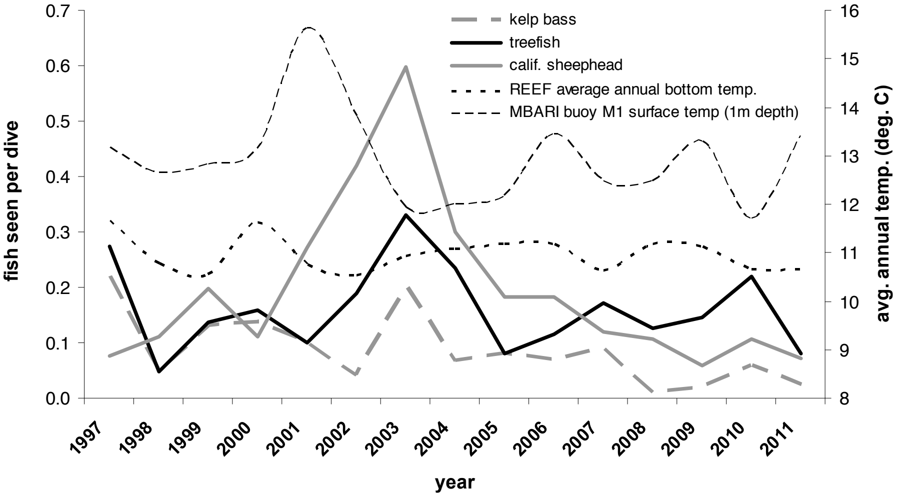
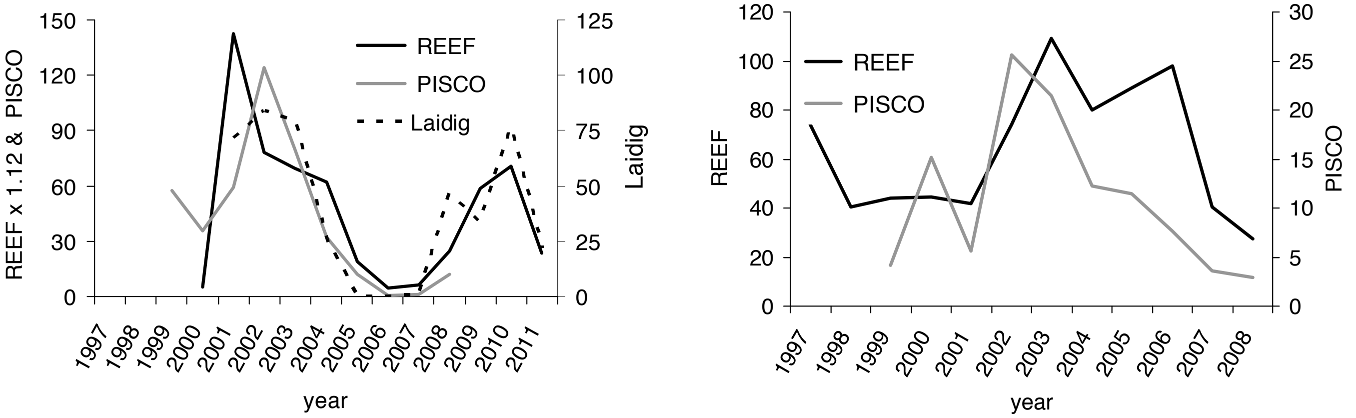
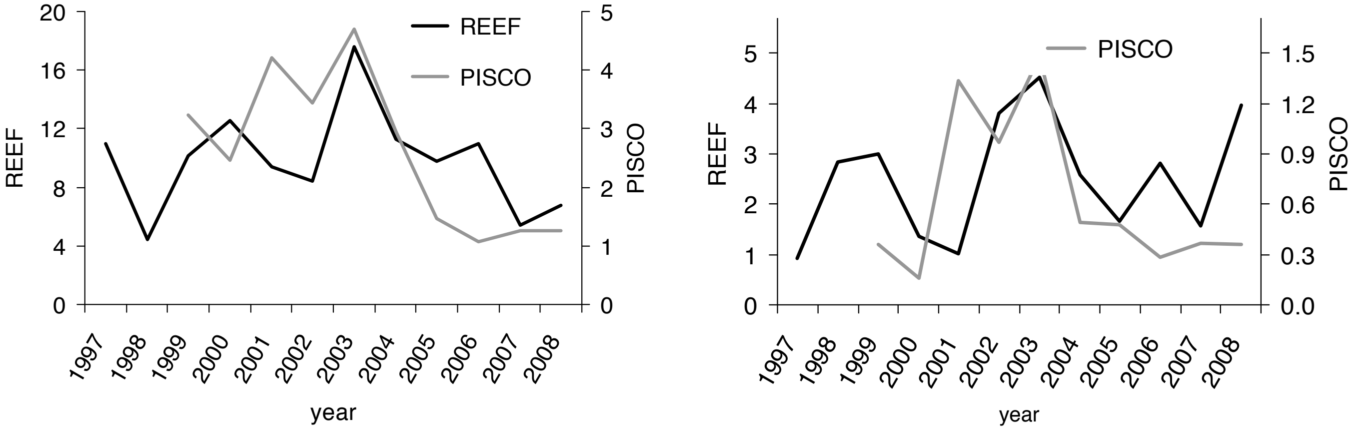


Figure 10. Warm water species annual average fish seen per dive over the period 1999 to 2011, normalized for bottom time. The three warm-water species are: California sheephead (*Semicossyphus pulcher*), kelp bass (*Paralabrax clathratus*), and treefish (*Sebastes serriceps*). Water temperature data from two sources also shown on the second Y-axis: MBARI buoy M1 surface temperature, and REEF divers' computer gauges' average annual bottom temperature.



a. YOY Rockfish, *Sebastes* spp., 1-5 cm.

b. Blue Rockfish, *Sebastes mystinus*, >5 cm.



c. Kelp Rockfish, *Sebastes atrovirens*, > 5 cm.

d. Black Rockfish, *Sebastes melanops*, > 5 cm.

Figure 11. Comparison between REEF and PISCO fish counts for several species of rockfish (*Sebastes*). PISCO counts are fish seen per 30 m transect, for the years 1999 to 2008. REEF counts are fish seen per dive, for the years 1997 to 2011, except for young-of-the-year (YOY) rockfish, which cover the years 2000 to 2011. For YOY rockfish, Laidig data (Laidig et al. 2007) are also shown. Laidig counts are fish seen in one minute intervals, for the years 2001 to 2011.

(figs. 4, 5, 6), all midwater rockfish species evaluated, including blue rockfish (*S. mystinus*), black rockfish (*S. melanops*), kelp rockfish (*S. atrovirens*), and olive/yellowtail rockfish (*S. serranoides / S. flavidus*) (grouped because virtually indistinguishable underwater), peaked in 2003, with a secondary peak in 2006 (fig. 7). The two species of small, schooling midwater fishes evaluated, senorita (*Oxyjulis californica*) and tubesnout (*Aulorhynchus flavidus*), exhibited relatively low numbers throughout the study period, punctuated by strong but brief peaks in numbers (fig. 8). Of the four species of seaperch examined, black seaperch (*Rhacochilus jacksoni*) and pile seaperch (*R. vacca*) followed a similar pattern, while rubberlip seaperch (*R. toxotes*) and striped seaperch (*Embiotoca lateralis*) peaked in 2003 and 2006, respectively (fig. 9). The three species of warm water species evaluated, which included California sheephead (*Semicossyphus pulcher*), kelp bass (*Paralabrax clathratus*), and treefish (*Sebastes serriceps*), all followed similar patterns (fig. 10). Two annual average temperature trends are also plotted on Figure 10: bottom temperature as reported by REEF surveyors (based on dive gauges or computers) and 1 m depth temperature at the MBARI mooring M1 in outer Monterey Bay (MBARI 2012).

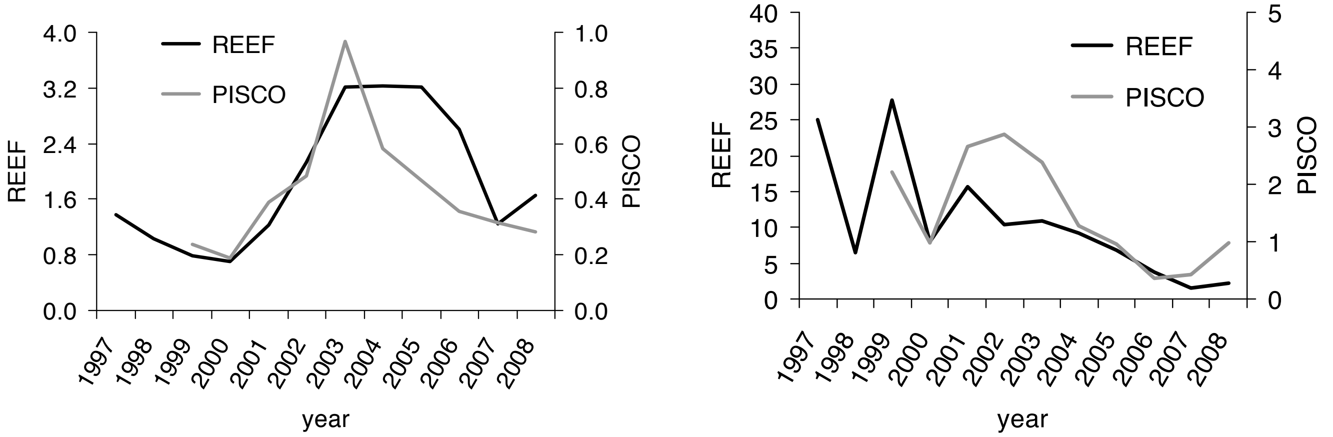
Comparison of REEF and PISCO data, 1999 to 2008

In order to evaluate the similarity in trends recorded between REEF and another organized monitoring effort conducted with a different methodology (PISCO), trends in several species based on the two data sets were examined. Trends in YOY rockfish are compared; YOY data collected by T. Laidig were also considered (fig. 11a). REEF surveyors measured peak numbers of YOY rockfish in 2001, followed by significant numbers in 2002–04, while PISCO documented a peak in 2002 with significant numbers in adjacent years 2001 and 2003, and Laidig counted high numbers between 2001–03. All three methods also documented a second upswing commencing in 2008 (fig. 11a).

TABLE 3
Comparison of REEF & PISCO Survey Results, 1999–2008

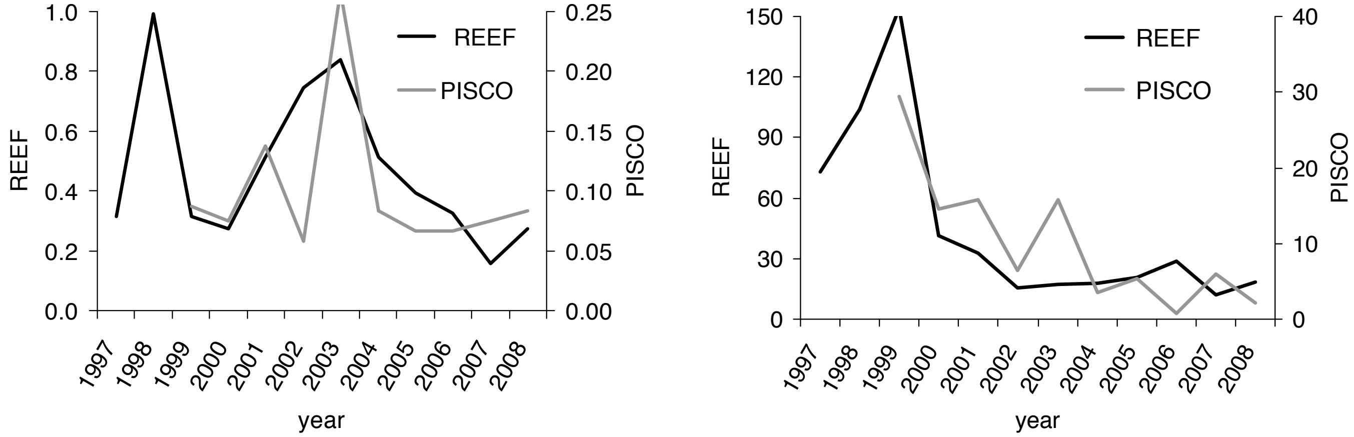
Common Name	Scientific Name	REEF / PISCO Ratio	Pearson Correlation Coefficient, r
YOY Rockfish	*Sebastes* spp.	1.12	0.66
Blue Rockfish	*Sebastes mystinus*	5.55	0.60
Black Rockfish	*Sebastes melanops*	4.65	0.29
Kelp Rockfish	*Sebastes atrovirens*	3.99	0.57
Kelp Greenling	*Hexagrammos decagrammus*	4.75	0.76
Painted Greenling	*Oxylebius pictus*	7.64, 4.79*	0.68, 0.82*
Cabezon	*Scorpaenichthys marmoratus*	4.46	0.62
Senorita	*Oxyjulis californica*	4.20	0.82
AVERAGE	Seven non-YOY species**	4.85***	0.932****

* with painted greenling years 1999-2001 removed
** all data included except YOY rockfish, n = 7 species x 10 years = 70 data pairs
*** 90% confidence interval (5% tails) = 4.85 ×/13%
**** p-value < 0.00001



a. Kelp Greenling, *Hexagrammos decagrammus*

b. Painted Greenling, *Oxylebius pictus*



c. Cabezon, *Scorpaenichthys marmoratus*

d. Senorita, *Oxjulis californica*

Figure 12. Comparison between REEF and PISCO data for several rocky reef fish species. PISCO counts are fish seen per 30 m transect, for the years 1999 to 2008. REEF counts are fish seen per dive, for the years 1997 to 2011.

Population trends for several other rocky reef fish species, as measured by REEF and PISCO, are compared in Figures 11b–d and 12a–d. Pearson's correlation coefficient (r) of yearly paired data comparisons for these species were calculated (table 3). All species exhibited a strong correlation between the abundance estimates generated from each of the data sets, with r exceeding 0.50 for seven of the eight species in the comparison study, and ranging as high as 0.82 for senorita (table 3). Black rockfish was the exception, with an r of 0.29. For most species, REEF's mean fish seen per RDT survey was four to five times that of a PISCO transect (table 3).

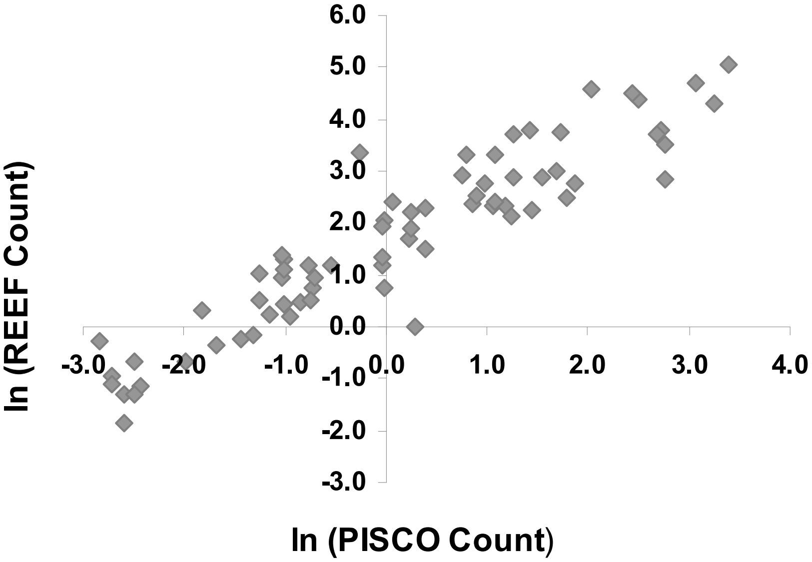


Figure 13. REEF counts versus PISCO counts plotted in log space, for seven species over ten years (n = 70, r = 0.932, $p < 0.0001$). REEF/PISCO mean multiplier = exp(ln(REEF)-ln(PISCO)) = 4.85 with 90% confidence interval of $^{x}/13\%$.

The exceptions were YOY Rockfish, with a very low multiplier (1.12), and painted greenling (*Oxylebius pictus*), with a high multiplier (7.64).

When data pairs for all seven non-YOY species over ten years were aggregated into a single analysis (n = 70), a very strong correlation was found (r = 0.932, $p < 0.00001$, fig. 13). The aggregate analysis indicated the REEF/PISCO multiplier is 4.85 with a 90% confidence interval of $^{x}/13\%$

DISCUSSION

The drop in visibility measured by REEF surveyors corresponded closely to the peaks in YOY rockfish documented by REEF data (figs. 2, 3) and others (fig. 5). The REEF YOY rockfish trends closely match those documented by Laidig and PISCO. The YOY peaks in 2001 and 2009–10 also coincide with the pelagic micronekton trawls of larval rockfish reported by Bjorkstedt et al. 2012, as well as the fluorescence (volts) anomaly measured by MBARI 2012 at surface and 60 m depths at mooring M1. These covariant trends substantiate the relationship between ocean conditions, plankton density, and rockfish recruitment widely reported in the literature (e.g., Carr and Syms 2006)

The data also suggest that the same blue rockfish cohort is being tracked as it ages from YOY to subadult to adult (fig. 4). This is evident in spikes of YOY rockfish (*Sebastes* spp., predominantly *S. mystinus*) followed two years later by peaks in subadult (>5 cm) and adult blue rockfish populations. It is also possible that the blue rockfish trend is caused by strong in- and out- migration to and from the nearshore reefs. However, radio-acoustic tracking (Jorgensen et al. 2006) demonstrate that these midwater schooling fish have surprisingly small home reef ranges, at least for the monthlong duration of that study, providing support for the idea that the REEF data reflect local, nonmigrating blue rockfish populations as they age. Trends for other rockfish species, peaking in 2003 after the 2001 YOY recruitment pulse, also suggest YOY to post-YOY aging (fig. 7).

Correlations between the REEF, PISCO, and T. Ladig data sets for all YOY rockfish species in central California (Monterey Peninsula) are very strong (fig. 5), suggesting all methods are successfully measuring the same underlying YOY rockfish populations.

Three peaks in YOY rockfish recruitment to inshore reefs over the last three decades were documented, with each peak smaller than the previous one (fig. 5). The successively smaller peaks may suggest a long-term downward trend in nearshore rockfish populations off northern and central California, or alternatively, that ocean conditions may be increasingly less favorable to larval rockfish survival and recruitment to nearshore reefs, or some combination thereof. Preliminary unpublished 2013 data (T. Laidig, per. comm. re ichthyoplankton trawls; REEF May 2013 Monterey field survey) indicates that the 2013 YOY rockfish recruitment may be very large, potentially reversing this apparent downward trend.

Population fluctuations for two prey species and three predator species are superimposed in Figure 6 to explore the hypothesis of whether a classic predator-prey cycle (Krebs et al. 2001; Estes et al. 2004) is being observed. Such a hypothesis is best vetted by a comprehensive population dynamics model that includes such considerations as the effect of changes in fishing regulations and pressures on predator mortality, relative contribution of different prey species to predator diet and influence of prey abundance on predator fitness, reproductive success, and reduced disease and mortality. Nevertheless, we briefly discuss potential causes for the patterns seen to encourage future population modeling efforts.

Population peaks seen in 2001 for YOY rockfish and speckled sanddab in the REEF data (fig. 6) closely matches micronekton trawls in outer Monterey Bay (Bjorkstedt et al. 2012). Rockfish larvae in the micronekton exhibit strong covariance with larval sanddab (*Citharicthys* spp.), Pacific hake (*Merluccius productus*), krill (euphausiids), and market squid (cephalopods), collectively known as the "groundfish assemblage." After a recruitment pulse, both YOY rockfish and speckled sanddab declined rapidly. YOY rockfish grow out of the REEF/RDT imposed 5 cm max YOY cohort in a year or less, aging into species-specific rockfish count categories that encompass both subadults and adults. After initial recruitment to the reef, YOY rockfish numbers rapidly decrease from the combined effects of predation and maturation into subadults. The secondary plateau in 2003 and 2004 is therefore due to additional recruitment. Due to the short life-span of speckled sanddab (3.5 years; Love 1996), their net decrease is likely due to predation in excess of post-2001 recruitment.

The recruitment pulse seen for YOY rockfish and speckled sanddab may also be indicators of an influx of other vertebrate and invertebrate prey. After the influx of prey species in 2001, kelp greenling, cabezon, and lingcod populations appeared to respond, rising to a peak in 2003 and declining thereafter. Lingcod are largely piscivorous, while kelp greenling and cabezon diets contain a larger fraction of invertebrates as well as small fish, including YOY rockfish (Love 2011). Hobson 2000 documented shifts in kelp greenling diets to YOY rockfish in heavy recruitment years. The observed population increases for both kelp greenling and cabezon may be due to a combination of YOY rockfish abundance and the concurrent abundance of other small fish (e.g., speckled sanddab) and invertebrates that recruited at the same time, fostered by the same oceanic conditions.

REEF surveyors record predator species at any size large enough to positively identify. If abundant prey increased either juvenile or adult predator survival rates and reproductive success (e.g., in the form of larger egg masses and decreased relative predation pressure on juvenile predators due to the abundance of alternative prey species), REEF data would document a relatively short term (one to three year) predator population response of smaller individuals. This response, consisting of small young individuals, is different from the much longer time needed to detect the presence of older reproductive females ("big mothers") associated with long-term improvements in fecundity and population resilience.

It is not immediately clear whether the increase and subsequent decline of the predator populations shown in Figure 6 reflects only local fertility and mortality rates. The trend may also include opportunistic immigration inshore from 2001 to 2003 when prey were plentiful, and then subsequent emigration to deeper waters as inshore reefs became less productive compared to deeper offshore waters. It is also important to note that changes to both commercial and recreational fishing regulations immediately prior to and during the period of this study may have had a significant effect on predator population mortality.

The sharp decline in senorita followed by an exponential increase in tubesnout populations (fig. 8) suggests that these schooling midwater species may flourish under different oceanic and ecological conditions. Senorita are a more southern species, so the peak in 1999 may follow a large recruitment during the strong El Niño of 1998 (Durazo et al. 2001). Tubesnout have northern affinities associated with La Niña and cooler conditions, with a population spike in 2007 corresponding to low MEI (multivariate ENSO index) values recorded in 2007 and 2008 (Bjorkstedt et al. 2012).

Seaperch population fluctuations appear to be largely unrelated to rockfish populations (fig. 9). This is not surprising given such dissimilar ecological niches occupied by rockfish and seaperch. The data were not normalized for boat versus shore dives or Monterey Bay versus Carmel Bay. Such variation has been shown to have little effect on YOY and blue rockfish and kelp greenling results (Wolfe and Pattengill-Semmens 2013), but the seaperch species may be more sensitive to dive site and associated habitat variation. Further analysis of the seaperch data, normalizing the data for dive site year-to-year variation, may be warranted.

Peaks in warm water species more prevalent along the southern California coast appear to lag one to two years after water temperature peaks, perhaps reflecting recruitment timing (fig. 10). The population peaks also coincide with dips in water temperature, a somewhat counterintuitive result unless one considers previous warmer years. Treefish and kelp bass population peaks in 2003 and 2010 follow not only temperature peaks, but perhaps more importantly, the YOY rockfish influxes in 2001 and 2009, suggesting synchronous recruitment or a predator population response.

REEF and PISCO comparison

Because REEF divers are encouraged to explore an entire reef, not limited by transect length and width, REEF's RDT survey method has proven superior to traditional transect methods in documenting the full fish species biodiversity of a reef (Pattengill-Semmens and Semmens 1998; Schmitt et al. 2002; Holt et al. 2013). While a better sense of species biodiversity is gained, individual counts of each species during RDT surveys are not as precise as traditional transect surveys such as PISCO. However, what is lost in precision on a single dive can be regained through a large number of dives in the same area.

The similarity of trends between the two data sets suggests that both methods are successfully measuring the same underlying fish population and detecting the same trends. Of the eight species studied for the comparison, black rockfish had the weakest Pearson correlation coefficient. This weaker correlation is likely due to the broad confidence intervals of the estimated abundance for this species in both data sets; black rockfish is a less common rockfish species with significant patchiness and wide spatial variation. An aggregate analysis comparing PISCO-REEF data pairs for seven non-YOY species over ten years shows a very strong correlation (fig. 13), even when the outlier cases of black rockfish and the first three years of painted greenling REEF counts are included.

PISCO transects consistently cover a benthic area of 60 square meters, and therefore, PISCO data can be used to calibrate REEF data to convert it to density. For most species, REEF survey counts are about 4.9 times larger than PISCO counts (table 3), suggesting that fish density (individuals/ m^2) can be approximated from REEF counts by dividing by 300 m^2 (4.9 x 60 m^2). Given that an average REEF diver may cover a distance of 250 m, with an average survey width of at least two meters, it appears that REEF surveyors do not scour the bottom as thoroughly as PISCO surveyors—an expected outcome given the nature of the roving, non-point aspects of the RDT compared to transect surveys.

Multipliers significantly lower than 4.9 suggest that REEF surveyors are undercounting in relation to PISCO compared to typical species (table 3). YOY rockfish have a very low multiplier (1.12). REEF's undercount of YOY rockfish compared to PISCO is probably due to two factors: (1) REEF surveys occur year-round, with peak survey months in May and July, while PISCO surveys are conducted from mid-August to late October when rockfish YOY are most prevalent, and (2) omissions by novice REEF surveyors who cannot yet positively identify (and therefore count) these small fish as YOY rockfish.

Because most fish species populations change incrementally from one year to the next, smoother density curves measured over time suggest more accuracy and less statistical noise. PISCO's year-to-year population fluctuations for painted greenling, a small cryptic bottom dwelling fish, appear smoother than REEF data. On the other hand, population trends based on REEF data for kelp greenling, cabezon, and senorita all follow smoother sigmoidal curves than that documented by the PISCO data set, which appear more stochastic or jagged, suggesting more statistical noise around an underlying smooth trend. These findings suggest that PISCO may more effectively survey small cryptic bottom species, while REEF may more effectively survey larger species, including those targeted by fisheries.

Using the quantitative estimate methods described here and in Wolfe and Pattengill-Semmens 2013, the REEF database can be used to explore many additional questions, such as: (1) Are there key differences in fish species assemblages at smaller spatial scales, such as between Monterey Bay and Carmel Bays? And (2) Can statistically significant differences over time be detected between reefs within and outside of recently established Marine Protected Areas?

Conclusion: The REEF database of fish surveys conducted by volunteer recreational divers provides a rich source of information about population trends in the Monterey Peninsula area. As this study shows, the REEF Survey Program has proven to be a viable and worthwhile long-term volunteer effort by recreational divers, supported by a small professional staff and collected at no cost to the scientists and resource agencies that have access to these data. The findings in this paper demonstrate the value of continuing to train recreational divers in REEF survey techniques in California in order to generate a consistently large number of surveys over future years. Volunteer citizen science data collected by REEF has great potential to augment, strengthen, and broaden academic and professional research data. With its fifteen-year baseline, the REEF database should prove useful in comparing fish populations inside and outside the Marine Protected Areas recently established in California as part of the California Marine Life Protection Act. Furthermore, the strong concordance between REEF and PISCO data sets for a wide range of species reveals their complementary nature and provides support for use of both data sets when seeking to evaluate trends in nearshore fish species in California.

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Paul Humann and Ned DeLoach founded REEF in 1990, and Lad Akins served as its executive director for many years—fostering the efforts of thousands of recreational divers to conduct fish and invertebrate surveys. Brice Semmens was instrumental in developing REEF's Roving Diver Technique and has served as a valuable scientific advisor. Tom Laidig provided YOY rockfish survey data. Both BS and TL reviewed several drafts of this paper and provided valuable comments. Staff from Monterey Bay National Marine Sanctuary and Monterey Bay Aquarium have encouraged and supported REEF surveyors through the years. Dan Malone graciously provided PISCO data for the analysis. REEF Outreach Coordinator, Janna Nichols, enthusiastically recruits and trains new divers, ensuring that the REEF database for the West Coast, including the Monterey area, will continue to grow. Keith Rootsaert generously designed Figure 1. Finally, the authors are indebted to the scores of divers who contributed fish surveys to the REEF database in the Monterey Peninsula area. Divers who each conducted ninety or more REEF surveys in the Monterey area include Kawika Chetron, Alan Dower, Rachid Feretti, Lisa Gee, Keith Rootsaert, Pam Wade, and Naomi Wooten.

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ANOMALOUS DISTRIBUTIONS OF PELAGIC JUVENILE ROCKFISH ON THE U.S. WEST COAST IN 2005 AND 2006

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ABSTRACT

A combination of midwater trawl surveys of pelagic juvenile rockfish on the U.S. West Coast provide data from 2004 to 2009, which represent the collaborative efforts of the National Marine Fisheries Service Southwest Fisheries Science Center, Northwest Fisheries Science Center, and the Pacific Whiting Conservation Cooperative to survey the waters of the California Current from the U.S.-Mexican border to the Columbia River 33°–46°N. We analyze six species of pelagic juvenile rockfish and evaluate the annual stability of their spatial distributions. Our results show that rockfish catches in 2005 and 2006 were shifted away from the core area of the survey, which has been sampled since 1983. In those years there was a bifurcation in their spatial distributions, with some species shifted to the north (*S. entomelas, S. flavidus,* and *S. pinniger*) and some species to the south (*S. jordani and S. paucispinis*). While the geographic distributions of fish in 2005 and 2006 were unusual, total abundance patterns were apparently unrelated to their spatial distributions. By 2007, the distributions of these species had recovered to pre-2005 conditions, especially for northern species. Standardized wind stress anomalies on the West Coast during the months preceding the surveys were evaluated in relation to the anomalous spatial distributions of catch. Results show that significant wind reversals occurred during February of 2005 and 2006, which is the peak of the parturition season.

INTRODUCTION

The National Marine Fisheries Service (NMFS) Southwest Fisheries Science Center (SWFSC) has conducted a midwater trawl survey during May–June since 1983 that is designed to estimate the abundance of pelagic juvenile rockfish (*Sebastes* spp.; Ralston et al. 2013). Prior to 2004 the survey was limited to the central California coast from Carmel to Bodega Bay (lat. 36°30'–38°20'N), but in 2004 the latitudinal extent of the survey was expanded 4-fold to encompass the region between the U.S.-Mexican border and Cape Mendocino (lat. 32°45'–40°00'N). Moreover, the expanded SWFSC survey was then coupled with a similar midwater trawl survey conducted by the Pacific Whiting Conservation Cooperative (PWCC) and the NMFS Northwest Fisheries Science Center (NWFSC) that was initiated in 2001 (Sakuma et al. 2006). In concert the combined surveys have provided near coastwide coverage in most years since (fig. 1). Catch rate data from the combined surveys are developed into pre-recruit abundance statistics, which are distributed to analysts for use in groundfish stock assessments conducted for the Pacific Fisheries Management Council[1]. Beyond that decidely prosaic function, the survey has developed a broader role in monitoring the overall distribution and abundance of the California Current forage community (e.g., Santora et al. 2011; Wells et al. 2012).

Upon consolidation of the two surveys, a workshop was held to evaluate how the spatial scale of sampling affected inferred recruitment patterns (Hastie and Ralston 2007). Of particular concern was whether data collected solely from the "core" region of the SWFSC survey (lat. 36°30'–38°20'N) were informative with respect to impending recruitment to rockfish stocks. Results presented in Field and Ralston 2005 had indicated that rockfish recruitment patterns on the U.S. West Coast were spatially correlated, with 51%–72% of year-to-year recruitment variability shared coastwide, at least for *Sebastes entomelas, S. flavidus*, and *S. goodei*. If survey results from the core survey area could be used to estimate recruitment in stocks with a much broader distribution, the extended time series developed by the SWFSC beginning in 1983 could be utilized in stock assessments.

Here we report results describing the spatial distributions of six species of pelagic juvenile rockfish captured in the combined midwater trawl survey. In particular, we evaluate the temporal stability of their distributions with respect to sampling in the core area only. We also present an analysis of the wind stress field in the months preceding the survey that attempts to explain changes in distributions.

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[1] Ralston, S. 2010. Coastwide pre-recruit indices from SWFSC and NWFSC/PWCC midwater trawl surveys (2001–10). Groundfish Analysis Team, Fisheries Ecology Division, Southwest Fisheries Science Center, NOAA Fisheries, 11 p.

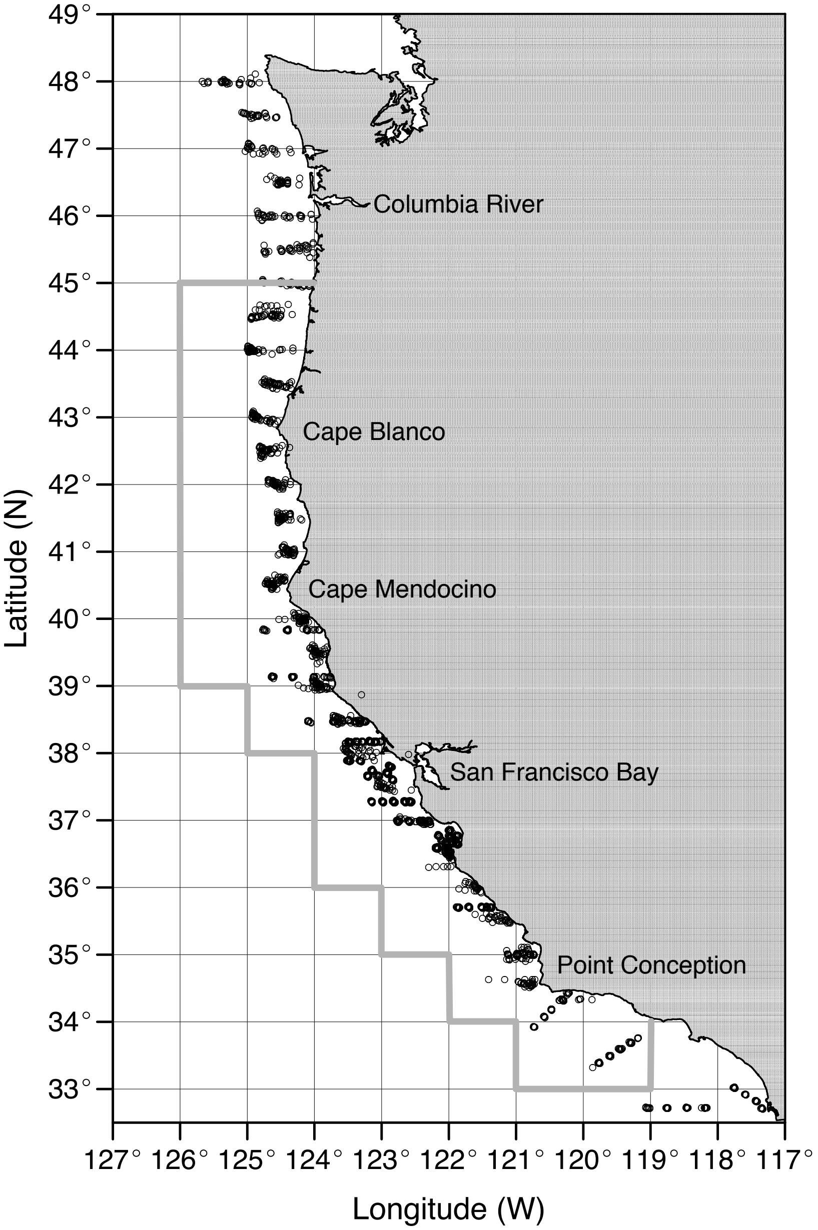

Figure 1. Map of the U.S. West Coast showing the spatial extent of the combined SWFSC-NWFSC pelagic juvenile rockfish midwater trawl survey (2001–09). Trawl sampling stations shown as small open circles; wind stress calculations based on 1° x 1° latitude-longitude cells occurring within the bold gray polygon.

