NOAA Technical Memorandum NMFS-NWFSC-139

Ecosystem Status Report of the California Current for 2017:

A Summary of Ecosystem Indicators Compiled by the California Current Integrated Ecosystem Assessment Team (CCIEA)

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U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
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Chris Harvey, Newell Garfield, Gregory Williams,
Kelly Andrews, Caren Barceló, Katie Barnas, Steven Bograd,
Richard Brodeur, Brian Burke, Jason Cope, Lynn deWitt,
John Field, Jennifer Fisher, Correigh Greene, Thomas Good,
Elliott Hazen, Daniel Holland, Michael Jacox, Stephen Kasperski,
Su Kim, Andrew Leising, Sharon Melin, Cheryl Morgan,
Stuart Munsch, Karma Norman, William T. Peterson, Melissa Poe,
Jameal Samhouri, Isaac Schroeder, William Sydeman, Julie Thayer,
Andrew Thompson, Nick Tolimieri, Anna Varney, Brian Wells,
Thomas Williams, and Jeannette Zamon

Northwest Fisheries Science Center
2725 Montlake Boulevard East
Seattle, Washington 98112

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Executive Summary

This document is a companion to the ecosystem status report (ESR) provided by the California Current Integrated Ecosystem Assessment team (CCIEA) to the Pacific Fishery Management Council (PFMC) in March of 2017. The CCIEA team provides such reports annually, as one component of the overall CCIEA goal of providing quantitative, integrative science tools, products, and synthesis in support of ecosystem-based management of marine resources in the California Current.

The indicators summarized in this report represent our best understanding of environmental, ecological, and socioeconomic conditions in the California Current Ecosystem approximately through 2016, though some time series are slightly more up-to-date and others slightly less so depending on the time required for data processing. The indicators have been codeveloped by the CCIEA team and the PFMC through an iterative process since the inception of the CCIEA project in 2009.

Oceanographic and climate-related indicators revealed a shift relative to the previous several years. Following the unprecedented warm anomaly of 2013–16 and the major El Niño event of 2015–16, most large-scale climate indices for the Northeast Pacific (the Oceanic Niño Index, the Pacific Decadal Oscillation, and the North Pacific Gyre Oscillation) returned to relatively neutral values. Coastal upwelling was relatively weak in the northern California Current throughout 2016; upwelling along the central coast was initially weak, but strengthened by summer, while upwelling on the southern coast was average to above-average. Snowpack rebounded from the extremely low levels of 2015, although much of the 2016 snow melted rapidly, leading to low streamflows; precipitation was well above average in early 2017.

Ecological indicators are expected to lag, to varying degrees, behind the shift in oceanographic and climate patterns. Copepod biomass off Newport, OR, was dominated by relatively energy-poor species as of fall 2016, similar to observations from the last several years. The spring/summer pelagic forage community was once again highly diverse in 2016. Surveys experienced poor catches of sardine (*Sardinops sagax*), market squid (*Doryteuthis opalescens*), and euphausiids. However, surveys had high but patchy catches of juvenile rockfish (*Sebastes* spp.), juvenile Pacific hake (*Merluccius productus*), and anchovy (*Engraulis mordax*). Chinook salmon (*Oncorhynchus tshawytscha*) escapements through 2014–15 varied by region and life-history type. Environmental conditions appear to have been poor for Chinook and coho salmon (*O. kisutch*) that went to sea over the past several years. California sea lions (*Zalophus californianus*) at the San Miguel Island colony experienced very poor foraging conditions to support pups in the 2015 cohort, though preliminary evidence suggests better conditions for the 2016 pups.

Socioeconomic indicators are primarily focused on fishing activity and on human wellbeing in fishery-dependent coastal communities. Commercial fishing landings and revenues declined markedly in 2015, driven mainly by drops in the harvest of Pacific hake, coastal pelagic species, and crabs. The diversification of commercial fishery landings continued the long-term declining trend at all scales (i.e., by state, vessel size, and ex-vessel revenue levels). An index of social vulnerability suggested that several commercial fishing-dependent coastal communities have disproportionately high social vulnerability, and therefore may be heavily impacted by shocks to commercial fishing revenues.

Introduction

Ecosystem-based management of fisheries and other marine resources has emerged as a priority in the U.S. (Ecosystem Principles Advisory Panel 1999, Fluharty et al. 2006, McFadden and Barnes 2009, NMFS 2016) and for many marine resource management agencies worldwide (Browman et al. 2004, Sainsbury et al. 2014, Walther and Möllmann 2014, Long et al. 2015). According to its official policy statement, the NOAA National Marine Fisheries Service (NOAA Fisheries) defines ecosystem-based fisheries management (EBFM) as "*a systematic approach to fisheries management in a geographically specified area that contributes to the resilience and sustainability of the ecosystem; recognizes the physical, biological, economic, and social interactions among the affected fishery-related components of the ecosystem, including humans; and seeks to optimize benefits among a diverse set of societal goals*" (NMFS 2016). This definition includes considerations of interactions within and among fisheries, protected species, aquaculture, habitats, and human communities that depend upon fisheries and related marine ecosystem services. It also includes consideration of the direct and indirect impacts of fisheries on other ecosystem components. An EBFM approach is intended to improve upon traditional fishery management practices that primarily are focused on the level of individual fished stocks.

Successful implementation of EBFM requires a considerable amount of effort and coordination, due to the formidable amount of information required and uncertainty involved. Research on marine systems and adjacent, associated systems amasses tremendous amounts of data from numerous disciplines. These data represent a wide range of processes and are expressed in currencies ranging from physical or chemical units to species biomass estimates to revenue streams or sociological measures. Assimilating this volume of diverse information into synthesis products is inherently difficult. Furthermore, even the best modern monitoring programs are still confronted with uncertainties because of the technical, logistical, and financial challenges of measuring statuses and changes in large, complex, and highly variable systems like the ocean and the human societies that depend upon and interact with it.

In response to this complexity and uncertainty, scientists throughout the world have developed many frameworks for organizing science and information in order to clarify and synthesize this overwhelming volume of data into science-based guidance for policymakers. NOAA Fisheries has adopted a framework called Integrated Ecosystem Assessment (IEA; Levin et al. 2008, Levin et al. 2009), which can be summarized in five progressive steps (Figure 1):

1. Identifying and scoping ecosystem goals, objectives, targets and threats.
2. Assessing the status and trends of the ecosystem through the use of valid ecosystem indicators.
3. Assessing the risk of key threats and stressors to the ecosystem.
4. Analyzing management strategy alternatives and identifying potential tradeoffs.
5. Implementing selected actions, and monitoring and evaluating management success.

As implied by Figure 1, this approach is iterative. Following the implementation of management actions, all other steps in the IEA loop must be revisited in order to ensure that a) evolving goals and objectives are clearly identified, b) monitoring plans and indicators are appropriate for the management objectives in mind, c) existing and emerging risks are properly prioritized, and d) management actions are objectively and regularly evaluated for success.

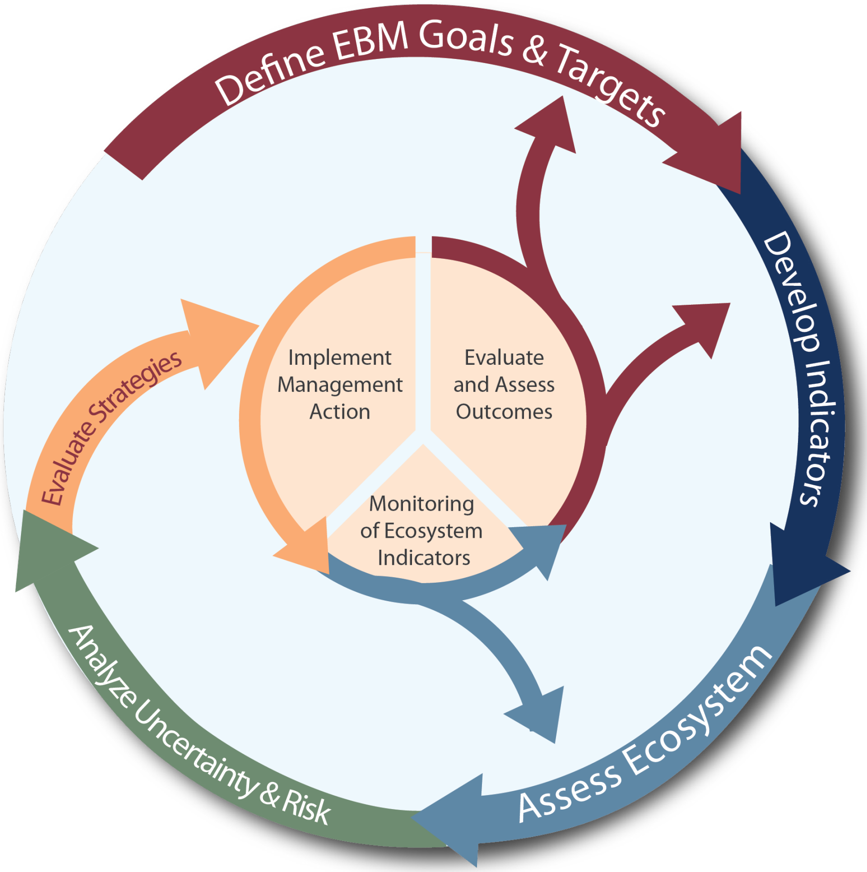

Figure 1. Loop diagram of the five progressive steps in iterations of the integrated ecosystem assessment (IEA) process. From Samhouri et al. (2014).

As the IEA framework was adopted at the national level, regional teams began implementing the IEA approach in different large marine ecosystems in U.S. waters. In 2009, NOAA line offices along the U.S. West Coast initiated the California Current Integrated Ecosystem Assessment (CCIEA). The CCIEA team focused on the California Current, a major current system oriented north–south at the eastern boundary of the northeast Pacific Ocean. The California Current flows along the West Coast of North America from central Vancouver Island, Canada, in the north, to Punta Eugenia, Mexico, in the south. Since its inception, and in keeping with the principles of ecosystem-based management, the CCIEA team has recognized that the California Current Ecosystem (CCE) is a dynamic, interactive, social–ecological system with multiple levels of organization and diverse goals and endpoints from the natural and social sciences (Figure 2). The challenging task of assembling and interpreting information from this broad range of disciplines, locations, and time frames engages over 50 scientists from NOAA's Northwest and Southwest Fisheries Science Centers, other NOAA offices, and colleagues from other agencies, academia, and nongovernmental entities. Information on CCIEA research efforts, tools, products, publications, partnerships, and points of contact is available on the CCIEA website.[1]

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[1] http://www.integratedecosystemassessment.noaa.gov/regions/california-current-region/index.html

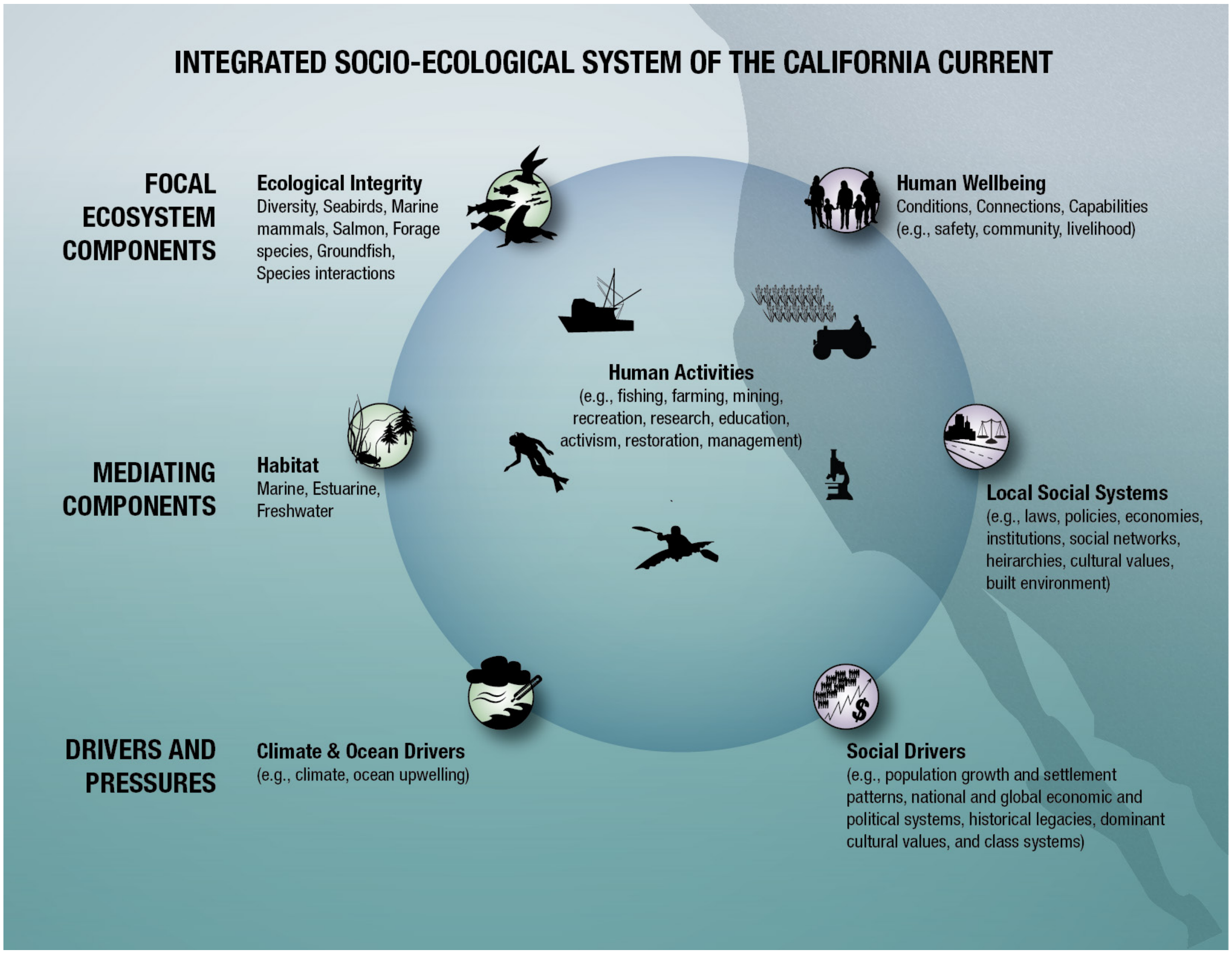

Figure 2. Conceptual model of the California Current social–ecological system. The model represents the complex and inextricable connections between natural components (left) and human components (center and right). These components are arranged in three tiers: 1) focal ecosystem components, which are often associated with broad objectives such as ecological integrity and human wellbeing; 2) mediating components, such as habitat and local social systems; and 3) drivers and pressures, which are generally external forces on the ecosystem. Human activities are placed at the center to emphasize their broad extent and because they are where management actions are directly implemented in order to achieve objectives elsewhere in the system. From Levin et al. (2016).

The primary management partner of the CCIEA team to date has been the Pacific Fishery Management Council (PFMC),[2] made up of representatives from California, Oregon, Washington, and Idaho; a representative of the West Coast indigenous tribes; four at-large members; one NOAA Fisheries member; and five nonvoting members representing key state and federal partners. The PFMC is the regional fishery management council that oversees federally managed fisheries and implementation of the Magnuson–Stevens Fishery Conservation and Management Act in the Exclusive Economic Zone off the U.S. West Coast.