MATERIALS AND METHODS

The combined midwater trawl survey became coastwide in 2004 (Hastie and Ralston 2007) and all sampling has occurred during May–June. However, in recent years (2010–12) survey coverage has been incomplete and comprehensive coastwide data are lacking; we therefore limit our findings to the period 2004–09. Biological sampling is conducted using a standard Cobb midwater trawl fitted with a 26 m headrope and a 9.5 mm (3/8") cod-end liner. Based on net mensuration data obtained with a Simrad ITI system, the height and width of the net when fishing averages 12 m, resulting in a sampled swath of ~144 m^2; a fine-mesh liner retains epipelagic nekton and micronekton. Trawling is conducted only at night due to net avoidance and the target depth for the trawl's headrope is 30 m. Quantitative sampling is obtained by standardizing the amount of trawl warp deployed during a tow to 85 m and using the Simrad ITI sensors to adjust vessel speed in real-time to maintain the depth of the headrope at 30 m. This practice produces a 20° angle of the trawl warp to the sea surface and, as a consequence, a consistent speed through the water. Trawls are further standardized by fishing the net for exactly 15 minutes at the target depth.

Upon completion of a trawl the contents of the codend are immediately sorted. All fish, cephalopods, and selected decapod crustaceans are enumerated, and several other key taxa (e.g., euphausiids, jellyfish, etc.) are either counted or estimated by expansion from a subsample. On SWFSC surveys all juvenile rockfishes are identified to species, frozen, and returned to the laboratory. Rockfish samples from the historical NWFSC surveys were immediately frozen and sent to the Fisheries Ecology Division, SWFSC for identification and enumeration following completion of the cruise. A more detailed description of sampling procedures is available in the survey's operations manual.[2]

Given that the absolute scale of latitudinal variation in survey sampling (1700 km) was ~15 times greater than the longitudinal scale (fig. 1), we consider latitude to be of primary importance and limit our analysis to that dimension. Thus, the annual spatial distribution of pelagic juvenile rockfishes in the survey was estimated by rounding the starting latitudinal position of each trawl to the nearest 1° (=111 km), resulting in 14 spatial strata (33°, 34°, …, 46°N). Species-specific catches were summed over all hauls occurring within a latitudinal stratum, and the total annual catch was determined by summing catches over strata. The annual number of hauls occurring within each stratum was also summarized and the annual total calculated. Annual species-specific catch-per-unit-effort (CPUE) statistics were then calculated as the ratio of the total annual catch to the total number of tows.

In addition, for each species, year, and latitudinal stratum, CPUE [fish · tow^{-1}] was calculated and species-specific annual spatial distributions were estimated by normalizing the stratified value to the annual sum, i.e.,

$$P_{s,y,l} = \frac{CPUE_{s,y,l}}{\sum_{l} CPUE_{s,y,l}},$$

where $\boldsymbol{P_{s,y,l}}$ is the proportion of annual CPUE of species $\boldsymbol{s}$ in year $\boldsymbol{y}$ taken in latitudinal stratum $\boldsymbol{l}$ and $\boldsymbol{CPUE_{s,y,l}}$ is the respective catch rate. The weighted average latitude of a species' annual catch was also estimated by computing the scalar (=dot) product of latitude values and the proportions of the total annual CPUE occurring therein.

We evaluated the relationship between winds in the months preceding the midwater trawl survey and the latitudinal distribution of pelagic juvenile rockfish sampled during the survey. For that analysis we queried the global derived monthly Fleet Numerical Meteorology and Oceanography Center wind and Ekman transport data (http://coastwatch.pfeg.noaa.gov/erddap/griddap/erdlasFnWPr.html). In particular, we tabulated wind stress values (τ_x and τ_y [N m^{-2}]) within twenty five 1°×1° cells off the U.S. West Coast (fig. 1) from 1970–2011. Wind stress values are largely proportional to the square of the zonal (east-west) and meridional (north-south) winds, i.e., $\tau_x \propto u^2$ and $\tau_y \propto v^2$ with sign maintained. From those data we calculated the long-term means (μ) and standard deviations (σ) of τ_x and τ_y for all latitude (i), longitude (j), and monthly (k) combinations to establish the seasonal and spatial climatology of the wind stress field on the U.S. West Coast. We also calculated standardized anomalies (Z-scores) of the winds according to:

$$Z_{x,i,j,k,t} = \frac{\tau_{x,i,j,k,t} - \mu_{x,i,j,k}}{\sigma_{x,i,j,k}}$$

where $Z_{x,i,j,k,t}$ is the standardized τ_x anomaly for latitude i, longitude j, month k, in year t, $\tau_{x,i,j,k,t}$ is the zonal wind stress at that place and time, $\mu_{x,i,j,k}$ is the mean zonal wind stress at that place and month, and $\sigma_{x,i,j,k}$ is the standard deviation of the zonal wind stress at that place and month. Standardized anomalies of the meridional wind stress ($Z_{y,i,j,k,t}$) were calculated in a similar manner.

The standardized anomalies were studied to identify statistically extreme wind events in the four months preceding the survey (January–April). For the year in question, the standardized anomalies ($Z_{x,i,j,k,t}$ and $Z_{y,i,j,k,t}$) were averaged over longitude and for each month the results ($\overline{Z}_{x,i,k,t}$ and $\overline{Z}_{y,i,k,t}$) were plotted against latitude (lat. 33.5°–44.5°N). In this analysis longitudinal averaging resulted in a negligible loss of information because the standardized anomalies are highly correlated between adjacent longitudinal cells (r = 0.94 and 0.91 for zonal and meridional scores, respectively). In addition, vector plots that combined zonal and meridional components of wind stress were generated by month and latitude to visualize monthly and latitudinal variation in the wind field.

RESULTS

From 2004–09 the combined SWFSC/NWFSC survey completed 1,639 midwater trawls at standard stations on the U.S. West Coast (table 1). Sampling in the 37° and 38°N latitudinal strata has been especially high because this region forms the long-term core area of the SWFSC midwater trawl survey (Ralston et al. 2013). The number of trawls within any particular year × latitude stratum ranged from 6–80 and averaged 20. Among year sampling effort has ranged from 212 to 306 hauls · yr^{-1}.

Six species of winter-spawning rockfish are relatively abundant and are regularly sampled in the combined

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[2] Sakuma, K., K. Baltz, J. Field, and S. Ralston. 2012. Operations Manual—Rockfish Recruitment and Ecosystem Assessment Survey Trawling Protocols. Groundfish Analysis Team, Fisheries Ecology Division, Southwest Fisheries Science Center, NOAA Fisheries, 23 p.

TABLE 1
Distribution of combined SWFSC/NWFSC midwater trawl samples at standard stations by year and latitude.

	Year						
Latitude	2004	2005	2006	2007	2008	2009	Total
33	12	17	19	16	19	10	93
34	13	16	12	12	11	6	70
35	14	11	22	10	9	10	76
36	18	25	23	11	13	14	104
37	70	77	57	80	36	65	385
38	54	47	70	63	29	54	317
39	15	15	21	15	18	16	100
40	12	12	19	19	13	12	87
41	14	12	11	9	12	13	71
42	6	10	10	15	8	14	63
43	12	11	12	11	14	9	69
44	13	10	8	10	7	11	59
45	16	11	13	13	12	12	77
46	14	9	9	12	11	13	68
Total	283	283	306	296	212	259	1,639

TABLE 2
Total catch at standard stations of six abundant pelagic juvenile rockfish (*Sebastes* spp.) taken in midwater trawl samples from 2004–09.

	Year						
Species	2004	2005	2006	2007	2008	2009	Total
S. entomelas	1,973	79	2	41	318	665	3,078
S. flavidus	1,160	28	3	3	91	219	1,504
S. pinniger	472	29	22	128	153	216	1,020
S. goodei	320	20	6	11	36	353	746
S. paucispinis	38	104	7	31	29	51	260
S. jordani	1,334	6,386	328	1,306	464	1,082	10,900
Total	5,297	6,646	368	1,520	1,091	2,586	17,508

midwater trawl survey (Ralston et al. 2013), including *S. entomelas* (widow rockfish), *S. flavidus* (yellowtail rockfish), *S. goodei* (chilipepper), *S. jordani* (shortbelly rockfish), *S. paucispinis* (bocaccio), and *S. pinniger* (canary rockfish). Catches of these species (table 2) demonstrate very high positive interannual covariation within the core survey area (Ralston et al. 2013). For the 2004–09 coastwide data, aggregate annual catches of the six species combined have ranged from 368 to 6,646 fish · yr^{-1}, representing an 18-fold fluctuation in abundance from 2005 to 2006. *Sebastes jordani* is the most abundant of the six species sampled in the survey (N = 10,900) and *S. paucispinis* is the least common (N = 260).

Annual catch rates (CPUE) have fluctuated markedly and are plotted on log-scale in Figure 2. Note that abundances generally declined from 2004 to 2006 and increased thereafter. Positive covariation in abundance among the six species is evident, as has been previously described (Ralston et al. 2013).

The 2004–09 spatial distributions of these six species in the catch are depicted in Figure 3. In the left column of the figure three members of the subgenus *Sebastosomus* are plotted; in the right column three members of the *Sebastodes* subgenus are shown. For the former group, 2005 and 2006 demonstrated a considerable distributional shift to the north that recovered in 2007 to prior conditions. For the latter group, *S. jordani* and *S. paucispinis* had an analogous shift in distribution to the south in 2005. Curiously, *S. goodei* revealed a strongly bimodal distribution in 2005 and a singularly unimodal distribution in 2006.

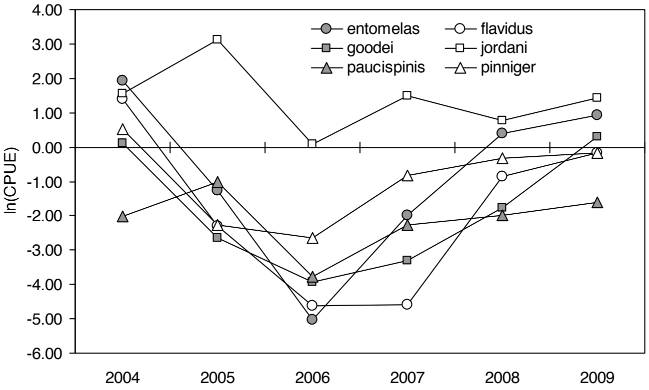

Figure 2. Annual trends in catch-per-unit-effort (CPUE) of pelagic juvenile rockfishes collected in the midwater trawl survey.

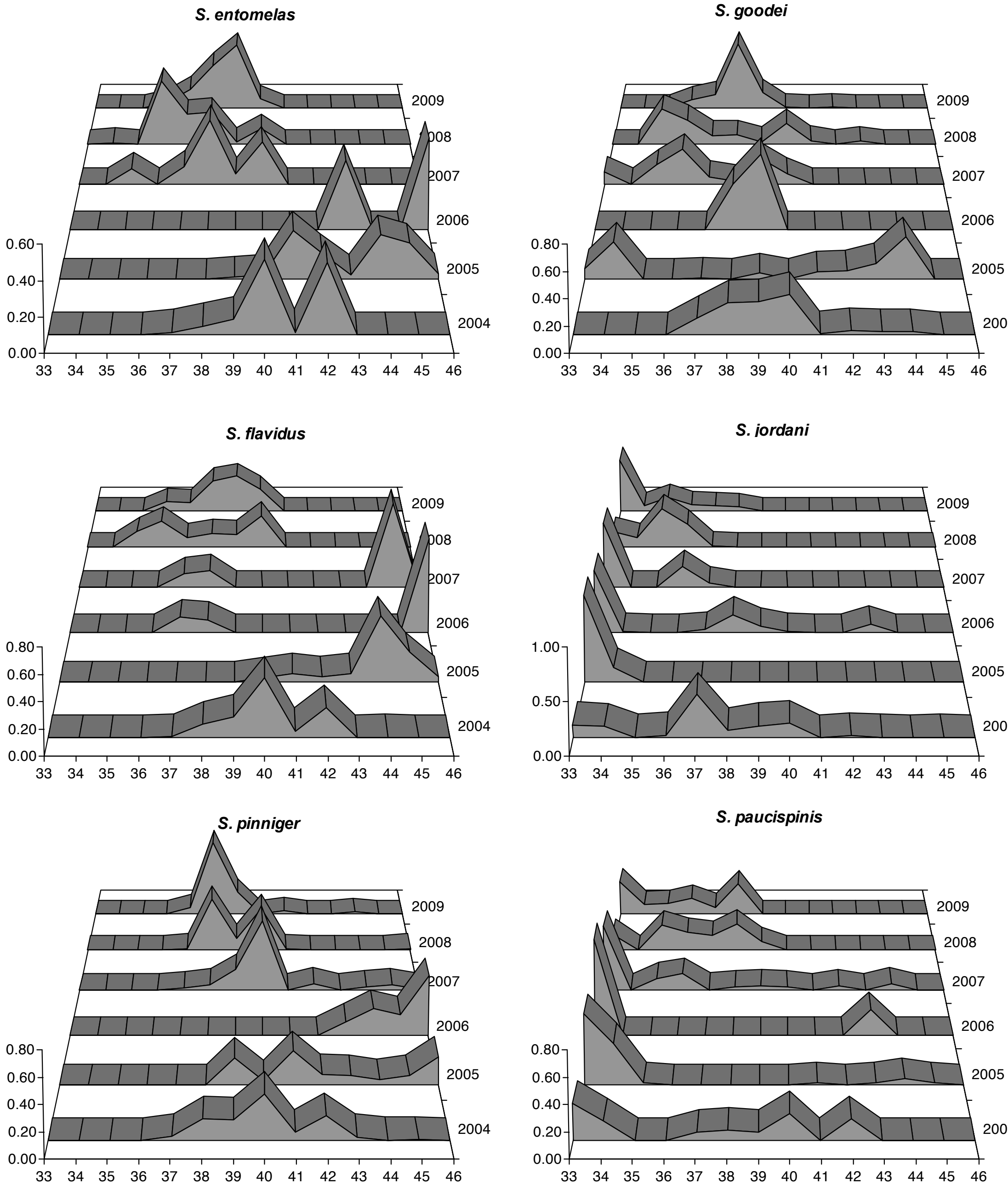

Figure 3. Spatial distributions of normalized CPUE for 6 *Sebastes* spp. from 2004–09. Plotted on the x-axis is latitude, on the y-axis is year, and on the z-axis is the proportion of spatially integrated annual CPUE.

The annual average latitude of CPUE for each of the species is plotted in Figure 4, which shows that in 2005 and 2006 there was an alteration in the spatial distribution of these pelagic juvenile rockfishes. Whereas in the first year of the survey the distribution of all six species was centered in the core area of the survey (37°–40°N), in 2005 there was a bifurcation in their spatial distributions, with some species shifted to the north (*S. entomelas*, *S. flavidus*, and *S. pinniger*) and some species shifted to the south (*S. jordani* and *S. paucispinis*). By 2007 the distributions of these species tended to recover to pre-2005 conditions, particularly for the northerly distributed species. *Sebastes goodei* demonstrated little variability in the average latitude of their catch.

To better understand the development of oceanographic conditions that may have led to these anomalous distributions in 2005 and 2006, we examined the climatology and standardized anomalies of zonal and meridional wind stresses in the 4 months preceding the survey. The seasonal and latitudinal climatology of

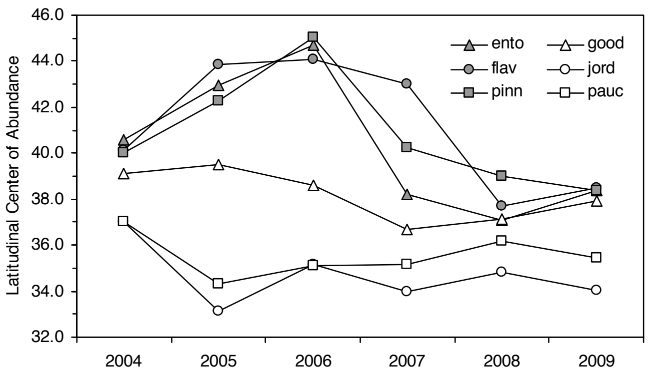

Figure 4. Time series of the average latitudes of survey catches for commonly-sampled juvenile rockfishes taken in the SWFSC-NWFSC midwater trawl survey (legend = first four letters of scientific name).

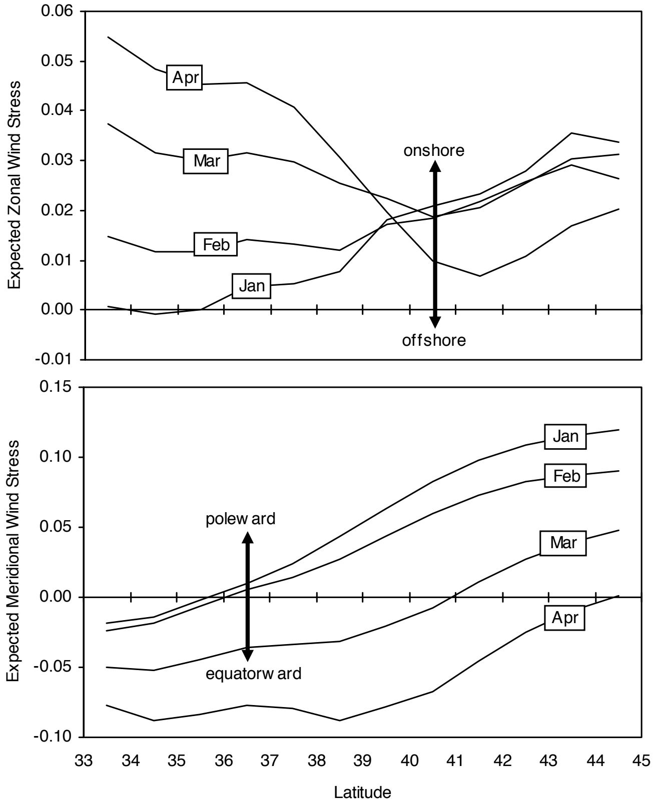

Figure 5. Climatology of wind stresses on the U.S. West Coast in the months preceding the midwater trawl survey (January–April). The upper panel shows zonal (east-west) winds and the lower panel depicts meridional (north-south) winds. Expected wind stresses are based on average values calculated over the period 1970–2011.

expected zonal and meridional wind stresses from January–April are plotted in Figure 5. Note that the spatial expression of zonal wind stresses interacts dramatically with month. In particular, in the south onshore wind stress increases markedly from January through April, whereas in the north onshore wind stress actually tends to decrease, especially in April. Likewise, there is a strong latitudinal gradient in the onset of equatorward meridional winds, which coincides with the spring transition to the upwelling season (Schwing et al. 2006). In the core area of the survey (37°–40°N) winds are generally equatorward in March, whereas in the north (41°–45°N) they are poleward, implying a divergence in the wind field.

To highlight statistically unusual wind conditions in the months preceding the survey we plot zonal ($\overline{Z}_{x,i,k,t}$) and meridional ($\overline{Z}_{y,i,k,t}$) standardized anomalies from 2004–09 in Figures 6 and 7, respectively. These results show that in 2005 strongly negative zonal winds existed during February in the central California region (lat. 37°–40°N), which reversed and became strongly positive by April (lat. 39°–41°N). Similarly, in February negative Z-scores of meridional winds occurred in the northern region (lat. 42°–44°N), which had reversed and become positive by April. Results for 2006 are somewhat different, i.e., relatively weak negative zonal Z-scores occurred in February but strong positive scores in March within the core region of the survey (lat. 37°–40°N). Meridional wind stresses, however, were characterized by strong negative Z-scores in February within the core region, which reversed and became positive in March.

It is useful to visualize the wind field in the months preceding the survey by examining vector plots of the climatology of wind stress and the observed wind stress in 2005 and 2006 (fig. 8). Results from January–March 2005 are presented in the left portion of the figure, whereas analogous results for 2006 are shown on the right. Note that scaling is identical in all six panels and that climatologically expected wind stresses are shown as a bold lines and the observed wind stresses are shown as fine lines with small open square symbols. Observe that by definition expected winds are identical in both years.

A careful examination of Figure 8 illustrates several points: (1) winds in January and March of 2005, although somewhat weaker than expected, were not markedly different in directionality from the climatology, (2) the strongly negative standardized anomalies of zonal winds in February 2005 were due to offshore winds in all areas north of 36°N, a time when onshore winds are expected, (3) at the same time, weak southerly winds occurred north of 36°, when strong northerly winds are expected, (4) winds in January and March 2006 were generally stronger than the climatology but largely similar in direction, (5) as in 2005, February 2006 was characterized by strong southerly winds that were opposite to the climatology north of 36°N.

DISCUSSION

We summarize six years of data from a pre-recruit survey of pelagic juvenile rockfish on the U.S. West Coast. The survey is designed to estimate on an annual basis the abundance of winter-spawning species, which collectively comprise some of the most important rockfish

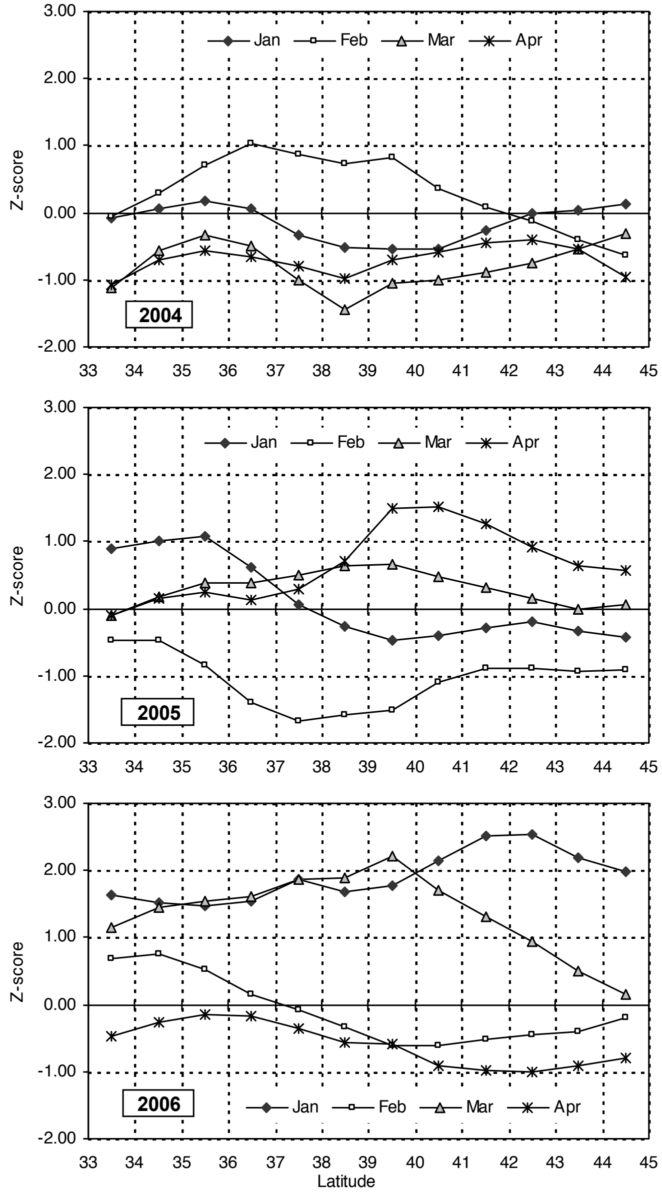

Figure 6. Seasonal and spatial variability in **zonal** wind stress from 2004–06 relative to the climatology. Z-scores are calculated as standardized deviations from the long-term mean (μ) and standard deviation (σ) (see text for further explanation).

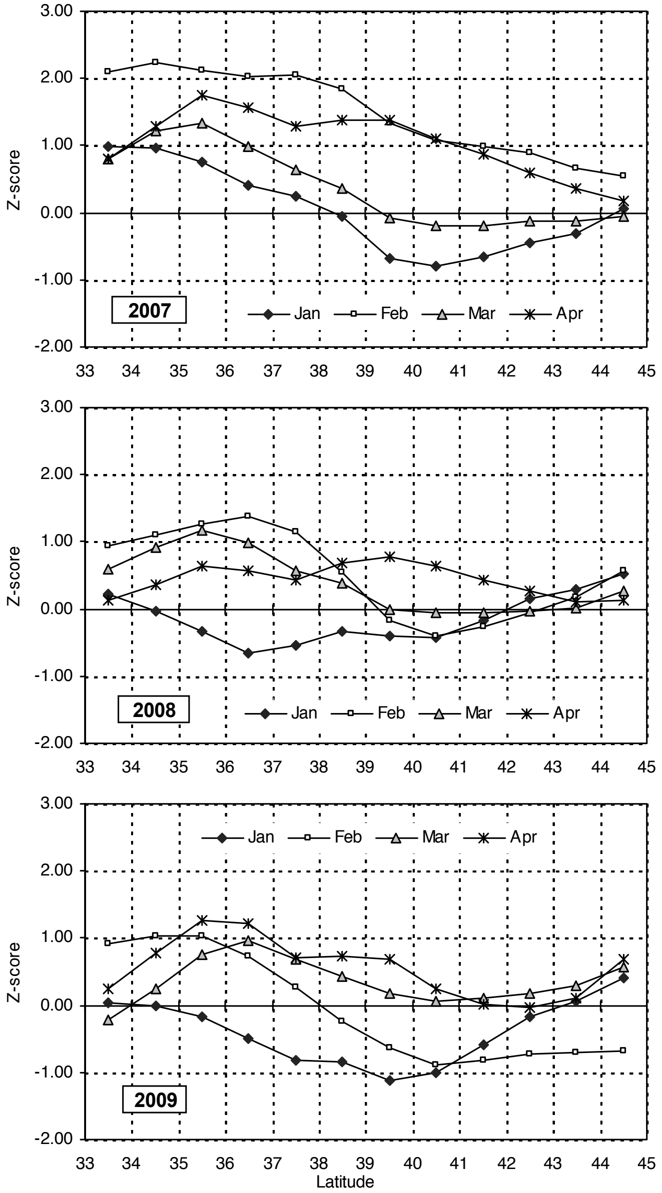

Figure 6 (cont'd). Seasonal and spatial variability in **zonal** wind stress from 2007–09 relative to the climatology.

stocks harvested in commercial and recreational fisheries in California, Oregon, and Washington (PFMC 2008). The parturition season of these species generally extends from December to March, but peaks in January–February (Wyllie-Echeverria 1987; Love et al. 1990; Love et al. 2002) and all exhibit an extended pelagic juvenile stage (Moser and Boehlert 1991) that lasts up to six months (Woodbury and Ralston 1991; Laidig et al. 1991). Previous studies have also indicated that year-class strength is established by the time the survey is conducted in May–June (Ralston and Howard 1995; Ralston et al. 2013). Thus, density-independent mortality during the larval stage is likely responsible for variable fisheries recruitment (Houde 1987, 2008).

Our results show that the spatial distribution of these young-of-the-year *Sebastes* was unusual in 2005 and 2006 (figs. 3 and 4), with some species shifted to the north (e.g., *Sebastosomus*) and others to the south (*Sebastodes*). It is noteworthy that members of the former subgenus tend to have more northerly latitudinal distributions as adults, whereas the latter subgenus is typically southerly in its distribution (Love et al. 2002; Williams and Ralston 2002; Ralston et al. 2013).

Our results reinforce the conclusions of the pre-

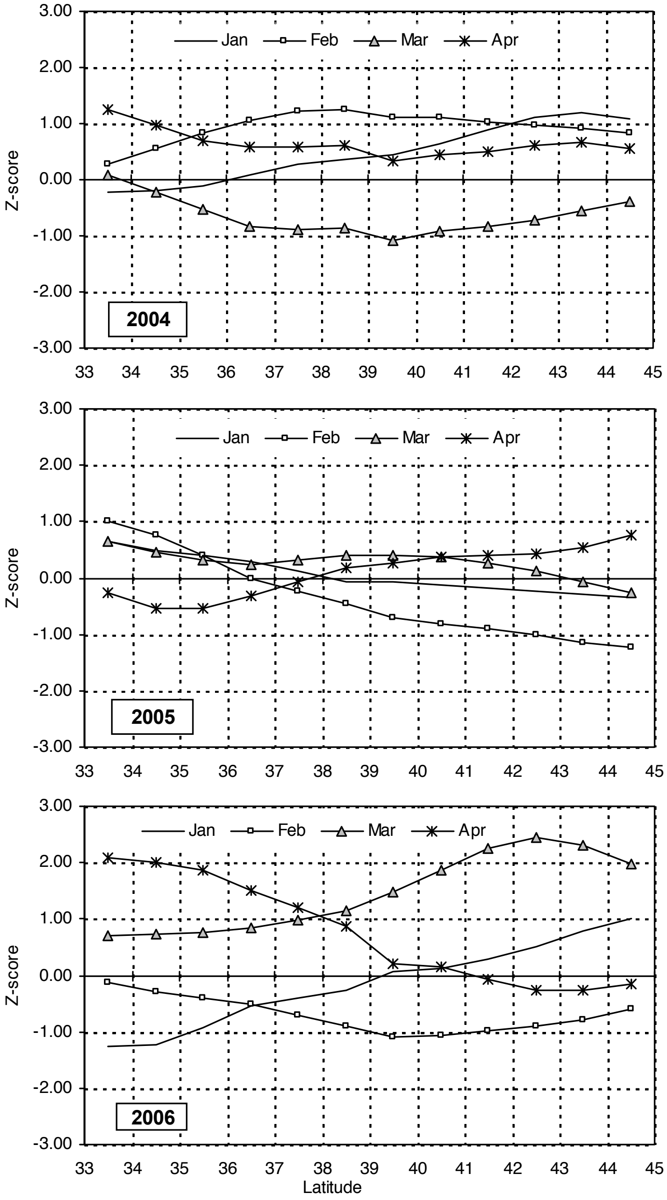

Figure 7. Seasonal and spatial variability in **meridional** wind stress from 2004–06 relative to the climatology. Z-scores are calculated as standardized deviations from the long-term mean (μ) and standard deviation (σ) (see text for further explanation).

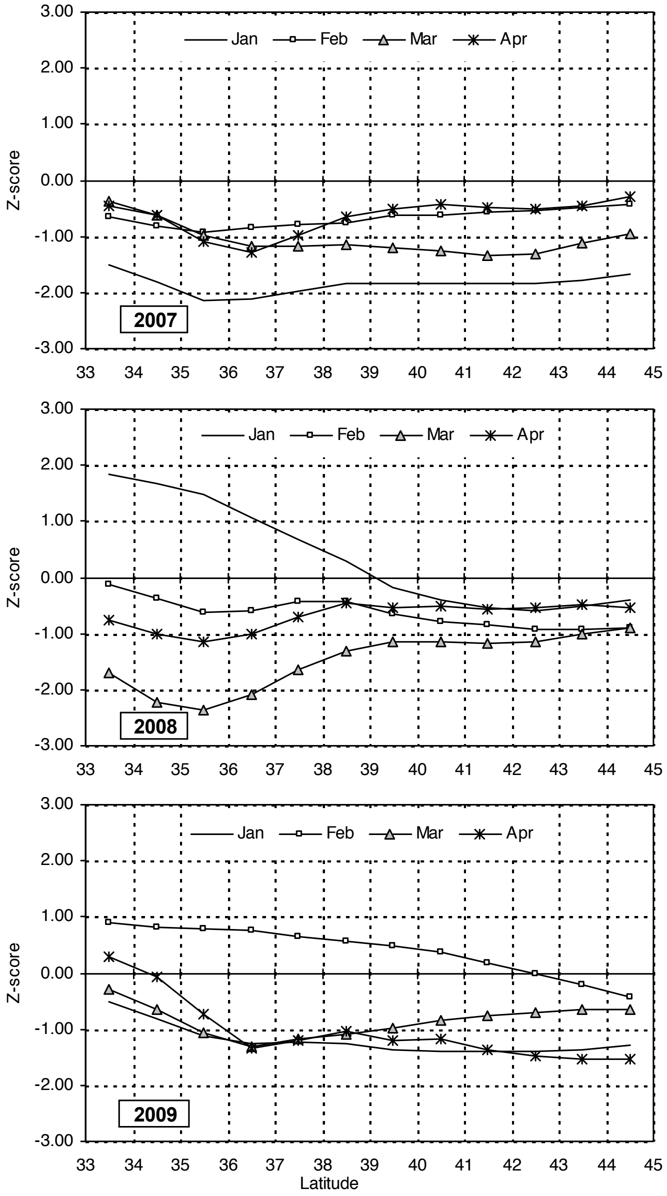

Figure 7 (cont'd). Seasonal and spatial variability in **meridional** wind stress from 2007–06 relative to the climatology.

recruit survey workshop (Hastie and Ralston 2007), which recommended that complete coverage of the U.S. West Coast is required to develop statistically valid indices of abundance for use in stock assessments. Ralston et al. 2013 demonstrated a significant positive correlation between indices of abundance from the "core" survey area and subsequent recruitment to several rockfish stocks. However, the precision of that relationship was low, precluding the incorporation of pre-recruit indices in assessment models derived from samples drawn solely from the core area. Similarly, Field et al. 2010 concluded that for *S. paucispinis*, sampling in the Southern California Bight is needed to develop suitable estimates of pre-recruit abundance.

While the distributions of fish were anomalous in 2005 and 2006, total abundance was apparently unrelated to their spatial distribution. As previously noted, there was an 18-fold fluctuation in the total abundance of pelagic juveniles sampled in the combined survey from 2005 to 2006, corresponding to the maximum and minimum values over the period of study. The maximum, observed in 2005 (N = 6,646), was due to large catches of *S. jordani* in the southern California Bight (table 2, fig. 3). Moreover, assessment models for two of the *Sebas-*

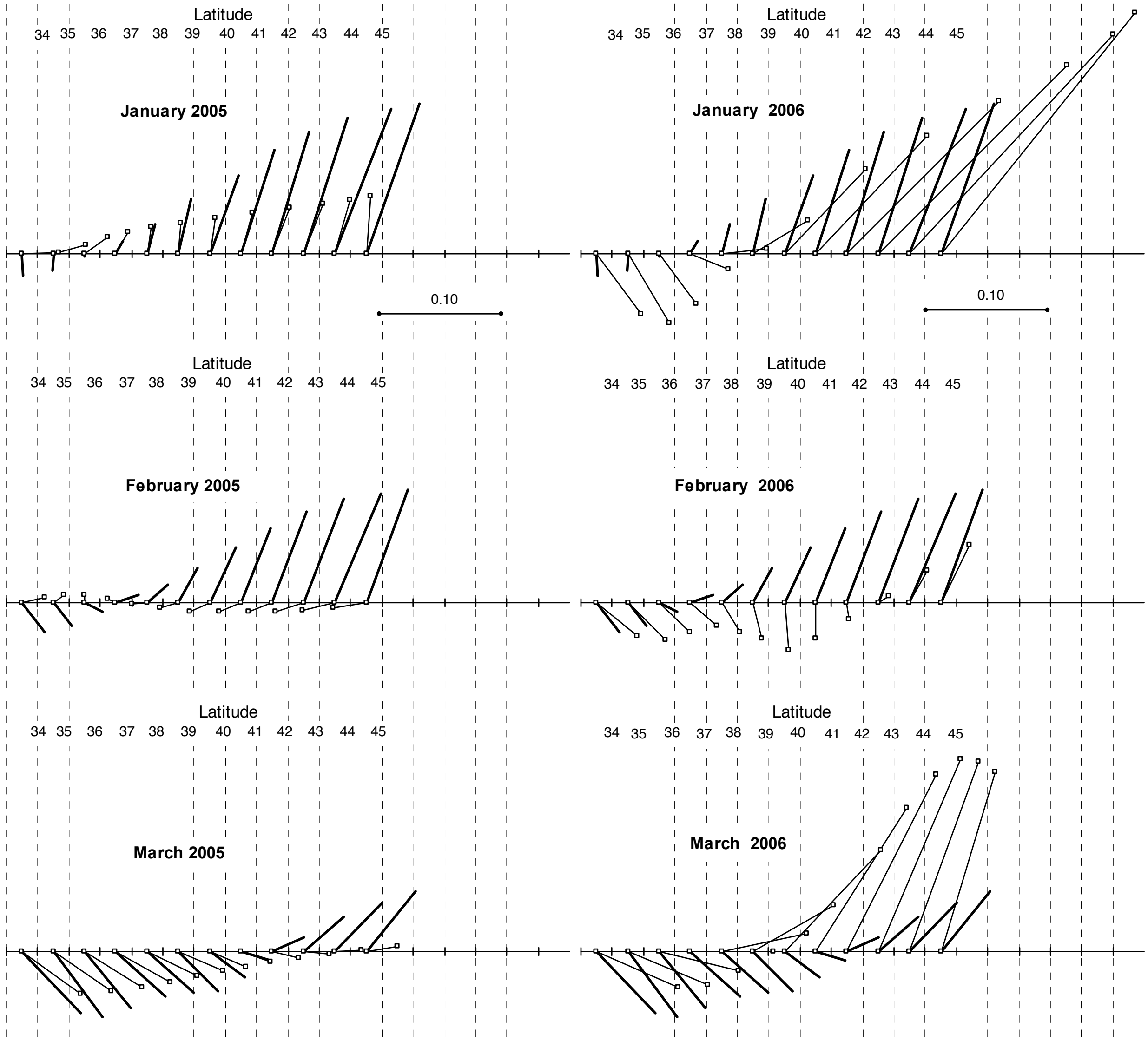

Figure 8. Latitudinal distributions of January–March wind stress vectors during 2005 and 2006 (fine lines with small open squares). Expected wind stress vectors based on climatological means are shown as bolded lines.

todes have been updated (*S. paucisipinis* [Field 2011] and *S. jordani*[3]), which indicate that 2005 and 2006 were relatively strong and weak year-classes, respectively. In contrast, both years appear to be weak for *S. goodei*. Hence, we conclude at this time that the peculiar spatial distributions that we describe would seem to offer little predictive capability vis-à-vis cohort strength. Nonetheless, this result should be investigated further when PFMC stock assessments for *S. entomelas*, *S. flavidus,* and *S. pinniger* are updated and recruitment time series become more reliably estimated.

Others have noted unusual conditions on the West Coast during the two years in question. In particular, Lindley et al. 2009 describe the failure of the 2004 and 2005 brood years of Sacramento River fall Chinook salmon, which precipitated unprecedented closures of California and Oregon ocean salmon fisheries in 2008 and 2009. In their evaluation of the potential causes of the brood year failures, Lindley et al. concluded that ocean conditions in the spring of 2005 and 2006, i.e., during outmigration from San Francisco Bay into the Gulf of the Farallons (lat. 37°–38°N), were responsible for the demise of those two cohorts. In particular, feeding conditions for juvenile salmon in those years were apparently very poor due to an absence of appropriate foods, which includes pelagic juvenile rockfish (Mills et al. 2007; Thompson et al. 2012; Thayer et al. in press). Likewise, there was a similar dearth of krill in the Gulf

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[3] John Field, personal communication, SWFSC Santa Cruz, March 2013.

of the Farallons during May–June of 2005 and 2006 (Santora et al. 2011; Wells et al. 2012).

The general state of the California Current during these two years, including a characterization of both physical and biological conditions, is discussed in detail in Petersen et al. 2006 and Goericke et al. 2007. Both reports concluded that delayed upwelling, especially in the northern portion of the California Current, led to a delay in the production cycle (Schwing et al. 2006), with concomitant effects on the biological communities that depend on the seasonal availability of food resources (Takahasi et al. 2012; Thompson et al. 2012). Other studies highlighting anomalous conditions during this period include Dorman et al. 2011, who argue that advection of krill north of Cape Mendocino in 2005 led to their starvation; and Brodeur et al. 2006, who reported an anomalous species composition in the nekton community of the northern California Current. With regard to the central California forage community, results presented in Bjorkstedt et al. 2012 (figs. 23 and 24), also show that the community composition of the micronekton sampled by the SWFSC midwater trawl survey in the core area during 2005 and 2006 was extreme, being dominated by an offshore pelagic assemblage indicative of El Niño-like conditions.

The general consensus within the research community is that delayed upwelling, as described by Schwing et al. 2006, was responsible for these various events (Peterson et al. 2006; Goericke et al. 2007). It is worth pointing out, however, that Schwing et al. measured annual variation in upwelling relative to the regional climatologic mean date when cumulative upwelling becomes positive, a statistic that depends strongly on latitude (fig. 5). For example, reference calendar dates at the "start" of the upwelling season from their Figure 1 are: January 15th at 36°N, March 1st at 39°N, and March 25th at 42°N. While relative temporal comparisons like this have some value, it may be more meaningful to undertake absolute temporal comparisons when considering the phenology of upwelling relative to the spawning season of exploited rockfish.

As an alternative, if at all locations one calculates cumulative upwelling statistics from a January 1st start date, cumulative upwelling during the "winter" mode (Black et al. 2011) in 2005 was actually greater than the climatology in the north (39° and 42°N), whereas it was less than the climatology in the south (33° and 36°N). The implication of this observation is that contemporaneous spatial variation in coastal upwelling during February–April of 2005 was greatly reduced, which we hypothesize influenced the subsequent spatial distribution of pelagic juveniles.

Because upwelling is largely driven by meridional winds, this alternative view of conditions in 2005 can be seen in Figure 7. Note for example that in 2005 there exists a substantial latitudinal gradient in February Z-scores, with negative values in the north and positive values in the south. Results presented in Figure 8 show that normal spatial variation in the wind field, as observed in the climatology, was altogether absent. Moreover, February 2005 zonal winds in central California were also quite unusual (fig. 6), being offshore from 36° to 45°N (fig. 8). A consideration of the winds in 2006 reveals similarities and differences relative to 2005. Perhaps most similar is that February 2006 also showed a very divergent pattern relative to the climatology (figs. 6, 7, and 8). Meridional winds were southerly from 36° to 42°N, when typically they are northerly. However, unlike 2005, January and March winds show greater spatial variability than would be expected based on the climatology.

February is a key month in the reproductive phenology of these species because that is when the annual production and accumulation of larvae is greatest (MacGregor 1986; Wyllie-Echeverria 1987; Love et al. 1990; Love et al. 2002; Ralston et al. 2003). *Sebastes* larvae are, moreover, vertically distributed in the mixed layer, primarily shallower than 50 m (Ralston et al. 2003; Auth et al. 2007). Consequently they are susceptible to advection due to the effects of surface wind stress. Under normal conditions, represented by the climatology, February winds north of 36°N are poleward and onshore (fig. 6). Such winds would tend to maintain larvae on the continental shelf, due to the direct effect of the zonal wind stress and onshore Ekman transport (downwelling) arising from the meridional wind stress.

In the central California region, we conjecture that the anomalous wind stress fields that occurred in February 2005 and 2006 (fig. 8), which zonally and meridionally were opposite in direction from expectation, transported the larvae of winter-spawning *Sebastes* offshore into poleward flowing winter currents (Petersen et al. 2010; Dorman et al. 2011). Under this hypothesis, the dearth of pelagic juveniles in the core region of the survey during May–June of those two years was due to unusual advective processes during the larval period. In fact, the incidence of statistically extreme oceanographic conditions in the California Current, such as the wind stress events depicted in Figures 6 and 7, would seem to be increasing in frequency (Sydeman et al. in press). Those authors presented evidence suggesting that increasing variance in the North Pacific Gyre Oscillation (Di Lorenzo et al. 2008) has resulted in a cascade of biological impacts on California populations of krill, juvenile rockfish, salmon, and seabirds, explaining in part the failure of the 2004–05 brood years of Sacramento River fall Chinook salmon (Lindley et al. 2009; Wells et al. 2012; Thayer et al. in press).

ACKNOWLEDGMENTS

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DISTRIBUTION OF PELAGIC JUVENILE ROCKFISH (*SEBASTES* SPP.) IN RELATION TO TEMPERATURE AND FRONTS OFF CENTRAL CALIFORNIA

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ABSTRACT

We analyzed a 17-year time series of midwater trawl data examining the relationship between pelagic juvenile rockfish (*Sebastes* spp.) catches and temperature and temperature fronts (gradients) along two cross-shelf transect lines off Davenport (36˚59.0'N) and Pescadero (37˚16.5'N), California. Hydrographic conditions and catches varied substantially from year to year, with general coherence observed between the two lines. However, there was greater variability in temperature and salinity off Pescadero in most years, while gradient intensity differed between the two lines in several years with no consistency as to which line had the strongest and most frequent fronts. Visual inspection of pelagic juvenile rockfish distribution in relation to kriged temperature at 30 m frequently showed elevated catches associated with fronts. Using linear mixed effects models, we found no statistically significant relationship between catch and temperature gradients, although the relationship between gradient strength and catch was universally positive. By excluding anomalous El Niño years, this trend was strengthened, with the combined data set showing a significant positive effect of maximum temperature gradient on catch. We consistently observed the strongest gradients at intermediate temperatures of 10–12˚C, coincident with more frequent occurrences of pelagic juvenile rockfish, suggesting that fronts can influence distribution.

INTRODUCTION

The spatial distribution of larval and juvenile fishes has been linked to hydrographic structure, especially fronts between dissimilar water masses, in several oceanographic settings (Grimes and Finucane 1991; Kingsford et al. 1991; Lochmann et al. 1997). Previous studies off central California have presented detailed examination and quantitative description of distributions of rockfish (*Sebastes* spp.) early life history stages (larvae through pelagic juveniles) in the context of hydrographic structure off central California and provide compelling evidence that distributions of larvae and juveniles are affected by features such as upwelling fronts (e.g., Larson et al. 1994; Sakuma and Ralston 1995; Wing et al. 1998; Bjorkstedt et al. 2002; Sadrozinski 2008; Woodson et al. 2013). Moreover, correlations between spatial patterns in rockfish settlement to shallow nearshore habitats and the occurrence of fronts near the coast suggest that frontal structures play an important role in the transport during rockfish early life history (Woodson et al. 2012).

Understanding how hydrographic structure influences distributions of larval and juvenile fishes can also have practical benefits, particularly with respect to the design of surveys and interpretation of their results. Since 1983, the Fisheries Ecology Division (FED) of the Southwest Fisheries Science Center (SWFSC), National Marine Fisheries Service (NMFS), National Oceanic and Atmospheric Administration (NOAA) has conducted a midwater trawl survey off central California to enumerate pelagic juvenile rockfish and assess the general state of the ecosystem. Recruitment indices based on the abundance and size (age) of pelagic juvenile rockfish have been used to investigate factors that determine year-class strength in economically important rockfish stocks and have been incorporated as data in assessments for several species (Field et al. 2010; PFMC 2008; Ralston et al. 2013). A key consideration in the use of any survey data is how well the survey represents the state of the populations being studied. Comparisons to estimates of recruitment strength derived from catch histories and the dynamic age structure of the adult stock suggest that indices based on age-standardized pelagic juvenile rockfish abundance perform reasonably well and are useful for capturing recruitment variability well in advance of estimates available through conventional stock assessment methods (Field and Ralston 2005; Ralston et al. 2013). One potential source of uncertainty is whether the survey design is sensitive to variability in hydrographic conditions at the time that data are collected, particularly with respect to the general characteristics of water masses in the survey region and how pelagic juvenile rockfish are distributed in relation to hydrographic structures such as fronts.

Discerning general patterns in how water mass characteristics and upwelling fronts influence distributions of pelagic juvenile rockfish, particularly in the context of the annual midwater trawl survey, is complicated by the highly dynamic nature of the coastal ocean off central California. This region tends to experience weak and highly variable upwelling (and storm-driven downwelling) during the winter months and more sustained, albeit fluctuating, upwelling during the spring and summer; the "spring transition" between these two general patterns (and the corresponding ecosystem response) varies in timing from year to year, but typically occurs between late March and late April (Parrish et al. 1981; Schwing et al. 1991). Upwelling fronts form between warmer, fresher oceanic water and colder, saltier water that upwells along the coast in response to wind-driven cross-shelf advection. Off central California, these fronts are most commonly generated at discrete upwelling centers anchored by headlands, but more develop through the spring and summer upwelling season as the cumulative effects of upwelling and relaxation events build up and influence coastal waters (Castelao et al. 2006; Largier et al. 2006).

Many of the rockfish species encountered in the midwater trawl survey (including some of the most abundant species, which have the greatest economic value) release their larvae into the plankton during the winter yet settle to nearshore demersal habitats as large, well-developed juveniles in the late spring and early summer months. Year-class strength appears to be determined in these stocks during the larval period (i.e., by oceanographic conditions during the winter and early spring) (Ralston and Howard 1995; Laidig et al. 2007; Ralston et al. 2013). For those species of rockfish that release their larvae into the plankton during the winter and early spring (i.e., when upwelling off central California is weaker and highly variable) there is limited evidence that larval rockfish can encounter and be influenced by upwelling fronts during winter months (Sadrozinski 2008), but it remains unclear whether associations with hydrographic features are established early in life or emerge later, after the onset of more sustained upwelling and the development of robust frontal systems. Two studies that identified close associations between fronts and rockfish early life history stages were focused on rockfish that exhibit a spring–summer reproductive strategy (Bjorkstedt et al. 2002; Woodson et al. 2012).

In this study, we analyze a 17-year time series of pelagic juvenile rockfish catches and concurrent hydrographic observations to assess patterns in distribution in relation to the state of the coastal ocean, using temperature and temperature fronts (gradients) as our primary indicators of hydrographic structure. We focus our analysis on observations made along two cross-shelf transects that have been consistently sampled each year: the Davenport line (36˚59.0'N) and the Pescadero line (37˚16.5'N) (fig. 1). These transects lie in a dynamic region influenced by the Point Año Nuevo upwelling center and the southern extent of the Point Reyes upwelling plume. Other key hydrographic features include the San Francisco Bay plume (which includes outflow from San Francisco Bay and oceanic waters trapped inshore of the Point Reyes upwelling plume) (Schwing et al. 1991; Sakuma et al. 1995; Wing et al. 1998) and occasional intrusions of oceanic water from offshore or warmer water from the northern part of Monterey Bay (i.e., from the upwelling shadow in the lee of the Point Año Nuevo upwelling plume) (Graham and Largier 1997; Woodson et al. 2009). The study spans a period (1987–2003) of dynamic variability in climate and environmental forcing, including two El Niño events (1992–93 and 1997–98 [Hayward 1993; Lynn et al. 1998]), a strong La Niña event (1999 [Hayward et al. 1999]), and an anomalous freshening event that originated in the subarctic and broadly affected the California Current in conjunction with a weak El Niño in 2002 (Venrick et al. 2003; Peterson et al. 2006; Ralston et al. 2013).

METHODS

Midwater trawl survey

Pelagic juvenile rockfish were collected during midwater trawl surveys conducted aboard the NOAA RV *David Starr Jordan* off central California (36˚30'–38˚20'N) from 1983 to 2003. While the survey area expanded to the U.S. Mexico border and just south of Punta Gorda (32˚45'–40˚00'N) from 2004 to the present (Sakuma et al. 2006; Ralston et al. 2013), we restricted our analysis to surveys conducted from early May through mid-June of 1987 to 2003, a period during which (a) surveys included three replicate quasi-synoptic "sweeps" off a grid of fixed stations off central California (fig. 1); and (b) the sampling protocols included collection of synoptic hydrographic data (conductivity, temperature, and depth [CTD] data, see below). Inclement weather or other logistical constraints occasionally disrupted sequential occupation of CTD and CTD-trawl stations, but every effort was made to preserve quasi-synoptic observations during each sweep.

Pelagic juvenile rockfish sampling

Samples were collected at night (typically 2100–0600 PDT) using a modified Cobb midwater trawl with a 26 m headrope and 9.5 mm mesh cod end and theoretical mouth opening of 12 m x 12 m, which was fished for 15 minutes at a target headrope depth of 30 m except at shallow water stations (<60 m) where the target headrope depth was 10 m (Wyllie-Echeverria et al. 1990; Sakuma et al. 2006; Ralston et al. 2013). For this analysis,

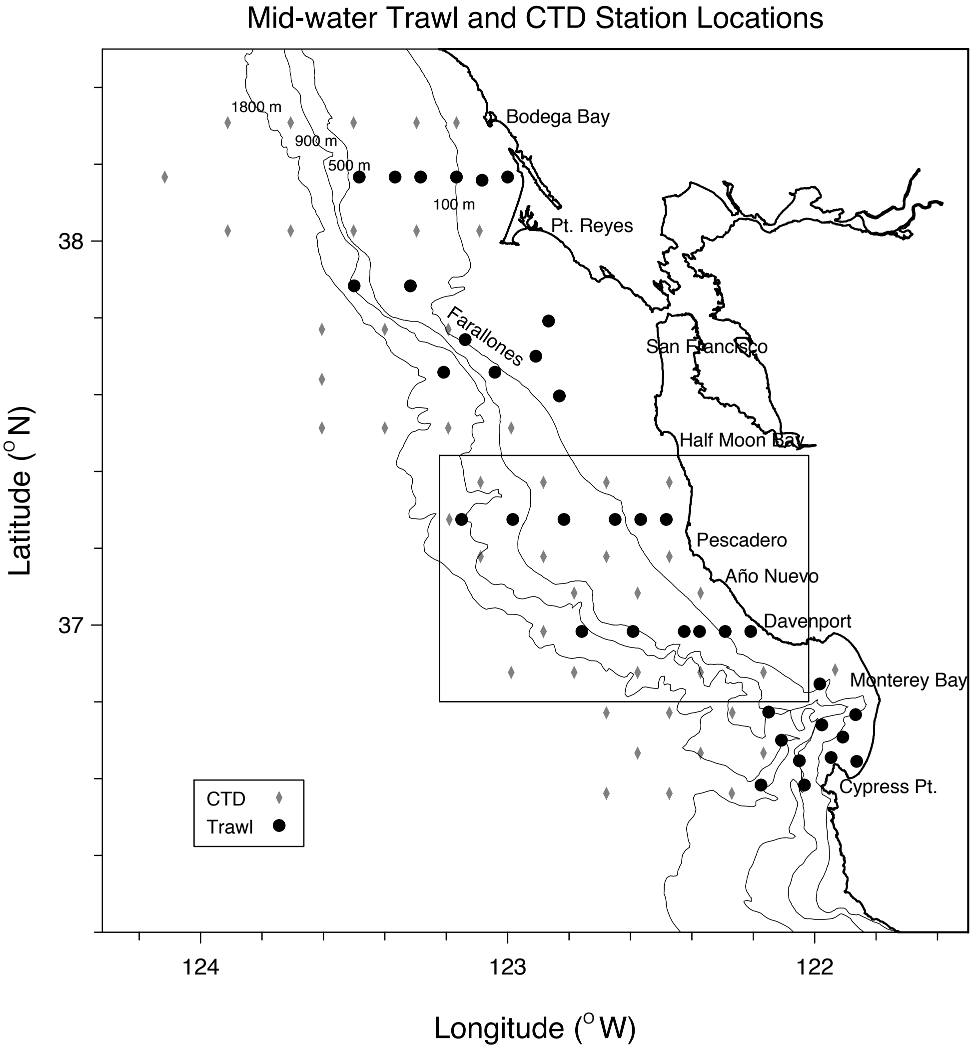

Figure 1. Midwater trawl and CTD station locations off central California. Observations from stations along the Davenport and Pescadero lines (within the rectangle) are analyzed in this study.

we restrict the data to stations where the trawl was fished at 30 m and exclude more inshore stations where shallower bathymetry required the net to be fished at 10 m. These shallow nearshore stations were also excluded from analysis because of difficulties in collecting consistent samples due to the frequency of large jellyfish catches that damaged the net or prevented quantitative sampling. All fish and select invertebrates from each trawl were sorted and enumerated at sea. More details on midwater trawl sampling and processing can be found in Ralston et al. 2013.

Hydrographic data

Vertical profiles of temperature, salinity, density, and other water properties were collected with CTD casts to a maximum depth of 500 meters (or within a few meters of the sea floor at stations over the shelf or upper slope). CTD casts were conducted at each trawl station, with additional casts conducted during the day at a series of stations that enveloped the trawl transect. Data from each cast were processed using SeaBird software; details on CTD deployments and data processing can be found in Sakuma et al. 1994.

We estimated spatial fields of temperature at 30 m depth by kriging quasi-synoptic observations collected during each sweep using functions in the ‘fields’ package in R (version 6.7; Furrer et al. 2012). From these fields, we extracted for each trawl station estimates of hydrographic conditions at 30 m and estimated the magnitude and heading of the strongest thermal gradient (i.e., the maximum increase in temperature over a 2 km line segment centered on each station). From the magnitude and heading of the maximum gradient vector, we calculated zonal (east-west) and meridonal (north-south) components of the gradient vectors. Zonal gradients represented the change in temperature in an east to

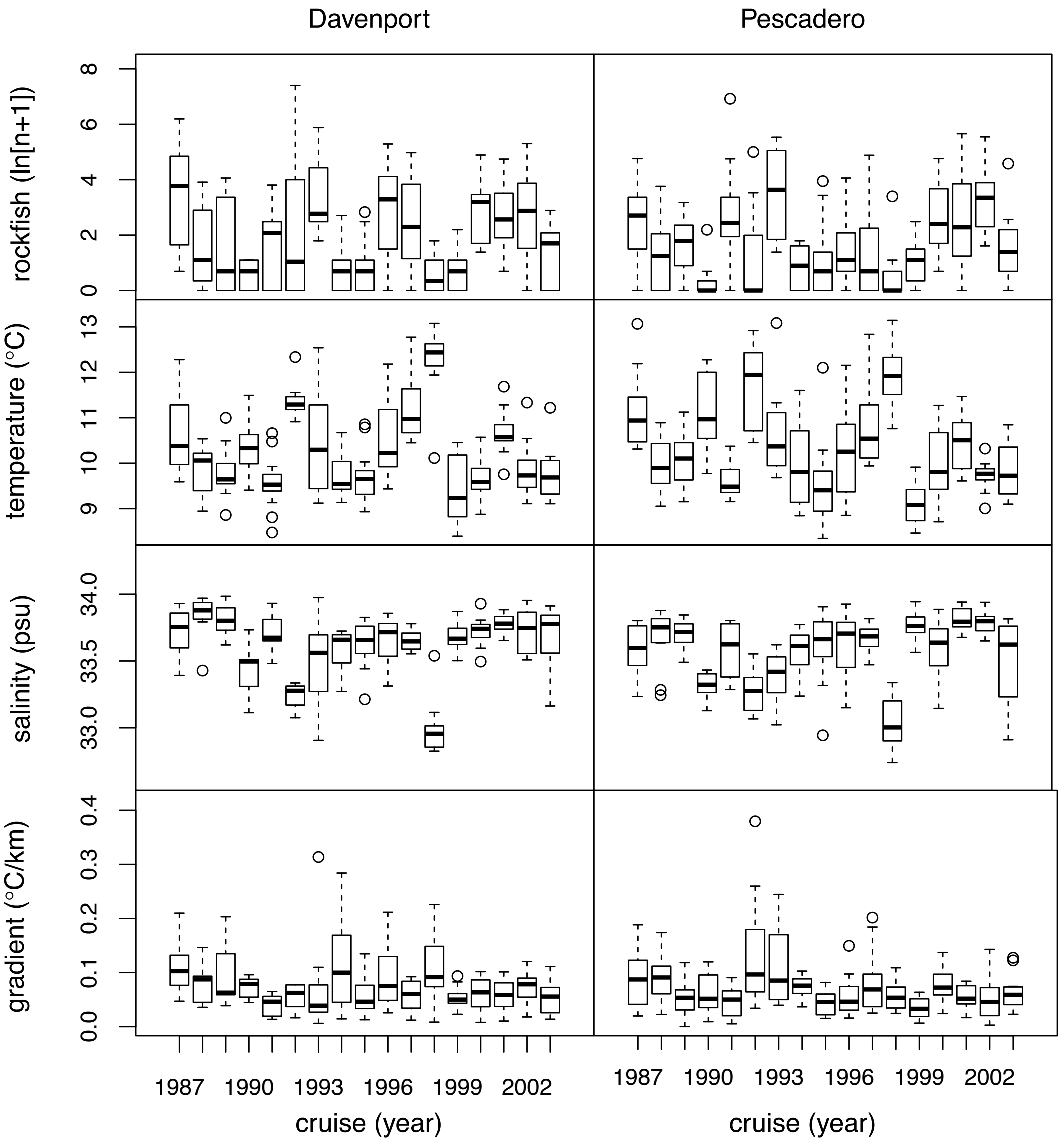

Figure 2. Summary of pelagic juvenile rockfish catch (ln(n+1)) and on-station temperature, salinity, and temperature gradient at 30 m for annual cruises along the Davenport and Pescadero lines. Dark central bars indicate median, box indicates interquartile range (IQR; i.e., 25th to 75th percentile), thin bars at end of lines indicate range of observations within 1.5 IQR of the median, and circles indicate more extreme low or high values.

west direction (e.g., a positive gradient indicated warmer water to the west), and meridional gradients were the change in temperature from north to south (e.g., a positive gradient indicated warmer water to the south). We also kriged temperature fields at 10, 20, and 40 m depth to supplement our interpretation of results from our main analysis, but do not include these in the quantitative analysis presented here.

Analysis

We visually inspected the spatial distribution of pelagic juvenile rockfish catches, scaled as a percentage of the total number captured on a given sweep, overlaid on contour plots of temperature at trawl depths (30 m) to identify cases where distributions suggested association with hydrographic features.

We fit linear mixed effects models (using package 'nlme' [version 3.1-104; Pinheiro et al. 2012] in R 2.15.1 [R Core Team 2012]) to examine relationships between abundance of pelagic juvenile rockfish in each haul, transformed as ln(n + 1), temperature, and temperature gradient. Based on visual inspection of bivariate relationships, fixed effects of temperature and temperature gradients on catch were modeled as, e.g.,

$$\ln(n + 1) \sim T + T^2 + \nabla_T$$

where T is water temperature and ∇_T is maximum gradient (a scalar value) of one of its two vector components (i.e., zonal or meridional gradients). Cruise and sweep (nested within cruise) were treated as random effects within the model. We examined the effects of maximum gradient and its zonal and meridonal components separately by fitting models to the combined data set and independently to data for each line. Preliminary analysis included models with quadratic gradient terms and models with interaction terms, but analysis returned non-significant parameter estimates for these additional terms, so we focus on results from the simpler models.

RESULTS

Hydrographic conditions encountered by the survey varied substantially from year to year, with years affected by the 1992–93 and 1997–98 El Niño events exhibiting expected increases in temperature and decreases in salinity (fig. 2). The abundance of pelagic juvenile rockfish captured along the Davenport and Pescadero lines varied coherently from year to year (fig. 2). Hydrographic conditions also varied more or less coherently, although there appears to be somewhat greater variability in temperature and salinity among stations along the Pescadero line in most years (fig. 2). The intensity of temperature gradients differed between the Davenport and Pescadero lines in several years, yet the line on which fronts were stronger or more commonly encountered was not consistent from year to year (fig. 2).

Over the course of the study period, most stations sampled water between ~9°–11°C and ~33.5–34 psu (figs. 2–3). Under warmer, fresher water conditions, substantial catches of pelagic juvenile rockfish were more common off Davenport than off Pescadero, while under cooler, saltier water conditions catches at Pescadero generally tended to be moderately higher (fig. 3). Catch-weighted mean temperature and salinity for the Davenport line was higher (10.33°C and 33.65 psu) than for the Pescadero line (10.18°C and 33.61 psu), counter to the pattern in mean conditions encountered at the trawl stations (10.20°C and 33.64 psu off Davenport and 10.25°C and 33.57 psu off Pescadero).

Visual inspection of the distribution of pelagic juvenile rockfish catches in relation to temperature fields at 30 m depth frequently identified patterns indicating elevated catch densities associated with fronts (fig. 4). On any given sweep, elevated densities of pelagic juvenile rockfish might be observed at fronts that fell into one of three non-exclusive classes: (1) along the Davenport line, rockfish were commonly associated with fronts bounding the southern extent of the upwelling plume anchored at Point Año Nuevo, including the offshore and inshore "corners" of this front (e.g., fig. 4a), (2) along the Pescadero line, rockfish were commonly associated with frontal structure formed by shoaling of isotherms towards the coast, often in connection with upwelled water from the Point Reyes upwelling center (e.g., fig. 4h), and (3) on either or both lines, rockfish could be associated with a more extensive, offshore upwelling front (e.g., fig. 4e for Davenport and fig. 4f for Pescadero). In many cases, such interpretations were corroborated or more strongly supported by examination of thermal structure at shallower depths, although often with some increase in the spatial offset between hydrographic structures and the apparent distributions of juvenile rockfish (data not shown). This appeared to be especially true in years affected by warmer conditions and downwelling, when temperature fields at 30 m depth near the coast were often more homogeneous, yet elevated densities of pelagic juvenile rockfish tended to coincide with weaker and shallower frontal structures consistent with one of the cases identified above (e.g., especially structure associated with upwelling off Point Año Nuevo).

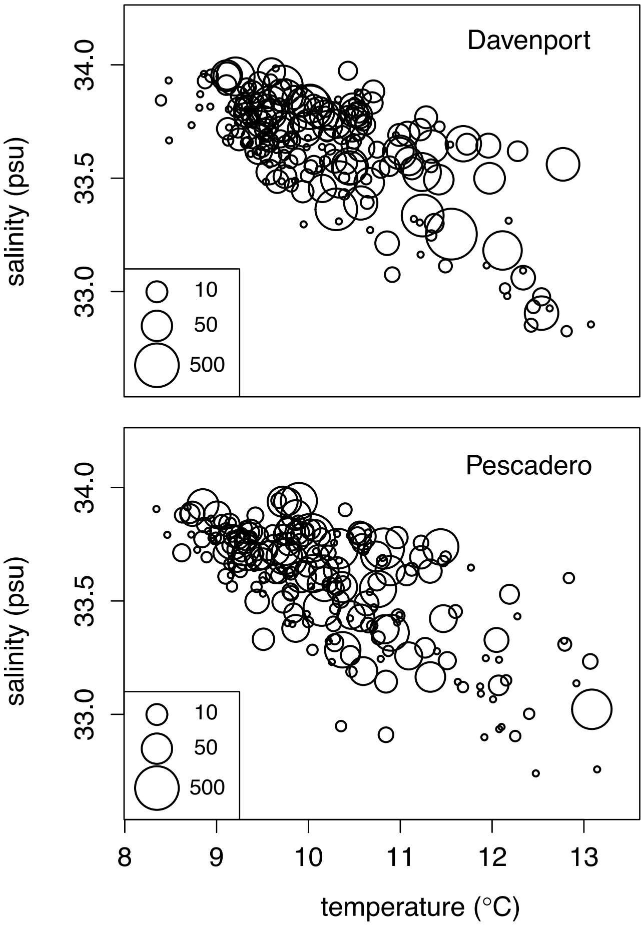

Figure 3. Pelagic juvenile rockfish catch in relation to temperature and salinity at 30 m off Davenport and Pescadero. The size of the circle represents the size of the abundance of pelagic juvenile rockfish.