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[2] http://www.pcouncil.org

The PFMC manages target species directly under policies outlined in its four fishery management plans (FMPs), and may incorporate nonbinding guidance from its Fishery Ecosystem Plan (FEP),[3] first published in 2013. Section 1.4 of the FEP outlined a reporting process wherein the CCIEA team provides PFMC with a yearly update on the status and trends of physical, ecological, and social ecosystem attributes of the CCE. Specifically, the report includes information related to:

- Climate and oceanographic drivers, at scales ranging from the North Pacific basin to regions of the U.S. West Coast and inland riverine systems.
- Key species groups (e.g., plankton, macroinvertebrates, fishes, marine mammals, and seabirds) that make up the California Current food web and support its overall ecological integrity.
- Fisheries-related human activities.
- The wellbeing of humans in coastal communities along the U.S. West Coast.

The report tracks ecosystem attributes through ecosystem indicators, most of which were derived through a rigorous indicator screening process developed by Kershner et al. (2011); details of specific CCIEA indicator screening exercises are documented elsewhere (Levin and Schwing 2011, Levin et al. 2013, Harvey et al. 2014).

The overarching purpose of the ecosystem status reports is to provide the PFMC with a general sense of the condition of the ecosystem, as context for its decisionmaking. In 2015–16, an FEP "initiative" was enacted to further align the indicators in the reports to the needs of the PFMC (see Supplemental Ecosystem Workgroup Report 2).[4] Since 2012, the CCIEA team has provided the PFMC with five ecosystem status reports, most recently in March 2017. The reports have previously been available as online sections of PFMC briefing books for meetings at which the CCIEA team provided reports (November 2012, March 2014–17; also available at CCIEA Publications: Reports[5]).

This Technical Memorandum is a companion document to the ecosystem status report delivered by the CCIEA team to the PFMC in March 2017, representing the status and trends of ecosystem indicators in the CCE through 2016 and, in some cases, early 2017 (Harvey and Garfield 2017a,b). It is intended to be the first in an ongoing annual series of Technical Memorandums that will provide a more thorough ecosystem status report of the CCE than the one we present to the PFMC. We will continue to provide the annual report to the PFMC, and this Technical Memorandum series will largely be based on that report. However, as this series evolves, the Technical Memorandums will incorporate more indicators and analyses, covering a broader range of ecosystem attributes. This is because the CCIEA team looks to support other management partners in addition to the PFMC, and our goal over the next several years is for our annual ecosystem status report to feature information in support of ecosystem-based management (EBM) in other sectors and services in addition to fisheries (Slater et al. 2017). The Technical Memorandum format should therefore enable increased information content, contributions from a broader range of authors, and value to a wider range of audiences than the reports produced to date. It is our hope that these improvements will lead to greater dialogue with potential partners and stakeholders; such dialogue and engagement is at the heart of the initial step of the IEA process (Figure 1), and is essential to each other step in all iterations as well.

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[3] http://www.pcouncil.org/ecosystem-based-management/fep/

[4] http://www.pcouncil.org/wp-content/uploads/2016/09/D1a_Sup_EWG_Rpt2_SEPT2016BB.pdf

[5] http://www.integratedecosystemassessment.noaa.gov/regions/california-current-region/publications.html

Notes on Interpreting Time Series Figures

Throughout this report, many data figures will follow one of two common formats, time series plots or quad plots, both illustrated with sample data in Figure 3; see figure caption for details. Time series plots generally contain a single dataset, whereas quad plots are used to summarize the recent averages and trends for multiple time series in a single panel, as when we have time series of multiple populations that we want to compare in a reasonably simple manner. Where possible, we also include estimates of error or uncertainty in the data. Generally, error estimates are standard deviations or standard errors in the observations. In coming years, we will include model fits to time series data where appropriate; model fits will most likely be derived from Multivariate Auto-Regressive State Space (MARSS) models, as has been recommended to the CCIEA team by the PFMC Scientific and Statistical Committee's Ecosystem Subcommittee (SSCES).

Sampling Locations

Figure 4 shows the CCE and major headlands that demarcate potential biogeographic boundaries, in particular Cape Mendocino and Point Conception. We generally consider the region north of Cape Mendocino to be the "Northern CCE," the region between Cape Mendocino and Point Conception the "Central CCE," and the region south of Point Conception the "Southern CCE."

Figure 4a also shows sampling locations for much of the regional climate and oceanographic data (see Regional Climate Indicators) presented in this report. In particular, many of the physical and chemical oceanographic data summarized in this document are collected on the Newport Line off Oregon and the California Cooperative Oceanic Fisheries Investigations (CalCOFI) grid off California. Physical oceanography sampling is further complemented by basin-scale observations and models.

Freshwater habitats worldwide can be spatially grouped into "ecoregions" according to the designations of Abell et al. (2008); see also Freshwater Ecoregions of the World, FEOW[6]). The freshwater ecoregions in the CCE are shown in Figure 4b (derived from FEOW), and are the basis by which we summarize freshwater habitat indicators relating to streamflow and snowpack (see Hydrologic Indicators).

The map in Figure 4c represents sampling for most biological indicators, including copepods (Northern Copepod Biomass Anomaly), forage species (Regional Forage Availability), California sea lions (Marine Mammals), and Seabirds. Not shown is groundfish bottom trawl sampling (see Groundfish), which covers most trawlable habitat on the shelf and upper slope (depths of 55–1,280 m) in U.S. waters; the blue and green polygons in Figure 4c roughly approximate the areal extent of the NOAA Fisheries West Coast groundfish bottom trawl survey (Keller et al. 2017).

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[6] http://www.feow.org

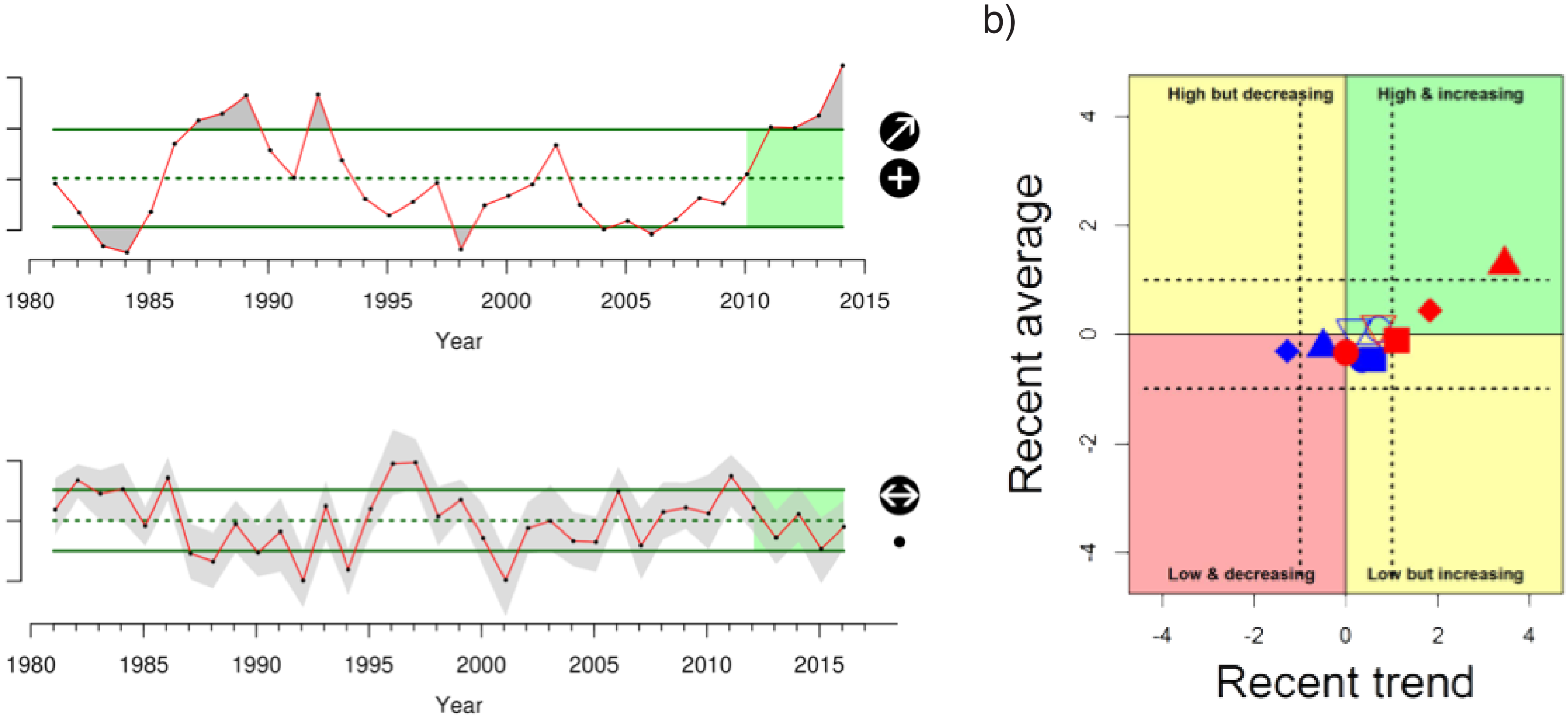

Figure 3. a) Sample time series plots, with indicator data relative to mean (dashed line) and ±1 SD, standard deviation (solid lines), of the full time series. Arrow at right indicates if the trend over the most recent 5 years (shaded green) is positive (↗), negative (↘) or neutral (↔). Symbol at lower right indicates if the recent mean was greater than (+), less than (–), or within 1 SD (·) of the long-term mean. When possible, time series include 95% confidence intervals (gray shading, lower panel). b) Sample quad plot. Each point represents one normalized time series. The position of a point indicates if the recent years of the time series are above or below the long-term average, and if they are increasing or decreasing; quadrants are "stoplight" colored to highlight the status of the indicator condition (where green = improving conditions, yellow = neutral, and red = declining conditions). Dashed lines represent ±1 SD of the full time series.

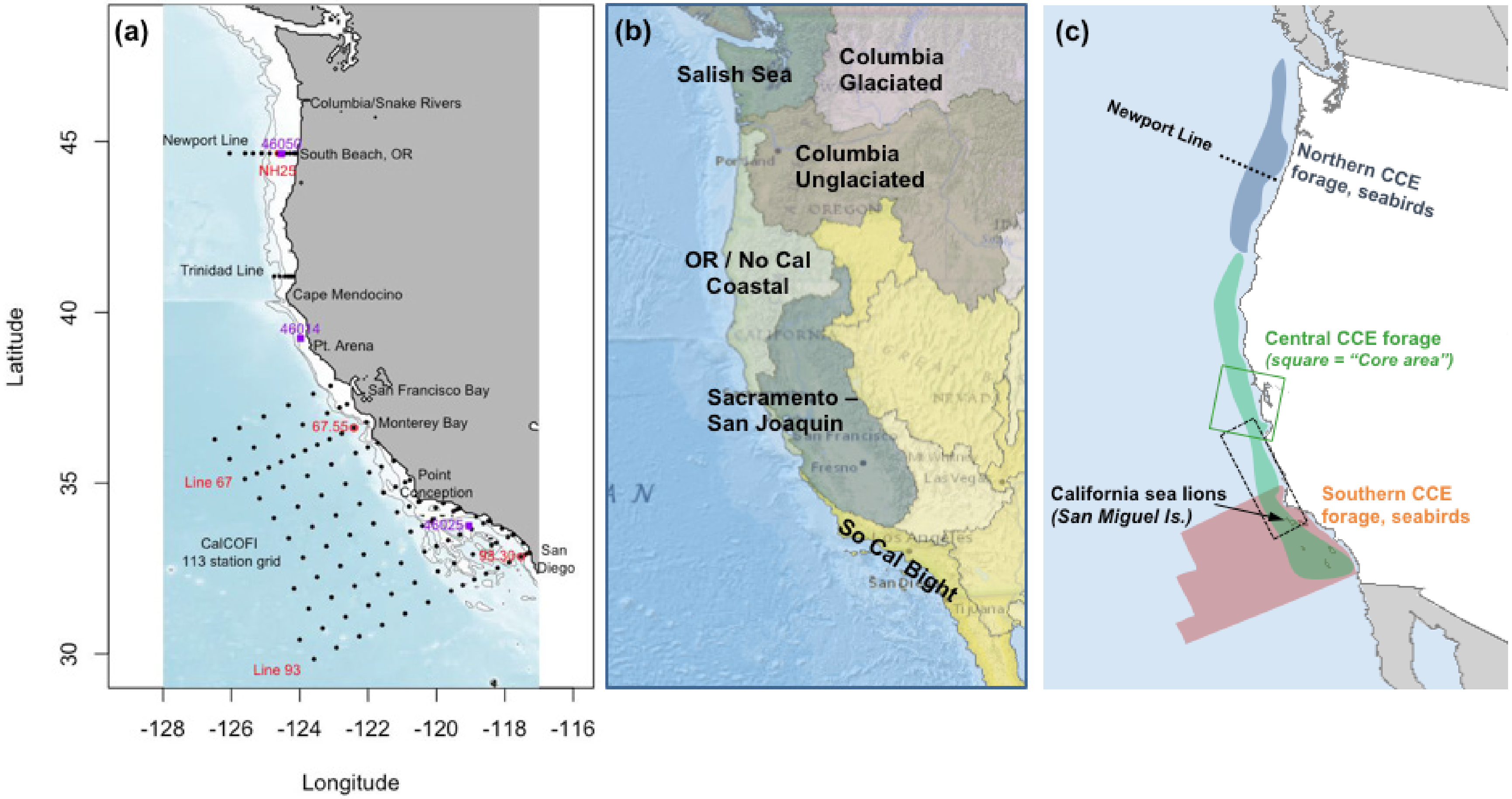

Figure 4. Maps of the California Current Ecosystem (CCE) and sampling areas. a) Key geographic features and oceanographic sampling locations. b) Freshwater ecoregions, where snowpack and streamflow indicators are measured. c) Biological sampling areas for copepods (Newport Line), pelagic forage species, seabirds, and California sea lions. Solid box = the "core" sampling area for forage in the Central CCE. Dotted box approximates the foraging area for adult female California sea lions from the San Miguel colony.

Climate and Ocean Drivers

Climate and ocean processes determine important ecosystem characteristics in the CCE, including water and air temperature, winds, currents and mixing of ocean waters, water chemistry, and precipitation. These environmental characteristics are important drivers of ecological processes and human activities. Overall, the northeastern Pacific Ocean has experienced exceptional climate variability in recent years, reaching new extremes for many indicators related to climate and ocean drivers. After a series of events beginning in 2013 that caused unprecedented warming in the CCE, conditions have changed since the summer of 2016 into the winter of 2016–17, producing cooler coastal waters and a succession of winter storms with high precipitation. A strong El Niño event peaked in the tropical Pacific in the winter of 2015–16, but its influence on the CCE was different than strong El Niño events of 1982–83 and 1997–98. Sea surface temperatures were exceptionally high, but the extent of heating into the water column was less than in past El Niño events (Figure 5). Late winter upwelling was not as weak, and upwelling was much stronger leading into the spring. The following sections provide in-depth descriptions of basin-scale, regional-scale, and hydrologic indicators of climate and ocean variability in the CCE.

Basin-Scale Indicators

The CCE is driven by atmosphere–ocean energy exchange that occurs on many temporal and spatial scales. To capture large-scale variability, the CCIEA team tracks three indices: the status of the equatorial El Niño–Southern Oscillation (ENSO), described by the Oceanic Niño Index (ONI); the Pacific Decadal Oscillation (PDO); and the North Pacific Gyre Oscillation (NPGO). Positive ONI and PDO values and negative NPGO values usually denote conditions that lead to low CCE productivity, whereas negative ONI and PDO values and positive NPGO values are associated with periods of high CCE productivity. These indices vary independently, so there is a wide range of observed variability in the CCE.