Catches of pelagic juvenile rockfish exhibited a dome-shaped relationship to temperature along the Pescadero line and a non-significant trend towards higher

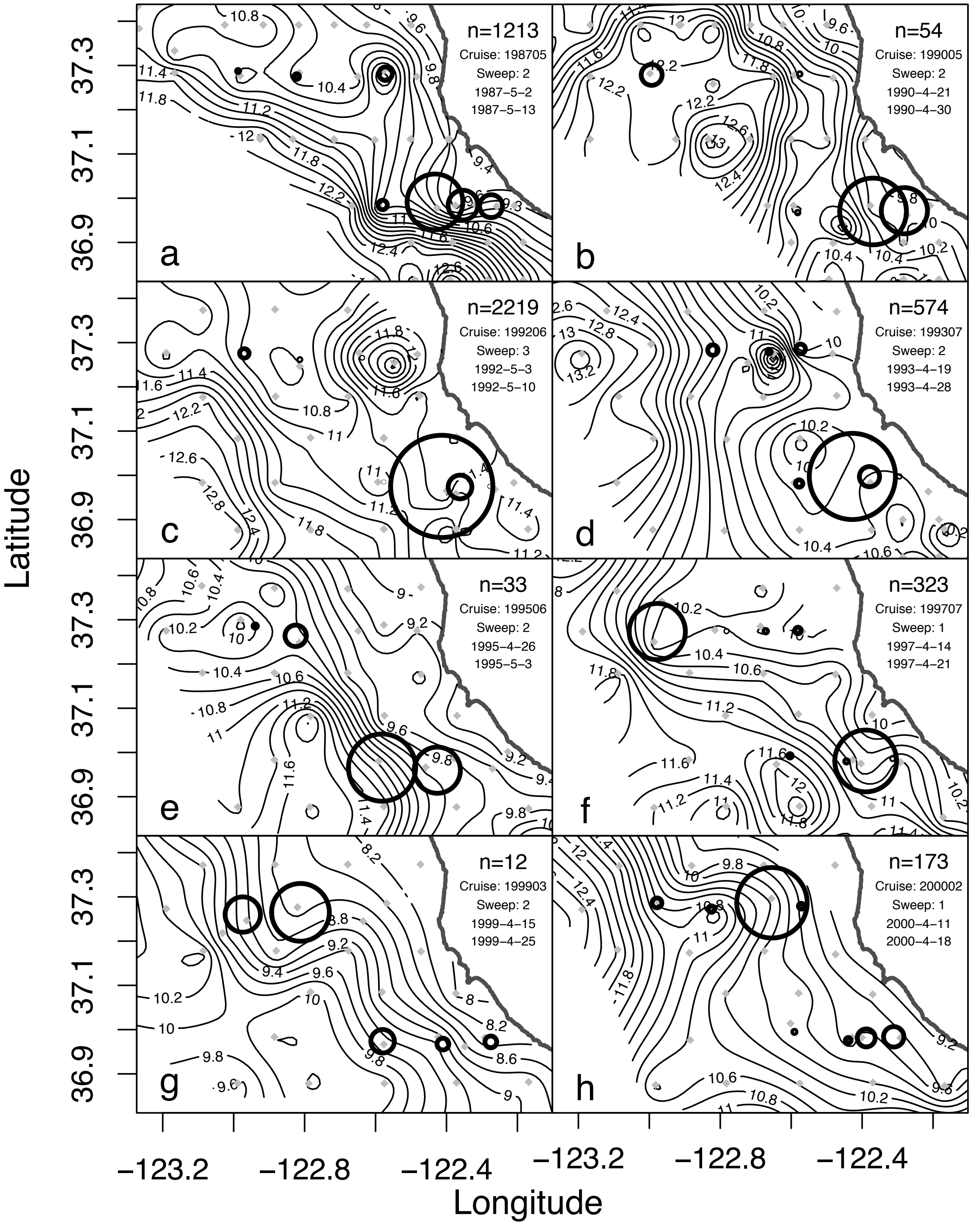

Figure 4. Select 30 m depth temperature contour maps illustrating variability in association of pelagic juvenile rockfish with hydrographic structure. Number in upper right corner of each plot indicates number of pelagic juvenile rockfish captured on the sweep. Also indicated are the cruise, sweep, and the dates over which the entire sweep throughout the core survey area (Monterey Bay to Point Reyes) was conducted. Solid circles indicate catch scaled by the proportion of the sweep's catch at each station. Grey diamonds indicate CTD stations from which data were used in developing the temperature map.

catches at stations with stronger maximum gradients (fig. 5, table 1). Catches along the Davenport line also were not significantly related to either gradient strength or temperature (table 1), but the lack of a relationship to temperature appears, at least in part, to be due to a bimodal distribution in the catch-temperature relationship (figs. 3, 6). Dome-shaped relationships between temperature and catch and non-significant (but positive) trends between gradient and catch were also observed when data were aggregated (using means) within sweeps

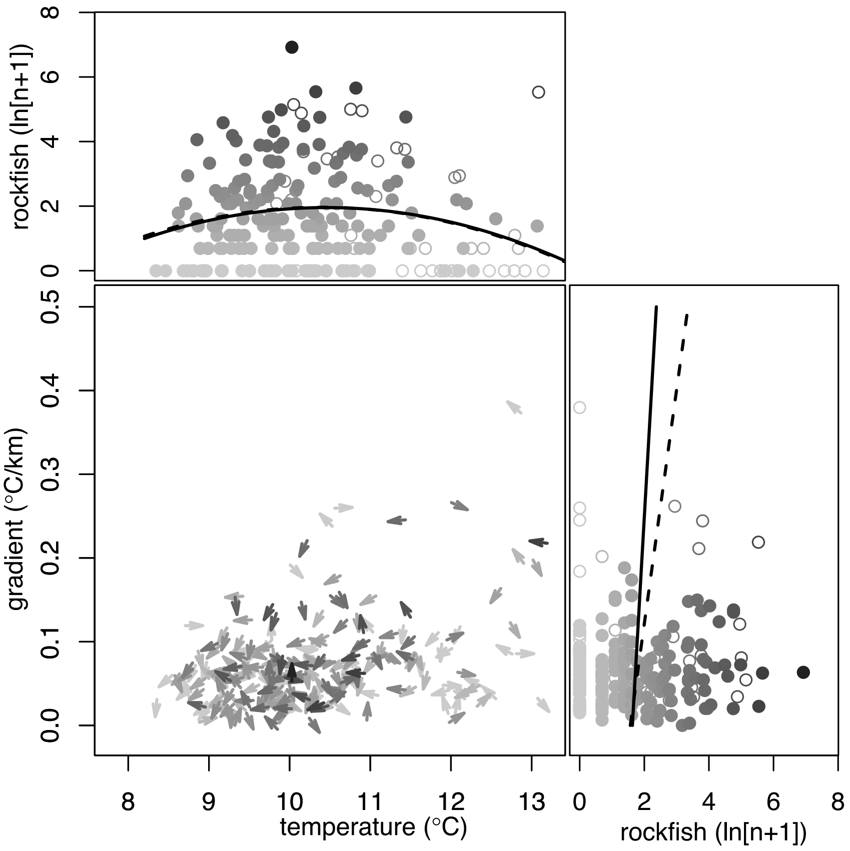

Figure 5. Relationships between pelagic juvenile rockfish catch, temperature, and gradient by station for the Pescadero line. Arrows indicate heading of gradient vector (i.e., direction of increasing temperature). Solid lines indicate model fits to full data set; dashed lines indicate model fits to data excluding "El Niño" years (open symbols). Greyscale shading scales with size of catch.

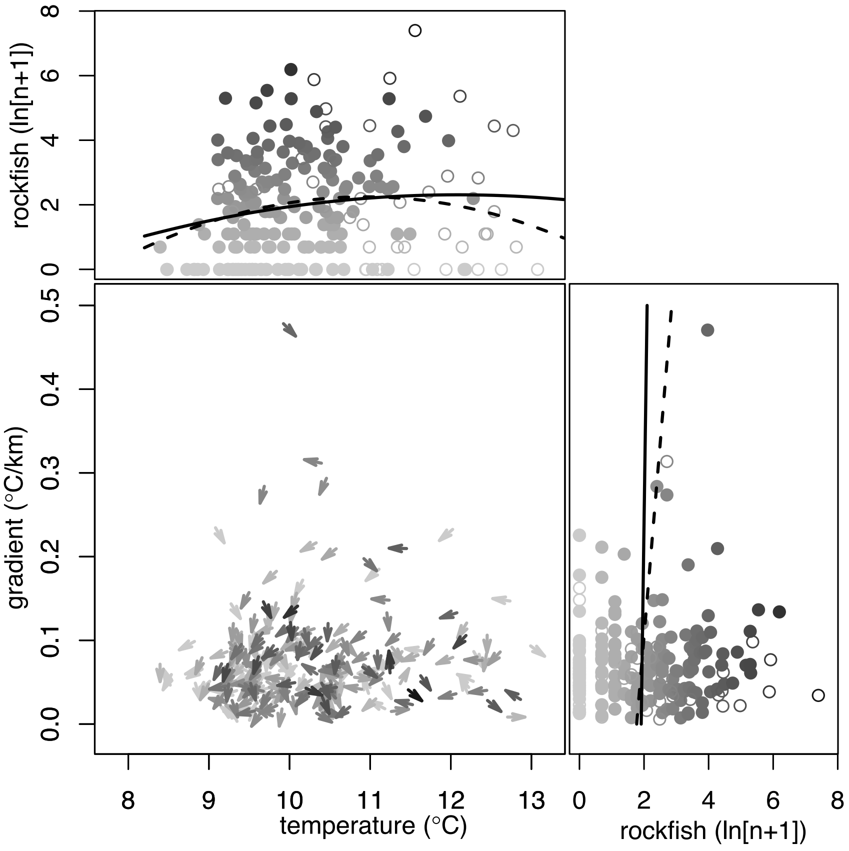

Figure 6. Relationships between pelagic juvenile rockfish catch, temperature, and gradient by station for the Davenport line. Arrows indicate heading of gradient vector (i.e., direction of increasing temperature). Solid lines indicate model fits to full data set; dashed lines indicate model fits to data excluding "El Niño" years (open symbols). Greyscale shading scales with size of catch.

TABLE 1

Linear mixed effects models of the relationships between pelagic juvenile rockfish catch (transformed as ln(n + 1)), temperature, and temperature gradient with cruise and sweep (nested within cruise) treated as random effects. For each gradient variable, upper row gives coefficients from fitted model, and lower row gives p-value associated with that coefficient.

All Years					Cool/non-ENSO				
Both Lines	Int	T	T2	Gradient	Both Lines	Int	T	T2	Gradient
Maximum	–15.389	3.232	–0.150	0.636	Maximum	–20.743	4.291	–0.204	3.191
	0.016	0.007	0.008	0.595		0.012	0.008	0.009	0.031
Zonal	–15.426	3.244	–0.151	0.445	Zonal	–21.178	4.400	–0.208	0.114
	0.160	0.007	0.008	0.679		0.012	0.007	0.008	0.935
Meridional	–15.052	3.166	–0.147	0.879	Meridional	–20.875	4.334	–0.205	1.742
	0.019	0.009	0.009	0.448		0.012	0.007	0.008	0.189
Davenport	Int	T	T2	Gradient	Davenport	Int	T	T2	Gradient
Maximum	–10.098	2.049	–0.085	0.366	Maximum	–23.095	4.604	–0.210	2.170
	0.356	0.324	0.387	0.834		0.122	0.116	0.141	0.243
Zonal	–12.672	2.556	–0.109	2.080	Zonal	–24.455	4.887	–0.223	0.985
	0.245	0.217	0.265	0.204		0.102	0.096	0.119	0.584
Meridional	–9.894	2.000	–0.082	1.308	Meridional	–22.471	4.480	–0.203	1.698
	0.362	0.331	0.397	0.475		0.136	0.130	0.159	0.369
Pescadero	Int	T	T2	Gradient	Pescadero	Int	T	T2	Gradient
Maximum	–18.770	3.944	–0.189	1.483	Maximum	–18.346	3.865	–0.186	3.576
	0.023	0.011	0.009	0.454		0.076	0.054	0.054	0.221
Zonal	–18.307	3.864	–0.184	–1.019	Zonal	–16.612	3.546	–0.170	–1.092
	0.026	0.012	0.010	0.483		0.109	0.077	0.079	0.627
Meridional	–18.118	3.831	–0.183	–0.473	Meridional	–17.252	3.680	–0.176	0.388
	0.027	0.013	0.011	0.776		0.098	0.069	0.071	0.860

or within cruises (figs. 7–8). Considered independently, neither zonal nor meridonal gradients had a significant effect on catch along the Pescadero line, though the trend was towards greater catches at stations where cooler water lay to the south and west, i.e., where fronts lay between upwelled water offshore and warmer waters associated with the San Francisco Bay Plume or poleward intrusions of oceanic water (figs. 4–5). Examination of catches in relation to zonal and meridonal temperature gradients along the Davenport line also yielded statistically non-significant results, with a weak trend for greater catches at stations where cooler water lay to the north and east, i.e., in a configuration consistent with upwelling extending from the Point Año Nuevo upwelling center (figs. 4, 6).

We repeated the station-level analysis for a data set that excluded years dominated by warmer temperatures related to strong El Niño events (1992, 1993, 1997, and 1998). In this analysis, catches of pelagic juvenile rockfish along the Davenport line exhibited a dome-shaped relationship to temperature (fig. 6) analogous to that observed along the Pescadero line (fig. 5), albeit with a somewhat higher range of temperatures. For both Davenport and Pescadero, the relationship between catch of pelagic juvenile rockfish and maximum temperature gradient strengthened yet remained non-significant (table 1). However, when the combined data set was considered, maximum temperature gradient was found to have a significant, positive effect on catch of pelagic juvenile rockfish (table 1). General trends between catch and temperature gradients remained the same for the Davenport line in the reduced data set, but the pattern for Pescadero switched to a (non-significant) tendency for catches to be larger at stations where cooler water lay to the north and west during non-El Niño years, i.e., at fronts affected by the southern, inshore end of the upwelling plume extending south from Point Reyes (figs. 4–6, table 1).

On any given cruise, much of the region surrounding the Davenport and Pescadero lines was marked by relatively weak horizontal temperature gradients, but the strongest gradients were most commonly and consistently observed in association with water between 10°C and 12°C (fig. 9). This pattern was also observed at shallower and deeper layers, with modest shifts in temperature related to depth (data not shown).

DISCUSSION

Our analysis of 17 years of midwater trawl survey data revealed several trends consistent with the hypothesis that pelagic juvenile rockfish are associated with hydrographic fronts. The relationship between gradient strength and catches of pelagic juvenile rockfish was universally positive (although typically not statistically significant) and was strengthened when the analysis excluded El Niño years. Moreover, the relationships

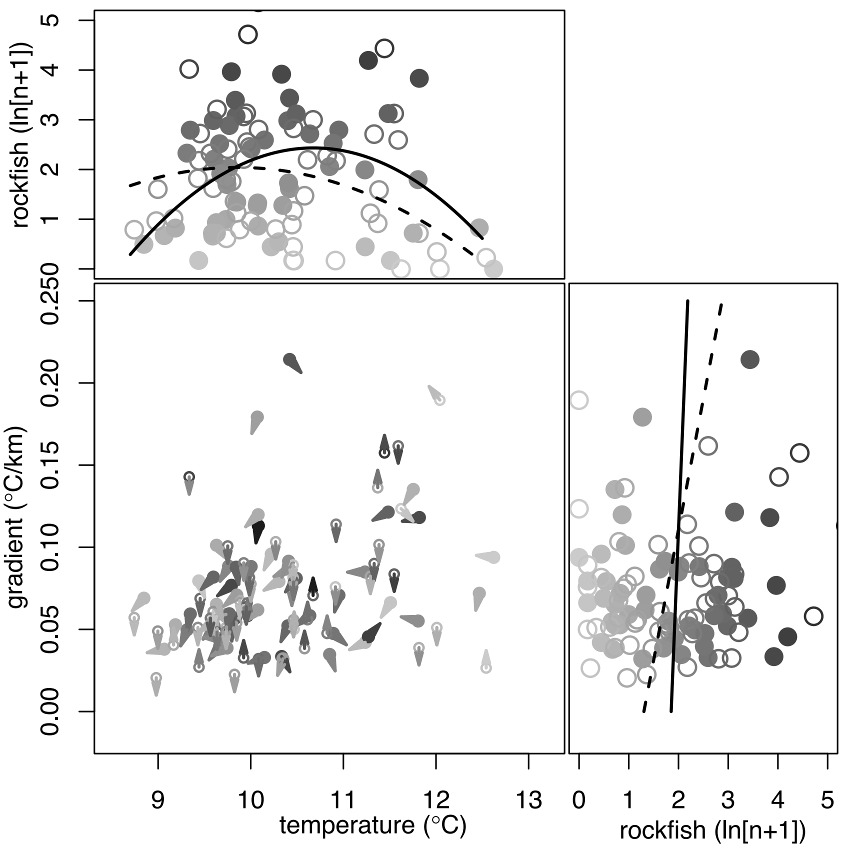

Figure 7. Relationships between pelagic juvenile rockfish catch, temperature, and gradient averaged by sweep. Solid symbols and lines indicate observations and model fits along the Davenport line, open symbols and dashed lines indicate results for the Pescadero line. Arrows indicate heading of gradient vector (i.e., direction of increasing temperature). Greyscale shading scales with size of mean catch.

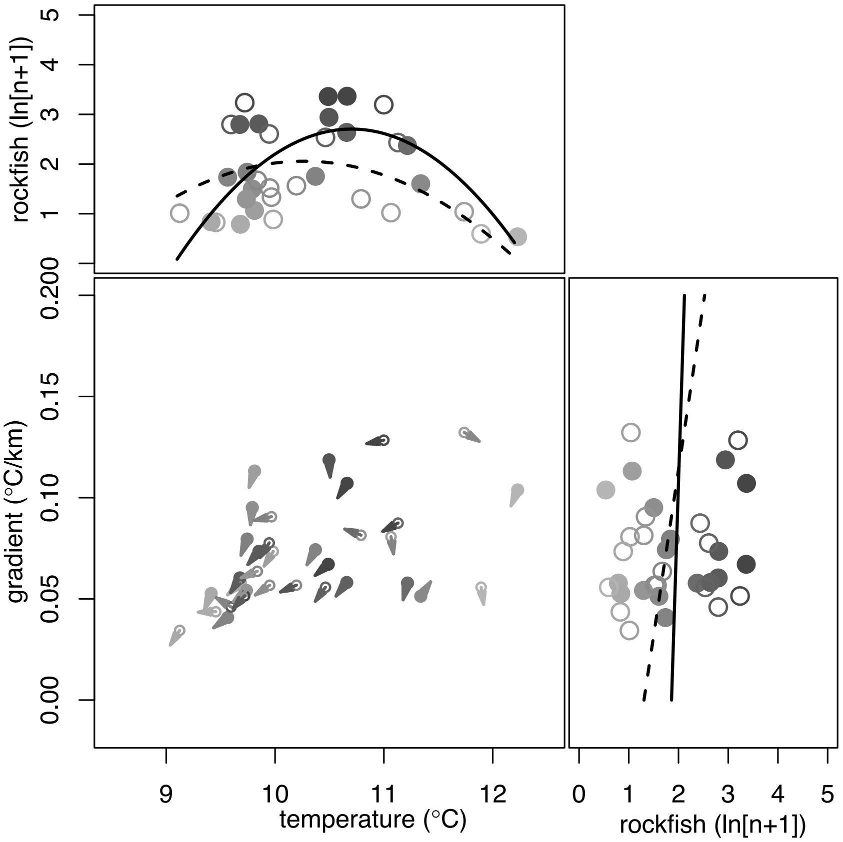

Figure 8. Relationships between pelagic juvenile rockfish catch, temperature, and gradient averaged by cruise. Solid symbols and lines indicate observations and model fits along the Davenport line, open symbols and dashed lines indicate results for the Pescadero line. Arrows indicate heading of gradient vector (i.e., direction of increasing temperature). Greyscale shading scales with size of mean catch.

between gradient heading (or the vector-valued zonal and meridional measures of thermal gradients) and catches of pelagic juvenile rockfish observed on each line is consistent with the dominant oceanographic structure typical of the region. This includes classical upwelling fronts with onshore-offshore structure or those bounding the southern and inshore extent of the upwelling plume advected from Point Año Nuevo and Point Reyes and "reverse" fronts between warmer water trapped inshore of upwelling plumes (e.g., warmer water from northern Monterey Bay trapped in the shadow of the Point Año Nuevo upwelling plume; Graham and Largier 1997) or advected poleward during relaxation events (e.g., Send et al. 1987; Wing et al. 1995). Further corroboration of these trends comes from visual inspection of catches overlaid on temperature fields, which indicates that pelagic juvenile rockfish are often more abundant at temperature fronts within the study area off central California (fig. 4).

We found that pelagic juvenile rockfish tend to be more frequently encountered in waters of intermediate temperature (i.e., around 10˚C to 12˚C at 30 m depth; figs. 5 and 6), which offers some circumstantial evidence that hydrographic fronts influence distribution off central California. These intermediate temperatures correspond to those typically observed in the thermocline in this region and thus are expected to be associated with fronts that form when the thermocline shoals in response to upwelling (Schwing et al. 1991; Sakuma et al. 1994 and 1995). Observed salinities also corroborate this interpretation (fig. 3). Moreover, the strongest temperature gradients observed in the study region consistently coincided with water in this temperature range (fig. 9). Together, these observations suggest that pelagic juvenile rockfish are commonly found in water masses linked to fronts, even when they are not in an area where the local horizontal gradients are particularly sharp. This conclusion is consistent with the results of simple visual inspection of catch distribution relative to the temperature field on almost any given sweep.

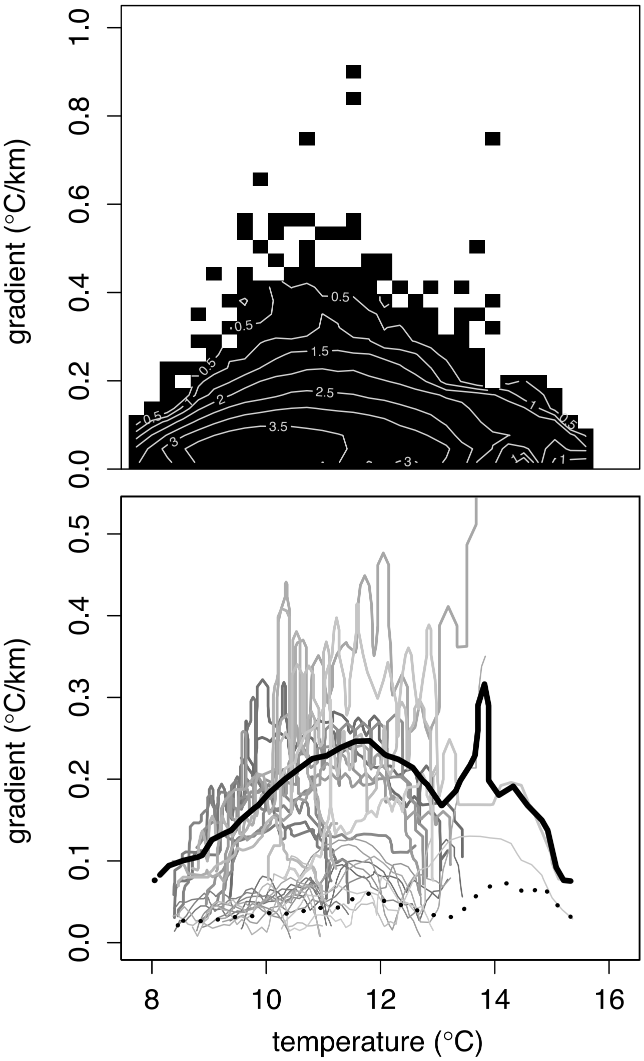

Figure 9. Upper panel: distribution of gradient strength as a function of temperature at 30 m for all cruises and sweeps. Dark areas indicate occurrence of particular (binned) combinations of temperature and gradient; grey contours indicate number of observations of each combination (in thousands). Lower panel: 99.5th (thick black line) and 50th (thick dashed line) percentile gradient strength v. temperature at 30 m. Cruise-specific 99.5th (thick grey lines) and 50th (thin grey lines) percentiles illustrate consistency of stronger gradients associated with intermediate temperatures for most cruises.

In some respects, the fact that we detected any pattern is somewhat surprising. The survey was not designed to target hydrographic features in this dynamic region, so opportunities to sample across hydrographic fronts were serendipitous and only recognized after the fact. Even when trawls occurred in the vicinity of fronts, the orientation of transects sometimes limited the potential for contrast in the data (e.g., due to stations falling along a front rather than spanning a front from one side to the other). Moreover, although each repeated sweep provides some opportunity for a quasi-synoptic view of this region, the observed distributions of pelagic juvenile rockfish relative to their hydrographic setting remain snapshots of a dynamic process contingent on the recent (and not so recent) history of the system. Otolith microchemistry studies by Woodson et al. 2013 showed that over a temporal period of five days, upwelling associated pelagic juvenile rockfish could in some instances traverse distances of up to 50–100 km. Furthermore, the age, extent, and spatial continuity of a front may matter as much or more than the strength of the gradient that defines the front in determining how it influences the distribution of pelagic juvenile rockfish and other elements of the coastal ecosystem. Indeed, it is possible that localized effects of fronts on distributions of pelagic juvenile rockfish may persist even as fronts weaken, or, especially in the case of larger juveniles, fish may not be advected offshore with fronts during active upwelling (cf. Larson et al. 1994), thus breaking any association with hydrographic structure that may have previously existed.

Our analysis provides insights to how pelagic juvenile rockfish are distributed with respect to hydrographic structure, but does little to explain absolute variability in abundance. Indeed, the analysis assigned a very small amount of variability in the abundance of pelagic juvenile rockfish to the fixed effects of temperature and temperature gradient, with much of the variability instead being attributed to the random effects of cruise (year) and sweep within cruise or remaining unexplained. This is entirely consistent with the hypothesis that large fluctuations in abundance reflect variability in recruitment success and supports previous reports linking the bulk of variability in abundance of pelagic juvenile rockfish to conditions that affect larval stages in the winter and early spring rather than conditions coincident with the midwater trawl survey (e.g., Ralston and Howard 1995; Laidig et al. 2007; Ralston et al. 2013). Unexplained variability is likely due to patchiness in the distribution of pelagic juvenile rockfish, changes in the structure of the coastal ocean, changes in response to variable wind forcing, and ontogenetic changes in how juveniles utilize pelagic habitats over the course of successive sweeps (e.g., changes in whether and how individuals maintain cross-shelf position, or attrition from the pelagic environment through settlement; Larson et al. 1994).

We recognize that our operational definition of a front (horizontal gradients in temperature at trawl depth) also constrains our ability to detect fish-front associations quantitatively. In several cases, catches of pelagic juvenile rockfish appear to be associated with shallow fronts that have weak signatures at depth. In some of these cases the apparent distribution of pelagic juvenile rockfish appears to be closely co-located with shallower fronts, while in others, their distribution appears to be slightly offset from the shallower hydrographic structure. This pattern is consistent with theoretical and empirical evidence that plankton associated with fronts are often located some distance away from the near-surface signature of the front (Franks 1992). Such interpretations must be made cautiously, however, given the limitations of our station-based sampling for resolving the spatial distribution of pelagic juvenile rockfish.

Notwithstanding these caveats, we believe that the trends that emerge from our analysis are informative and warrant further investigation of associations between spatial distributions of pelagic juvenile rockfish and hydrographic fronts. A greater understanding of these relationships offers the potential to improve the utility of the pre-recruit indices derived from the survey results. For example, the 1999 year class was exceptionally strong for many rockfish stocks, yet few pelagic juveniles were captured during that year's survey. However, the survey that year encountered universally cold water—the trawls fished waters colder than the lower range of the "optimal" temperature range identified here. This raises the possibility that pelagic juvenile rockfish were not as available to the survey in 1999 as in other years, although it is not clear whether this was because they were offshore of the survey area, in slightly warmer waters shallower than the target trawl depth, or had already settled out (perhaps assisted by onshore flow at depth associated with the strong upwelling that occurred during 1999).

Understanding fish-front associations also has implications for improving our ability to link recruitment success to environmental and climate variability. Recruitment success of commercial groundfish species has been shown to be related to variability in the timing of spring transition (Holt and Mantua 2009) as well as sea level anomalies during/after the spawning season (Ralston et al. 2013). Results from this and previous studies suggest that association with hydrographic fronts may occur throughout rockfish early life history stages (Bjorkstedt et al. 2002; Sadrozinski 2008), although factors that affect the establishment and continuity of such associations and their ecological consequences for growth and survival require further investigation. In this regard, observations of unusually high catches of pelagic juvenile rockfish at fronts during warm, El Niño years (e.g., 1992) suggests that such years may provide a useful contrast to more productive years for evaluating the ecological consequences of fronts for rockfish early life history stages. Indeed, it may be that what fronts are formed in such years play a stronger role in selecting individuals who survive. For example, greater productivity and reduced temperatures in frontal regions may yield a more favorable energetic balance or starker variability in the distribution of prey and may promote aggregation (i.e., limit the likelihood that individuals' foraging behaviors will lead them away from fronts). In any case, understanding how fronts affect the ecology of larval and juvenile rockfish during unproductive years is likely to yield insights into how fronts influence recruitment more generally.

Looking forward, we are developing methods to quantify three-dimensional frontal structure and how pelagic juvenile rockfish associate with these structures. Analyses based on results from realistic ocean circulation models (e.g., Petersen et al. 2010) may also prove informative in teasing out mechanisms that influence fish-front associations and the implications of variable forcing and our ability to observe these dynamics, as well as the implications of variable forcing on distribution of pelagic juvenile rockfish relative to the survey region. Ideally, statistical and modeling analysis of data sets such as the one considered here will be complemented by process-oriented field studies intensively sampling hydrographic features to resolve the distribution of pelagic juvenile rockfish relative to frontal structures (e.g., Sakuma and Ralston, unpublished data; Bjorkstedt et al. 2002) and how rockfish early life history stages are exposed to upwelling processes in general (e.g., Woodson et al. 2013). Such analyses will need to account for how catches (and front strength) vary relative to the regional environment and at more local scales (e.g., account for whether a front is a locally strong feature, even if stronger fronts exist elsewhere at the same time) and will lay the foundation for investigating how swimming and other behaviors affect the distribution of larval and juvenile rockfish during periods when year-class strength and settlement patterns are determined.

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INTERANNUAL VARIABILITY OF HUMBOLDT SQUID (*DOSIDICUS GIGAS*) OFF OREGON AND SOUTHERN WASHINGTON

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ABSTRACT

Previous studies have shown that oceanographic conditions influence the distribution of range-expanding Humboldt squid (*Dosidicus gigas*), but broad-scale temporal and spatial distribution analyses are limited. Interannual variability in Humboldt squid occurrence is largely undocumented north of California. We combined annual occurrences noted by fishermen with fisheries-dependent and fisheries-independent data between 2002–11 from 42.0080°N, 131.0000°W to 46.7008°N, 131.0000°W. Humboldt squid more frequently occurred at a sea surface temperature range of 10.5°–13.0°C, sea surface height anomalies from –4.0–1.0 m, 0.26–3.00 mg m^{-3} chlorophyll *a*, and sea surface salinity range of 32.2–32.8 psu. Dissolved oxygen levels were bimodal, between 3.0–4.5 ml L^{-1} and 6.0–7.0 ml L^{-1} at 30 m depth. Maps of estimated likelihood of occurrence generated by nonparametric multiplicative regression were consistent with observations from fishermen. When Humboldt squid become abundant in northern California Current waters, research should include seasonal variability and oceanographic conditions at multiple depths.

INTRODUCTION

The Humboldt squid (*Dosidicus gigas*), also known as jumbo flying squid, is an opportunistic predator that has experienced episodic range expansions from the Eastern Tropical Pacific into South America and the California Current system. Humboldt squid sightings off of the South American coast have been documented since the 19th century and in 2002 they were seen as far south as Chiloe Island in southern Chile (Alarcón-Muñoz et al. 2008). In the northern California Current system, Humboldt squid were documented in the 1930s off California with increasing occurrences since 2002 (Field et al. 2007; Litz et al. 2011). Humboldt squid have been seen as far north as Alaska (in 2004, Cosgrove 2005) and were first documented in southern Oregon in 1997 (Pearcy 2002). Peak density in Oregon occurred in 2009 (Litz et al. 2011); however, reported sightings in this area have decreased between 2009 and 2011 (Bjorkstedt et al. 2011; Marissa Litz, Oregon State University, pers. comm.).

Humboldt squid live 1–2 years, have rapid growth rates, and high-energy demands (Nigmatullin et al. 2001; Zeidberg and Robison 2007). As a large predator, there is concern that future Humboldt squid expansion will result in a decline in valuable commercial fishery stocks and impact coastal food webs in the California Current (Field et al. 2007). Humboldt squid have the ability to alter food sources and foraging strategies based on varied environmental conditions (Bazzino et al. 2010). These squid have been known to prey on Pacific herring (*Clupea pallasii*) (Field et al. 2007), mackerel (*Scomber japonicas*) (Sato 1976; Ehrhardt et al. 1983), sardines (*Sardinops sagax*) (Ehrhardt et al. 1983; Markaida and Sosa-Nishizaki 2003), hake (*Merluccius productus*) (Markaida and Sosa-Nishizaki 2003), rockfish (*Sebastes* spp.) (Field et al. 2007), and salmon (*Oncorhynchus* spp.). The valuable Pacific hake (*Merluccius productus*) fishery is of particular concern, as Humboldt squid are known to associate with hake schools and a decline in Chilean hake (*M. gayi*) biomass was attributed to an increase in Humboldt squid off the Chilean coast in 2001–06 (Alarcón-Muñoz et al. 2008). In Oregon, Humboldt squid presence coincided with a decline in juvenile Pacific hake, which was in contrast to recent abundance trends (Litz et al. 2011).

Previous research has indicated that oceanographic factors may contribute to the variable temporal and spatial population range of Humboldt squid (Gilly et al. 2006; Field et al. 2007; Zeidberg and Robison 2007), and direct evidence of what is driving that expansion is still being actively researched (Bazzino et al. 2010). It has been proposed that warming oceans, the expansion of the oxygen minimum layer (OML), and large climatic processes such as the El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) could influence Humboldt squid migration patterns through modifications of environmental conditions, community structure, and prey availability (Nigmatullin et al. 2001; Brodeur et al. 2006; Gilly et al. 2006; Bograd et al. 2008; Keyl et al. 2008; Mejía-Rebollo et al. 2008; Bazzino et al. 2010; Rosa and Seibel 2010; Litz et al. 2011; Stewart et al. 2012). Although changing ocean conditions (Stewart et al. 2012) and response to high productivity levels (Field et al. 2012) may enable expansion and seasonal migration into the northern California Current, Humboldt squid occurrence is limited by their ability to migrate to available spawning habitat (Staaf et al. 2011; Field et al. 2012).

In Oregon, there is no monitored fishery for Humboldt squid and their distribution is largely undocumented. Species distribution modeling (SDM), also known as habitat suitability modeling, may be able to aid in the understanding of Humboldt expansion off Oregon. Statistical habitat models investigate the relationship between species and their environments and can be utilized to further describe and predict potential habitat (Franklin 2009; McCune 2011). Squid fishery data have been analyzed using GIS (Valavanis et al. 2004; Sanchez et al. 2008; Chen et al. 2010), generalized additive models (GAMs) (Lefkaditou et al. 2008; Sanchez et al. 2008; Litz et al. 2011), and maximum entropy (Maxent) (Lefkaditou et al. 2008) for sea surface temperature (SST), chlorophyll *a* (chl *a*), sea surface salinity (SSS), bathymetry, sea level anomalies, and large-scale oceanic processes. Although these are common habitat modeling methods, it has been argued that these models can prove to be inappropriate if species/environmental relationships are unimodal and interactive (McCune 2011). Nonparametric multiplicative regression (NPMR) may be a more appropriate habitat modeling approach because it fits a local mean to the predictive points, allows the data to have any shape, and allows for environmental variable interaction, and complex nonlinear responses (McCune 2006).

A recent study investigating the correlation of oceanographic conditions to Humboldt squid catch in the northern California Current system found that Humboldt squid presence has been closely associated with salinity, while abundance corresponded best with station depth, subsurface temperature, salinity, and density (Litz et al. 2011). Using GAMs, Litz et al. 2011 analyzed seasonal fishery-independent survey and oceanographic data from the National Oceanic and Atmospheric Administration (NOAA) Fisheries Predator and Stock Assessment Improvement Plan (SAIP) from 2004–09 off Oregon and Washington. Litz et al. 2011 found Humboldt squid present in 60 of the 947 total trawls, and established that Humboldt squid abundance corresponded best with a station depth of 1000 m, 11°–13°C subsurface water temperature, 32.4–32.8 psu, and a density of 24.5–25.0 kg m^{-3} at 20 m. While their results provided significant baseline information for Humboldt squid monitoring in the Pacific Northwest, Litz et al. 2011 expressed need for broader scale distribution data analysis.

The goal of this study is to establish distribution data and explore the relationship between broad-scale temporal and spatial oceanographic conditions and Humboldt squid occurrence off Oregon and southern Washington so as to contribute to baseline information on Humboldt squid interannual variability. Due to the coarse-scale of our data, we did not seek to explain squid behavior or migratory patterns. This study analyzes aggregate Humboldt squid occurrence information from three fishery-independent surveys, fisheries-dependent data from one observer program, and sightings by fishermen with annual remote sensing and field oceanographic data from 2002–11.

METHODS

Study Area

The study area is in the northeast Pacific Ocean, United States. Our research is focused predominantly off the Oregon coast to 131.0000°W but includes some data points off southern Washington (42.0080°N, 131.0000°W to 46.7008°N, 131.0000°W). The range of the study area was chosen to enable the inclusion of nearshore and offshore Humboldt squid occurrences (fig. 1).

Positive Occurrences and Oceanographic Conditions

Positive occurrences, or sightings of one or more Humboldt squid, were compiled from fishermen, fisheries-dependent observer records, and fisheries-independent surveys between 2002–11 for a total of 339 positive occurrences (fig. 1, table 1). Temporal and spatial data on Humboldt squid occurrence was collected by interviewing 54 fishermen. Interviews were conducted by telephone, e-mail, and in-person from October 2011–May 2012. Of those 54 interviewed, 20 fishermen sighted Humboldt squid between 2002–11 for a total of 173 positive occurrences. Fishermen's data ranged from recollection to detailed logbook records. Although some fishermen provided a specific latitude and longitude, a majority of the fishermen provided sightings based on depth and topography. Fisheries-dependent catch

TABLE 1
2002–11 Humboldt squid occurrence data from the Hake Acoustic, Predator, and SAIP Surveys, A-SHOP, and Fishermen sources.

Year	Number of Positive Occurrences from Hake Acoustic Survey	Number of Negative Occurrences from Hake Acoustic Survey	Number of Positive Occurrences from Predator Survey	Number of Negative Occurrences from Predator Survey	Number of Positive Occurrences from SAIP Survey	Number of Negative Occurrences from SAIP Survey	Number of Positive Occurrences from At-sea Hake Observer Program	Number of Negative Occurrences from At-sea Hake Observer Program	Number of Positive Occurrences from Fishermen
2002	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	9
2003	0	20	N/A	N/A	N/A	N/A	N/A	N/A	6
2004	N/A	N/A	0	106	12	41	N/A	N/A	9
2005	0	18	0	118	2	79	N/A	N/A	5
2006	N/A	N/A	1	94	9	40	11	497	9
2007	0	22	0	73	8	64	18	490	24
2008	N/A	N/A	0	59	1	67	30	482	26
2009	11	20	11	72	16	71	14	496	64
2010	N/A	N/A	0	11	0	54	22	507	15
2011	0	11	0	20	0	67	N/A	N/A	6
Total	11	91	12	553	48	483	95	2472	173

Positive occurrences (presence points) include one or more Humboldt squid. Negative occurrences (absence points) are equivalent to where sampling occurred but Humboldt squid were not encountered. The light gray box indicates data used in NPMR species distribution modeling. In 2009 there were the greatest number of Humboldt squid occurrences. No Humboldt squid were observed by the fishery-independent surveys in 2011.

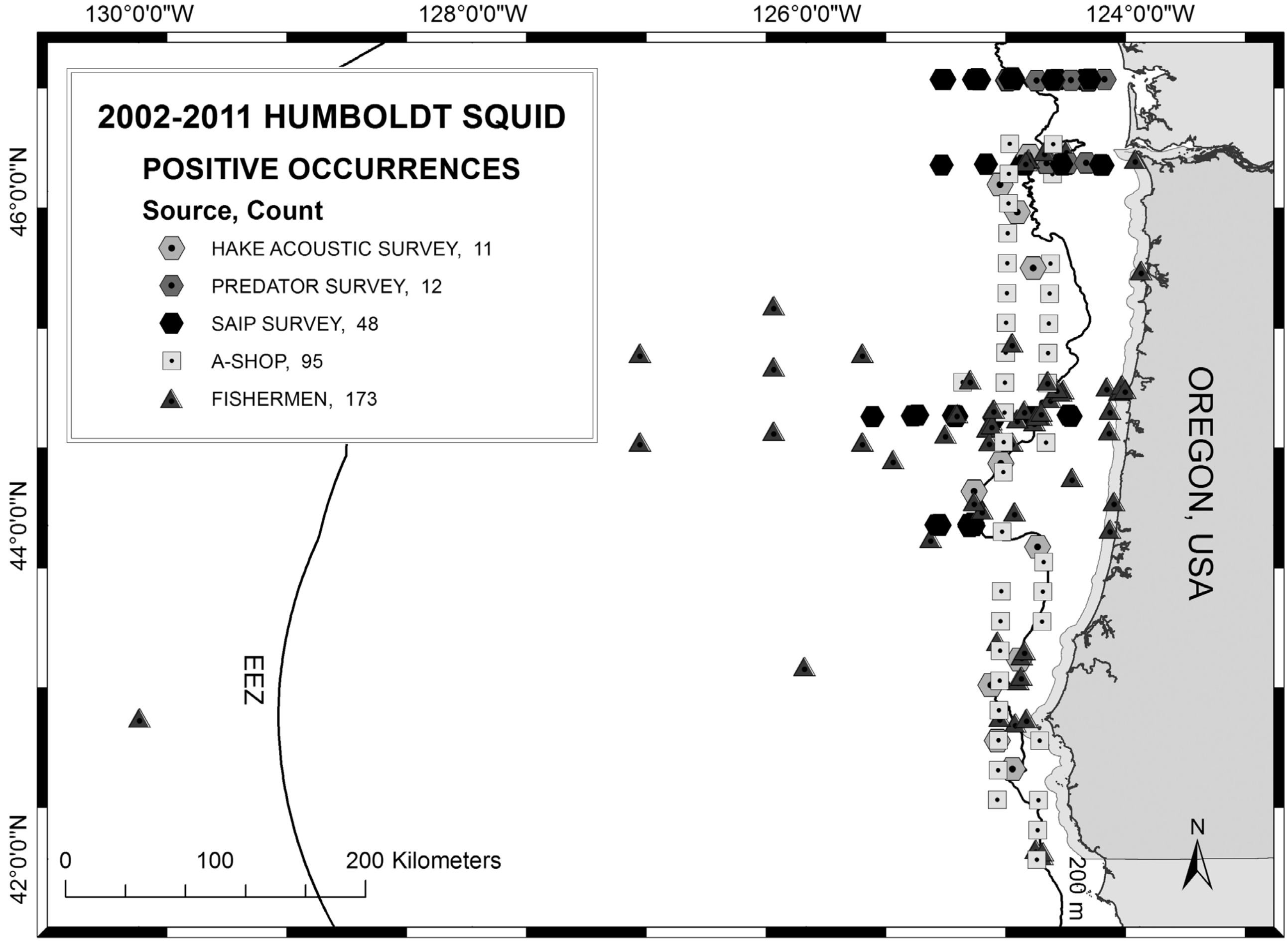

Figure 1. Study area extent with 2002–11 positive Humboldt squid occurrences from the Hake Acoustic Survey, Predator Survey, SAIP Survey, A-SHOP, and Fishermen. Negative occurrences are not illustrated. Positive occurrences shown include one or more Humboldt squid. For the NPMR modeling process, only survey and A-SHOP data were used.

TABLE 2
Descriptions of remote sensing and in situ oceanographic variables (SST, Chl *a*, SSH, DO at 30 m depth, and SSS).

Ocean condition	Type	Satellite	Resolution	Description	Acquired using	Source
SST (°C)	Moderate Resolution Imaging Spectroradiometer (MODIS)	Aqua	4 km/pixel	11µ Nighttime seasonal composite	Marine Geospatial Ecology Tools (MGET) in ArcGIS 10	oceancolor.gsfc.nasa.gov
Chl *a* (mg/m^3)	Moderate Resolution Imaging Spectroradiometer (MODIS)	Aqua	4 km/pixel	11µ Nighttime seasonal composite	Marine Geospatial Ecology Tools (MGET) in ArcGIS 10	oceancolor.gsfc.nasa.gov
SSH anomalies (m)	Composite satellite altimetry from archiving, validation, and interpretation of satellite oceanographic data (AVISO)	Jason 1&2/ MERIS ENVISAT	1/3° x 1/3° (approx. 28 km/pixel)	SSALTO/DUACS DT; global DT-REF merged MLSA SSH (gridded monthly)	Marine Geospatial Ecology Tools (MGET) in ArcGIS 10	aviso.oceanobs.com
DO at 30 m (ml/L)	in situ	N/A	in situ	Interpolated using inverse distance weighting in ArcMap 10.0 (Esri 2012); gridded to 28 km	N/A	http://www.nodc.noaa.gov and Childress (2010)
SSS (psu)	in situ	N/A	in situ	Interpolated using inverse distance weighting in ArcMap 10.0 (Esri 2012); gridded to 28 km	N/A	http://www.nodc.noaa.gov

data was provided by the NOAA NWFSC At-sea Hake Observer Program (A-SHOP) where there was a minimum of three vessels fishing and were provided gridded by 20 x 20 km cells. The A-SHOP recorded 95 positive Humboldt squid occurrences and 2,472 negative occurrences between 2006–10. NOAA NWFSC Joint U.S./Canada Pacific Hake Acoustic Survey Database (Hake Acoustic), and NOAA NMFS NWFSC (SAIP and Predator studies) provided fisheries-independent Humboldt squid data. The Hake Acoustic surveyed biannually from 2003–11 and documented 11 positive occurrences and 91 negative occurrences. The Predator and SAIP studies provided data from 2004–11 and observed 12 positive Humboldt squid occurrences and 553 negative occurrences, and 48 positive occurrences and 483 negative occurrences, respectively. This study utilizes the same Predator and SAIP studies data for 2004–09 from Litz et al. 2011 and unpublished data for 2010–11. The data sources with monthly information recorded positive Humboldt squid occurrences from June–December. However, A-SHOP and most fishermen data were provided on an annual scale. Due to restricted temporal resolution of the data, presence and absence records from all sources were grouped annually. The data were then standardized to the environmental predictor variable with the lowest resolution, 28 square km cells, for modeling.

Consistent with previous model results (Valavanis et al. 2004; Lefkaditou et al. 2008; Sanchez et al. 2008; Chen et al. 2010; Litz et al. 2011), we selected physical and chemical oceanographic parameters associated with Humboldt squid distribution (Nigmatullin et al. 2001; Brodeur et al. 2006; Gilly et al. 2006; Bograd et al. 2008; Keyl et al. 2008; Mejía-Rebollo et al. 2008; Bazzino et al. 2010; Rosa and Seibel 2010; Litz et al. 2011; Stewart et al. 2012). Annual average SST (°C), chl *a* (mg m^{-3}), mean sea level anomalies (MSLA) for sea surface height (SSH, m), 30 m dissolved oxygen (30 m DO, ml L^{-1}), and SSS (psu) were chosen as oceanographic predictor variables for 2002–11 (table 2). Temporal resolution of each environmental parameter was restricted by annual squid occurrence data. We assumed that any seasonal changes in the study area would be reflected in the overall mean annual response, because sample sizes restricted our ability to investigate relationships between squid occurrence and oceanographic variables on shorter time scales.

Satellite data for SST and ocean color and compiled satellite altimetry data for MSLA-SSH were acquired for analysis through Marine Geospatial Ecology Tools in ArcMap 10.0 (Esri 2012). To model the data across the study area, inverse distance weighting in ArcMap 10.0 (Esri 2012) was used to spatially interpolate continuous surfaces for annual mean values of 30 m DO and SSS based on annual point data obtained from NOAA's

National Ocean Data Center World Ocean Data Select database (www.nodc.noaa.gov) and Oregon Fishermen in Ocean Observing Research (Childress 2010). All analyses were performed using the interpolated surface for SSS and 30 m DO. The environmental predictor variables were averaged for all values within a 28 square km cell. Values for SST, chl *a*, SSH, 30 m DO, and SSS were extracted at each positive squid occurrence point. Kernel density plots were developed for exploratory analysis of the overall trend in spatio-temporal fluctuations of the density distribution of environmental conditions across the study area vs. the observed distribution of environmental conditions where Humboldt squid occurred from 2002–11. All density estimations were performed in R (R Development Core Team 2012) version 2.15.0.

Model Selection

To explore the relationship between Humboldt squid occurrence and the environment, oceanographic predictors of Humboldt squid likelihood of occurrence from the NOAA fisheries data were modeled using NPMR in HyperNiche (v2.11) software (McCune and Mefford 2004). NPMR was chosen because it enabled the consideration of multiple oceanographic predictor variables simultaneously and we assumed the response of Humboldt squid to the predictor variables would be complex, nonlinear, and would contain interactions between the predictor variables (McCune 2006). NPMR estimates probability of occurrence by modeling species response to environmental factors by multiplicatively combining all predictors (McCune 2006). Through a cross-validation process, the method uses a local model with a set of predictor variables (Yost 2008). The leave-one-out cross-validation applies local smoothing functions using kernel functions, estimating a target point by weighting nearby observations in the predictor space (McCune 2006).

We followed the binary modeling method from McCune 2011. For a mathematical interpretation of the NPMR model see McCune 2006, and for an additional detailed explanation of the modeling process see Yost 2008. Presence and absence information were only available from the fisheries-independent survey and fisheries-dependent observer program data; therefore, fishermen data could not be used in the model process. The data used in the model included 166 Humboldt squid positive occurrences (presence points) and 3,599 negative occurrences (absence points) from 2003–11 (table 1). Annual SST, chl *a*, SSH, 30 m DO, and SSS were used as environmental predictor variables for the model.

A local mean (LM) based on a Gaussian weighting function (LM-NPMR) was used as the local model to calculate probability of occurrence. Within the software, a model search was utilized to select a model with the most optimum combination of predictor variables, to choose the standard deviations used in the Gaussian smoothers for each predictor variable (tolerances), and to evaluate model performance (Yost 2008). Within the software settings, a moderate neighborhood size was selected with a 5% range in order to protect against overpredicting or estimating a response in a region without data. The model neighborhood size is the amount of data bearing on the response estimate at any particular point (McCune 2011). We used three evaluation statistics. For a binary response, the statistic used to evaluate model fit is the log likelihood ratio (logB), which provides a measure of optimization for model selection. LogB is the ratio of cross-validated estimates from a fitted model to estimates over a "naïve" model, or the species average frequency of occurrence (i.e., prevalence) in the data set (Schroeder et al. 2010; McCune 2011). Second, we evaluated model performance using the area under the receiver operator characteristic curve (AUC) (Hanley and McNeil 1982). An AUC represents the proportion of correctly predicted presences and absences. An AUC value greater than 0.5 indicates that the model discriminates better than chance. Third, we used the improvement %, or the ratio of cases with species probability estimates improved over the observed species prevalence (Schroeder et al. 2010).

Fitted response surfaces were created to illustrate the effect of interacting environmental conditions on the probability of Humboldt squid occurrence as well as the response curves for the model. Maps of the model prediction output for the year with the greatest positive occurrences in the survey and observer data, 2009, and the least positive occurrences, 2011, were created in ArcMap 10.0 (Esri 2012). Prediction maps were utilized to visually compare the predicted likelihood of Humboldt squid occurrence with overlaid observed positive occurrences made by fishermen, which were not included in the model.

RESULTS

Positive Occurrences and Observed Ocean Conditions

Positive Humboldt squid occurrences varied greatly across years 2002–11 (table 1). In the study area, Humboldt squid occurrences were greatest in 2009 with 116 positive occurrences, and virtually absent in 2011 with 6 positive occurrences. The majority of positive squid occurrences took place 124.4000°W to 125.0000°W in proximity to the shelf-break at the 200-m isobath (fig. 1). Kernel density plots of annual mean SST, chl *a*, SSH, 30 m DO, and SSS in the study area (environment) and at positive squid occurrence sites (observed) suggest that Humboldt squid have some affinity for particular environmental conditions (fig. 2). From 2002–11, Hum-

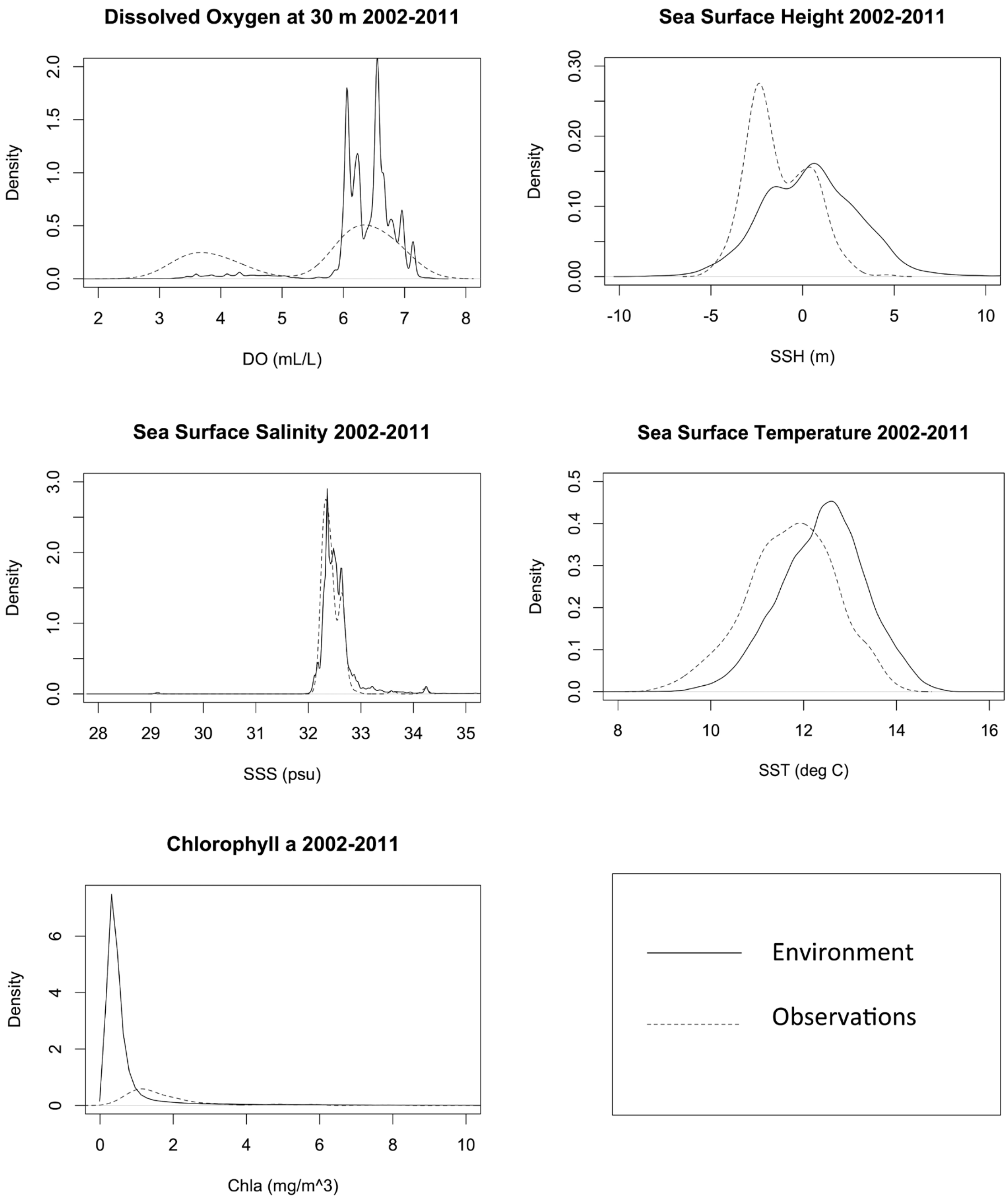

Figure 2. Kernel density plots for 30 m DO (ml L^{-1}), SSH (m) anomalies, SSS (psu), SST (°C), and chl *a* (mg m^{-3}) distributed across the study area (environment; solid) and at positive squid occurrences (observed, dashed) from 2002–11. Humboldt squid were more frequently observed at 3.0–4.5 ml L^{-1} and 6.0–7.0 ml L^{-1}, –4^{-1} m, 32.2–32.8 psu, 10.5°–13.0°C, and 0.26–3.00 mg m^{-3}.

boldt squid more frequently occurred over a SST range of 10.5°–13.0°C; average 11.7°C and sea level anomalies for SSH from –4.0–1.0 m; average –1.3 m. Positive squid occurrences were greatest at 0.26–3.00 mg m^{-3}; average 1.90 mg m^{-3} chl *a* concentrations. Squid response to DO at 30 m depth was variable with a bimodal response at 3.0–4.5 ml L^{-1} and 6.0–7.0 ml L^{-1}; average 5.5 ml L^{-1}. Humboldt squid most frequently occurred at a SSS range of 32.2–32.8 psu; average 32.5 psu.

Model Evaluation and Output

Alternative models from the model search process in NPMR are titled by number. LM-NPMR binary Model 960 was chosen as the best model for predicting the probability of Humboldt squid occurrence yielding a logB of 35.91, a cross-validated AUC of 0.810, and an improvement % of 76.1 % for the fisheries-independent and dependent presence/absence data (table 3). Based on the model results, the best predictors for Humboldt

TABLE 3
HyperNiche (V. 2.11) model evaluation for NPMR presence and absence model.

Binary LM-NPMR 960			
Average neighborhood size (N*)	**Minimum neighborhood size**		
178.7	1		
Input predictor	**Min**	**Max**	**Range**
chl *a* (mg/m^3)	0.24	19.79	19.55
SST (°C)	9.362	14.35	4.989
SSH (m)	–9.108	7.525	16.63
SSS (psu)	32	35.99	3.992
30 m DO (ml/L)	3.261	7.197	3.936
Model 960 predictor	**Tolerance**	**Tolerance %**	
chl *a* (mg/m^3)	0.977	5	
SST (°C)	0.748	15	
SSS (psu)	0.399	10	
30 m DO (ml/L)	0.394	10	
LogB	**Cross-validated AUC**	**Improvement %**	
35.91	0.81	76.1	

Hake Acoustic, Predator, SAIP surveys and the A-SHOP data from 2003–11 for 166 Humboldt squid presence points and 3,599 absence points were modeled using NPMR. LM-NPMR 960 was chosen as the most parsimonious model. Based on model results, annual average chl *a* (mg/m^3), SST (°C), SSS (psu), and 30 m DO (ml/L) are the best predictor variables for Humboldt squid likelihood of occurrence with a logB of 35.91, AUC of 0.810, and an improvement % of 76.1%.

squid likelihood of occurrence at 28 square km resolution were determined to be chl *a*, SST, SSS, and 30 m DO. Counter to previous research by Chen et al. 2010, our best fit model did not include SSH, suggesting that SSH anomalies are not a good indicator of squid presence. Fitted response surfaces are given in Figure 3 and the response curves in Figure 4. Geographic information system (GIS) probability maps of Humboldt squid likelihood of occurrence overlaid with observed fishermen sightings within the study area in the year 2009 and 2011 are given in Figure 5.

DISCUSSION

Response and Predictor Variables

Our results suggest that oceanographic conditions are linked to Humboldt squid occurrence in Oregon based on information compiled from fishermen, NOAA fisheries surveys, and observer program data. LM-NPMR model results indicate that 30 m DO is a viable explanatory variable for Humboldt squid likelihood of occurrence. Nutrient-rich bottom waters with low DO content are brought to the surface by upwelling events (Venegas et al. 2008). Humboldt squid are highly tolerant to low DO and unlike other squid, they are able to suppress metabolic activity in the OML and maintain

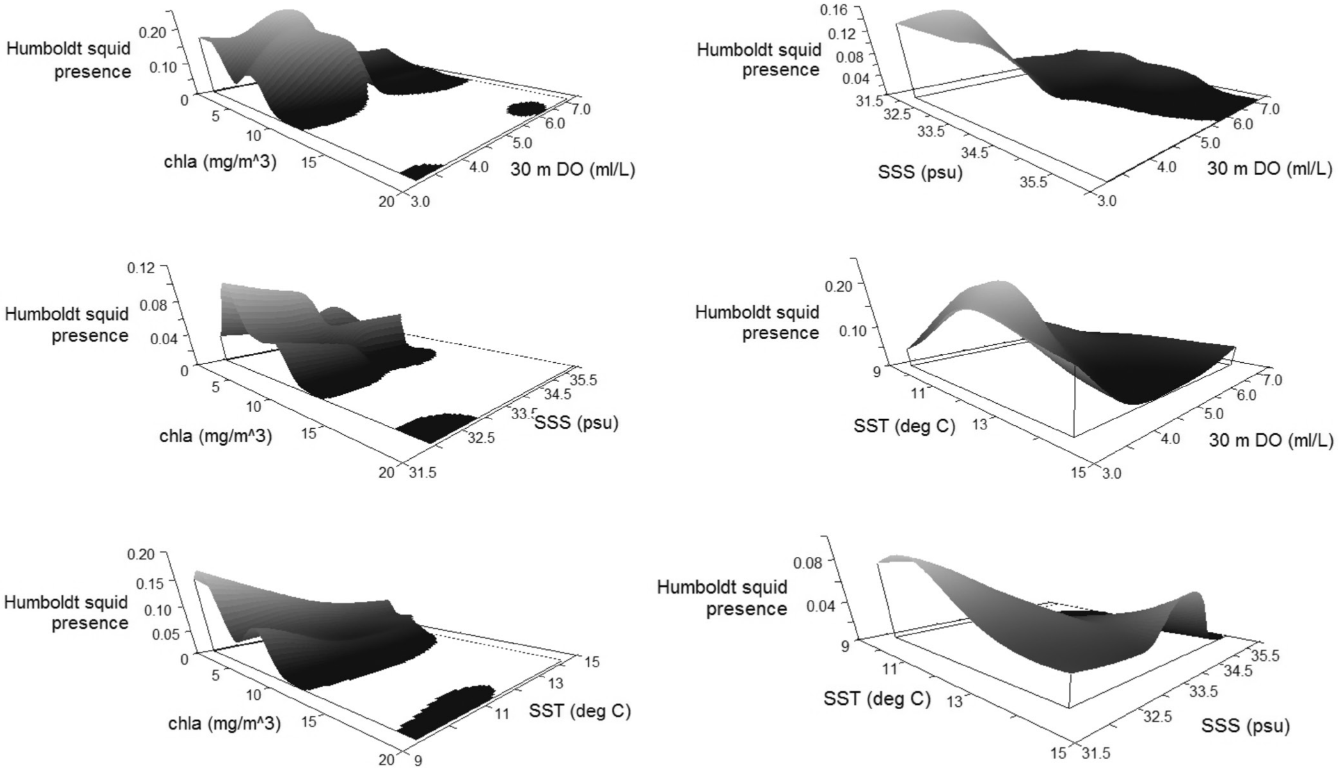

Figure 3. Three-dimensional projected response surfaces from LM-NPMR Model 960. Surfaces represent predictor variable interactions between chl *a* (mg m^{-3}), 30 m DO (ml L^{-1}), SSS (psu), and SST (°C) and the impact on positive Humboldt squid occurrence.

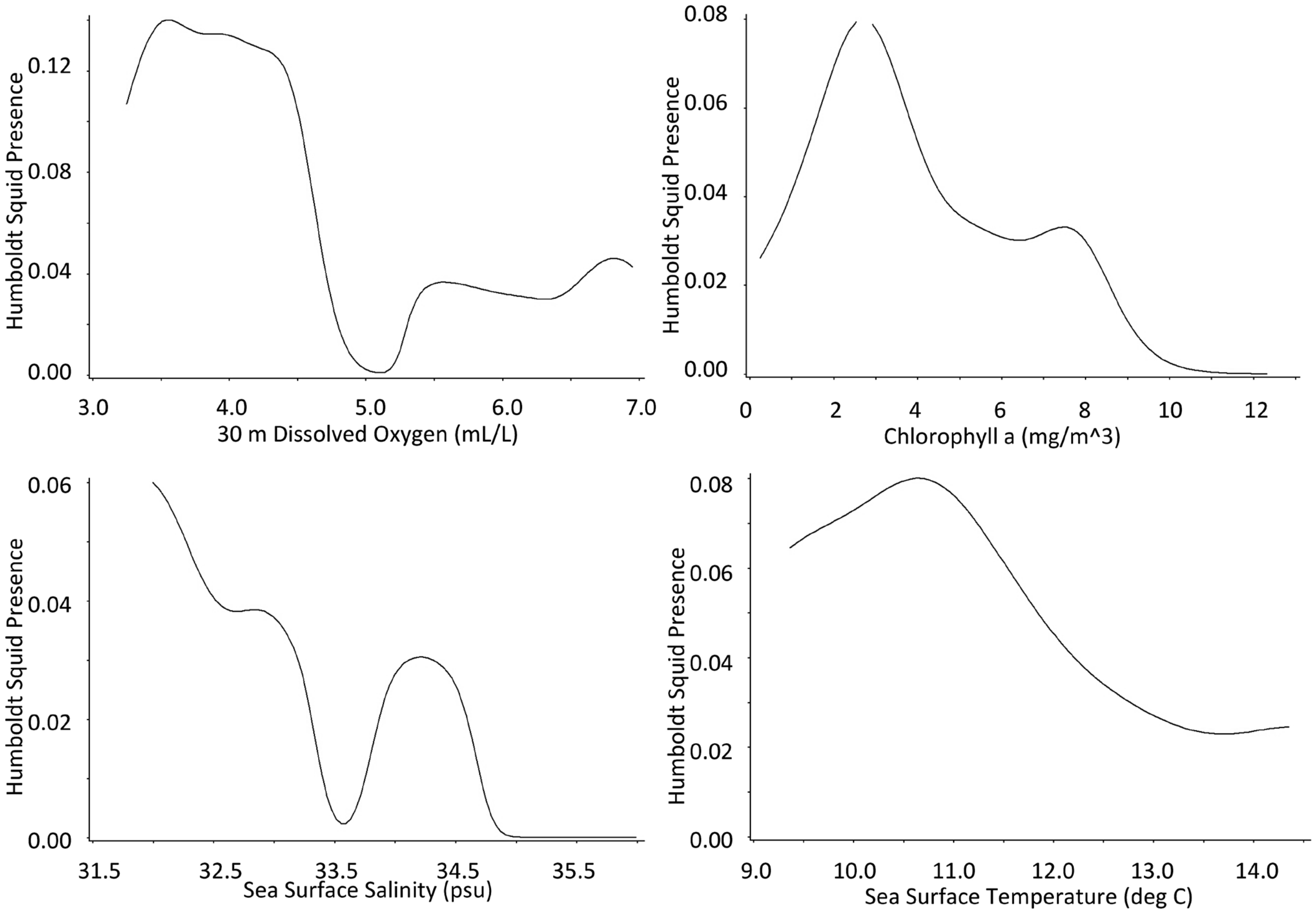

Figure 4. Predicted response to 30 m DO (ml L^{-1}), chl *a* (mg m^{-3}), SSS (psu), and SST (°C) by Humboldt squid derived from NPMR.

activity levels (Gilly et al. 2006). Humboldt squid display diel fluctuations greater than 250 m in vertical movement, where they are found to exploit the OML and avoid high surface temperatures during the day (Gilly et al. 2006; Bazzino et al. 2010; Rosa and Seibel 2010).

Shelf water DO concentrations have been decreasing and the OML has shoaled up to 90 m in the California Current (Bograd et al. 2008) and up to 100 m in the eastern subarctic Pacific (Whitney et al. 2007). Hypoxia has been observed off Oregon since 2002 (Chan et al. 2008) with an unprecedented occurrence of anoxia in the inner-shelf (<50 m) and expansion of hypoxia from the shelf to the inner shelf in 2006 (Chan et al. 2008). Litz et al. 2011 found that in 2009 Humboldt squid density was greatest in the hypoxic waters off of the Columbia River. A greater number of DO measurements are needed to create a robust interpolated surface for DO and further analysis of the effect of DO concentrations on Humboldt squid occurrence should be a research priority.

Our results suggest that SST and chl *a* content are additional predictor variables for Humboldt squid likelihood of occurrence. SST has been used as a significant predictor of squid habitat using a GIS (Valavanis et al. 2004), Maxent, and GAMs modeling approaches (Lefkaditou et al. 2008; Litz et al. 2011). Humboldt squid can tolerate wide temperature ranges (Bazzino et al. 2010, Staaf et al. 2011). Humboldt squid thermal plasticity is a key factor to their episodic range expansion (Field et al. 2012). Adult Humboldt squid have been reported to have a temperature threshold of 25°C in the laboratory with an average metabolic rate range between 10°–20°C (Rosa and Seibel 2010) and a daytime preferred temperature range of 10°–14°C at seawater depths greater than 10 m (Bazzino et al. 2010). Our results are consistent with previous research by Litz et al. 2011 for 20 m depth seawater temperature data through 2009 indicating an increase in positive Humboldt squid occurrence at 10.5°–13.0°C from 2002–11. Since these temperatures are too cold for Humboldt squid spawning, squid must migrate to spawn (Staaf et al. 2011) resulting in fluctuations in positive occurrences in the study area.

Our results were similar to previous habitat modeling approaches performed for short-fin squid using GIS

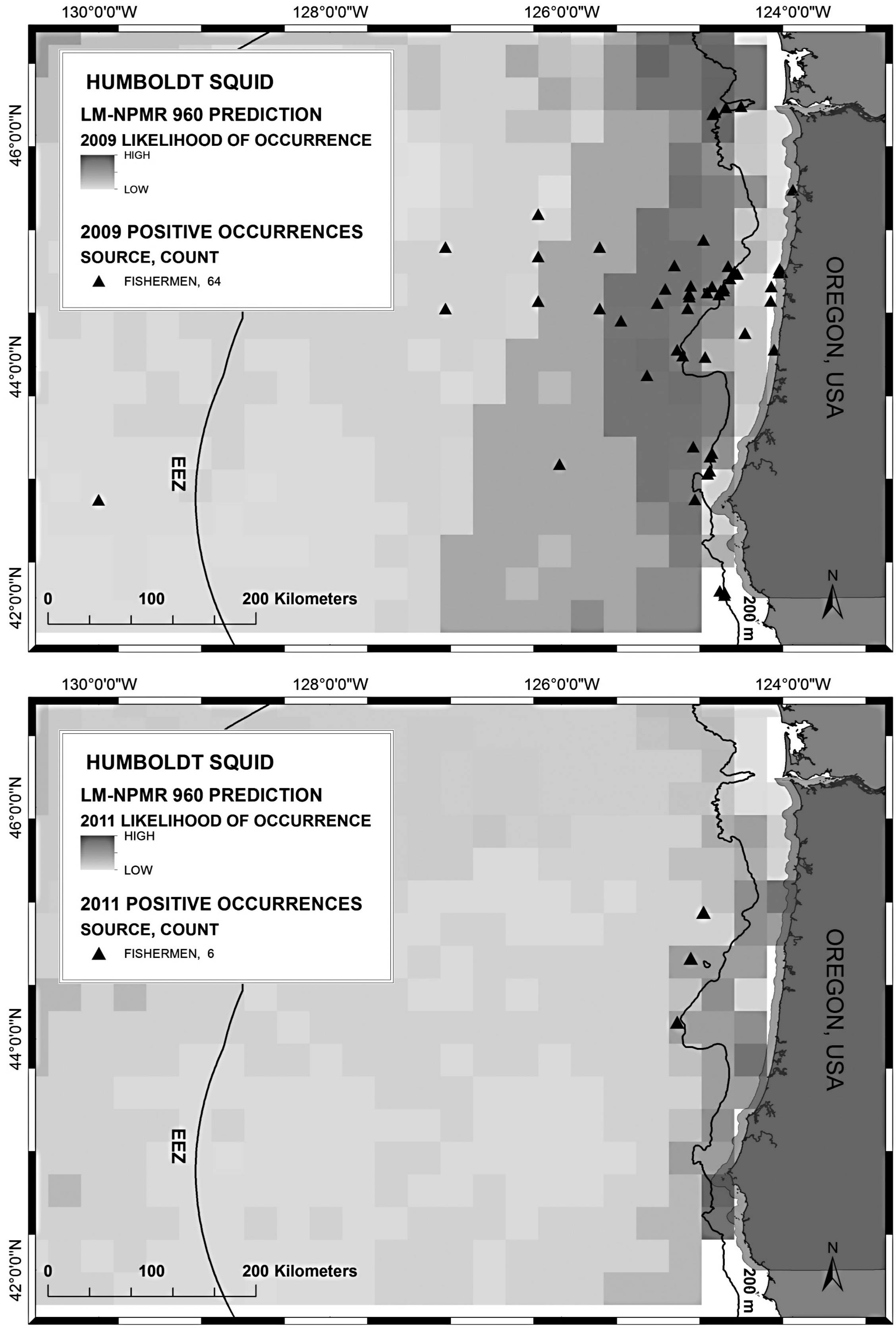

Figure 5. Maps of predicted likelihood of positive Humboldt squid occurrence in 2009 and 2011 overlaid with observed positive occurrences from fishermen not included in the NPMR model.