ENSO events impact the CCE by modifying the jet stream and storm tracks, deepening the nearshore thermocline, and generating coastal currents that enhance poleward transport of equatorial and subequatorial waters (and species). A positive ONI indicates El Niño conditions, which usually means more storms to the south, weaker upwelling, and lower primary productivity in the CCE. A negative ONI means La Niña conditions, which usually lead to higher productivity. The PDO is related to sea surface temperature (SST), and is derived from sea surface temperature anomalies (SSTa) in the Northeast Pacific, which often persist in "regimes" that last for many years. In positive PDO regimes, coastal SSTa in the Gulf of Alaska and the CCE tend to be warmer, while those in the North Pacific Subtropical Gyre tend to be cooler. Positive PDOs are associated with lower productivity in the CCE. The NPGO is a low-frequency variation of sea surface height, indicating variations in the circulation of the North Pacific Subtropical Gyre and the Alaskan Gyre, which in turn relate to the source waters for the CCE. Positive NPGO values are associated with increased equatorward flow, along with increased surface salinities, nutrients, and chlorophyll-*a*. Negative NPGO values are associated with decreases in such values, implying fewer subarctic source waters and generally lower productivity.

This past year saw the ONI shift from El Niño to neutral and even La Niña conditions, the PDO switch from strongly positive to neutral, and the NPGO move from strongly negative to neutral (Figure 6). Each of these indices would suggest a return to conditions of higher productivity. However, the Northeast Pacific and the CCE continued to show the aftereffects of the very anomalous conditions experienced during 2013–16. The large marine heat wave, a.k.a. "the Blob" (Bond et al. 2015), dissipated in fall 2016 in the Northeast Pacific, but anomalously warm surface waters were present in the Gulf of Alaska and immediately along the North American west coast during the winter (Figure 7). Summer SSTa showed no lasting influence of the El Niño event, with anomalies average to slightly below-average along the coast from Vancouver to San Diego. However, temperatures in subsurface waters of the Northeast Pacific remained warm, with anomalies >1°C down to 160 m and >0.5°C down to below 200 m (Harvey and Garfield 2017b). This deep warming is interpreted as a remnant effect of the marine heat wave.

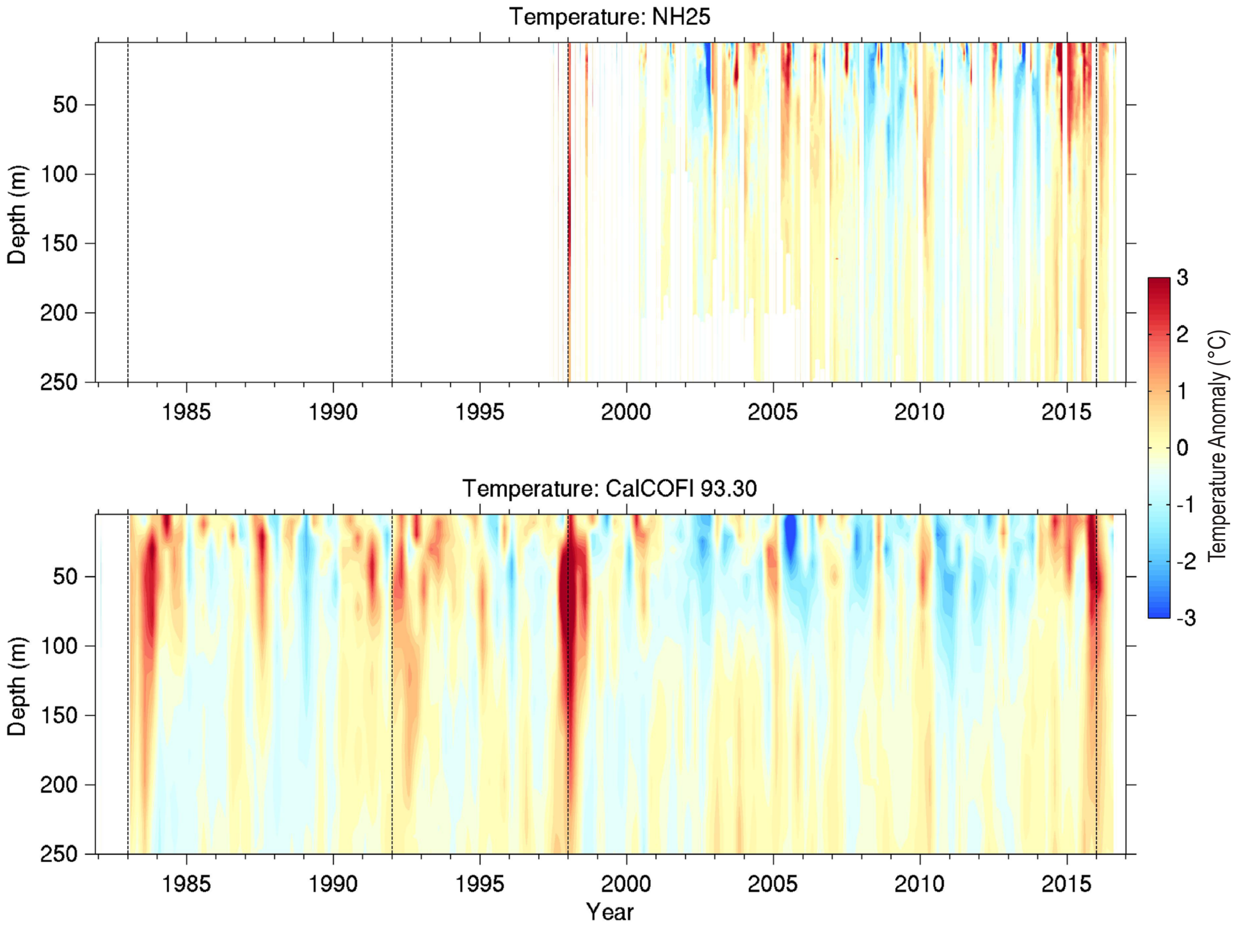

Figure 5. Time–depth temperature contours from nearshore stations NH25 and CalCOFI 93.30 (see Figure 3a). Vertical lines mark El Niño events. Newport Hydrographic (NH) line temperature data are from Dr. Bill Peterson (NOAA). CalCOFI hydrographic line data are from the CalCOFI website.[*] CalCOFI data before 2016 are CSV format files from the Access database, while 2016 data are preliminary CSV files from the CTD (conductivity, temperature, depth) database.

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[*] http://calcofi.org/data.html

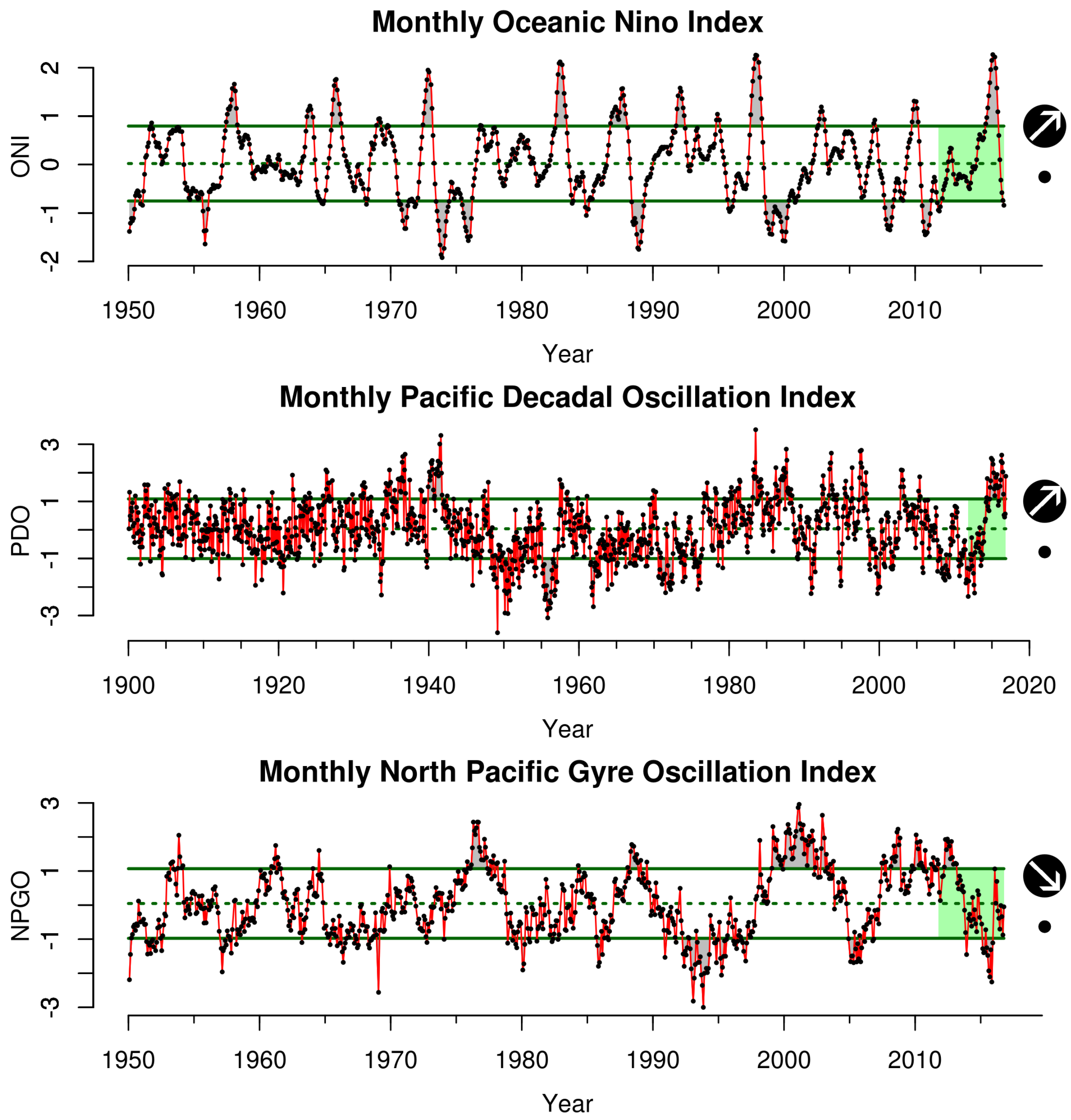

Figure 6. Monthly values of the Oceanic Niño Index (ONI; 1950–2016), Pacific Decadal Oscillation (PDO; 1900–2016), and the North Pacific Gyre Oscillation (NPGO; 1950–2016). Lines, colors, and symbols are as in Figure 3a. Oceanic Niño Index information and data are from the NOAA Climate Prediction Center.[*] Pacific Decadal Oscillation data are from Dr. Nate Mantua (NOAA) and are served by the University of Washington Joint Institute for the Study of the Atmosphere and Ocean (JISAO).[†] North Pacific Gyre Oscillation data are from Dr. Emanuele Di Lorenzo (Georgia Institute of Technology).[‡]

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[*] http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_change.shtml

[†] http://research.jisao.washington.edu/pdo/

[‡] http://www.o3d.org/npgo/

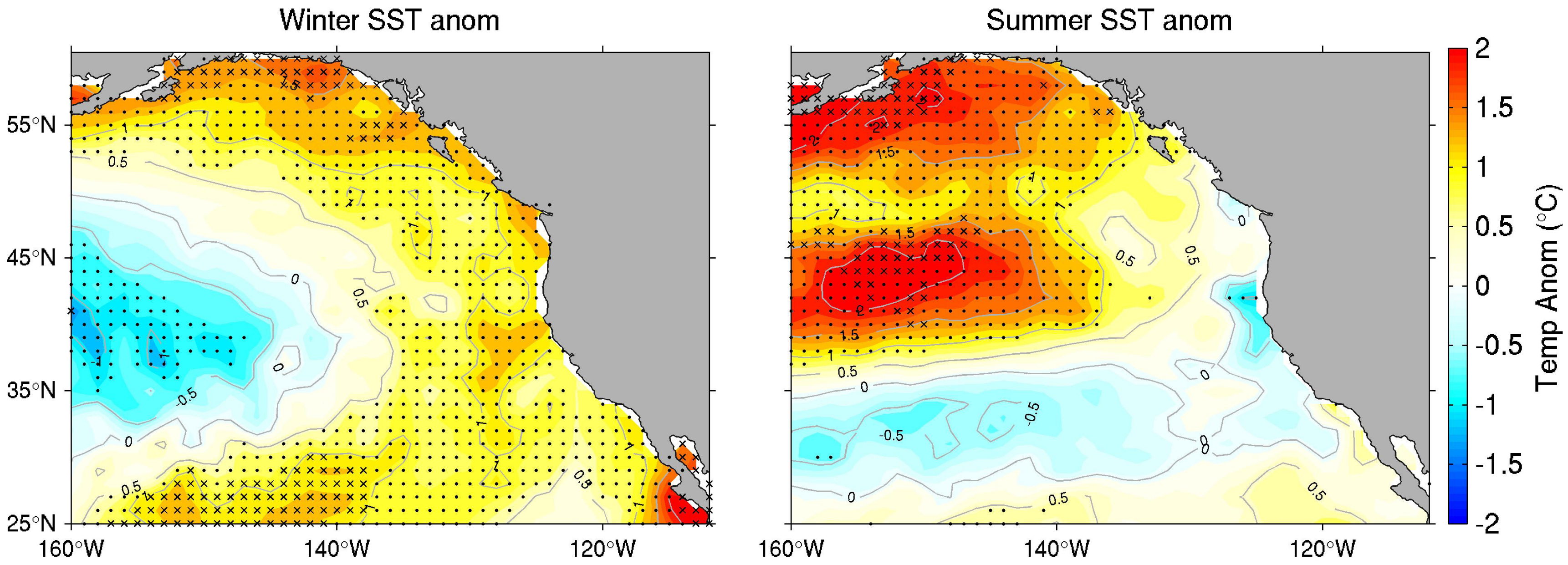

Figure 7. Sea surface temperature anomalies (SSTa) in winter (Jan–Mar, left) and summer (Jul–Sep, right), 2016. The time series at each grid point began in 1982. Positive anomalies of the marine heat wave and El Niño are seen in the Gulf of Alaska in winter and summer, and off Baja California in winter. Black circles mark cells where the anomaly was >1 SD above the long-term mean. Black Xs mark cells where the anomaly was the highest of the time series. Sea surface temperature maps are optimally interpolated remotely-sensed temperatures (Reynolds et al. 2007). The daily optimal interpolated Advanced Very High Resolution Radiometer (AVHRR) SST can be downloaded from the NOAA SWFSC Environmental Research Division Data Access Program (ERDDAP).[*]

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[*] http://upwell.pfeg.noaa.gov/erddap/griddap/ncdcOisst2Agg.html

Another marine heat wave formed off Baja California in 2014 and strengthened in 2015, keeping nearshore SSTs >0.5°C above normal. This event was likely caused by weaker atmospheric forcing in the Southern California Bight and along the Mexican coast (Leising et al. 2015, McClatchie et al. 2016). By summer 2016, SSTs in this region dropped to near-average values (Figure 7).

In summary, while the 2015–16 El Niño was one of the largest ever recorded in terms of equatorial warming and the ONI, the large-scale environmental response of the CCE was dominated in the north by the lingering impacts of the marine heat wave, with only moderate influence from the El Niño, whereas in the south, the CCE was more strongly influenced by the El Niño. Thorough summaries of these dynamics are in Leising et al. (2015) and McClatchie et al. (2016). These large-scale forces help explain the dynamics of some biological indicators in Focal Components of Ecological Integrity, below.