Essential Fish Habitat modeling (Valavanis et al. 2004), GAMs, and Maxent presence/absence survey data (Lefkaditou et al. 2008) in which chl *a* content was a main predictor of squid occurrence. Chl *a* content can be a proxy for productivity and DO content. We feel that the chl *a* signal could also be an indicator of their spatial distribution in relation to prey availability and fishing effort since most squid were observed around the shelf-break. Future analysis should include more detailed offshore sampling of Humboldt squid in order to evaluate the significance of chl *a* as a main-effect environmental predictor, taking seasonal fluctuations in this variable into account.

Higher SST (Schwing et al. 2002) and lower chl *a* (Chavez et al. 2002) can be found during El Niño events. Water temperature regime shifts caused by La Niña/El Niño events modify environmental conditions and food availability and therefore can potentially change Humboldt squid migration routes (Nigmatullin et al. 2001; Keyl et al. 2008; Mejía-Rebollo et al. 2008). Humboldt squid were first documented in Oregon during the strong El Niño in 1997–98 (Pearcy 2002). Although research has indicated that El Niño events may be one driver for Humboldt squid expansion, it is important to note that Humboldt squid were observed in both fishermen data and survey data during neutral ENSO years and La Niña years between 2002 and 2011. Zeidberg and Robison 2007 found that while El Niño driven expansions and a warm water affinity may have facilitated Humboldt squid presence in central California, these conditions do not dictate their distribution due to their physiological plasticity. Therefore, as a result of complex environmental interactions, considering the contribution of individual oceanographic variables in addition to long-term climatic processes may be more appropriate for establishing when Humboldt squid are most likely to occur off Oregon and southern Washington.

Model Limitations, Sources of Uncertainty, and Error

Numerous habitat modeling techniques are available and NPMR might not be the most suitable approach for a particular data set. NPMR is computationally expensive and is not optimal for extremely small datasets ($n < 10$ times the number of critical habitat factors) or presence only data. Furthermore, it is not suitable if the relationship between the response variable and predictor variables is linear, there is only one predictor variable, or the values of one predictor variable doesn't influence the response to other predictors (McCune 2011). Additionally, if the goal of the research is to predict the equilibrium range of a species, NPMR may underestimate the range of species undergoing expansion or overestimate a range of a species undergoing contraction by the inclusion of geographic variables (Reusser and Lee 2008).

In this study we overcame these limitations by having a sufficiently large data set in which our goal was to predict Humboldt squid occurrence within the proscribed study area extent. While this study was successful in mapping the distribution of Humboldt squid occurrence and the modeling matches expected outcomes, there were sources of uncertainty and error inherent in our data set. Potential sources of error include presence and absence records, interpolation of 30 m DO and SSS surfaces, and annual aggregation. False presence and absence records could have been present in the occurrence data from the observer program and fishermen. With the exception of sightings from two fishermen who targeted Humboldt squid in 2009, positive occurrence records were comprised of bycatch only information, making it difficult to distinguish false records. Although the fishermen data varied in degree of accuracy, the broad resolution that the occurrences were analyzed for did not affect the distribution mapping greatly and contributed to the analysis because it was less uniform and acted as test data for the HyperNiche LM-NPMR model.

Interpolation of SSS and 30 m DO surfaces from in situ measurements were established based on a varying number of measurement points per year. Less data for certain years resulted in spatial clustering, which decreases variability in areas with fewer measurements. This could have resulted in inaccuracies in the projected values. However, despite spatial clustering, relative changes in concentrations of DO at 30 m depth and SSS were captured in the interpolated surfaces because the in situ measurements spanned the study area extent.

Limitations in the temporal resolution of the A-SHOP and fishermen data resulted in the annual aggregation of all occurrences and oceanographic data. Humboldt squid are known to migrate seasonally along the California Current and make seasonal offshore-onshore movements (Field et al. 2012). Additionally, oceanographic conditions vary seasonally. Therefore, annual analysis could have reduced a potential signal of seasonal influences in Humboldt occurrence. However, positive squid occurrences varied highly across years and any seasonal changes in the environmental data, although smoothed, would still be reflected in the overall mean response.

CONCLUSION

This was the first use of NPMR to map Humboldt squid potential habitat in the study area, and based on our results, chl *a*, SST, SSS, and 30 m DO influence the likelihood of Humboldt squid occurrence. For our study purposes, HyperNiche LM-NPMR 960 appeared to be the most appropriate modeling approach to analyze the relationship between broad-scale oceanographic conditions and baseline Humboldt squid distribution. Visual interpretation of the estimated likelihood of occurrence map outputs for 2009 and 2011 show that predicted Humboldt squid occurrence is consistent with observations from fishermen.

Although examination of annual SSH, SST, chl *a*, 30 m DO, and SSS provided insight into the relationship between the environment and Humboldt squid occurrence, it is critical to consider the influence of prey availability in Humboldt squid migration. Additionally, we feel that it is necessary to evaluate Humboldt squid response to seasonal variability in the oceanographic conditions. Collecting more off-shelf data would be beneficial and provide for a more robust analysis. We recommend that future research include regional occurrences and analysis of SST, SSS, SSH, chl *a*, and DO at varying depths as well as bathymetry. We hope that our results contribute to better understanding Humboldt squid behavior and the impact of Humboldt squid migration in order to help direct future management efforts.

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COMPUTING AND SELECTING AGEING ERRORS TO INCLUDE IN STOCK ASSESSMENT MODELS OF PACIFIC SARDINE (*SARDINOPS SAGAX*)

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ABSTRACT

From 2007 to 2010, Pacific sardine stock assessments relied on traditional methods to compute and include ageing errors in the integrated assessment model, Stock Synthesis (SS). Traditional methods assumed that all age readers were unbiased and estimated ageing imprecisions by averaging across all fish that were assigned a given age *a* by one or more readers. In this study, we used the Ageing Error Matrix (Agemat) model to compute ageing imprecisions, based on classification matrices that quantified the probability of a fish of true age *a* to be assigned an age *a* or some other age *a*', *P*(*a*' | *a*). Using sardine samples collected from Mexico to Canada and aged in five laboratories, we compared three Agemat models, assuming that: (1) the most experienced reader from each laboratory was unbiased (model A); (2) no bias but different standard deviation (*SD*) at age among readers (model B); and (3) no bias, but similar standard deviation at age among readers (model C). We evaluated the performance of this model using the Akaike information criterion corrected for finite sample sizes. Sardine ages ranged from 0 to 8, with increasing reader *SD* with age. Model C performed better than models A and B, across all data sets and laboratories, and thus was recommended for including ageing imprecisions in sardine assessment models. However, the observed differences in *SD* across ages and readers called for a better standardization of ageing protocols among laboratories and for applying new methods to reduce potential bias in estimating the oldest age classes.

INTRODUCTION

Ageing errors can influence the process of estimating demographic parameters for fish populations, the performance of assessment models, and ultimately management measures derived from these analyses. Estimation of biological parameters, such as maturity-at-age, length-at-age, and weight-at-age may be biased in the presence of these errors. Fishing data such as catch-at-age and catch-per-unit effort indices may be affected as well. Further, in assessment models, these errors may smooth out estimates of recruitment and total allowable catch allocated to fisheries (Reeves 2003). Consequently, ageing errors can significantly mask important stock-recruit relationships and potentially the effects of environmental factors on year-class strength (Fournier and Archibald 1982; Richards et al. 1992).

New statistical models that can take account of both bias and precision in estimating ageing errors have been developed in recent years (e.g., Richards et al. 1992; Punt et al. 2008). These newer models can estimate the true age distribution of a population based on multiple age-readings of individual fish, particularly when fish were aged from a validated ageing method. In these models, age-reading errors are represented using classification matrices that quantify the probability of a fish of true age *a* to be assigned an age *a* or some other age *a*', *P*(*a*' | *a*). Parameters of various functions can be estimated from these models to determine the relationship between true age and estimated age. Because these statistical models are based on the maximum likelihood method, they allow for considerable flexibility in the relationship between true age and the expectation and imprecision of the estimated age (Richards et al. 1992; Punt et al. 2008). However, because all assessment models are not uniformly parameterized or structured, it can be difficult to select and include ageing errors in some models. For example, integrated assessment programs have been used to include ageing errors per reader in modeling fish stocks harvested off southern Australia (Punt et al. 2008), whereas Stock Synthesis (SS, Methot 2000) does not support data from multiple readers. In SS only one vector of ageing error can be input in the model. Thus, it is important to develop approaches to compute and include errors in SS models when multiple readers participate in the age production. To address this issue, we will use as a model species, the Pacific sardine (*Sardinops sagax*), a trans-boundary fish that is exploited from Mexico to Canada and whose age determination for stock assessment required the involvement of several readers within and across laboratories.

Since the 1990s Pacific sardine stocks have been assessed using age-structured models (Deriso et al. 1996;

Conser et al. 2004; Hill et al. 2007, 2009). Although many of these models could include age-reading errors, a systematic estimation of these errors has never been conducted for sardine samples collected from Mexico to Canada. Butler et al. 1996 used traditional methods (i.e., Beamish and Fournier 1981; Chang 1982) to assess age-reading imprecisions for fish collected during the 1994 Daily Egg Production Method (DEPM) survey, however these estimates could not be applied to age-data time series used in past assessment models. Hill et al. 2007, 2009 also used traditional methods to compute the mean standard deviation-at-age (*SDa*) for all readers that participated in a 2004 tri-national sardine ageing workshop (i.e., involving age readers from Mexico, the USA, and Canada). These estimates were included in the assessment models, although they represented a snapshot in time and did not account for differences in age estimation between fisheries or laboratories. Traditional methods generally focused on computing either precision (i.e., Beamish and Fournier 1981; Chang 1982) or bias (Campana et al. 1995; Morison et al. 1998), but not both. Therefore, these methods are not appropriate to develop age-reading error matrices for use in stock assessment models (Punt et al. 2008).

The otolith is the preferred hard part used to age Pacific sardines collected along the North American Pacific coast. A methodology for determining age of Pacific sardines from whole, un-sectioned otoliths was established by Yaremko 1996 and is currently used in ageing laboratories in Mexico, the USA and Canada. The Yaremko 1996 method summarized and integrated techniques developed during the historical sardine fishery in the 1940s and 1950s (Phillips 1948; Walford and Mosher 1950; Mosher and Eckles 1954), and during the recovery of the stock in the 1980s and 1990s (Butler 1987; Barnes and Forman 1994). McFarlane et al. 2010 proposed a preliminary method to age fish older than 1 year collected off British Columbia (BC), which consisted of polishing otoliths on their distal and proximal (sulcus) sides. Comparing their method to the otolith surface ageing of Yaremko 1996, McFarlane et al. 2010 found that the polished otolith method could improve the identification of the first and the second annuli. In addition, fish aged from the polished otolith method were found to be 1 to 3 years older than when aged from whole otoliths.

However, the polished otolith method is not currently being used for age production, because the approach needs further evaluation for sardine collected throughout their range. Although McFarlane et al. 2010 assessed potential bias in older fish relative to the Yaremko 1996 method, these comparisons were not based on known age fish or validated ages. Therefore, there were considerable uncertainties in the age differences detected by McFarlane et al. 2010 between the two approaches. Further, older clupeids are often the most difficult to age using a standard-zone counting method (Rogers and Ward 2007), as their otolith thickness increases and the marginal increments are narrower compared to younger fish. As most fish collected in BC are older than 2 years old, it is not known whether the polished method would produce significantly different ages from the whole otolith method if applied to younger fish caught off California and Mexico. Finally, because the assessment of the northern sardine stock relied on the ageing contribution from Mexico, Canada, and the USA, and given the preliminary nature of McFarlane et al. 2010 study, the Yaremko 1996 otolith ageing method remains the primary means used among all ageing laboratories.

The primary objective of this study was to estimate and compare age-reading errors for Pacific sardines that were collected from Mexico to Canada and that were aged in five different ageing laboratories: (1) The Centro Interdisciplinario de Ciencias Marinas (CICIMAR, Baja California Sur, Mexico); (2) the California Department of Fish and Wildlife (CDFW, CA, U.S.); (3) the Southwest Fisheries Science Center (SWFSC, CA, U.S.); (4) the Washington Department of Fish and Wildlife (WDFW, WA, U.S.); and (5) the Pacific Biological Station (PBS) of the Department of Fisheries and Ocean (DFO, BC, Canada). A second objective of this study was to develop a quantitative approach to select and include ageing error matrices in the sardine stock assessment models that use the SS framework (Hill et al. 2011). These objectives were based on recommendations from the Pacific sardine 2009 Stock Assessment Review Panel. This review panel required more systematic age-reading comparisons among Pacific sardine ageing laboratories and better estimation and integration of age-reading errors in future assessment models.

MATERIALS AND METHODS

Sample Collection

Pacific sardines were collected from the DEPM survey and from port sampling of commercial fishery landings from Mexico to Canada. DEPM samples were collected during the 2004–11 April surveys from San Diego to San Francisco (CA). Port sampling data were collected using various designs (Hill et al. 2009) but were assumed to be representative of four major fisheries: the Mexican fishery, from Ensenada to Magdalena Bay (Mex, Mexico); the California fishery (CA, including the southern and central California fisheries); the Pacific Northwest fishery (PNW, including Oregon, Washington), and the British Columbia (BC, Canada) fishery. The DEPM survey and the port samplings are respectively detailed in Lo et al. 2005 and Hill et al. 2009.

Otolith age-reading

Pacific sardines were aged from unpolished whole otolith pairs by readers located at five ageing laboratories: CICIMAR, CDFW, SWFSC, WDFW, and PBS. All laboratories used the conventional technique of otolith age-reading described in Yaremko 1996, although with slight variations. The method is straightforward and generally recommends that: (1) the age reader immerses the otolith in distilled water for about three minutes; and (2) the age reader counts the number of annuli observed on the distal side of the otolith using a light microscope. An annulus is defined as the interface between an inner translucent growth increment and the successive outer opaque growth increment (Fitch 1951; Yaremko 1996). The method assumed a July 1 birth date for all individual fish hatched in U.S. waters within a calendar year. Although the spawning peak is typically in April, Pacific sardines continue to spawn throughout the summer months. The July 1 birth date assumption coincides with the recruitment of age-0 fish into the USA fishery, and thus this birth date accounts for fish born off California in the spring and off Oregon and Washington in summer. Age assignment by readers is based on the capture date and the interpretation of the most distal pair of growth increments:

1. Fish caught in the first semester of a calendar year have not yet reached their July 1 birth date; therefore their most distal pair of opaque and translucent increments should not be counted, even if exhibiting the early beginning of a second opaque increment (Yaremko 1996).
2. Fish caught in the second semester of a calendar year have completed a year since their last birth date; therefore their age is equal to the number of annuli counted in their otolith.
3. The marginal increment is categorized as opaque or translucent, wide or narrow, allowing a confidence rating to be assigned to the age determination.

Since the 1990s, all five ageing laboratories have used this method for Pacific sardine collected along the Pacific coast. The CDFW and SWFSC laboratories strictly followed the procedures outlined by Yaremko 1996, thus all otoliths were submerged in distilled water and observed using reflected light on a black background at the 24X resolution. However, the WDFW ageing protocol slightly modified the method, by immersing the otoliths in full-strength alcohol. Fish caught in the Pacific Northwest are generally older than those caught in California, and it appears that alcohol may enhance the readability of their otoliths under the 24X resolution. At the CICIMAR ageing laboratory, the method was modified by fixing whole otoliths on glass slides (sulcus side down) using the synthetic resin Cytoseal, and by counting the inner annual increments at 16X resolution and the marginal increments at the 40X resolution. Note that the recommended 24X resolution was not selected because the light microscopes that are currently used at CICIMAR provided only 2 options, the 16X and the 40X resolutions. Further, at the CICIMAR laboratory, no birth date was assumed because of a long protracted spawning season (i.e., November to April) followed by a minor season that peaks in July off the coast of Bahia Magdalena. Thus the ages reported from fish collected in Magdalena Bay were similar to the number of annuli counted in otoliths. Finally, the PBS ageing laboratory followed the method of Yaremko 1996, but assumed a January birth date for all fish collected off British Columbia. Otoliths were submerged in distilled water and observed with a dissecting scope up to a maximum magnification of 50X, using reflected light against a dark background. Magnification and brightness were adjusted as necessary to clarify annuli and determine the presence of check marks. As for the CDFW, SWFSC, and WDFW ageing laboratories, ages reported by the PBS readers accounted for both capture and birth dates.

Age-reading data

Age-reading data from each fishery and survey were organized in data sets, which were defined as sets of otoliths that were aged by the same group of readers. A total of 10 data sets were used in this study, with total sample sizes (*N*) varying from 145 to 959 otoliths (table 1). In each data set, fish that were assigned a similar age combination among readers were grouped, and the absolute frequency of observed samples (*n*) for each unique age combination was computed. Each one of these unique age combinations among readers was input in the model as one observation associated with its absolute frequency (*n*). Thirteen age readers participated in this study, and each reader was provided with a unique identification number (*ID*). The number of readers per data set is presented in Table 1. All readers participating in this study were certified by their respective laboratory, but with varying degree of experience.

For the Mexican fishery, sardines were collected in Magdalena Bay during the 2005 fishing season. All fish collected in this bay were aged by a single reader (reader 13) at the CICIMAR ageing laboratory. Otoliths were first read in December 2006 and then re-read in June 2011.

In the California fishery, sardine samples were collected from port landings in southern California (San Pedro to Santa Barbara) and central California (Monterey Bay region) from 2005 to 2011. Depending on the year of collection, three to five CDFW readers participated in the age estimation process (table 1). Data sets were built based on time of collection (one to two years)

TABLE 1
Number of Pacific sardine otoliths (*N*) and age-readings (*R*) per otolith, data set, laboratory, and for each fishery or survey.

Ageing Laboratory	Fishery/Survey	Data set	Collection Year	Reader ID	*R*	*N*
CICIMAR	Mex	1	2005	13	2	240
		2	2005	1,2,3	3	219
		3	2007	2,4,5,6	4	148
CDFW	CA	4	2008–2009	2,4,5,6,7	5	507
		5	2008–2009	2,5,6,7	4	145
		6	2010–2011	2,5,6	3	266
WDFG	PNW	7	2009	8,9	2	711
PBS	BC	8	2007	10,11	3	283
CDFW-SWFSC	DEPM	9	2004, 2006	1,12	2	360
		10	2005–2011	2,12	2	959

using only completely reported age-reading combinations (i.e., observations containing one or more missing values were discarded). For the 2008–09 period, two different data sets (4 and 5) were used in the modeling process, to account for turnover among readers.

In the PNW, sardine samples were collected off Oregon during the summer of 2009. All otoliths were aged by readers 8 and 9 from the WDFW (table 1) in March and April of 2010. In model A, reader 8 was most experienced and was assumed to be unbiased.

British Columbia fishery samples were collected from July to September of 2007. Whole otoliths from BC were first aged separately by readers 10 and 11 (table 1). Then, each otolith was re-aged simultaneously by both readers to estimate a best, resolved age (*RA*). Taking into account this ageing protocol, we assumed that the resolved age was more likely to be unbiased.

Sardine samples from DEPM cruises were collected during the spring season from 2004 to 2011. Age determinations were done by readers 1 and 2 from CDFW and reader 12 from the SWFSC. There were no overlapping age-readings between readers 1 and 2; therefore, two different data sets were built for the DEPM survey (table 1).

Ageing error estimation

We used the Ageing Error Matrix (Agemat) model developed by Punt et al. 2008 to estimate age-reading error matrices by reader. The model computed ageing-error matrices based on otoliths that had been aged multiple times by one or more readers, while assuming that: (1) ageing bias depends on reader and the true age of a fish; (2) the age-reading error standard deviation depends on reader and true age; and (3) age-reading error is normally distributed around the expected age. Hence, the probability to assign an age *a*' to a fish of true age *a* was computed following Equation 1:

$$P^i(a'\,|\,a,\phi) = \int_{a'}^{a'+1} \frac{1}{\sqrt{2\pi}\sigma_a^i(\phi)} \exp\left[\frac{-(a'-b_a^i(\phi))^2}{2(\sigma_a^i(\phi))^2}\right] da', \quad (1)$$

where b_a^i is the expected age when reader *i* determines the age of a fish of true age *a*, σ_a^i is the standard deviation for reader *i* and for fish whose true age is *a*, and ϕ is the vector of parameters that determines the age-reading error matrices. The values for these parameters were estimated by maximizing the following likelihood function, assuming there was some set of *J* otoliths that was read by all readers:

$$L(A\,|\,\beta,\phi)=\Pi_{j=i}^{J}\,\Sigma_{a=L}^{H}\beta_a=\Pi_{i=1}^{I}\,P^i(a_{i,j}\,|\,a,\phi) \quad (2)$$

where $a_{i,j}$ is the age assigned by reader *i* to the j^{th} otolith; *L* and *H* are respectively the minimum and the maximum ages, and *A* is the entire data set of age-readings. The βs are nuisance parameters that can be interpreted as the relative frequency of fish of true age *a* in the sample.

For the purpose of this study we were mostly interested in estimating the *SD*s for the different fisheries and the DEPM survey. We defined three model scenarios, based on different assumptions about *SD*s among readers: (1) model A assumed that age-readings from the most experienced reader for one or two data sets were unbiased, and accordingly *SD*s for all readers were estimated based on this assumption; (2) model B assumed no bias in estimated ages for all readers, but *SD*s were different among readers; (3) model C assumed no bias in estimated ages for all readers, but the readers had similar *SD*s. Firstly, we compared the fit of each model to the age-reading data graphically, by plotting the predicted frequency (*n*) for a given age combination among readers versus the observed frequency for each model by data set. Secondly, we used the Akaike information criterion with a correction for finite sample sizes (*AICc*) to compare the fits among the three models and ultimately to select the best model, determining whether there was enough evidence to support the assumption of equality of *SD*s among readers for the data sets considered in a given model. Note that model C was the only model that could be used in the current SS version, i.e., 3. The validity of using this model was tested against models A and B that are commonly used to introduce errors in assessment models.

We assumed that the functional form of random ageing error precisions followed either Eq. 3 or 4.

$$\sigma_a = \sigma_L + (\sigma_H - \sigma_L)\,\frac{1-\exp(-\delta(a-1))}{1-\exp(-\delta(a_{max}-1))} \tag{3}$$

where, σ_L and σ_H are respectively the standard deviation of the minimum and the maximum age in a given data set, and δ is a parameter that determines the extent of linearity between age and the age-reading standard deviation.

$$CV_a = CV_L + (CV_H - CV_L)\,\frac{1-\exp(-\delta(a-1))}{1-\exp(-\delta(a_{max}-1))} \tag{4}$$

where CV_L and CV_H are respectively the coefficient of variation of the minimum and the maximum age in a given data set (Richards et al. 1992; Punt et al. 2008).

For the DEPM survey, the PNW and BC fisheries all three models were used. In these cases, the most experienced readers (DEPM and PNW) and the resolved ages (BC) were assumed to be unbiased in model A, whereas the functional form for ageing bias for all other readers was assumed to follow Equation 5:

$$E_a = E_L + (E_H - E_L)\,\frac{1-\exp(-\beta(a-1))}{1-\exp(-\beta(a_{max}-1))} \tag{5}$$

where E_a is the expected age of a fish of age a; E_L and E_H are respectively the minimum and the maximum ages in a given data set; a_{max} is a pre-specified maximum age; and β is a parameter that determines the extent of linearity between age and the expected age.

For all model runs, the maximum expected age for sardines was set to be 15, based on current maximum age used in assessment models (Hill et al. 2011). Based on length frequencies, scale, and otolith ageing analyses, previous authors have reported that Pacific sardine can live longer than 12 years, thus by convention age 15 was established to be the maximum of the probable 11–15 age group (e.g., Marr 1960; Wolf 1961; Murphy 1967). Further, the maximum *SD* allowed in model runs was 100. Very high *SD*s such as 100 would result from insufficient observed samples combined with inexperience in ageing older fish. This occurred once in model B for readers 2 and 7 and for the 2008–09 CA samples and in model A for reader 9 for the 2009 PNW samples. In these cases, *SD* was not plotted for these readers. Finally, to better describe the variability of the age-reading data, we conducted pairwise comparisons of age combinations among readers for each data set, by establishing 4 levels of agreement in age assignment between pair of readers: (1) low, <65%; moderate, 65% to 74%; high 75% to 84%; and very high, ≥ 85%.

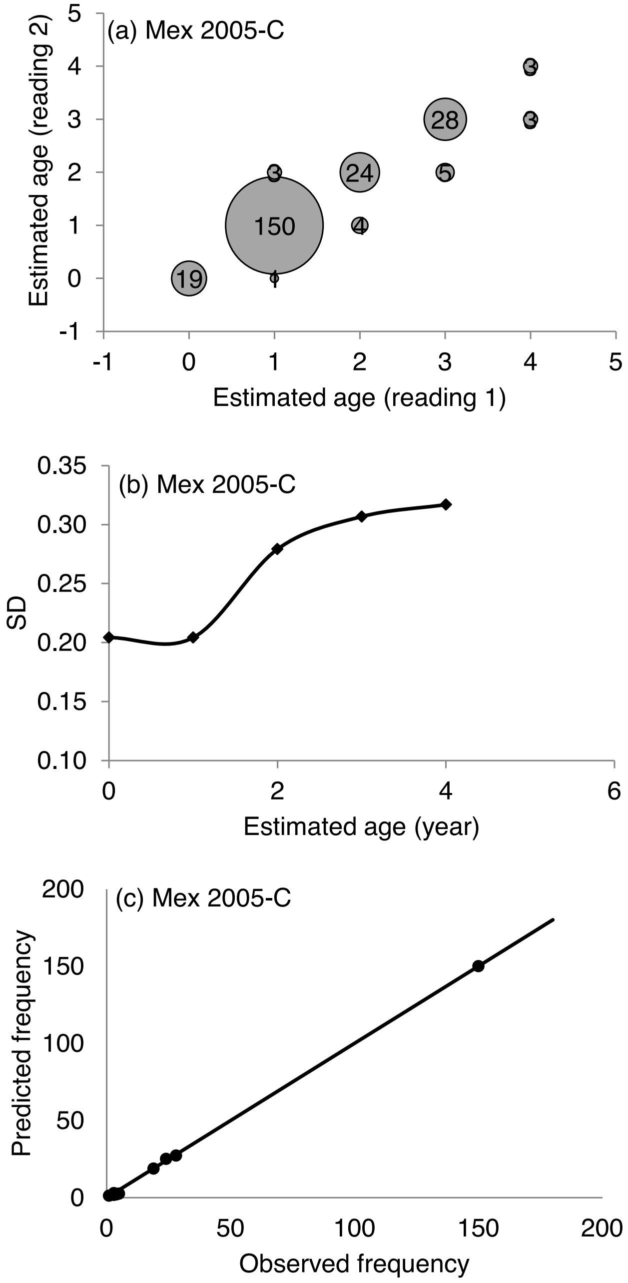

Figure 1. Age and standard deviation estimated for fish collected in Magdalena Bay, Mexico in 2005: (a) agreement plot for pairwise comparison of ages estimated by 1 CICIMAR reader from 2 readings. Number and bubble size represent the frequency of observed age combinations; (b) Standard deviation (*SD*) estimated from model C; and (c) diagnostic plot for the fit of model C to the data.

RESULTS

Because both age readings for the Mexican fishery were performed by one reader, no ageing bias was assumed. Agreement between the two readings was very high from age 0 to age age 3 (≥ 85%), but low for age 4 (50%) (fig. 1a). As expected, *SD* increased with age, varying from 0.20 at age 0 to 0.30 at age 4 (fig. 1b). Compared to other laboratories, *SD*s estimated in Mexico

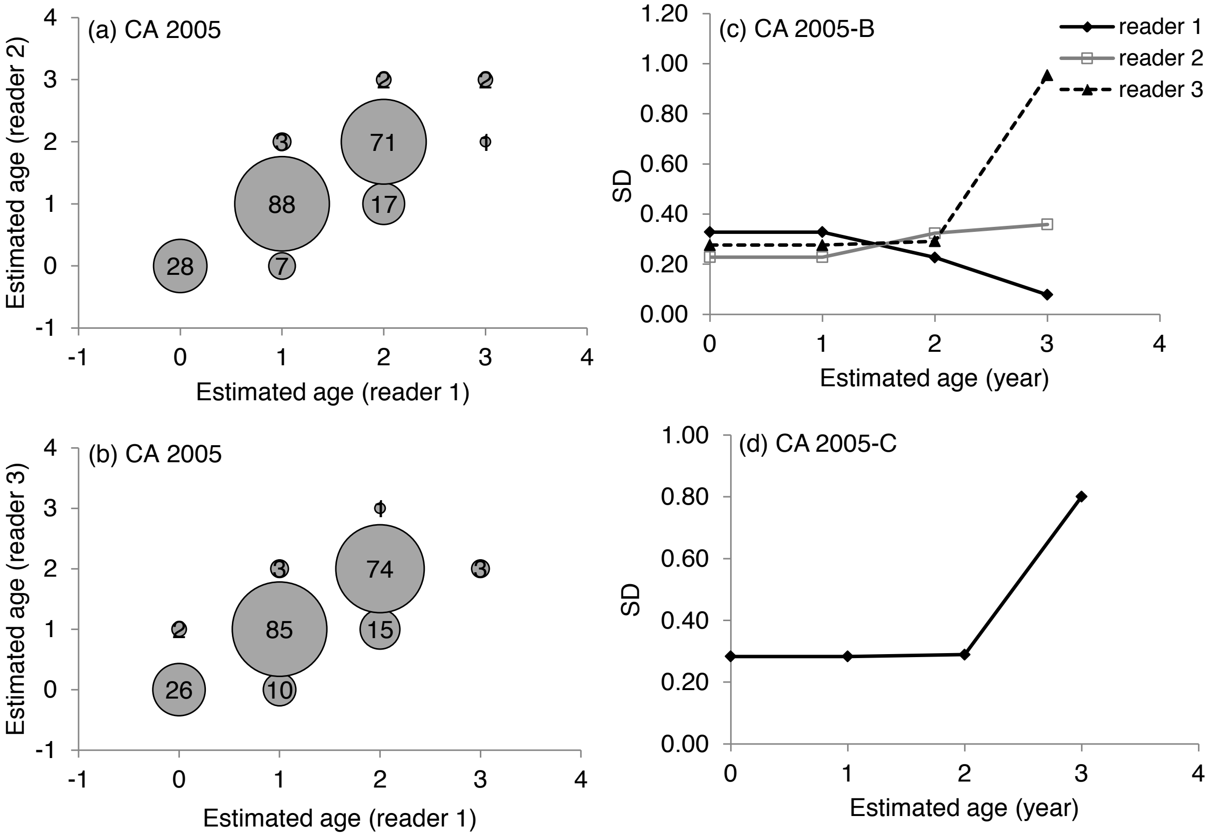

Figure 2. Age and standard deviation estimated for fish collected off California in 2005: (a–b) agreement plots for pairwise comparison of ages estimated by readers 1, 2, and 3. Number and bubble size represent the frequency of observed age combinations; (c) Standard deviation (*SD*) estimated from model B; and (d) *SD* estimated from model C.

TABLE 2

Comparison of models A, B, and C per fishery or per survey and by collection year, based on the Akaike information criterion corrected for finite sample sizes (*AICc*). *Eff N* is the effective sample size input or estimated by each model, and *p* is the number of parameters estimated from each model.

Fishery/ Survey	Model	Estimation	Bias Data set	*N*	Input *Eff N*	Model *Eff N*	*Eff N* Ratio	Total Likelihood	*p*	*AICc*
ENS	B	No	1	240	240	1333.71	5.56	322.78		
	B	No	2	219	219	299.16	1.37	416.50	13	15.71
	C	No	2	219	219	253.68	1.16	423.87	7	2.43
	B	No	3	148	148	235.32	1.59	315.99	17	27.20
	C	No	3	148	148	76.79	0.52	337.98	8	5.39
CA	B	No	4	507	100	69.50	0.69	862.47	27	49.27
			5	145	100	22.11	0.22			
	C	No	4	507	100	75.32	0.75	855.52	15	19.11
			5	145	100	25.02	0.25			
	B	No	6	266	160	159.21	1.00	342.14	15	21.66
	C	No	6	266	160	146.29	0.91	346.32	9	7.51
PNW	A	Yes	7	711	700	2992.13	4.27	1476.56	16	18.20
	B	No	7	711	700	254.03	0.36	1494.12	13	11.91
	C	No	7	711	700	206.54	0.30	1502.38	10	5.69
BC	A	Yes	8	283	260	221.32	0.85	798.38	21	32.52
	B	No	8	283	260	47.64	0.18	878.85	15	18.41
	C	No	8	283	260	69.21	0.27	839.69	9	5.25
DEPM	A	Yes	9	360	70	69.85	1.00	2464.35	28	42.31
			10	959	800	801.89	1.00			
	B	No	9	360	70	63.51	0.91	2666.45	22	29.42
			10	959	800	25.34	0.03			
	C	No	9	360	70	70.70	1.01	2782.58	16	16.78
			10	959	800	17.88	0.02			

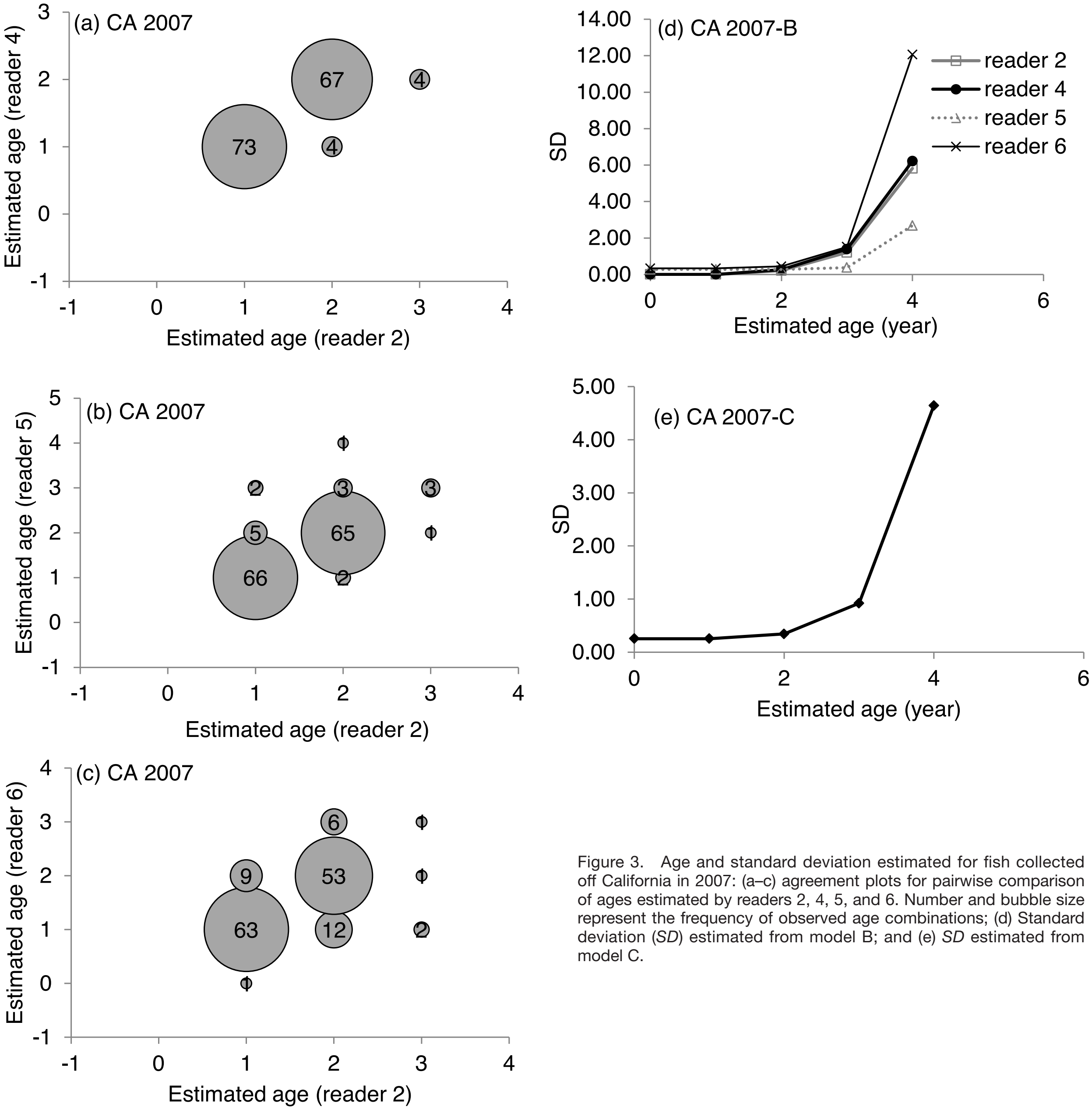

Figure 3. Age and standard deviation estimated for fish collected off California in 2007: (a–c) agreement plots for pairwise comparison of ages estimated by readers 2, 4, 5, and 6. Number and bubble size represent the frequency of observed age combinations; (d) Standard deviation (*SD*) estimated from model B; and (e) *SD* estimated from model C.

were generally smaller for ages 3 and 4. The goodness of fit of model C to the age-reading data is shown in Figure 1c, which plots the observed frequency of each age combination between the two readings in Figure 1a (e.g., 150 fish were assigned age 1 by both readings, whereas 5 were assigned age 3 at the first reading, but age 2 at the second) against the frequency predicted by the Agemat model. These data showed no evidence of over-dispersion, because most of the points lay on the 1:1 line plot (fig. 1c). Thus, we concluded that the fit of model C to the Mexican age-reading data was adequate. Note that for simplifying the presentation of the results, the diagnostic plots will not be shown for the other age-reading data sets, although the quality of model fits to these data will be reported below.

Age-reading imprecisions were estimated for the CA fishery by reader and period of sample collection (table 2). In the 2005 and 2007 periods, there was very high agreement (≥ 85%) between readers in assigning ages 0, 1, and 2 to sardine samples, leading to similar *SD*s among readers from age 0 to age 2 (figs. 2, 3). However, agreement varied from low to very high among readers in estimating age 3, resulting in considerable variability in the *SD*s at that age (figs. 2, 3). For the 2008–09 period, readers 4 and 7 highly agreed with reader 2 in assigning age 0 (92%), moderately in assigning age 1

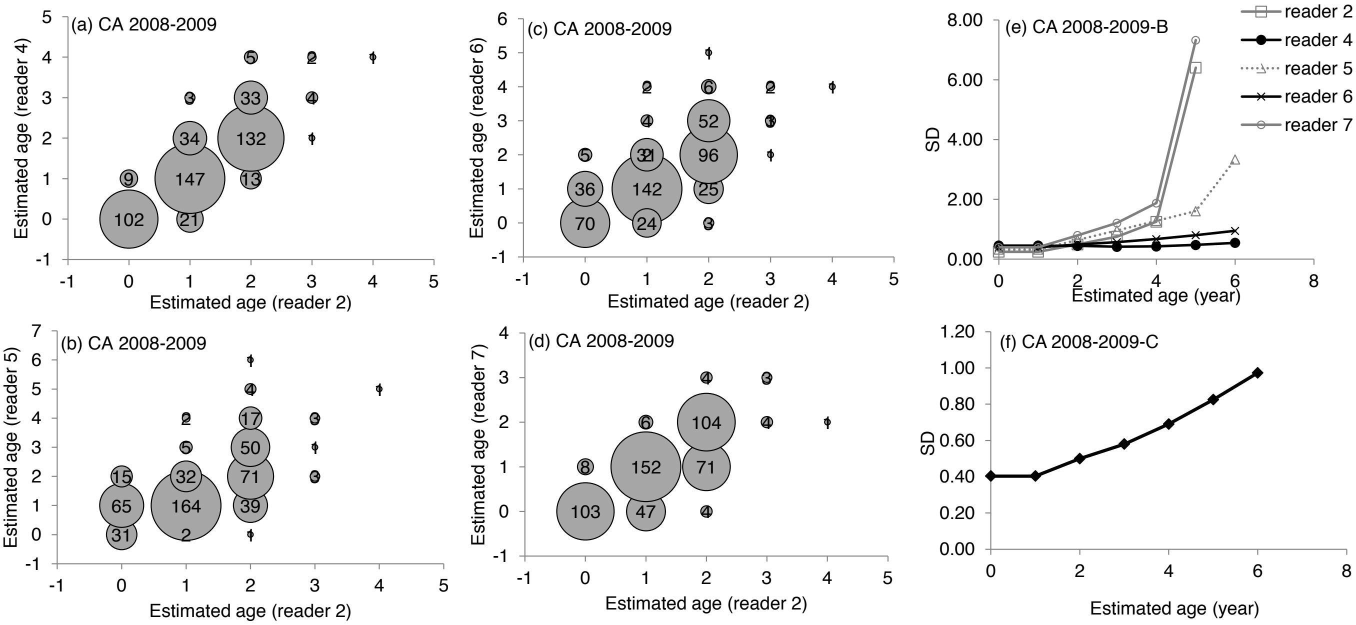

Figure 4. Age and standard deviation estimated for fish collected off California in 2008–09: (a–d) agreement plots for pairwise comparison of ages estimated by readers 2, 4, 5, 6, and 7. Number and bubble size represent the frequency of observed age combinations; (e) Standard deviation (*SD*) estimated from model B; and (f) *SD* estimated from model C.

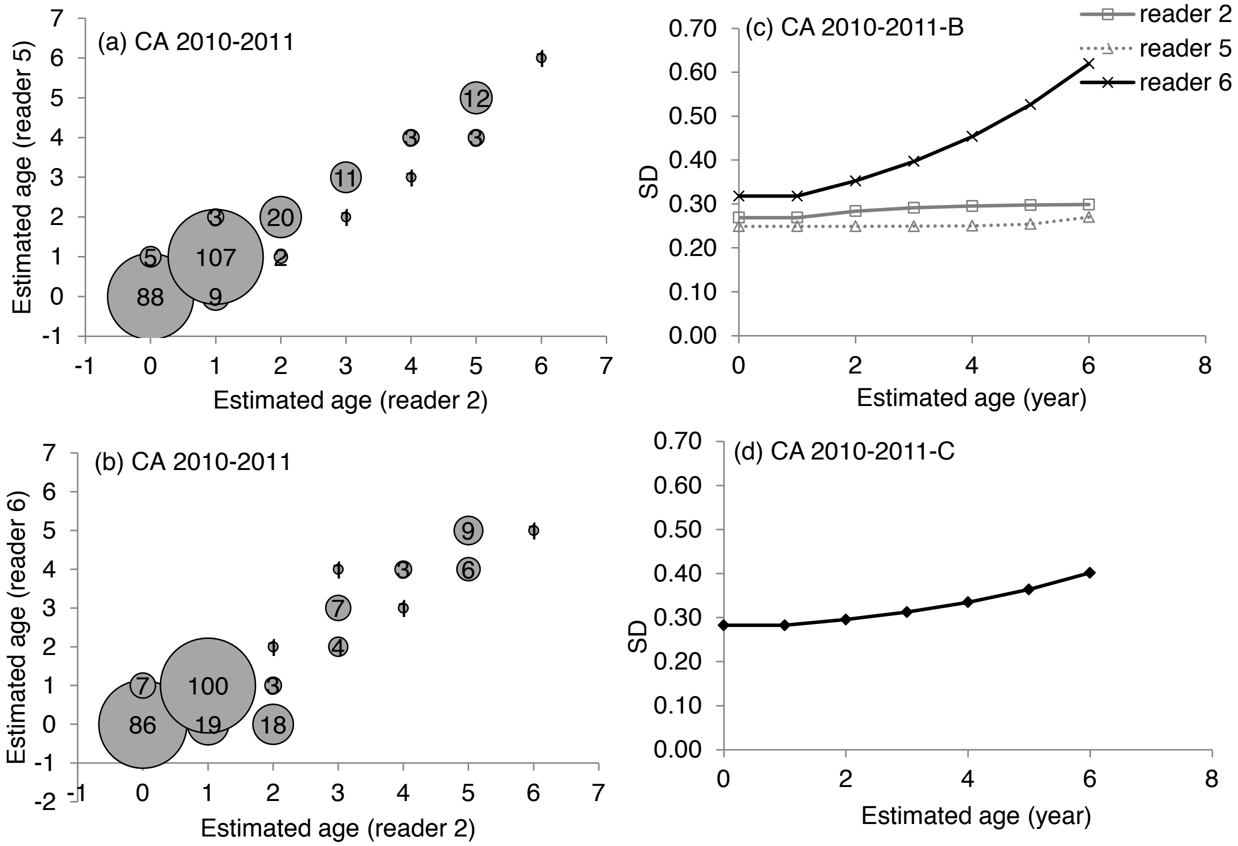

Figure 5. Age and standard deviation estimated for fish collected off California in 2010–11: (a–b) agreement plots for pairwise comparison of ages estimated by readers 2, 5, and 6. Number and bubble size represent the frequency of observed age combinations; (c) Standard deviation (*SD*) estimated from model B; and (d) *SD* estimated from model C.

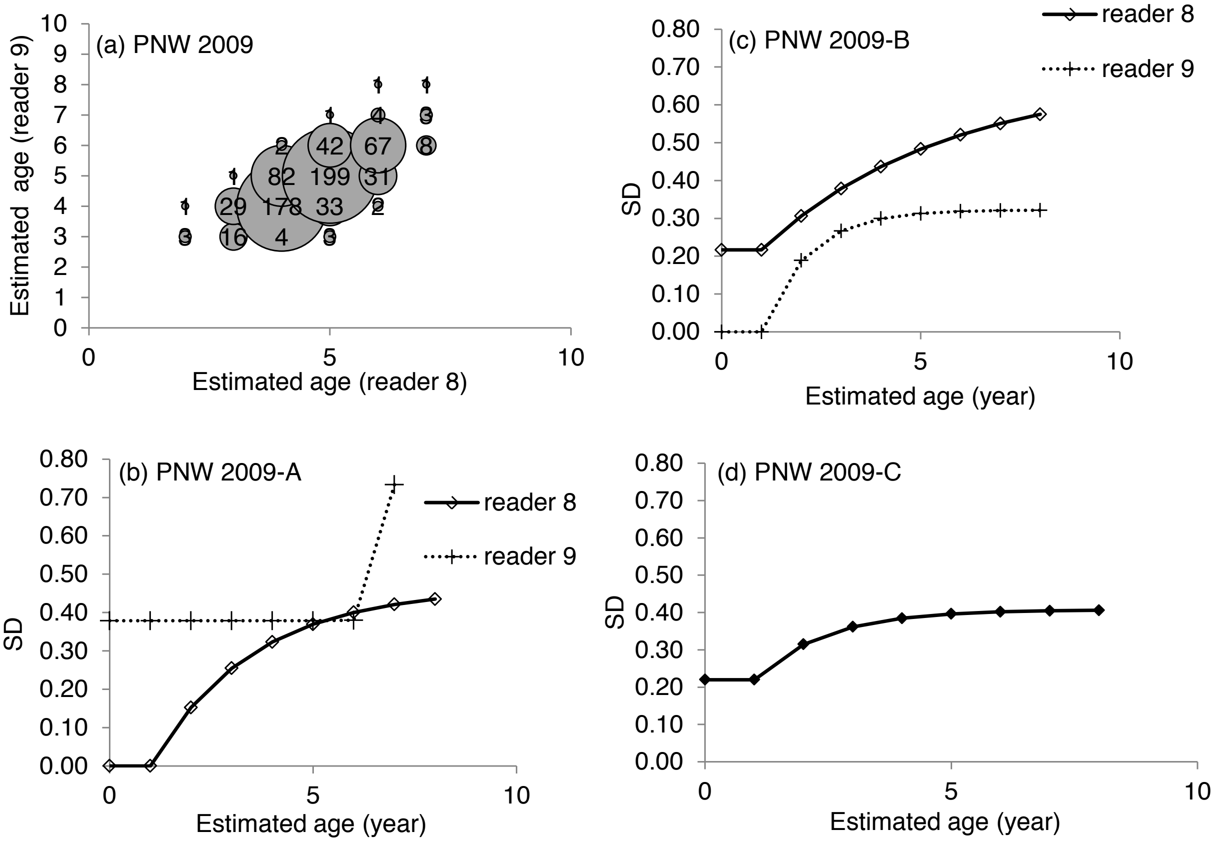

Figure 6. Age and standard deviation estimated for fish collected off the U.S. Pacific Northwest (PNW) fishery in 2009: (a) agreement plots for pairwise comparison of ages estimated by readers 8 and 9. Number and bubble size represent the frequency of observed age combinations; (b) Standard deviation (*SD*) estimated from model A; (c) *SD* estimated from model B; and (d) *SD* estimated from model C.

(72–74%), but their agreement in estimating age 3 was generally low, i.e., <65% (figs. 4a, 4d). Reader 5 highly agreed with reader 2 in estimating age 1(80%), but for all other ages agreement was low between these two readers (fig. 4b). In contrast reader 6 had low agreement with reader 2 across all ages (fig. 4c). As a result *SD*s estimated for the 2008–09 period were similar from age 0 to 2 but differed from age 3 to 6 (fig. 4e). In 2010 and 2011, agreement between pairs of readers was very high for age 0 and 1(≥ 85%), thus *SD* estimates were closely similar at these ages (fig. 5). Further, reader 2 had very high agreement with reader 5 in assigning age 2, but not with reader 6. Reading agreement from ages 3 to 5 was generally low, resulting in different *SD*s among readers (fig. 5). Finally, the fits of models B and C showed no over-dispersion for fish aged during the 2005, 2007, and 2010–11 periods for the CA fishery. However, for the 2008–09 period, both models B and C showed considerable over-dispersion in their fits to the age-reading data sets. Changing the assumption on the functional form of the random ageing error precision could not improve these fits. Finally, for each one of the time periods considered, model C that assumed equality of *SD* among readers had a lower *AICc* than model B (table 2; figs. 2d, 3e,4f, 5d), indicating that model C generally performed better than model B.

Standard deviations at age for fish collected in the PNW were estimated for all three models. Agreement between readers was moderate in assigning ages 4 and 5, but low in estimating all other ages, i.e., <65% (fig. 6a). In model A, the unbiased reader (8) had the lowest *SD* at age, except for ages 5 and 6 (fig. 6b). In contrast, model B showed the opposite pattern, with the highest SD at age for the unbiased reader, across all ages (fig. 6c). The fit of model A to the PNW age-reading data showed no evidence of over-dispersion and thus was considered to be adequate. Although both models B and C showed reasonable fits to the age-reading data, these models underfitted the most frequent age combination. Despite this misfit, the model C had a lower *AICc* value than models A and B (table 2, fig. 6d).

Ageing errors were computed for all three models, A, B, and C, for fish collected from the BC fishery. Agreement between the *RA* and reader 10 was very high (90%) in assigning age 3, moderate in assigning ages 4 and 6 (60–70%), but low in assigning ages 5, 7, and 8 (<65%) (fig. 7a). In contrast, reader 11 highly agreed with the *RA* in assigning ages 3 and 4 (80%), moder-

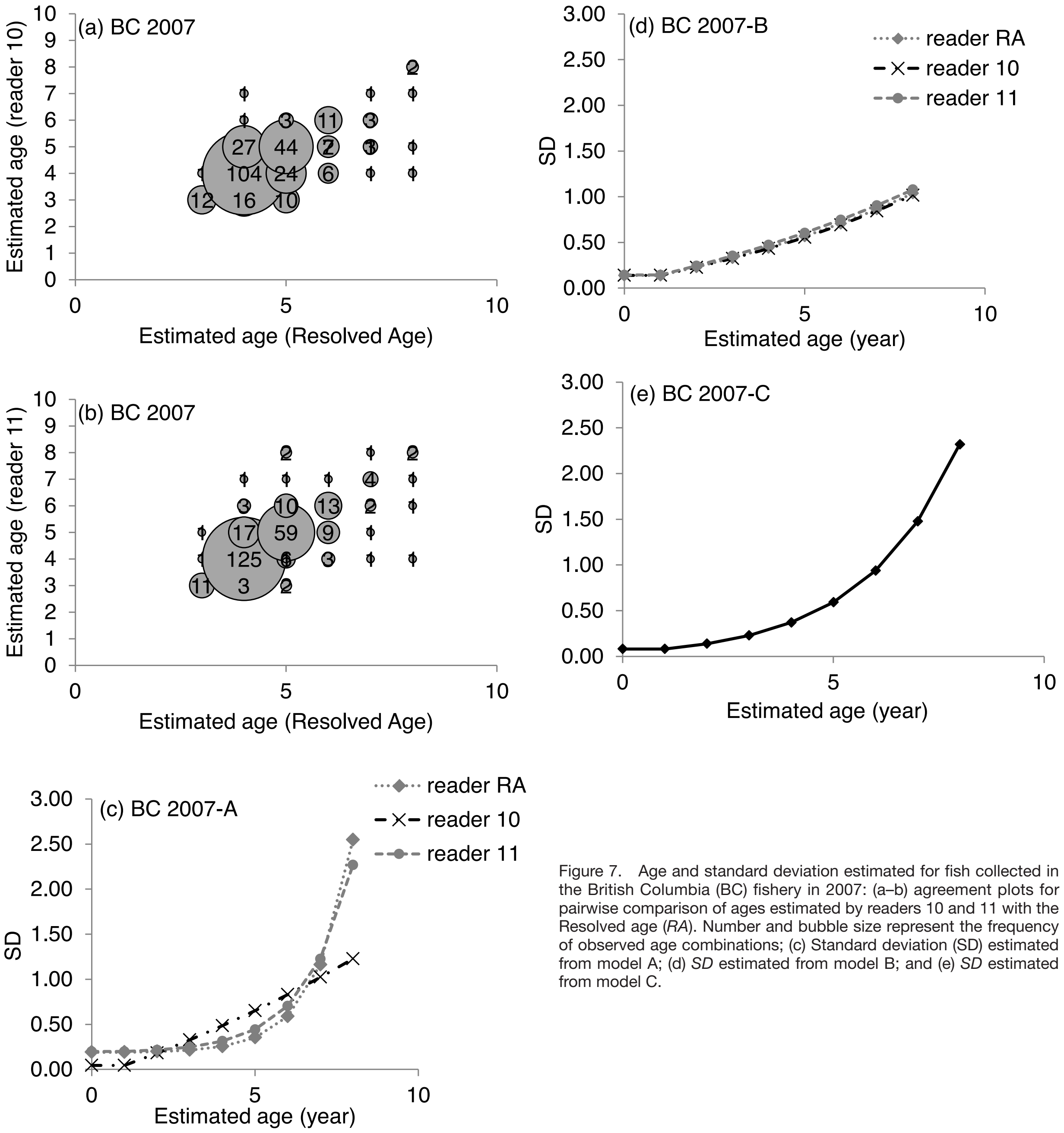

Figure 7. Age and standard deviation estimated for fish collected in the British Columbia (BC) fishery in 2007: (a–b) agreement plots for pairwise comparison of ages estimated by readers 10 and 11 with the Resolved age (*RA*). Number and bubble size represent the frequency of observed age combinations; (c) Standard deviation (SD) estimated from model A; (d) *SD* estimated from model B; and (e) *SD* estimated from model C.

ately in assigning age 6, but little in assigning ages 7 and 8 (40%–50%) (fig. 7b). There was little difference among the three readings in *SD* estimated from model A, except for age 8 (fig. 7c). Model B showed closely similar *SD*s among readers 10, 11, and the best/resolved age estimates (fig. 7d). Model A generally fit the age-reading data better than models B and C, but all three model fits showed little over-dispersion. Finally, model C had a lower *AICc* than models A and B (table 2, fig. 7e), indicating that model C performed better than the other two models.

For the DEPM survey, all three models were used to estimate *SD* at age and by reader. Agreement between the pair of readers was generally low across all estimated ages (figs. 8a, 8b). Consequently, there were considerable differences in *SD* estimated for all three readers. In model A, the unbiased reader (1) had lower estimates of *SD* at age than the other two (fig. 8c). In model B, the SWFSC reader had higher *SD*s for ages 0 to 2 than the CDFW readers; whereas for ages 5 to 6, estimates of *SD* at age for the SWFSC reader were consistently lower (fig. 8d). Model A fitted both data sets well; whereas model B and model C fitted well to data set 9 but poorly to the data set 10. Changing the assumption on the functional form of the random ageing error precision could

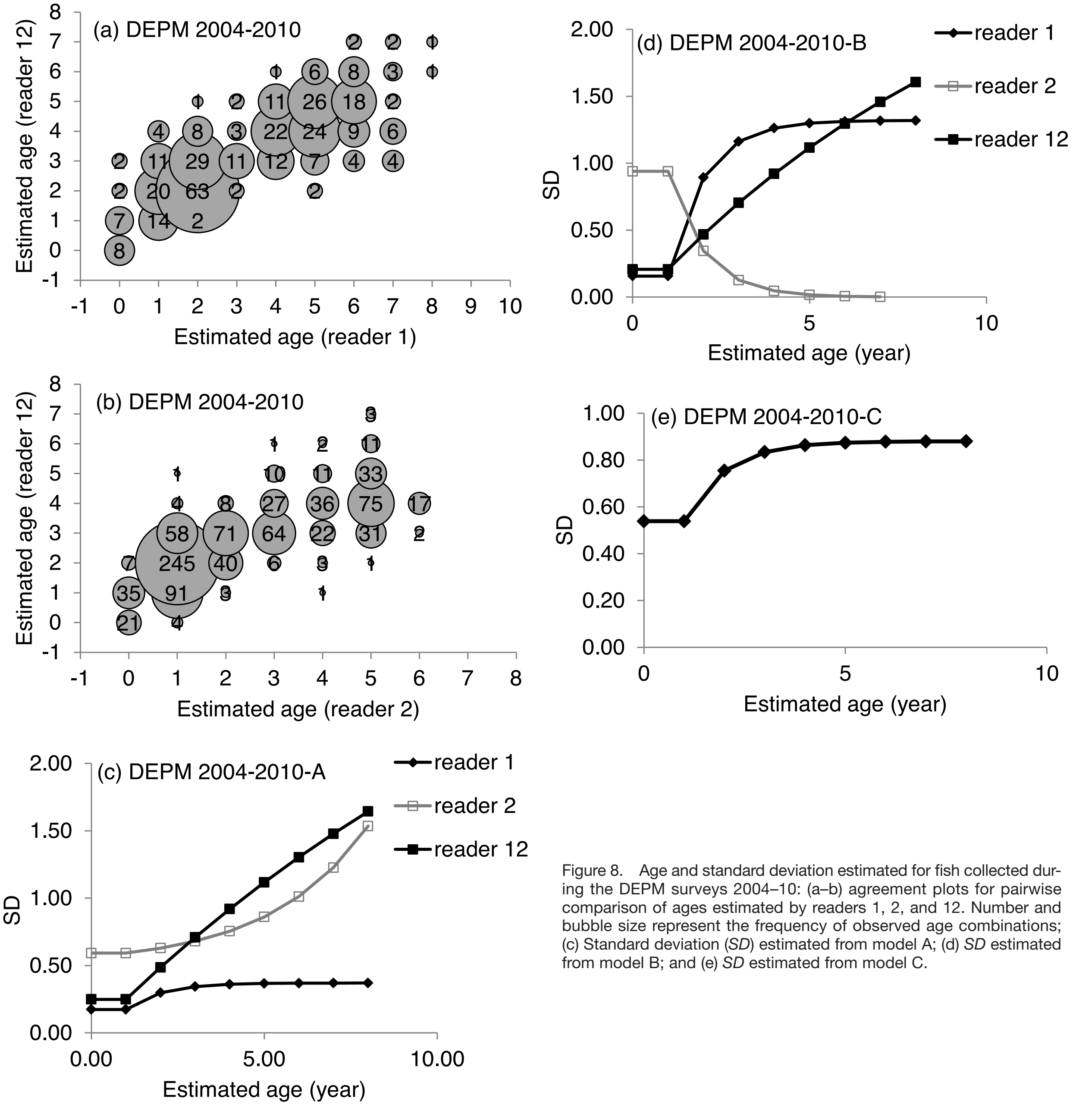

Figure 8. Age and standard deviation estimated for fish collected during the DEPM surveys 2004–10: (a–b) agreement plots for pairwise comparison of ages estimated by readers 1, 2, and 12. Number and bubble size represent the frequency of observed age combinations; (c) Standard deviation (*SD*) estimated from model A; (d) *SD* estimated from model B; and (e) *SD* estimated from model C.

not improve these fits. Nevertheless, model C had a lower *AICc* than models A and B (table 2, fig. 8e).

DISCUSSION

Ageing imprecisions estimated for Pacific sardines collected along the Pacific coast showed considerable differences among ages, readers, and laboratories. Estimated ages ranged from 0 to 8, and thus were much below the maximum expected age of sardine, 15 years (Hill et al. 2011). Regardless of laboratory, *SD* increased with age, indicating higher imprecision in counting annuli in older fish otoliths. Except for the Pacific Biological Station, *SD* estimated for the oldest fish (ages 4–8) showed greater differences among readers than those estimates for the youngest individuals (ages 0–3). The bulk of the sardine population off California is made up of fish younger than 4 years (Hill et al. 2011), thus the likelihood of sampling older fish is lower than in BC, where older fish migrate during the fall (Lo et al. 2011; Demer et al. 2012). Thus, besides the difficulty of ageing older fish, these results partly reflect reader experience in ageing older sardines. Further, the Yaremko 1996 method was not consistently applied across all laboratories, with significant modifications in the use of media and microscope resolutions. Although the impact of the use of resin or alcohol instead of water on age determination has not yet been evaluated, the change of magnifications could significantly affect the magnitude of ageing errors observed among laboratories. Except for the DEPM survey, a limitation of this study was that no common sets of otoliths were aged by all readers. Hence, testing the effect of medium quality and levels of magnification across laboratories could not be achieved. Therefore, we recommend establishing an otolith exchange program where all readers from all laboratories age fish from the same set of otoliths and use standardized ageing protocols. This program would be a more valuable approach to compare ageing imprecision across ages, readers, and laboratories. Nevertheless, the results of this study highlighted the need to improve and to standardize the application of the ageing method across laboratories.

By comparing the three hypothesized models, we showed the model that assumed similar *SD* among readers performed better than those that assumed different *SD*s among readers, across all age-reading data sets. This model had lower *AICc*, even in cases where the diagnostic plots showed considerable over-dispersion in model fitting to the age-reading data. These results suggested that assuming equal *SD* between readers within a laboratory was quantitatively a reasonable assumption. This assumption appeared to allow for better estimation of the variance contained in the data. Except for the DEPM survey, all data sets were produced by readers belonging to the same laboratory. Within a laboratory, readers are typically trained similarly and often by the most experienced reader and thus would apply closely similar techniques during the ageing process. However, assuming similar *SD*s across laboratories may be problematic, as shown by the results from the DEPM age-reading data sets. Both CDFW readers had lower standard deviations at age 0 and 1 than the reader from the SWFSC, but their *SD*s for ages 4 to 8 were higher (see model B, fig. 8d). These systematic differences in *SD* reflected both the degree of experience and consistency in applying the method within each laboratory. Therefore, for age-reading data sets produced by readers within the same laboratory, the assumption of equality of standard deviation can be used to select and include ageing imprecisions in the sardine stock assessment model. However, another limitation of our study is that Stock Synthesis 3 could only use data produced by model C, precluding the direct comparison of the outcomes of the three models within the assessment modeling framework. Likewise, it would be valuable to develop sardine assessment models in SS versions that can allow the inclusion of ageing errors from any of the three assumed models.

Although we assumed that one reader was unbiased in model scenario A, this assumption was based on reader experience and age corroboration but not on age validation (Kalish et al. 1995; Kimura et al. 2006; Campana 2011). To date, there are no fish of known age to determine age-reading accuracy of Pacific sardines. CDFW has established a training set of otoliths that has been used for age corroboration among readers and to train and certify new age readers. Because this training set does not include any fish whose ages were validated, it cannot be used to address issues concerning ageing bias. While the periodicity of sardine growth increments have been corroborated in juvenile fish (Butler 1987) and in age 1–2 fish (Barnes and Foreman 1994), to our knowledge age corroboration from annuli in older mature fish has never been conducted. As patterns of increments in young fish cannot be applied to older fish, the lack of verification of increment formation in each and every age group can lead to systematic bias in age determination (Campana 2011). Most concerns regarding bias remain with ageing fish older than four years old (i.e., the age 5^+- group). This age group was more frequent in the Pacific Northwest and British Columbia fisheries. Interpreting increments at the edge of older fish otoliths was challenging for all readers because it is usually difficult to differentiate check marks from annuli. For example, in the first year of life, a wide opaque increment near the focus followed by a fine translucent ring can be interpreted as a check mark; whereas the same mark present in a more distal area of the otolith may be interpreted as an annulus (Yaremko 1996). Thus, although we focused on quantifying ageing imprecision in this study, we recognize there may be systematic bias in the overall ageing process. Statistical models cannot account for such potential bias, which may ultimately affect the estimation of mortality and growth rates of the northern sardine population. Current stock assessments assumed a fixed natural mortality rate ($M = 0.4$ yr^{-1}) across all ages, which may mask the impact of ageing bias in the oldest age classes on estimating demographic parameters. Further, the natural mortality rate was estimated for fish collected in the historical fishery (Murphy 1966), prior to the full recovery of the sardine stock (McCall 1979), and thus warrants new evaluation. As sardines have reoccupied the U.S. Pacific northwest and British Columbia since the 2000s, the catches taken by these fisheries (Hill et al. 2011) and their impact on growth, mortality and recruitment processes have substantially increased. Hence, it is imperative to develop and apply new methods to accurately age fish collected in these fisheries. Therefore, a second recommendation from this study would be to conduct in the short term a coast-wide evaluation of the polished method (McFarlane et al. 2010) for age 3^+ fish collected from Mexico to Canada.

Further, this evaluation could be coupled with a long term tagging experiment to address and quantify ageing bias in Pacific sardine.

Because the model that assumed similar *SD*s among readers consistently had the lowest *AICc*, we suggest that it can be used to estimate and include standard deviation-at-age in future SS models of Pacific sardines, particularly when the assessments are developed on age-reading data that can be partitioned by fishery and by laboratory. However, a more systematic study based on a common set of otoliths needs to be conducted to test the validity of this assumed model for computing ageing imprecisions from data that involved readers from different laboratories.

ACKNOWLEDGMENTS

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THE SARDINE FISHERY OF THE GULF OF CALIFORNIA

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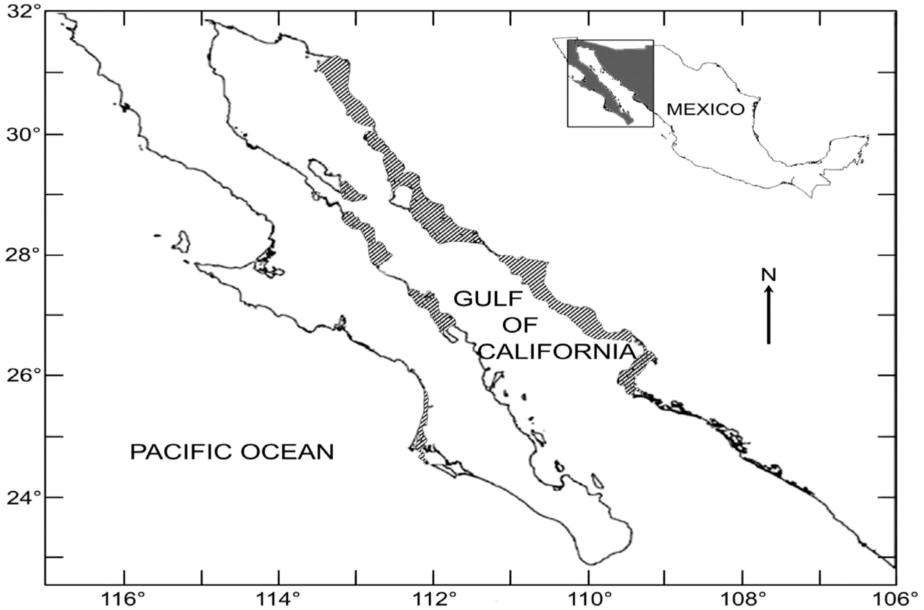

Figure 1. The Gulf of California, showing the areas where the sardine stock is exploited. (Modified after Lanz et al. 2008).

ABSTRACT

In the sardine fishery of the Gulf of California (1969–2012), the annual catch declined to ~400,000 mt in 2010–12 (average: 129,000 mt), after three years of high harvest (average >532,000 mt · yr^{-1}). The fishing intensity was relatively stable up to 1997, fishing 5,000 days per season, increasing in 2008 and 2009 to 15,000 and 28,700 days, respectively. Fishing trips increased steadily from 40 to 80 trips per vessel in the last five years. Total profits follow the same trend as the catch, ranging between $1–12 million in most seasons, with four peaks. In 12 years, the fishery produced more than 15 times the cost of fishing operations. Oceanographic conditions determine abundance levels, and significant correlations exist between population estimates and the Pacific Decadal Oscillation Index. Climate and fishing intensity are the main responsible forces; to ensure a stable fishing activity, we recommend that fishing effort should range between 4,000 and 6,000 fishing days per season.