Regional Climate Indicators

Seasonal high pressure over the Gulf of Alaska and low pressure over the U.S. Southwest drive the upwelling-favorable winds that fuel the high spring–summer productivity that is typical of the CCE. Upwelling is a physical process of moving cold, nutrient-rich water from deep in the ocean up to the surface, and is forced by strong, northerly alongshore winds. Upwelling is critically important to productivity and ecosystem health in the CCE, as it is local coastal upwelling that allows the primary production at the base of the food web. The most common metric of upwelling is the Bakun Upwelling Index (UI), which is a measure of the magnitude of upwelling anywhere along the coast. The timing, strength, and duration of upwelling in the CCE are highly variable by region and by year. The cumulative upwelling index (CUI) is one way to display this variability. The CUI provides an estimate of the net influence of upwelling on ecosystem structure and productivity over the course of the year. The CUI integrates the onset date of upwelling-favorable winds (the "spring transition"), a general indication of the strength of upwelling, relaxation events, and the end of the upwelling season.

Upwelling strength displayed significant regional variability during 2016, with the least favorable conditions in the Northern CCE. At lat 45°N (near Newport, OR), strong downwelling from January through March was followed by average upwelling from April to July; CUI at this latitude was much lower than the strong upwelling of 2015 (Figure 8), and similar to the reduced upwelling of the 1998 El Niño event (McClatchie et al. 2016). At lat 39°N (near Point Arena, CA), the spring transition to upwelling began weakly in mid-March and strengthened in May, leading to above-average upwelling by July and comparable CUI to 2015 by August. In the Southern California Bight (lat ~33°N), the CUI was close to the long-term mean during the beginning of the season, and above average after June. This is in stark contrast to the reduced upwelling seen throughout the year in 1998 following that year's comparably large El Niño. Additional upwelling information for 2012–16 is summarized in Harvey and Garfield (2017b).

Although CUI was stronger in the south than the north in 2016, productivity did not increase concomitantly as one might expect. This is likely because of increased stratification and a deeper thermocline in this region, due to the lingering effects of the marine heat wave, plus the influence of the 2015–16 El Niño event (McClatchie et al. 2016).

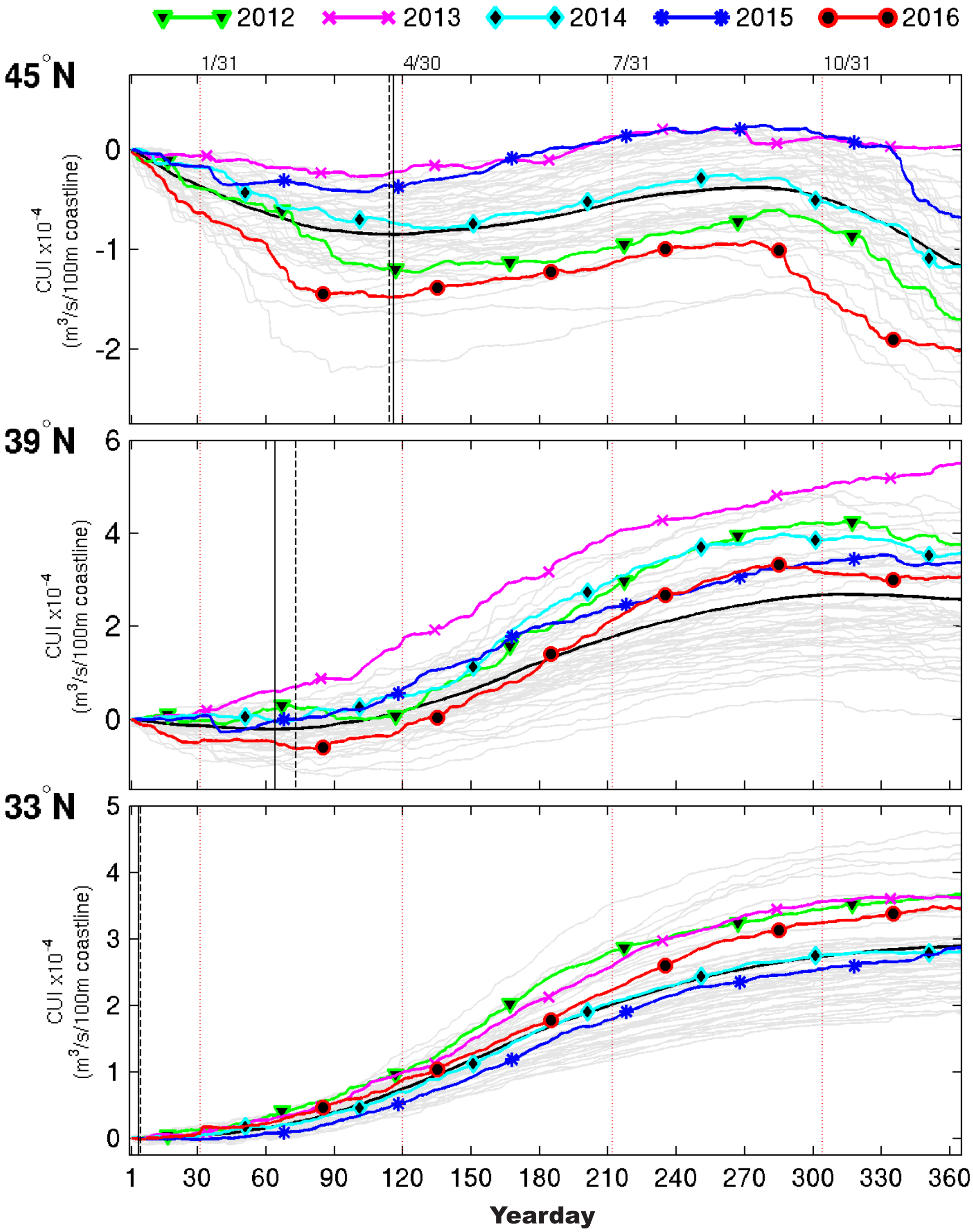

Figure 8. Cumulative Upwelling Index (CUI) at three latitudes, 1967–2016. Black trend = long-term mean; gray trends = 1967–2011; colored trends = 2012–16. Black vertical lines mark the 2016 spring transition date (dashed) and long-term mean spring transition date (solid). Dotted red vertical lines mark the ends of January, April, July, and October. Cumulative Upwelling Index curves are calculated from the six-hourly upwelling index product.*

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* http://upwell.pfeg.noaa.gov/erddap/tabledap/erdUI216hr.html

Hypoxia and Ocean Acidification

Nearshore dissolved oxygen (DO) levels and ocean acidification (OA) are related to the strength of coastal upwelling. DO is required for organismal respiration, and DO levels are dependent on a number of physical and biological processes, including circulation, air–sea exchange, and community-level production and respiration. Waters with DO levels below 1.4 ml/L (2 mg/L) are considered to be hypoxic. Low DO can compress habitat and cause stress or even die-offs for sensitive species. OA is caused by increased levels of anthropogenic CO_2 in seawater, which impacts the chemical environment of marine organisms by reducing both pH and carbonate ion concentrations. A key indicator of OA effects is aragonite saturation state, a measure of how corrosive seawater is to organisms with shells made of aragonite (a form of calcium carbonate). Values <1.0 indicate corrosive conditions that have been shown to be stressful for many CCE species, including oysters, crabs, and pteropods. Upwelling, which drives primary production in the CCE, also transports hypoxic, acidified waters onto continental shelves, where increased community-level respiration can further reduce water-column DO and exacerbate OA (Chan et al. 2008, Feely et al. 2008).

At the three stations shown here, DO was seasonally variable, with peaks in the winter, but all measurements were consistently above the hypoxia threshold of 1.4 ml/L in 2016 (Figure 9). The five-year annual trend at each site has been stable, but there is evidence of seasonal increases in DO. Briefly, station NH25 off Newport, OR, has experienced increasing winter DO over the past five years. At the nearshore station 93.90 off southern California, DO has declined since 1984, driven mainly by winter values, and was ~1 SD below the mean in winter 2016. However, the recent trend is stable and possibly increasing based on seasonal averages. At the offshore station 90.90, summer DO has increased in recent years. Nearshore DO values are almost always lower than those offshore (93.30 vs. 90.90 in Figure 9). Additional data are summarized in Harvey and Garfield (2017b).

In nearshore waters off Newport, OR (station NH5), aragonite levels at 40 m depth are typically saturated (>1.0) during the winter and spring, and then fall below 1.0 in the summer and fall; this was the case again in 2016 (Figure 10). Further offshore (station NH25) at 150 m depth, aragonite saturation state follows the same seasonal cycle but across a narrower range, and aragonite levels at this area and depth are almost always <1.0. However, aragonite levels were elevated slightly in the anomalous conditions of the past two years. In fact, according to seasonal data, winter aragonite levels have increased over the past five years at both stations (Harvey and Garfield 2017b).

Hydrologic Indicators

Freshwater conditions are critical for salmon populations and for estuarine habitats that support many marine species. The freshwater indicators presented here focus on snowpack and streamflow, and are summarized by freshwater ecoregion (Figure 4b). Snow-water equivalent (SWE) is the total water content in snowpack, which provides a steady source of freshwater into the summer months. Maximum streamflows in winter and spring are important for habitat formation, but can cause scouring of salmon nests. Minimum streamflows in summer and fall can restrict habitat for in-stream juveniles and migrating adults. All three indicators are influenced by climate and weather patterns, and will be affected as the effects of climate change intensify.

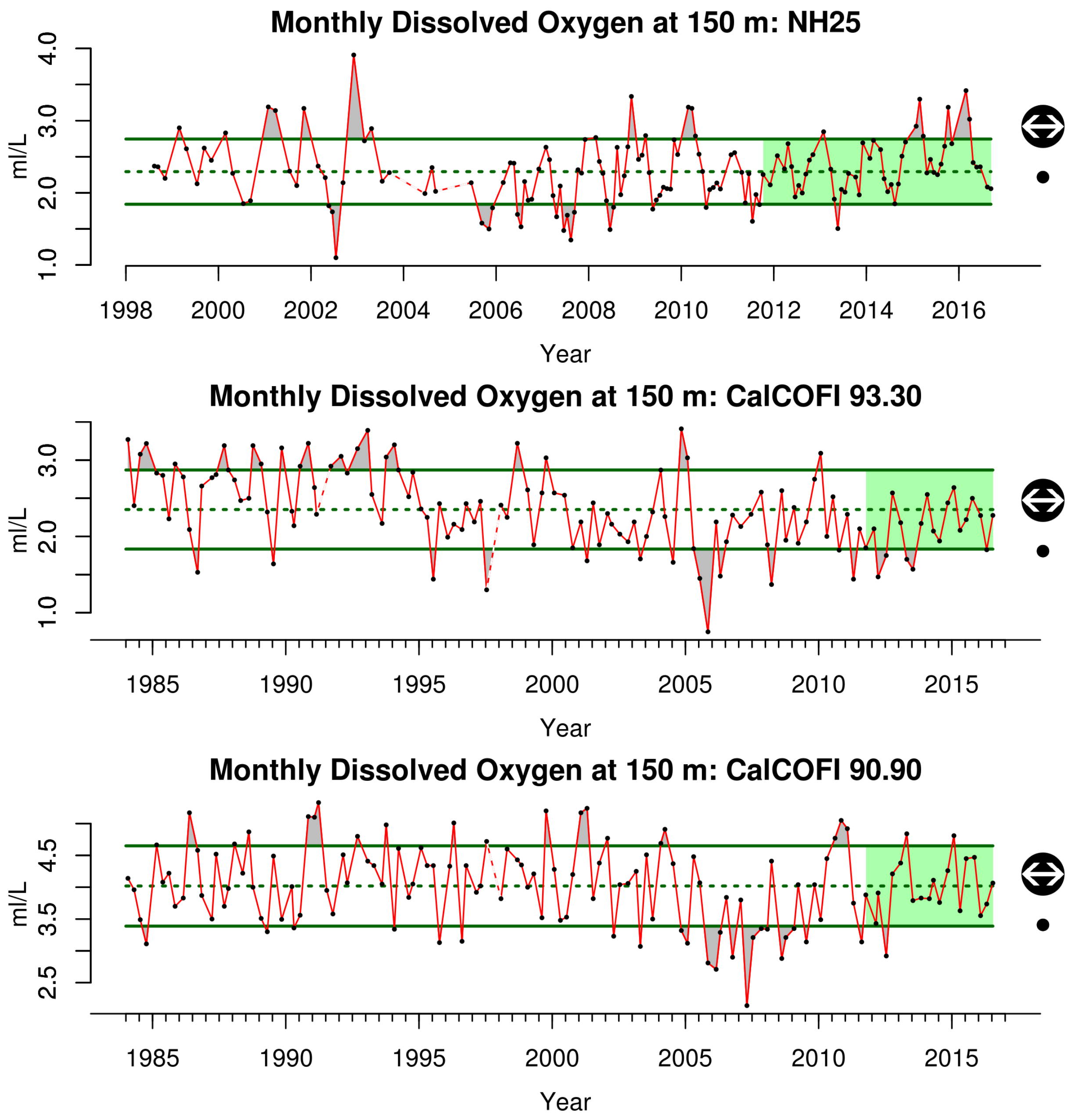

Figure 9. Dissolved oxygen (DO) at 150 m depth off Oregon and southern California through 2016. Stations NH25 (Newport, OR) and 93.30 (Southern CA) are <50 km from shore; station 90.90 (Southern CA) is >300 km from shore. Lines, colors, and symbols are as in Figure 3a; dashed red lines indicate data gaps >6 months. Newport Hydrographic (NH) line DO data are from Dr. Bill Peterson (NOAA). CalCOFI hydrographic line data are from the CalCOFI website. Note: CalCOFI data before 2016 are from the bottle data CSV database, while 2016 data are preliminary data from the CTD CSV database.

After years of steady declines and a historic low in 2015, SWE returned to average levels in all ecoregions in 2016 (Figure 11). However, despite the rebound of SWE in early 2016, high spring and summer air temperatures resulted in rapid snowmelt. These factors led to an increase in maximum flows in 2016, although not to levels considered dangerous to most salmon stocks. The early and rapid melt helped contribute to worsening trends in minimum flow in most of the ecoregions (Harvey and Garfield 2017b). SWE in 2017 was on pace to exceed 2016 following a series of winter storms earlier this year (Harvey and Garfield 2017b).

We summarized streamflow using quad plots that compile recent status and trends in flow anomalies at the finer spatial scale of individual Chinook salmon (*Oncorhynchus tshawytscha*) evolutionarily signifcant units (ESUs, sensu Waples 1995). Here, high and increasing maximum flows are regarded as undesirable (i.e., the red quadrant of the max flow plot in Figure 12) due to the potential for scouring redds; low and decreasing minimum flows are also undesirable (the red quadrant of the min flow plot) because of the potential for stress related to temperature, oxygen, or space. The maximum flow events are within ±1 SD of long-term averages and generally lack signficant trends, although four ESUs indicate a recent increase (Figure 12, left). On the other hand, miminum flow anomalies have worsening trends for many ESUs, particularly those sensitive to low-flow conditions, such as the Sacramento winter run and the Klamath/Trinity ESUs (Figure 12, right).

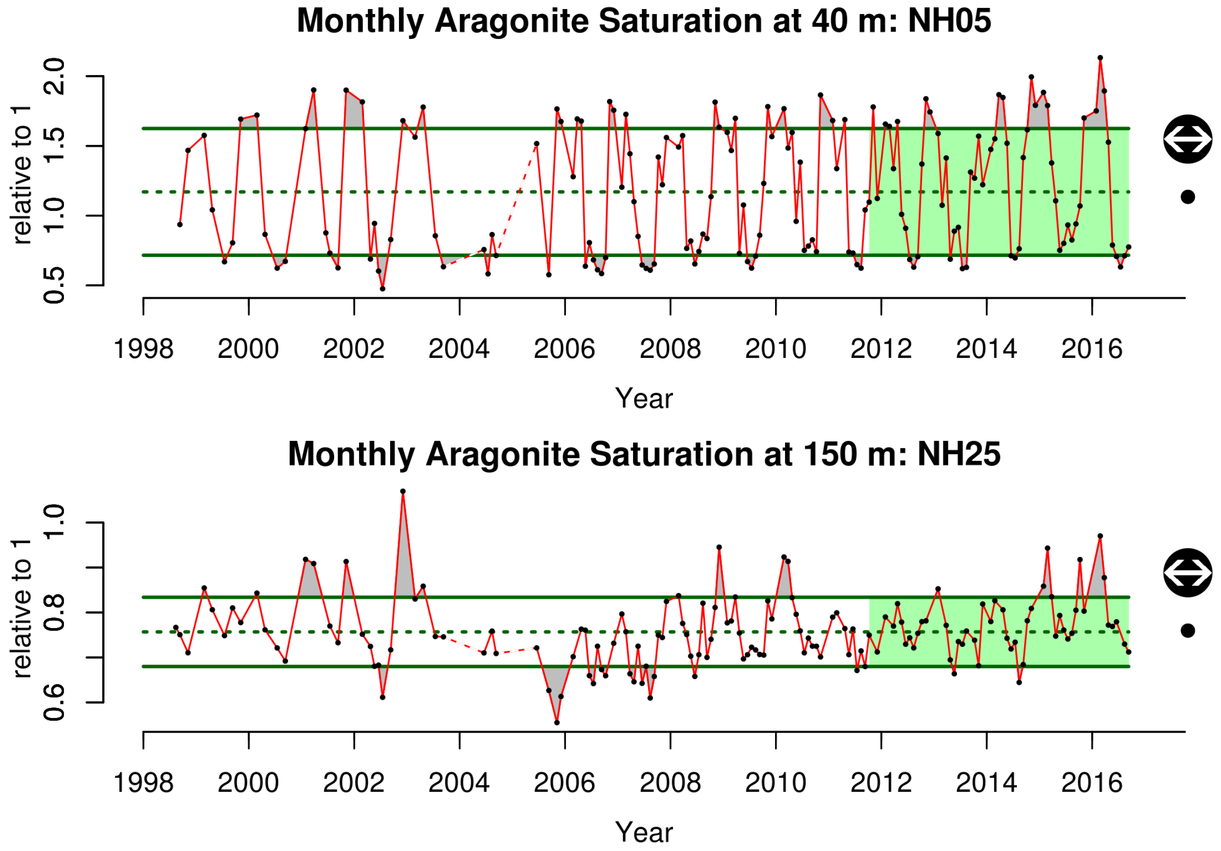

Figure 10. Monthly aragonite saturation values off of Newport, Oregon, 1998–2016. Lines, colors, and symbols are as in Figure 3a; dashed red lines indicate data gaps >6 months. Aragonite saturation state data were provided by Dr. Bill Peterson (NOAA).

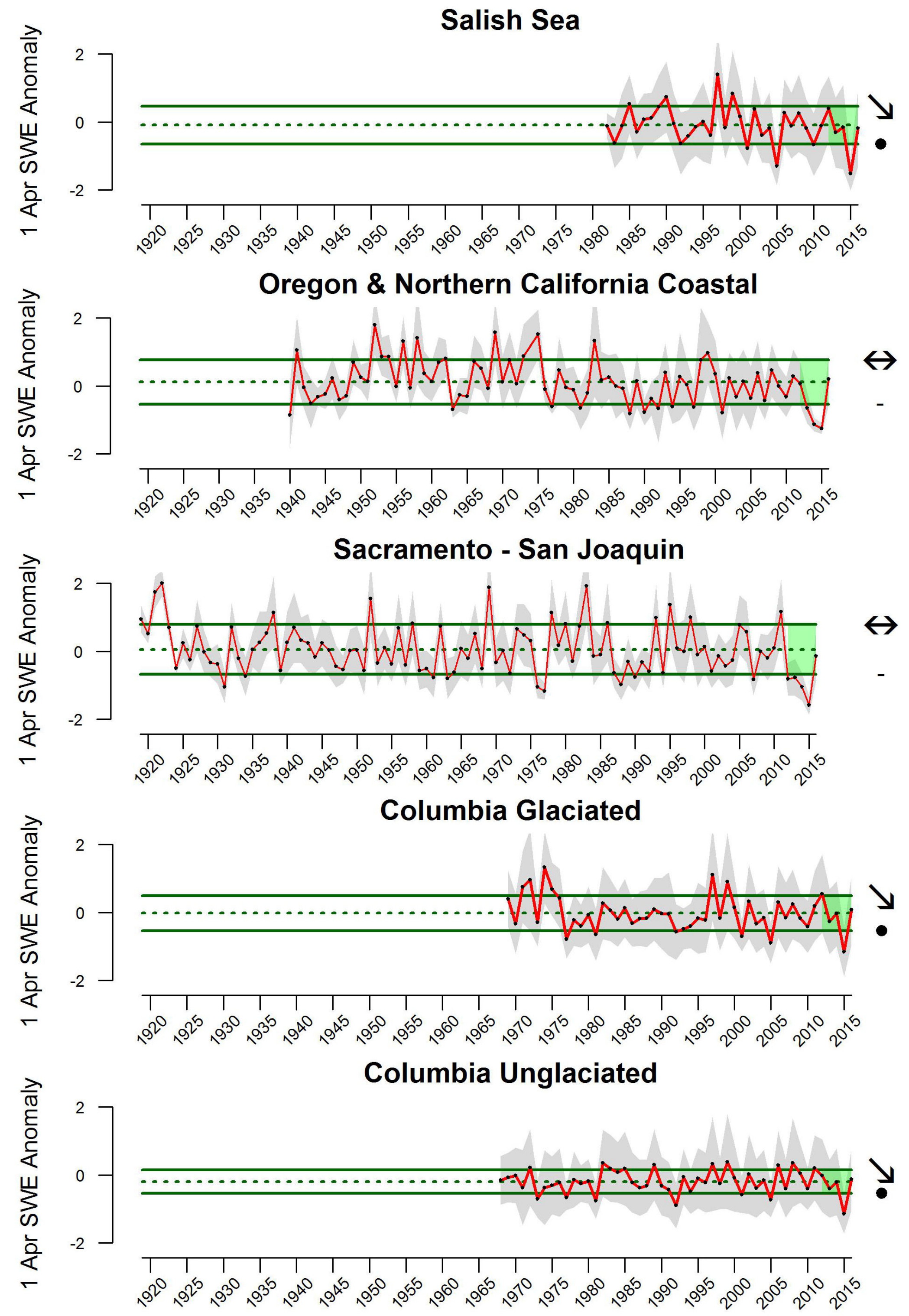

Figure 11. Anomalies of April 1st snow-water equivalent (SWE) in five freshwater ecoregions of the CCE through 2016. Lines, symbols, and colors are as in Figure 3a. Ecoregions are mapped in Figure 4a. SWE data are from the California Data Exchange Center's Resources snow survey[*] and the Natural Resources Conservation Service's SNOTEL sites[†] in WA, OR, CA, and ID.

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[*] http://cdec.water.ca.gov/snow/current/snow/index.html

[†] http://www.wcc.nrcs.usda.gov/snow/

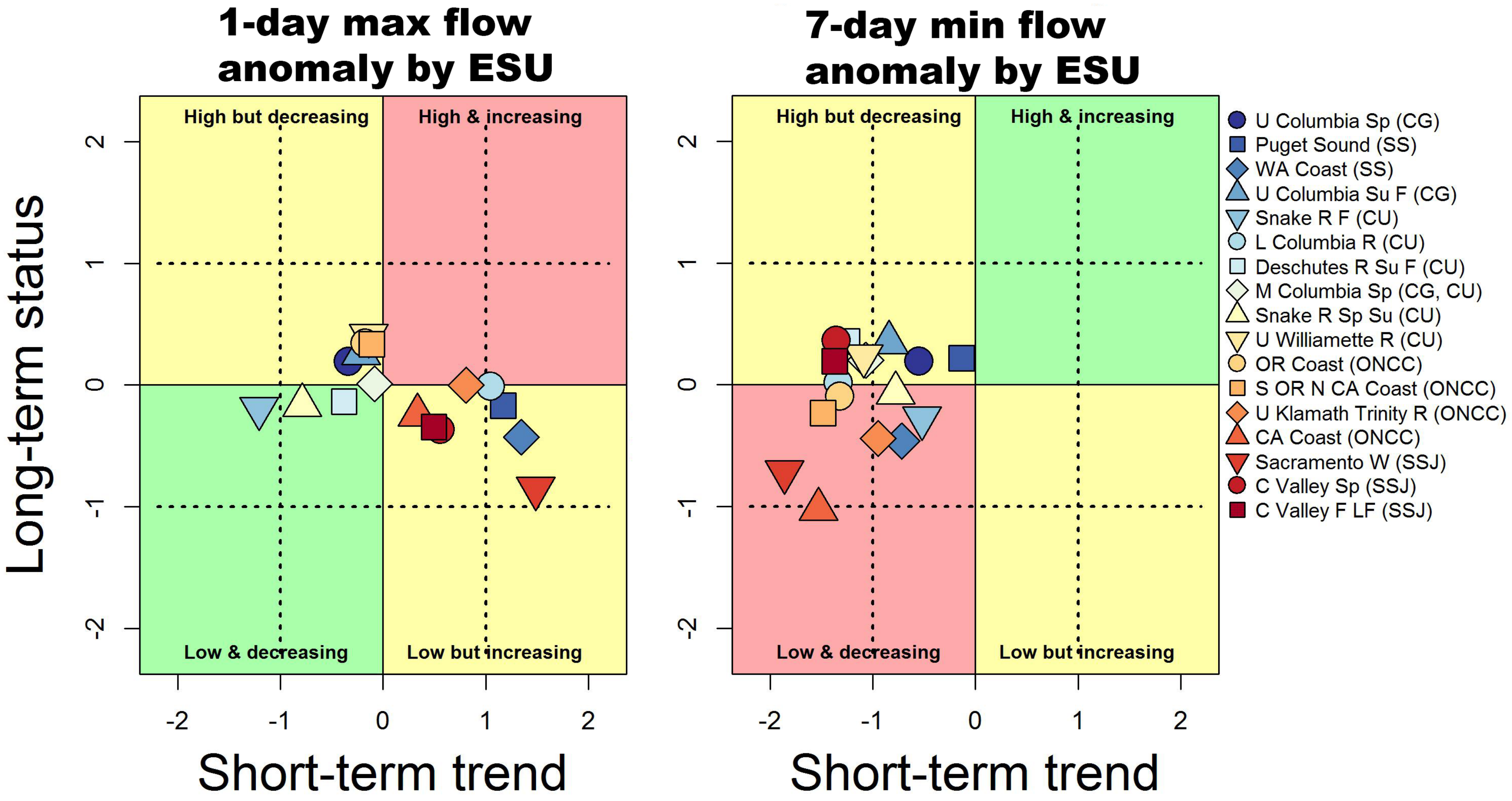

Figure 12. Quad plots of status and trends of maximum and minimum flow in 17 Chinook salmon evolutionarily significant units (ESUs) in the CCE through 2016. The five-year status and trends of flow for each ESU are divided into green (improving conditions), yellow (neutral), and red (declining conditions). Symbols of ESUs are color-coded from north (blue) to south (red). Quad plot lines and base colors are as in Figure 3b. Minimum and maximum streamflow data were provided by the U.S. Geological Survey.[*]

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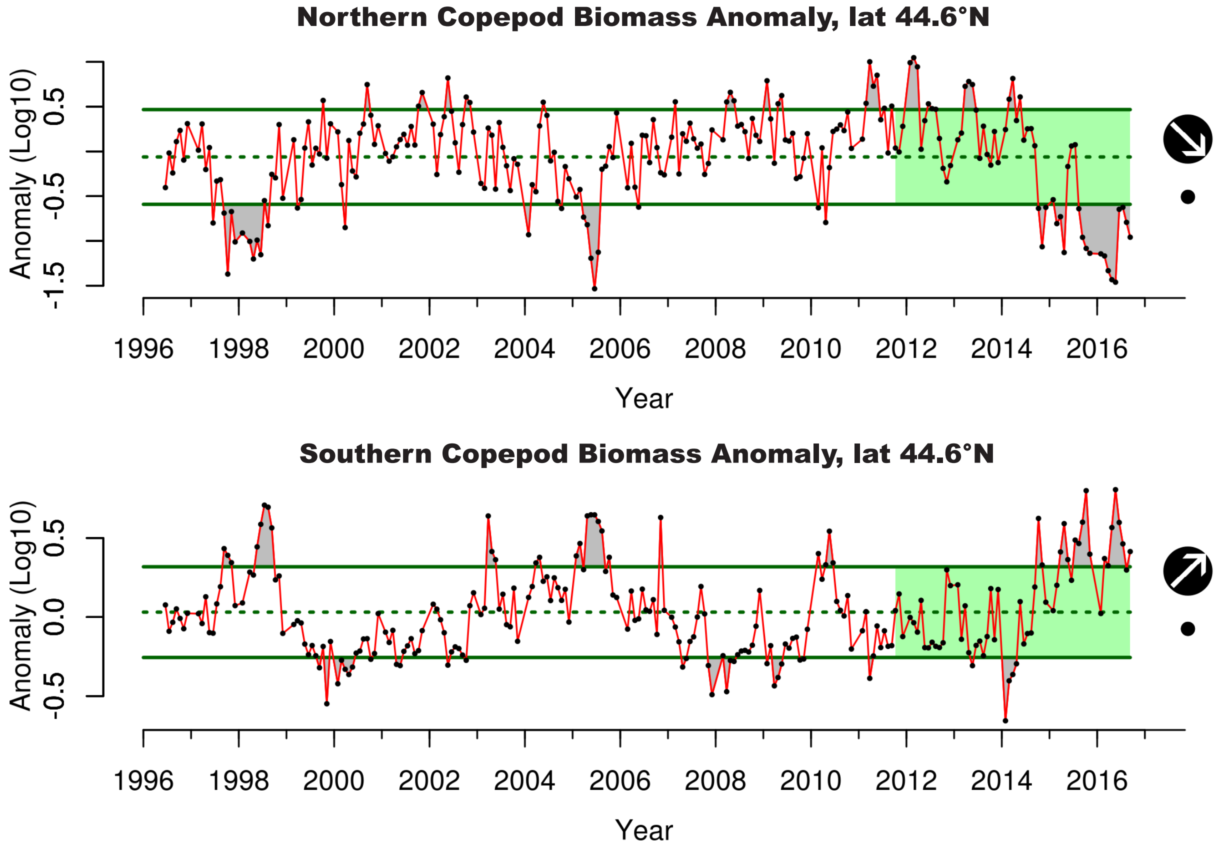
[*] http://waterdata.usgs.gov/nwis/sw

Focal Components of Ecological Integrity

The CCIEA team examines many indicators related to the abundance and condition of key species, the dynamics of community structure, and ecological interactions. Many CCE species and processes respond very quickly to changes in ocean and climate drivers, while other responses may lag by many years. These dynamics are challenging to predict. Over the last several years, many ecological integrity metrics have indicated conditions of poor productivity at low trophic levels and poor foraging conditions for many predators. In 2016, we also continued to observe unexpected community structure in pelagic waters throughout the CCE. It remains to be seen how different populations have been affected, or whether 2017 will represent a shift away from the unproductive conditions observed since 2014.