INTRODUCTION

Depletion of the sardine fishery of the West Coast of North America has stimulated numerous studies trying to understand causes, such as climate change, overfishing, schooling behavior, or interaction with other pelagic species, particularly anchovy (Murphy 1966; Sokolov 1973; Sokolov and Wong 1973; MacCall 1979; Cisneros-Mata et al. 1995). In the Gulf of California (fig. 1), a large quantity of sardine was found in the late 1960s; its exploitation began in 1969 (fig. 2). The peak yield was reached in 2009, with a catch of over 580,000 metric tons (mt). This was followed by an abrupt decline, with a catch of about 88,000 mt in 2012. About 85% of the annual catch is used to produce fish meal, mostly for animal feeds (http://www.msc.org/track-a-fishery/fisheries-in-the-program/certified/pacific/gulf-of_california-mexico-sardine; Feb. 2013). External forces affecting the sardine fishery are related to the demand for fish meal, where the aquaculture sector consumed

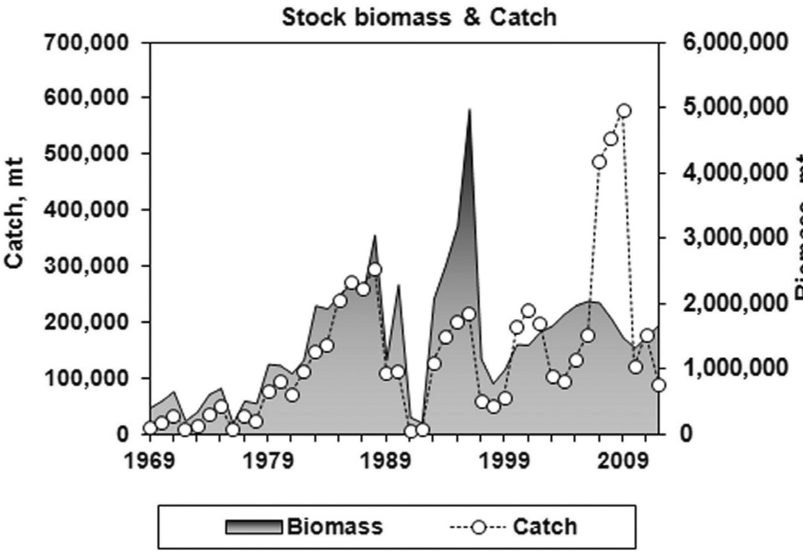

Figure 2. Sardine catch and stock biomass (mt) in the Gulf of California since 1969.

20–25 million mt, from which 23% is used in aquaculture (Tacon et al. 2006). In northwestern Mexico, shrimp cultivation has had an exponential increase in the last few decades, currently producing >60,000 mt, which in turn, imposes a strong demand for fish meal. This leads to a perception that the fish meal supply is limited and the demand in increasing. This increases the fishing pressure on the sardine, greatly increasing the risk of overfishing (Herrick et al. 2006, 2009). Six other species and an undetermined mix of other stocks are part of the catch. The biomass of the bycatch exceeds 100,000 mt and is also used as fish meal (SAGARPA 2012).

The highest sardine catch of the Gulf of California was almost comparable to the highest catch recorded off the California coast, amounting to 664,000 mt in 1936 and a biomass peak of 3.6 million mt in 1934 (Murphy 1966; MacCall 1979). This story seemed to be repeated one more time, now in the Gulf of California. For this reason, an updated assessment of the gulf sardine fishery was carried out, with the aim of examining the catch trend, since the origin of this fishery and other bioeconomic activities and climatic variables are possible factors responsible for variability and decline. Finally, some recommendations for sustainable exploitation are proposed.

METHODS

Catch and effort

Data for the Gulf of California sardine fishery was available for the 1969–2008 fishing seasons (Nevárez et al. 2010). Data for 2006–12 was obtained from the statistical records available for the landing sites in the State of Sonora. An estimate of the expected total catch in the Gulf of California for the years when no other data were available was calculated as the mean proportion of the years 2006–08. This provided a catch data series through 2012. The number of vessels and nominal effort were available from the report by Nevárez et al. 2010 and similar data were estimated for 2009–12 by applying the same procedure for missing data. According to the Marine Stewardship Council (MSC 2013), each fishing trip lasts 1 to 2 days, so each fishing trip was multiplied by 1.5 to get an estimate of the number of fishing days in the fishing season (fig. 3). According to the MSC, each vessel has a crew of eight fishers, such that the number of vessels (25 m long) per year provided the total number of workers.

With 15 years of catch data and the growth parameter values *K*, *L*, t_o of the von Bertalanffy growth model, length–weight parameter values (*a, b*), age of first catch (*tc*), and age of first maturity (*tm*) as biological variables, plus the sardine value at the dock, the fishing cost per boat-day, number of boats, and length (in days) of the fishing season (table 1), it was possible to determine other variables useful for a bio-economic assessment and diagnosis of the fishery with the FISMO simulation model (Chavez 2005): total number of days per fishing season, total profits, profits per boat and per worker, as well as the benefit/cost ratio. Estimates of the catchability coefficient q were based on the relationship $F = qf$, where F is the fishing mortality and f is the fishing effort in days. Most fisheries are now at the stage of full exploitation or overexploitation of the stocks, with fishing fleet capacity in excess (Gréboval 2003; Munro and Clark 2003; Kirkley and Squires 2003). Under these conditions, fishing effort (f) is no longer proportional to the stock size. For this reason, the estimation of F was deliberately made to avoid the use of f, as advised by the traditional meth-

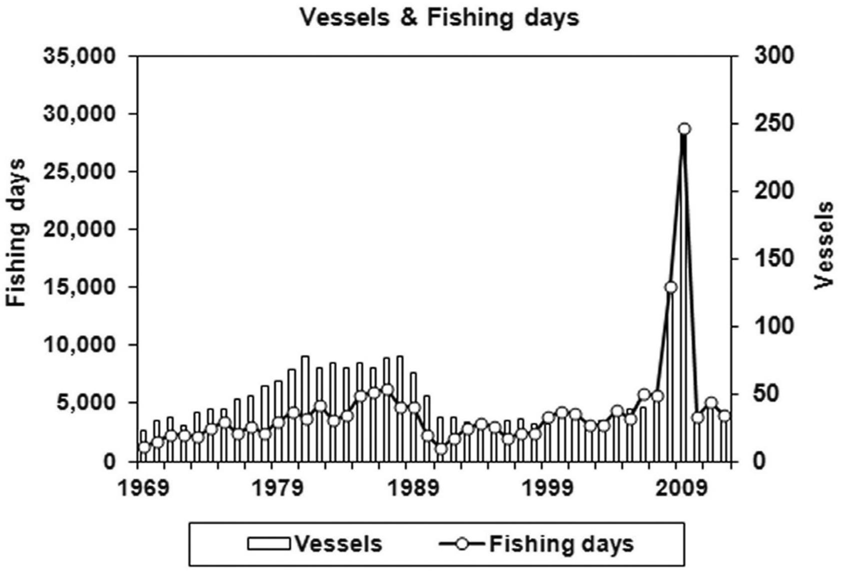

Figure 3. Trends of the fleet size and fishing effort of the sardine fishery.

TABLE 1

Population parameters, social and economical values of the sardine fishery in the Gulf of California used as input for use with the fisheries simulation model. *K*, *L*, *W*, and *to* are from the von Bertalanffy growth model; *a*, *b* are from the length–weight relationship; age units are years. *M* is the natural mortality; *Phi'* is growth performance; Coef. Fitting fleet in arbitrary units; Catch value, costs of fishing, and profits are in $US and correspond to the 2012 fishing season, as well as the B/C ratio.

Variable	Value	Source or units
K	0.45	Hill et al. 2009
L	31	cm, Hill et al. 2009
W	206	g, from the length–weight equation
-to	0.17	Hill et al. 2009
a	0.00637	Froese & Pauly 2011
b	3.07	Froese & Pauly 2011
M	0.6750	As 3/*K*, after Jensen 1997
Phi'	2.6	Estimated by the model
Value/kg	0.07	Cisneros unpublished
Cost/day	253	$US
Longevity	7	Years, as 3/*K*
Age of first catch	1	Marine Stewardship Council 2013
Maturity age	1	Hill et al. 2009
Coef. fitting fleet	0.0005	Estimated by the model
Num. of Boats	47	Nevárez-Martínez et al. 2010
Days/boat/season	85	Nevárez-Martínez et al. 2010
Num. of trips	3,995	Nevárez-Martínez et al. 2010
Profits	14,012,438	Estimated by the model
Benefit/Cost	14.9	Estimated by the model
Fishers/Boat	8	Marine Stewardship Council 2013

ods applied in fisheries biology. Here, F was estimated for the last 15 years of catch data, using the catch equation in the simulation model (described in the following paragraph); the model estimates of F for each year were directly calculated from the catch equation by performing an approximation of successive values until observed and simulated catch were equal. The f is known for the whole data series from 1969 to 2012 and was used as a variable linked to the economic forces implicit in the fishery. Hence, a mean q value was obtained for the last 15 years and this mean was applied year by year to the F equation just described for estimates of F of the earlier catch data (before the years analyzed by the model). With this procedure, an analysis of the data series since the beginning of the fishery can be made. Other authors have found a relationship between catchability as a function of the stock biomass (Arreguín-Sánchez and Pitcher 1999; De Anda-Montañez et al. 1999; Martínez-Aguilar et al. 2009). For this reason, a function was used, but in the years where a q value was estimated, a pattern between stock size and q was not found ($R^2 = 0.019$, $p = 0.89048$).

The age and growth rate of exploited stocks is a condition imposed by the need for estimating growth rates of all of the exploited populations. Fortunately, many studies focus on sardine stocks; it is now possible to determine growth rate without the need to start the assessment with a sampling program. The power regression used to transform length into weight is $W = a \cdot L^b$.

The initial assessment of the stock was made with catch data for the last 15 years and then it was reconstructed for the 43-year period of the fishery. Changes in abundance over time were determined by using the catch data as a reference for estimating population size. Growth parameters were taken from Hill et al. 2009. Estimates of the age composition of the catch were made, and further analysis, including scenarios of feasible harvesting strategies, were calculated with the FISMO simulation model (Chávez 2005), which transforms catch data into age structure of the population. The age structure of the stock in each year was estimated by assuming a constant natural mortality (*M*), adding the fishing mortality (*F*) estimates that were different for each age class, and the total mortality was determined, using $Z = M + F$ in each year. The age structure was determined after the estimation of the number of one-year-old recruits and then used to calculate catch-at-age, as proposed by Sparre and Venema 1992. This was integrated into the simulation model, as:

$$Y_{a,y} = N_{a,y} \cdot W_{a,y} \; \frac{F_t}{(F_t + M)} \; (1 - e^{(-F_t - M)}) \quad ,$$

where $Y_{a,y}$ is the catch-at-age a of each year y, $N_{a,y}$ is the number of sardines at age a in year y, $W_{a,y}$ is the sardine weight equivalent to $N_{a,y}$, F_t and *M* are as described earlier. The values of $Y_{a,y}$ were adjusted by varying the initial number of recruits and linked to the equations until the condition of the catch recorded and simulated catch were equal by varying *F* for each year. The catch equation was applied for each year in the time series.

For estimating natural mortality (*M*), the criterion of Jensen (1996, 1997) was followed, using $M = 1.5\ K$. The stock biomass and the exploitation rate $E = F / (M + F)$, were estimated for each age class in every fishing year analysed by the model after transforming the numbers per age into their corresponding weights. With estimates provided by the simulation model, a mean value of the catchability coefficient was obtained, and with this value, it was possible to estimate *F* and other variables for the whole series of catch records. A diagnosis of the status of the fishery was made, and recommendations of the most convenient fishing intensity to maintain sustainability were made. The stock-recruitment relationship was applied by using the equation by Beverton and Holt 1957. Intensity of recruitment depends to a great extent on stock size.

Model simulation

The simulation model reconstructs the age structure over time and different exploitation scenarios (fishing intensities and the age-at-first catch) to maximize biomass, profits, and social benefits, as well as the number of fishermen and maximum profit per fisherman, adopting the ideas of Chávez (1996, 2005) and Grafton et al. 2007.

The approach to the socioeconomics of the fishery concerns only fishing activities and was made through consideration of the costs of fishing per boat per fishing day ($253), number of boats (47 in the 2012 fishing season), number of fishermen per boat (8), and the number of fishing days during the initial fishing season (85). The catch value per kg ($0.07) is the price at the dock before added value. The difference between the costs of fishing (C) and the catch value (the benefit, B) is known, so the value divided by the cost is the B/C ratio (table 1). In the simulation, the costs of fishing per boat-day and catch value were assumed to be constant over time. The information of the 2012 fishing season allowed us to reconstruct the biological and economic trend of the fishery for the last 15 years and was estimated for the data series, as well as the 30 years of simulation. This used the estimates of fishing mortality over time as a reference and its correspondence to the economic variables.

Bioeconomic analysis

This part of the description is based on the so-called stock effect (Hannesson 2007), which are the costs and benefits occurring only during fishing activities; therefore, costs and benefits after catches were landed were not considered. Therefore, the approach is quite simplistic because the market forces are left out of the analysis. Hence, costs are linked to fishing effort and economic benefits or profits, and the catch value (catch times its value per kg) from which costs (costs per daily trip multiplied by the number of trips) are substracted. By this approach, a detailed diagnosis of how profitable the fishing can be is provided and it is easy to perceive why, in many fisheries, stock declines at some point resulting from excessive fishing pressure; at that point, the fishery reduces its fishing effort and the activity becomes an economic crisis because there are no profits.

RESULTS

Stock biomass and catch

The stock biomass describes a clear pattern of oscillation, possibly induced by climatic variability rather than fishing intensity (fig. 2). The fishery was simulated by Nevárez-Martínez et al. 1999 and the analysis presented here is an update with additional information. We found that in the first five years, the stock size was ~500,000 mt and the catch was below 33,000 mt. Then there was a decrease of biomass to 167,000 mt that was followed by a major increase that reached 3 million mt in 1988, followed by a sudden decline with a catch of just 7,500 mt in 1992 (fig. 2). The highest biomass was recorded in 1996 with an abrupt increase that reached almost 5 million mt. After 1996, the biomass was maintained, but the catch suddenly increased to almost 600,000 mt in 2009, leading to a low catch of only 89,000 mt in 2012.

Fishing effort

Examining the fishing activity by the number of boats and fishing days (fig. 3), a relationship between these two variables and stock biomass is not very clear, except in 1990 when there was a large decrease of biomass that affected the fishing effort. In 2007–09, there was an abrupt increase in catch that was not related to high

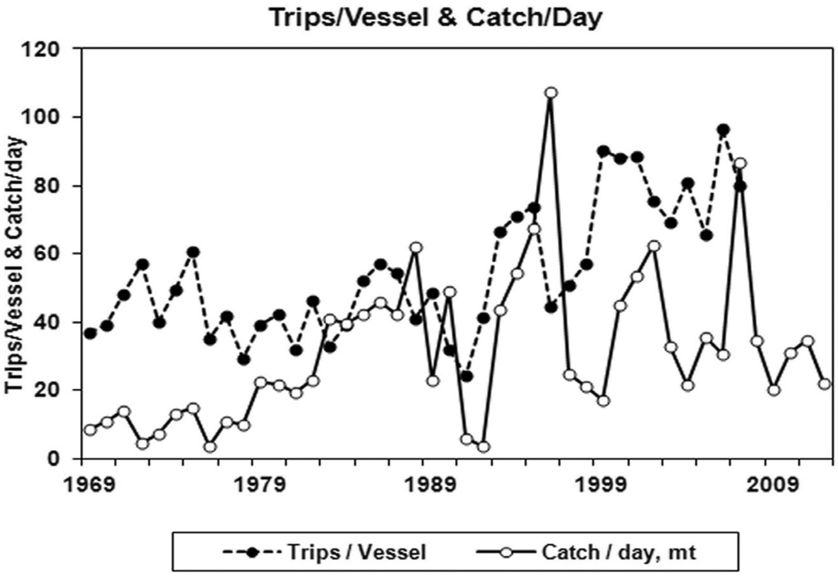

Figure 4. Number of trips of each fishing season per vessel, and catch per unit of effort (mt · day^{-1}) of the sardine fishery in the Gulf of California.

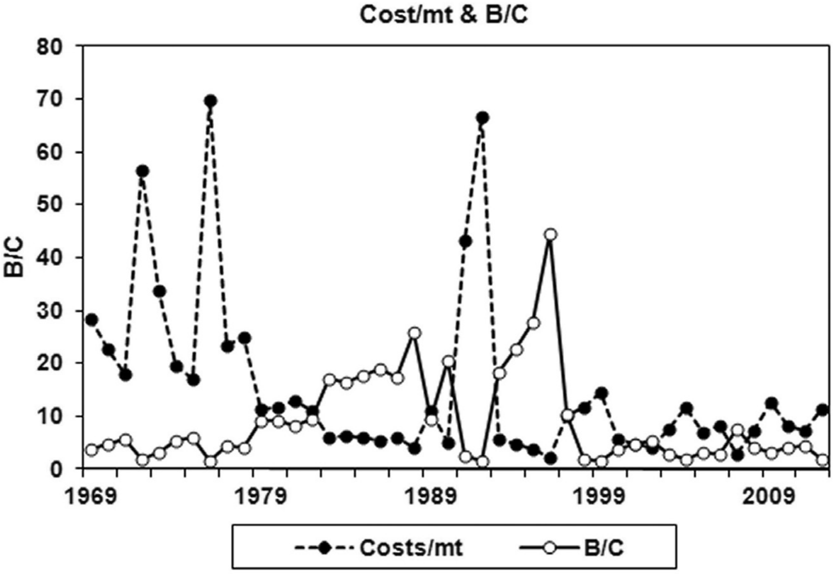

Figure 5. Benefit/cost ratio and Costs per mt of the sardine fishery of the Gulf of California.

biomass (fig. 2). Instead, there was an increase in fishing capacity created by a huge increase to 242 vessels and nearly 28,000 fishing days. This may have resulted from high catchability not shown in the q values. A detailed examination of fishing intensity was made by looking into fleet behavior; it is evident that there was a change in the attitude of fleet owners, which since 1993 decided to increase the number of trips per fishing season from a mean of 47 before that year to about 85 in 2009 (fig. 4). By contrast, the catch per unit of effort was dramatically variable, with a decreasing trend in the last four years of the series, when catches were below 40 mt/day, lower than yields in the 1980s.

Bioeconomic analysis

The benefit/cost trend shows that this fishery is very productive and can remain productive for a long time if it is carefully managed, since 13 fishing seasons yielded profits that were >15 times the cost of fishing operations (fig. 5); however, the increase in fishing intensity after 1993 caused a reduction in the benefits to about half the income of the 1980s. Simulation indicates that the maximum potential economic yield is $F = 0.3$, which may generate $11 million.

The costs of fishing were variable and usually high in the early years of the fishery ($18–60/mt), decreasing for some years to less than $7/mt and then increas-

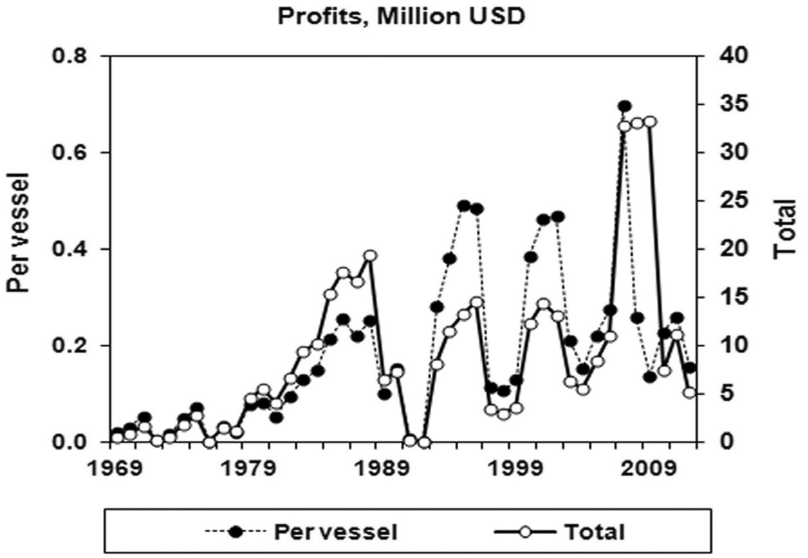

Figure 6. Total profits and profits per vessel of the Gulf of California sardine fishery.

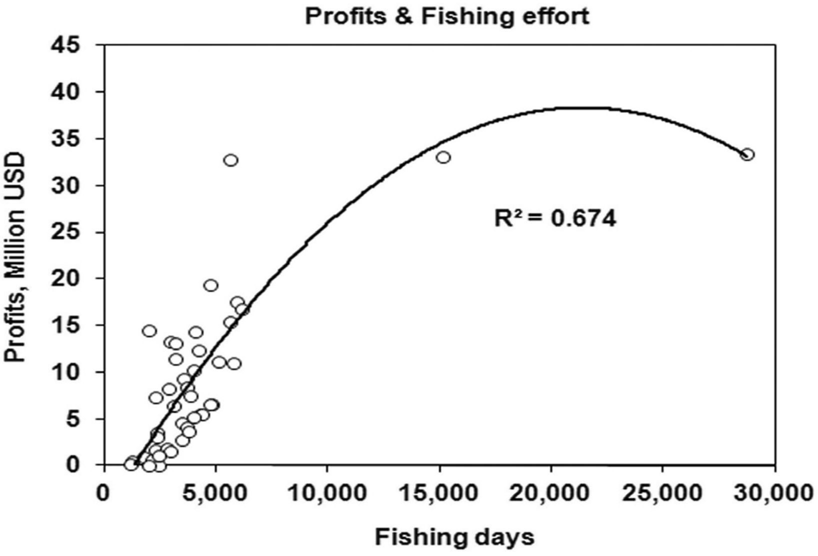

Figure 7. Total profits as a function of fishing effort in the Gulf of California sardine fishery.

ing again to $65/mt in 1992, when the lowest catch was recorded. Afterwards, the costs ranged from $3–14/mt (fig. 5). The profits of the sardine fishery indicate that with a few exceptions, each vessel produced $4–28 million since the mid-1980s. In 1991 and 1992, when the catch was below 8,000 mt, profits decreased to $0.02 million. In 2007, when the catch increased to 490,000 mt with only 47 vessels, each vessel produced its largest profits, $0.7 million. This exceptional profit led to an increase in 2008 and 2009 of 127 and 242 vessels, respectively. This reduced each vessel's profits to $0.14 million (fig. 6). Other years with high profits, nearly $0.5 million per vessel, were 1995–96 and 2001–02, which resulted from high yields, with less than 32 vessels (fig. 6). Total fishery profits were highly variable, but with a tendency to increase. Historical records suggest that the fishery has been profitable, producing up to $33 million per season, with low risk of overexploitation when the fishing effort was between 4,000 and 6,000 days (fig. 7).

Social benefits

Based on a constant number of fishermen per vessel, the number of direct jobs in the fishery ranged from 185 workers in the first year to 1,935 workers in 2009. The trend increased, except for the last three seasons, with only 261–344 workers (fig. 8). Assuming an equitable distribution of income per vessel, there was an upward trend in profits, reaching a maximum of the mean trend

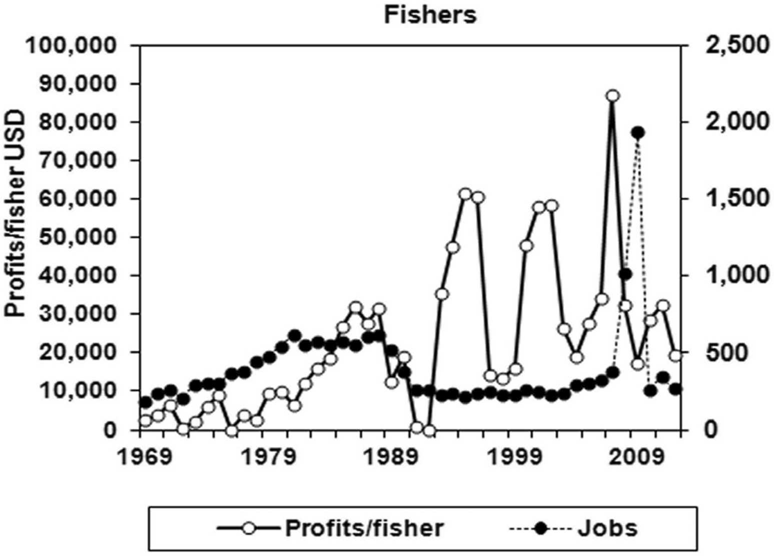

Figure 8. Social impact of the Gulf of California sardine fishery, expressed as the number of direct jobs, the fishermen, and the economic benefit per fisherman, assuming an equitable distribution of the income.

in 2011, \$32,000/worker in 2010–11; however, in 1976, 1991, and 1992, the profits per worker were critically low, ranging from \$4,700 to \$6,975/worker. In contrast, high profits occurred in 1996 and 1997 (up to \$61,000/worker), and the highest in 2007 (\$ 534,000/fisher). The maximum sustainable yield is the maximum yield that is attained at a certain *F* value (F_{MSY}). The fishery at $F_{MSY} = 0.35$ would produce 2,073 direct jobs. The *F* at the maximum economic yield, that is, producing the maximum economic return, is $F_{MEY} = 0.3$, which would produce 2,131 direct jobs. Under current conditions, the fishery provides 381 jobs, but in five fishing seasons with peak yields, it provided more than 1,500 jobs (fig. 8).

To find a concurrent cause of the recent decline in the stock biomass and the catch, the possible effect of climate variability was explored. Historical data series of six climate indices (SOI, anomalies of SOI, LOD, NAOI, ACI, and AFI) were compared with the stock biomass since 1969, when catch data records began. Significant correlation was found only between the stock biomass and PDOI, when compared to the rising catch periods, in 1969–96 ($r^2 = 0.5124$, $p = 0.0004342$), and 1997–2012 ($r^2 = 0.7499$, $p = 0.00002185$), as shown in Figs. 9A and 9B. The comparison with other indices was lower; however, the figures suggest that climate variability may play an important role in drastic changes in the stock biomass of this fishery, as occurs along the coast of California (Murphy 1966; MacCall 1979; Lluch-Belda et al. 1986, 1991).

DISCUSSION

The sardine fishery is a typical resource population with a short life cycle that responds rapidly to pulses of high productivity, but at the same time, is exposed to dramatic decreases when exposed to extreme increases in fishing effort (Cisneros-Mata et al. 1995; Barange et al. 2009; MacCall 2009; Martínez-Aguilar et al. 2009). This is particularly true in fisheries where management practices are inaccurate or insufficient, leading to major impact on the stock biomass, overall profits, and available jobs. This situation suggests that monitoring stock assessment provides opportunistic advice to fisheries before economic crises arise. The industry can take action to maintain the stock biomass at constant, sustainable levels.

For estimating mortality rate (*M*), several authors explored the problem (Chávez 1995; Jensen 1996; Cubillos 2003; Charnov et al. 2012). Chávez 1995 made a comparison of six methods to estimate *M*, based on data of 75 fish stocks, where *M* was used as a dependent variable and longevity was an independent variable. One year later, Jensen 1996 found a more convincing approach, stating that *M* and two other invariants are an expression of fundamental ecological functions, not just statistical relations. Cubillos 2003 agrees with Jensen and proposes a variation to estimate *M*. Likewise, Charnov et al. 2012 examine the relationship between *M* and the von Bertalanffy growth equation, reaching a solution similar to that of Jensen.

Apart from 2008 and 2009, the fishing effort may be considered roughly constant. By examining the trends of fishing effort and profits, it is evident that they describe the same variability; therefore, the peaks are caused mainly by the catch-per-day and secondly by the whole catch. The peaks in stock biomass available for exploitation stimulated the increase in fishing effort that produced high profits for one or two fishing seasons, followed by large decreases in biomass, fishing effort, and profits.

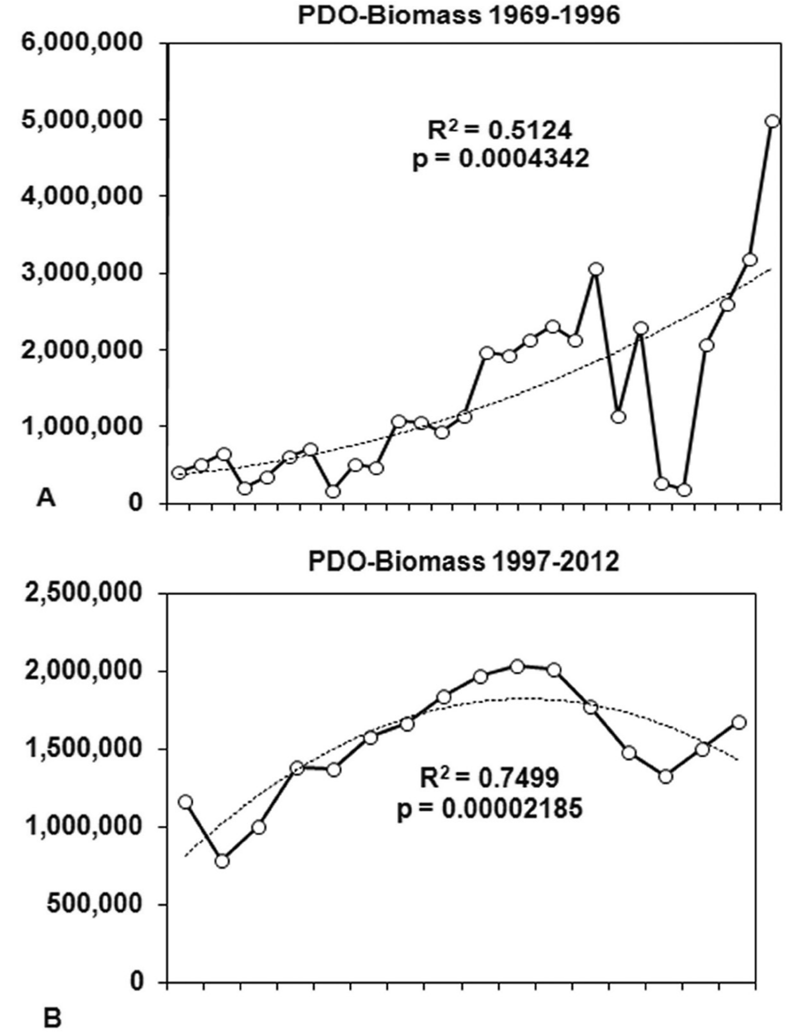

Figure 9. Trend of the sardine stock biomass in the Gulf of California as a dependent variable and the Pacific Decadal Oscillation Index (PDOI) as an independent variable since the beginning of the fishery. (A) 1969 to 1996. (B) 1997 to 2012. Significant correlations were found in the period of catch increase (A), and in the period of stock decline (B).

With the formulas that we used, once the catch data were transformed into their corresponding numbers and biomass-per-age class, then the catch equation was applied. The economic data are the costs linked to the fishing days and the profits to the value of the catch minus the costs of fishing, such that all results are affected by the stock size, that is, they are closely linked to the dynamics of the population being analyzed. When a fishery has been underexploited, there is surplus production of biomass and this may reach a very large quantity, but when it has been exploited near or more than its maximum capacity, the spawning stock biomass is gradually reduced.

In recent years, climate variability induced a favorable change in the stock biomass that allowed catch increases in the coastal California stock (Hill et al. 2005, 2007, 2009), as well as the Gulf of California stock. In the gulf, this significant increase led to the sardine fishery being certified as sustainable in July 2011 by the Marine Stewardship Council 2013. For this reason, keeping fishing effort at less than 6,000 days seems reasonable, although the recent decline in catch led to a reduction by 900 days (5,108 days in 2011), and should not increase during the next few years so that the stock can be restored. Simulation of the expected catch by assuming that the climate will not cause an adverse effect on survival suggests that, with the fishing intensity just proposed, the stock biomass would allow twice the catch volume landed in 2012, which was more than 170,000 mt. Trends in catch and stock biomass suggest that other forces, apart from the fishing intensity, are responsible for its variability. Studies have looked for a reasonable explanation of this variability (Huato and D. Lluch-Belda 1987; Lluch-Belda et al. 1986, 1991, 2003; Lluch-Cota et al. 1999;

Hammann et al. 1988; Holmgren-Urba and Baumgartner, 1993; García-Morales et al. 2012). The comparison with other climatic indices was lower, however, the figures suggest that climate variability may play an important role of drastic changes in the stock biomass of this fishery, as occurs along the coast of California (Murphy 1966; MacCall 1979; Lluch-Belda et al. 1986, 1991). At present, it is not possible to conclude which one of these two factors is more important in the decline of the stock biomass—climate variability or fishing mortality. Both factors have played a very important role in the decline of catch. The gulf sardine is considered a migratory visitor by Bakun et al. 2009; however, others assume that the gulf stocks are separate from the West Coast (Schwartzlose et al. 1999). There is evidence that the stocks are essentially isolated and despite some connection, it is nonsignificant (Vrooman 2011).

Moreover, the simulation suggests that, by increasing the age of first catch from 1 to 3, the catch would increase from 88,800 mt to 93,000 mt, and the profits would increase from $5.7 million to $6.0 million. For some unexplained reason, there is no difference in catch or profits with tc = 2.

Shin et al. 2005 states that regimes of exploitation of catching immature fish causes an evolutionary change in the size and age-structure of populations, leading to smaller size and average age of capture. In addition, an unexplained increase in ecological density caused by an unknown change in the habitat that may have stimulated an increase in schooling behavior is another aspect that should affect population structure. This may modify the predator-prey interactions (Froese et al. 2008), which may affect the stability of the community and the pelagic ecosystem (Bascompte et al. 2005) of sardines. This could induce a reduction of the *MSY* level affecting the economic value of this fishery (Trexler and Travis 2000). At current levels, this fishery has been economically efficient, and it is not clear whether a significant increase in *F* should be applied to achieve the *MEY* because the uncertainty induced by climate variability may lead to a sudden and unexpected decrease in the stock biomass available for exploitation. For this reason, it may be preferable to adopt a cautionary approach by keeping the fishery at reasonably low levels of fishing intensity of 4,000 to 6,000 fishing days per season. For a management regimen to ensure the highest possible stock biomass, the current fishing condition should be changed, not only because the size at sexual maturity is strongly correlated with growth, maximum size, and longevity (Froese and Binohlan 2000), but also because the yield and profits could be higher than the current situation. Additionally, overfishing of recruits has adverse effects on the population because this reduces the spawning stock (Pauly et al. 1989). Innovative management frameworks may be required to determine defensible trade-offs between precaution and resource exploitation (Bakun et al. 2009). Unfortunately, the natural variability of the stock biomass evidenced in our results constrains the possibility to consider optimum exploitation values as reliable management options.

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