Northern Copepod Biomass Anomaly

Copepod biomass anomalies represent interannual variation in biomass of two groups of copepod taxa: northern copepods (e.g., *Pseudocalanus mimus*, *Acartia longiremis*, and *Calanus marshallae*), which are “cold-water” species rich in wax esters and fatty acids that appear to be essential for pelagic fishes, and southern copepods (e.g., *Acartia tonsa*, *Calanus pacificus*, *Calocalanus* spp.,



Northern Copepod Biomass Anomaly, lat 44.6°N

Southern Copepod Biomass Anomaly, lat 44.6°N

Figure 13. Monthly northern (top) and southern (bottom) copepod biomass anomalies from 1996–2016 in waters off Newport, OR. Lines, colors, and symbols are as in Figure 3a. Copepod biomass anomaly data were provided by Dr. Bill Peterson (NOAA).

Clausocalanus spp., *Corycaeus anglicus*, *Ctenocalanus vanus*, *Mesocalanus tenuicornis*, and *Paracalanus parvus*), which are “warm-water” species that are generally smaller and have lower lipid content and nutritional quality. In summer, northern copepods usually dominate the coastal zooplankton community as represented by collections along the Newport Line (see Figures 4a and 4c), while southern copepods dominate the community during winter. This pattern is often altered during El Niño events and/or when the PDO is positive, leading to higher biomass of southern copepods (Keister et al. 2011, Fisher et al. 2015). Threshold values for the anomalies have not been set, but positive values of northern copepods in summer are correlated with stronger returns of Chinook salmon to Bonneville Dam, and values >0.2 are associated with better survival of coho salmon (*Oncorhynchus kisutch*; Peterson et al. 2014).

With the exception of a brief period during summer 2015, the northern copepod anomaly has remained >1 SD below the long-term mean since the autumn of 2014 (Figure 13, top). During this same period, the southern copepod biomass anomaly increased significantly and was strongly positive in much of 2016 (Figure 13, bottom). These anomaly patterns are consistent with warm surface waters and poor feeding conditions for pelagic fishes, and reflect a sustained departure from the generally productive ocean conditions for much of 2011–14. Moreover, 17 species of copepods have been collected since autumn 2014 that had not been observed in these waters previously. It appears that many of these exotic copepod species were offshore, central Pacific species, not the typical southern species that are often transported northward to the Newport Line during major El Niño events.

Regional Forage Availability

This section describes trends in forage availability, based on spring/summer research cruises that have been conducted independently in three different regions (Figure 4c) for decades. The species shown below represent a substantial portion of the available forage in the regions sampled by the cruises. *We consider these regional indices of relative forage availability and variability, not indices of absolute abundance of coastal pelagic species* (CPS). Absolute abundance estimates should come from stock assessments and comprehensive monitoring programs, which these surveys are not. Moreover, the regional surveys that produce these data use different methods (e.g., gear selectivity, timing, frequency, and survey objectives); thus, the amplitudes of each time series are not necessarily comparable among regions.

The CCE forage community is a diverse portfolio of species and life history stages, varying in behavior, energy density, and availability to predators. Years with abundant pelagic fish, market squid (*Doryteuthis opalescens*), and krill (e.g., *Euphausia pacifica* and *Thysanoessa spinifera*) are generally associated with cooler waters, strong upwelling, and higher productivity (Santora et al. 2014, McClatchie et al. 2016). Here, we present the forage indicators in quad plots analogous to Figure 3b; time series data are summarized elsewhere (Harvey and Garfield 2017b).

Northern CCE

The Northern CCE survey targets juvenile salmon in June in surface waters, but also catches juvenile and adult pelagic fishes, market squid, and gelatinous zooplankton. Except for jack mackerel (*Trachurus symmetricus*), recent average catch-per-unit-effort (CPUE) of most forage species were within 1 SD of the long-term mean and showed no discernable short-term trends (Figure 14). Sardine (*Sardinops sagax*) and anchovy (*Engraulis mordax*) CPUEs remained near the lowest levels observed in this survey's time series (Harvey and Garfield 2017b). The two main species of gelatinous zooplankton were within the long-term mean range, although the small water jelly *Aequorea* sp. declined from 2015 and the large sea nettle *Chrysaora* was relatively uncommon. Anecdotally, a related survey in this region, which uses different methods and only began in 2011, caught many adult anchovy near the Columbia Plume, and saw evidence of anchovy spawning off Oregon in 2015 and 2016. The related survey also showed a steep drop in krill in 2015 and 2016, concurrent with an increase in gelatinous salps. The survey also found young-of-the-year (YOY) rockfish (*Sebastes* spp.) and Pacific hake (*Merluccius productus*) more abundant in 2016 than previous years.

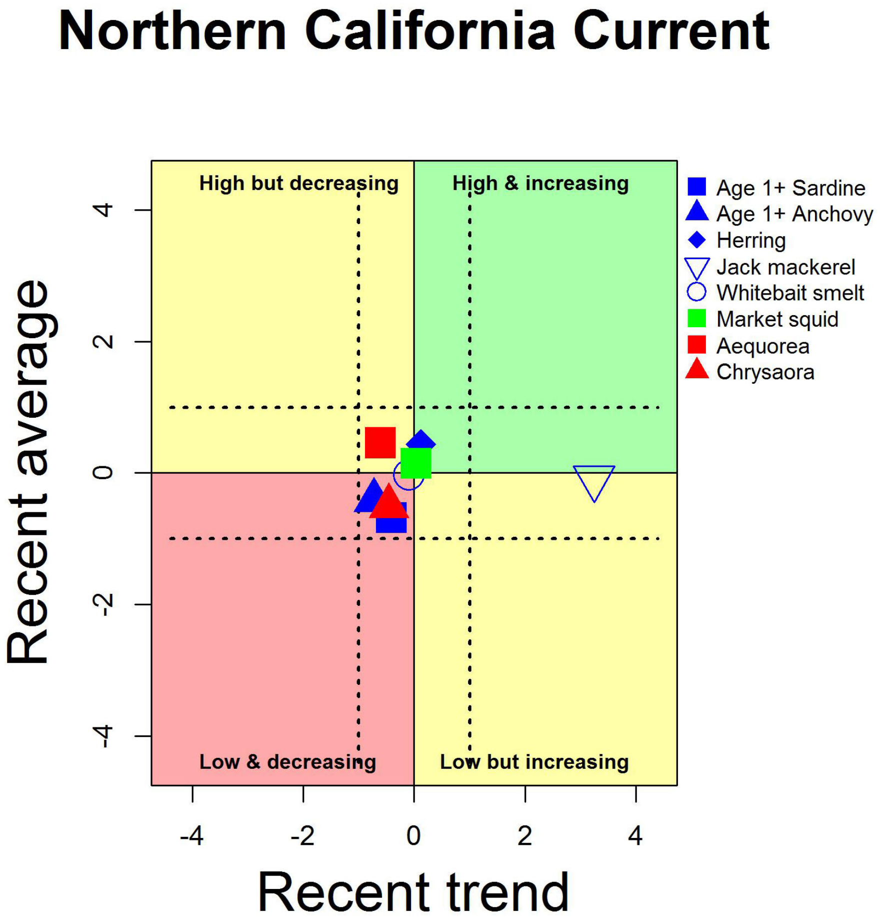


Figure 14. Means and trends of CPUE for key forage in the Northern CCE. Means and trends are from 2012–16 and normalized relative to the full time series (1999–2016). Lines, colors, and symbols are as in Figure 3b. Pelagic forage data from the Northern CCE were provided by Dr. Ric Brodeur (NOAA) and were derived from surface trawls conducted as part of the Bonneville Power Authority Plume Survey.

Central CCE

Data presented here are from the "core area" of a survey (see Figure 4c) that targets YOY rockfishes, but also samples other forage fishes, market squid, and zooplankton. The Central CCE forage community in 2016 exhibited many of the anomalous catch levels and trends observed in recent years. Adult sardine and anchovy CPUEs remained relatively low, whereas YOY rockfish CPUE was above average for the fourth year in a row (Figure 15; see also Harvey and Garfield 2017b). YOY Pacific hake CPUE also maintained its recent increase, and YOY sanddabs (*Citharichthys* spp.) remained above the long-term mean. Krill and market squid CPUE have declined in recent years, particularly squid since 2014. *Chrysaora* jellyfish also declined, though that may be due to avoidance of sites where *Chrysaora* has fouled sampling gear in the past. However, salps were relatively abundant, as were warm-water species such as pelagic crabs (*Pleuroncodes planipes*; data not shown).

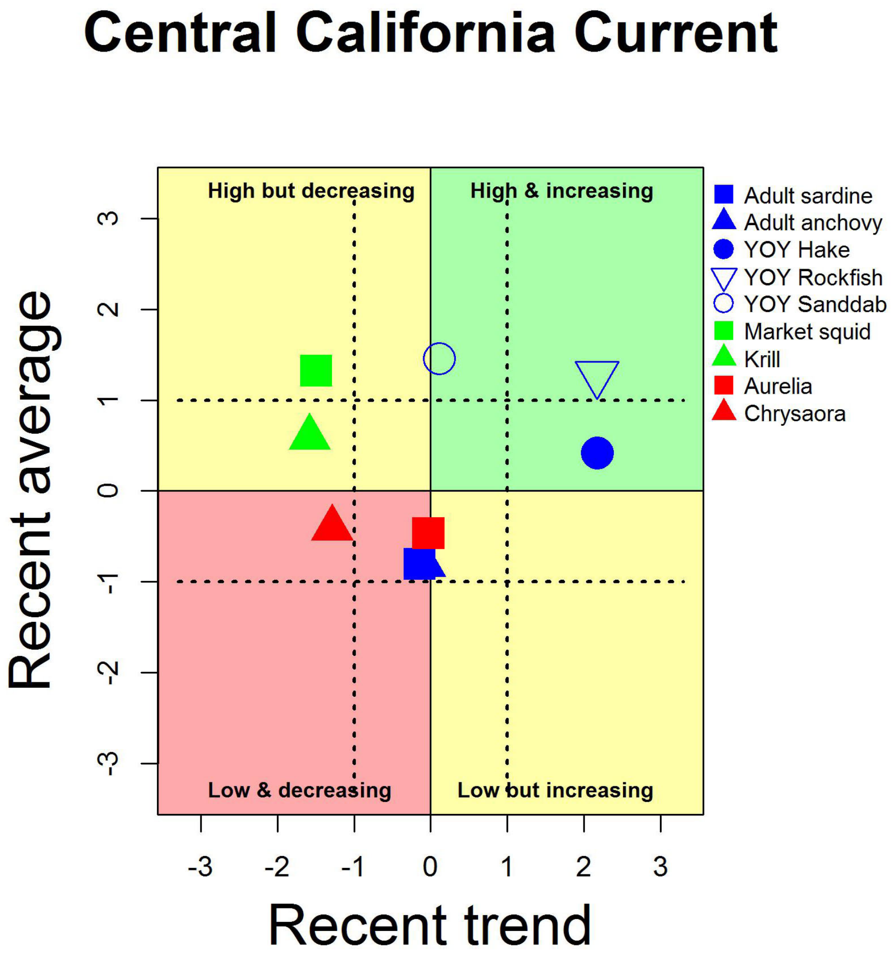


Figure 15. Means and trends of CPUE for key forage in the Central CCE (core area). Means and trends are from 2012–16 and normalized relative to the full time series (1990–2016). Lines, colors, and symbols are as in Figure 3b. Pelagic forage data from the Central CCE were provided by Dr. John Field (NOAA) from the SWFSC Rockfish Recruitment and Ecosystem Assessment Survey.*

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* https://swfsc.noaa.gov/textblock.aspx?Division=FED&ParentMenuId=54&id=20615

Southern CCE

The forage abundance indicators for the Southern CCE come from larval fish surveys conducted by CalCOFI. The larval biomass is assumed to correlate with the spawning stock biomass (SSB) of forage species such as sardine, anchovy, market squid, shortbelly rockfish (*Sebastes jordani*), and some mesopelagic species. Recent CPUE for the four species that have been analyzed through 2016 were within ±1 SD of their long-term means, but anchovy showed a significant increasing trend while market squid show a recent decline (Figure 16). The increase in larval anchovy CPUE in recent years is consistent with anecdotal nearshore observations of large schools of adult anchovy in the Southern California Bight.

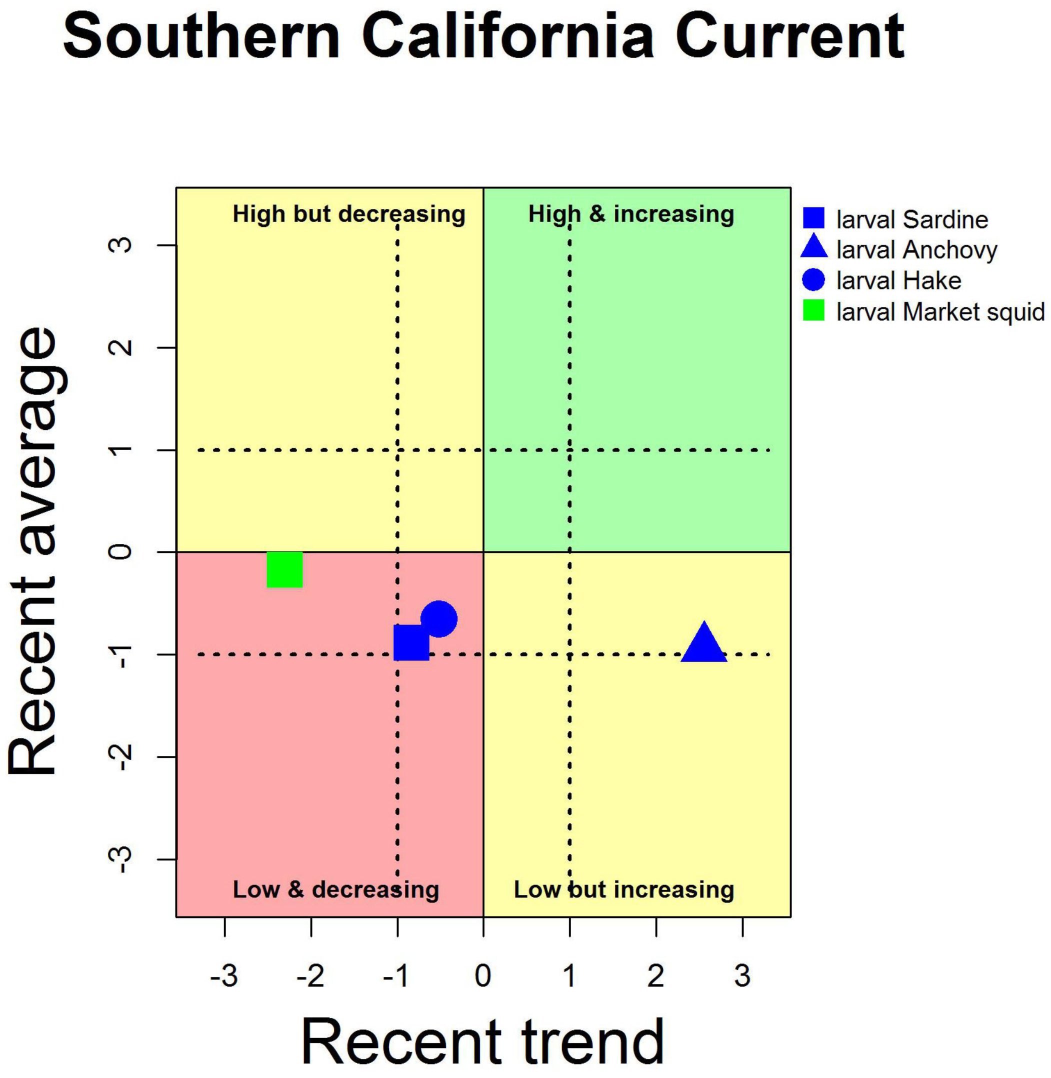

Figure 16. Means and trends of CPUE for key forage in the Southern CCE. Means and trends are from 2012–16 and normalized relative to the full time series (1990–2016). Lines, colors, and symbols are as in Figure 3b. Pelagic forage data from the Southern CCE were provided by Dr. Andrew Thompson (NOAA) and were derived from spring CalCOFI surveys.

Salmon

For indicators of the abundance of Chinook salmon populations, we compare the trends in natural spawning escapement along the CCE to evaluate the coherence in production dynamics, and also to get a more complete perspective of their status across the greater portion of their range. When available, we use escapement time series back to the 1970s; however, some populations have shorter time series (for example, Central Valley Spring starts in 1995, Central Valley Winter starts in 2001, and Coastal California starts in 1991). Here, we present the Chinook salmon escapements in quad plots; time series data for specific populations are summarized elsewhere (Harvey and Garfield 2017b).

Due to data limitations, California Chinook salmon escapements are updated only through 2015. Generally, California Chinook salmon escapements were within 1 SD of their long-term averages (Figure 17), although 2015 escapements were generally near the low end of the normal range (Harvey and Garfield 2017b). Most California stocks have neutral trends over the last decade, which is a noteworthy change from our last report: trends that had been positive for Central Valley Fall, Klamath Fall, California Coast, and Northern CA/Southern OR are now neutral after poor escapements in 2013, 2014, and/or 2015 (Harvey and Garfield 2017b). Central Valley Winter Run Chinook salmon have had relatively low escapements since 2007 following high escapements in 2005–06, leading to the recent negative trend.

For Oregon, Washington, and Idaho Chinook salmon stocks (updated through 2014), most recent escapements were close to average (Figure 17). The exception was Snake River Fall Chinook, which have experienced a series of large escapements since 2009 (Harvey and Garfield 2017b). Ten-year trends for northern stocks were either neutral or positive, with three (Lower Columbia, Snake River Fall, and Snake River Spring) having significantly positive trends from 2005–14.

Predicting exactly how the climate anomalies of 2013–16 will affect different brood years of salmon from different parts of the CCE is difficult, despite concerted efforts by many researchers (e.g., Burke et al. 2013, Wells et al. 2016). However, many signs suggest below-average returns may occur for Fall Chinook, Spring Chinook, and coho stocks returning to the Columbia Basin. The poor hydrological conditions of 2015 (see Hydrologic Indicators) were problematic for both juvenile and adult salmon. As noted above, the Northern Copepod Biomass Anomaly is positively associated with Chinook and coho salmon returns in the Columbia River basin (Peterson et al. 2014), and its low levels in recent years do not portend well. The Northern Copepod Biomass Anomaly is just one part of a long-term effort by NOAA scientists to correlate oceanographic conditions and pelagic food web structure with salmon productivity (e.g., Burke et al. 2013). Their assessment is that physical and biological conditions for smolts that went to sea between 2013 and 2016 are generally consistent with poor returns of Chinook and coho salmon to much of the Columbia Basin in 2017, as depicted in the "stoplight chart" in Table 1.

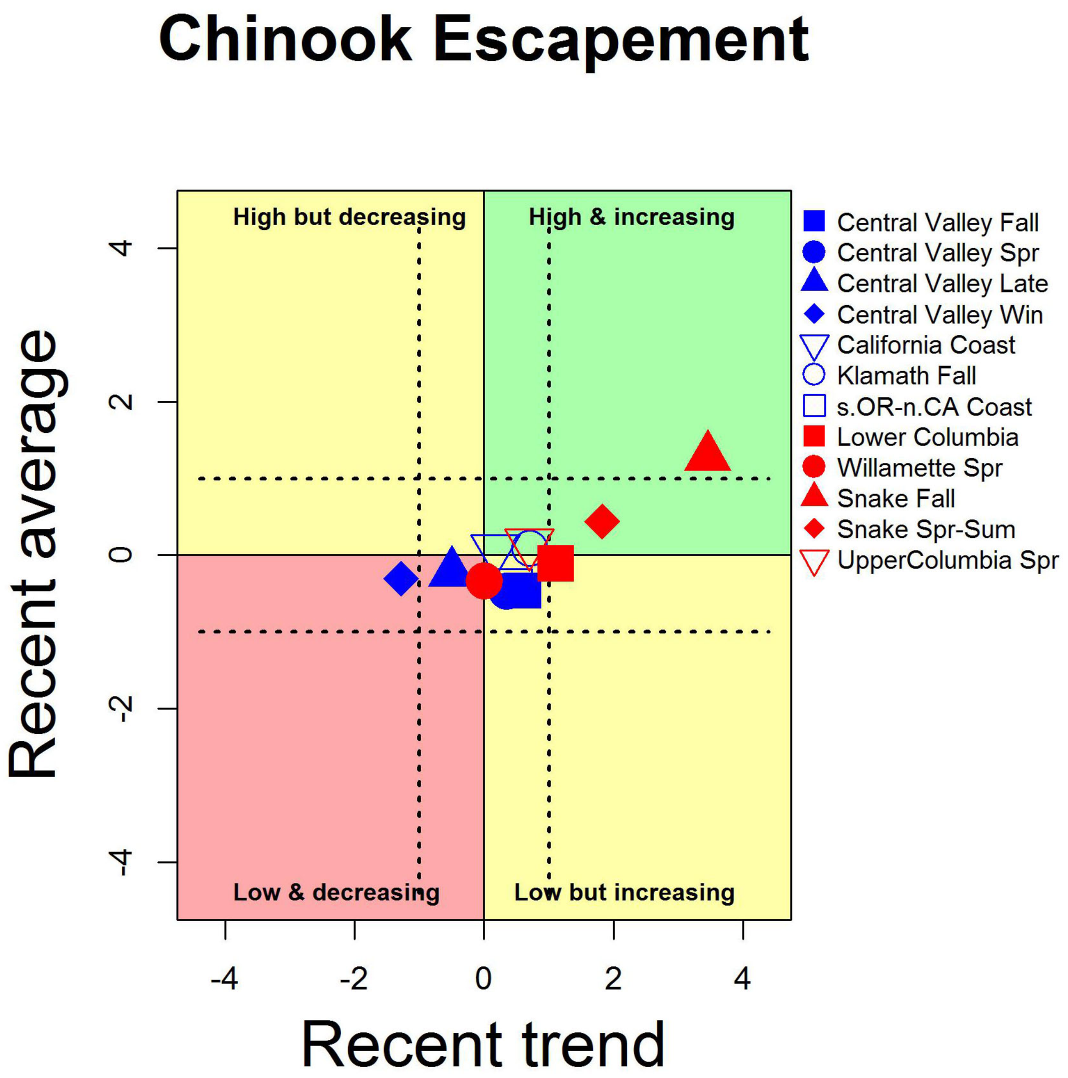

Figure 17. Chinook salmon escapement anomalies through 2015. "Recent average" is mean natural escapement (includes hatchery strays) from 2006–15 relative to the mean of the full time series. "Recent trend" indicates the escapement trend from 2006–15. Base colors and lines are as in Figure 3b. Chinook salmon escapement data were derived from the California Department of Fish and Wildlife,[*] from Pacific Fishery Management Council preseason reports,[†] and from NWFSC's "Salmon Population Summary" database.[‡]

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[*] http://www.dfg.ca.gov/fish/Resources/Chinook/CValleyAssessment.asp

[†] http://www.pcouncil.org/salmon/stock-assessment-and-fishery-evaluation-safe-documents/preseason-reports/2016-preseason-report-i/

[‡] https://www.webapps.nwfsc.noaa.gov/sps

Table 1. “Stoplight” table of basin-scale and local–regional conditions for smolt years 2013–16 and likely adult returns in 2017 for coho and Chinook salmon that inhabit coastal Oregon and Washington waters in their marine phase. Green = improving conditions, yellow = neutral, and red = declining conditions; these are based on rankings of all years sampled, e.g., if a parameter in a given year ranks among the top third most favorable years recorded, it is green, but if it ranks among the top third least favorable years, it is red. Courtesy of Dr. Bill Peterson (NWFSC).

	Smolt year				**Adult return outlook**	
Scale of indicators	**2013**	**2014**	**2015**	**2016**	**Coho, 2017**	**Chinook, 2017**
Basin-scale						
PDO (May–Sept)	🟨	🟨	🟥	🟥	🟥	🟥
ONI (Jan–Jun)	🟨	🟨	🟥	🟥	🟥	🟥
Local and regional						
SST anomalies	🟨	🟨	🟥	🟥	🟥	🟥
Deep water temp	🟥	🟥	🟥	🟨	🟨	🟥
Deep water salinity	🟥	🟥	🟨	🟨	🟨	🟨
Copepod biodiversity	🟩	🟨	🟥	🟥	🟥	🟥
Northern copepod anomaly	🟩	🟩	🟥	🟥	🟥	🟥
Biological spring transition	🟩	🟥	🟥	🟥	🟥	🟥
Winter ichthyoplankton biomass	🟨	🟥	🟩	🟩	🟩	🟩
Winter ichthyoplankton community	🟨	🟨	🟥	🟥	🟥	🟥
Juvenile Chinook catch (Jun)	🟩	🟨	🟥	🟨	🟥	🟥
Juvenile coho catch (Jun)	🟩	🟨	🟨	🟨	🟨	🟨

Groundfish: Stock Abundance and Community Structure

The CCIEA team regularly presents the status of groundfish biomass and fishing pressure based on the most recent stock assessments. About one-third of the species in the groundfish Fishery Management Plan (FMP) have been formally assessed since 2007. Two key indicators derived from these stock assessments are summarized here. The first indicator describes how close groundfish population abundances are to biomass targets or limits, including being in "overfished" status. It is expressed on the x-axis of Figure 18 in terms of the spawning output (SO) of the mature population biomass. Specifically, it is the ratio of SO in the terminal year of the assessment ($SO_{terminal}$) to the target SO that supports maximum sustainable yield (SO_{MSY}) for that stock. For flatfishes, SO_{MSY} is assumed to be 25% of the theoretical SO of an unfished population; for other groundfishes, SO_{MSY} is assumed to be 40% of unfished SO. The target reference point (TRP) for $SO_{terminal}/SO_{MSY}$ is 1.0. If $SO_{terminal}/SO_{MSY}$ falls below the established limit reference point (LRP; 0.5 for flatfishes, 0.6 for all other groundfishes), then the stock is designated to be overfished, and a rebuilding plan with various management measures will be implemented.

The second key groundfish indicator describes the fishing rate and whether or not "overfishing" (i.e., fishing greater than the target fishing rate) is currently occurring on assessed stocks. Overfishing technically occurs when catches exceed overfishing limits (OFLs), but not all assessed stocks are managed by individual OFLs. Our best alternative was to compare fishing rates to proxy fishing rates at maximum sustainable yield (F_{MSY}), which are used to set OFL values. The y-axis of Figure 18 is therefore not a direct measure of overfishing, but rather a measure of whether fishing rates are above proxy-MSY fishing rates ($F_{30\%}$ for flatfishes, $F_{50\%}$ for other groundfish). This occurs when the ratio of $F_{terminal}/F_{MSY}$ is >1.0, i.e., above the horizontal dashed line in Figure 18.

Most of the recently assessed groundfish species are near or above the biomass LRPs, and are thus not in an overfished status (Figure 18). Only two stocks (Pacific ocean perch [*Sebastes alutus*] and yelloweye rockfish [*S. ruberrimus*], both last assessed in 2011) remained below the rockfish LRP as of their most recent assessment. Only two stocks (black rockfish [*S. melanops*] stocks in California and Washington, both assessed in 2015) were being fished above F_{MSY} in their most recent assessments.

Because 2017 was a year in which many stock assessments were conducted, the information in Figure 18 will be updated substantially in the 2018 ecosystem status report, as well as in the 2018 iteration of this Technical Memorandum series.

As noted in Regional Forage Availability, YOY rockfish were highly abundant in the Central CCE in 2015 and 2016, and results from both shipboard and scuba surveys also revealed large numbers of pelagic and post-settled juvenile rockfish along the Washington coast in 2016. Given the anomalously warm and unproductive oceanographic conditions of 2013–16, these findings run counter to what we might have expected from conceptual models linking climate and productivity conditions to groundfish populations (Harvey and Garfield 2017b). It will be several years before these fish are large enough to be caught in bottom trawls; thus, we will have to wait to determine how groundfish populations changed following the recent climate anomalies.

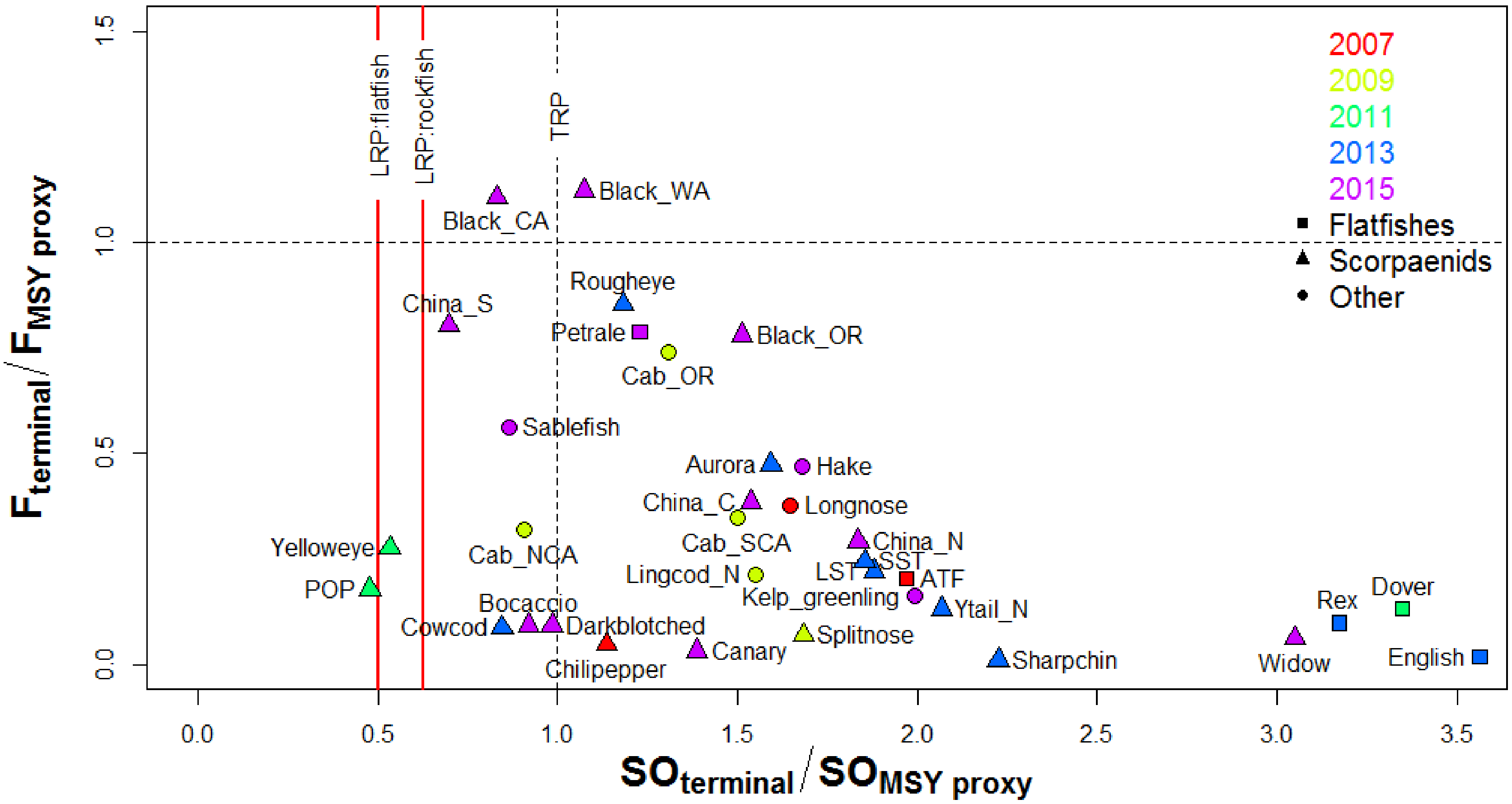


Figure 18. Stock status of CCE groundfish, based on spawning output (SO) and fishing rate (F) from the most recent stock assessment of each stock. The x-axis is an indicator of the biomass of the stock, expressed as SO in the terminal assessment year relative to SO at the theoretical stock biomass associated with maximum sustainable yield (MSY). The y-axis is an indicator of fishing pressure, expressed as F in the terminal assessment year relative to F consistent with MSY. Horizontal dashed line = overfishing rate limit reference. Vertical lines = biomass target reference point (TRP, dashed line) and limit reference points (LRP, solid lines; falling to the left of these lines indicates overfished status for flatfish or rockfish/other groundfish). Symbols indicate groupings of taxa; colors indicate year of most recent assessment. Groundfish stock status data were provided by Dr. Jason Cope (NOAA) and were derived from NMFS stock assessments.

Marine Mammals

California sea lions (*Zalophus californianus*) are permanent residents of the CCE, breeding on the Channel Islands and feeding throughout the CCE, and so are good indicators for the population status of pinnipeds in the system. California sea lions may also be sensitive indicators of prey availability in the Central and Southern CCE: the sea lion pup count in the San Miguel Island breeding colony relates to prey availability for adult females during gestation (October–June), while pup growth is related to prey availability to adult females during the 11-month lactation period (Melin et al. 2012).

Over recent years, California sea lion adult females experienced extremely poor feeding conditions (Figure 19). Pup counts declined from 2011–15, and pup growth was near historic lows in at least three of the last five cohorts. These results, coupled with high rates of springtime pup stranding and mortality in 2013–16, reflect the extent of poor foraging conditions for pinnipeds in the Central and Southern CCE and may foretell a decrease in the California sea lion adult population. Other pinniped species that breed in this region but forage further offshore (Guadalupe fur seals [*Arctocephalus townsendi*] and northern fur seals [*Callorhinus ursinus*]) also experienced poor pup growth in the same time period.

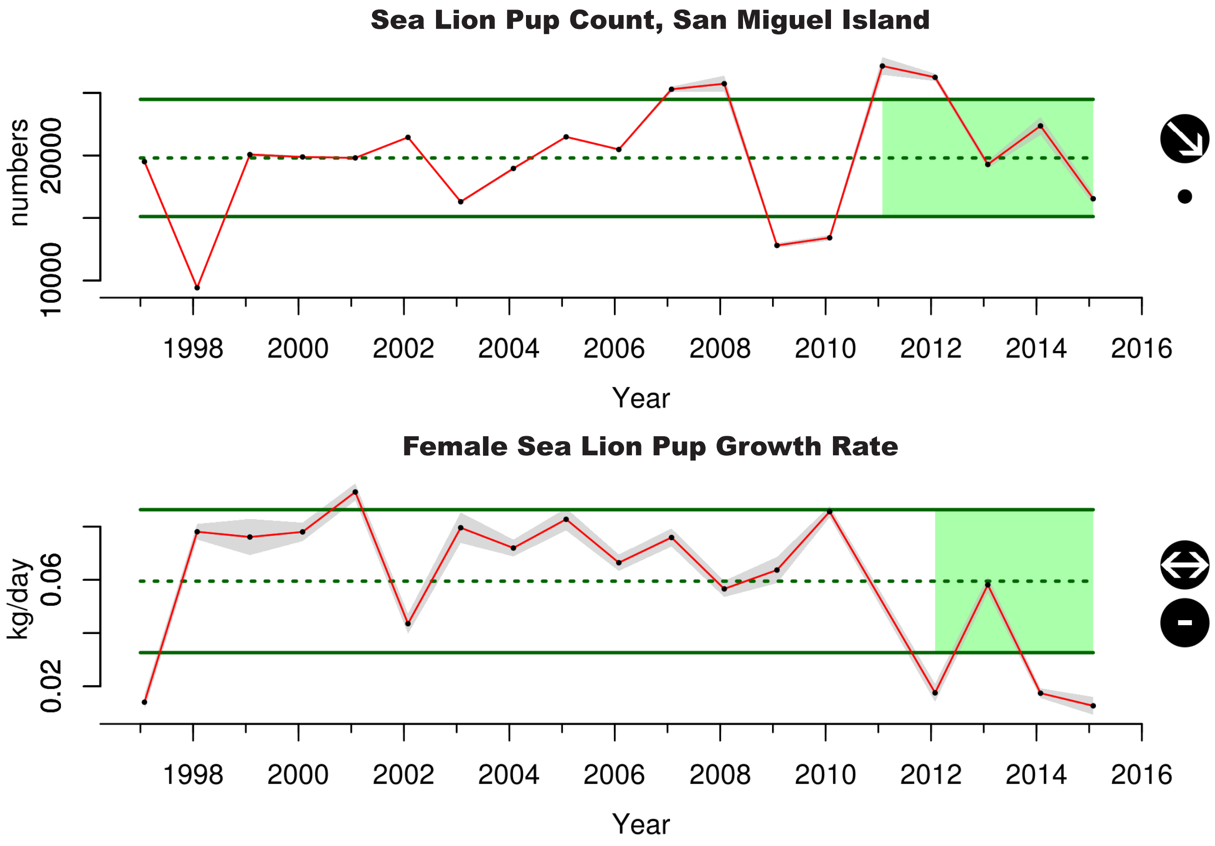


Figure 19. California sea lion pup counts at San Miguel Island (top) and estimated mean daily growth rate of female pups from 4–7 months (bottom) for the 1997–2015 cohorts. Lines, colors, and symbols are as in Figure 3a. California sea lion data were provided by Dr. Sharon Melin (NOAA).

Preliminary results suggest that the 2016 cohort of California sea lion pups at San Miguel was more abundant and experienced better early growth than the preceding four cohorts, implying that foraging conditions may have improved.

Seabirds

Seabird species richness data were unavailable for this report, so we instead present regional time series for three key species. Data are derived from visual shipboard surveys during sampling cruises in regions shown in Figure 4c. Sooty shearwaters (*Ardena grisea*) migrate from the southern hemisphere to the CCE in spring and summer to prey on small fish and zooplankton near the shelf break. Cassin's auklets (*Ptychoramphus aleuticus*) and common murres (*Uria aalge*) are resident species that feed over the shelf; Cassin's auklets prey on zooplankton, while common murres target small fish.

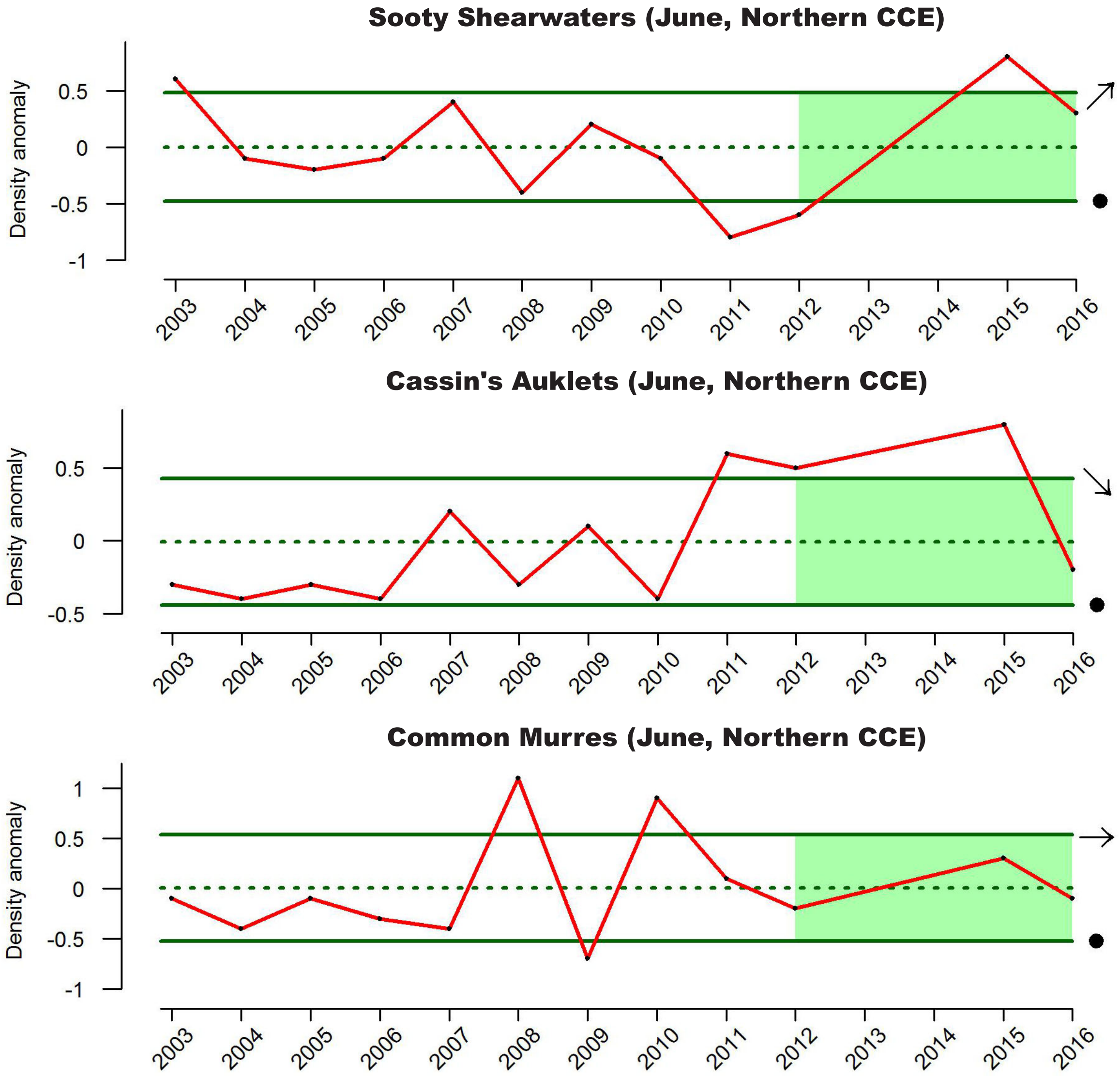
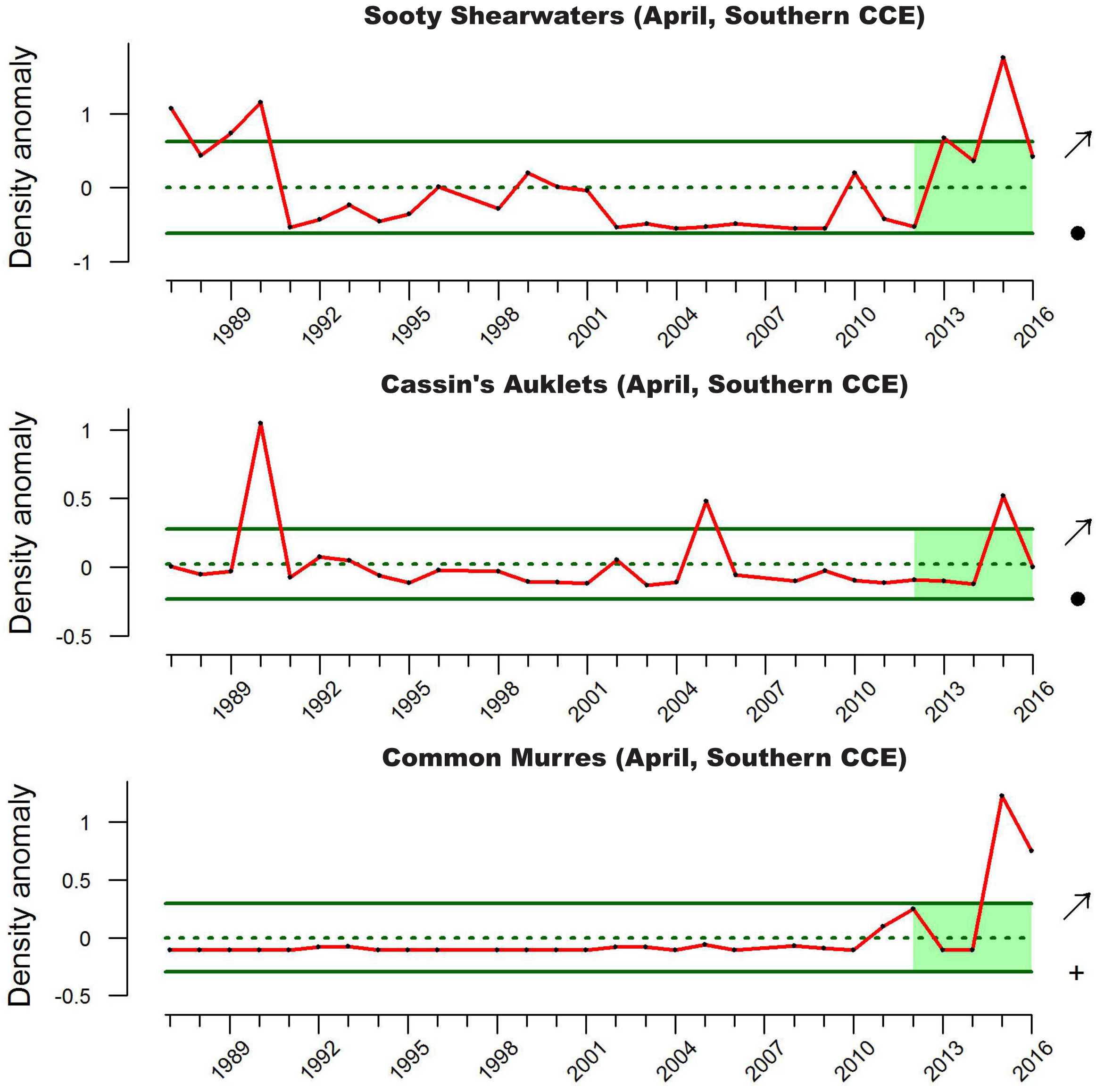


Figure 20. Anomalies in at-sea densities of sooty shearwaters, Cassin's auklets, and common murres in June in the Northern CCE through 2016. Lines, colors, and symbols are as in Figure 3a. Seabird abundance data from the Northern CCE were collected and provided by Dr. Jeannette Zamon (NOAA).

In the Northern CCE sampling area, all three species exhibited temporal variability, particularly since the mid-2000s (Figure 20). Sooty shearwaters have increased in recent years, while Cassin's auklets declined in 2016, possibly related to an exceptional mortality event in 2014–15. Common murre counts showed no trend. (Note: No data were collected in 2013 or 2014.)

In the longer Southern CCE time series, sooty shearwaters had increasing springtime density trends over the past five years (Figure 21), which represents a return to densities observed in the late 1980s. Common murre densities had been minimal since data collection began in 1987 until an uptick in 2011, followed by strongly positive anomalies in 2015 and 2016. By contrast, Cassin's auklets in the Southern CCE have been just below average density over the last 10 years.



Sooty Shearwaters (April, Southern CCE)

Cassin's Auklets (April, Southern CCE)

Common Murres (April, Southern CCE)

Figure 21. Anomalies in at-sea densities of sooty shearwaters, Cassin's auklets, and common murres in April in the Southern CCE through 2016. Lines, colors, and symbols are as in Figure 3a. Seabird abundance data from the Southern CCE are from CalCOFI surveys, courtesy of Dr. Bill Sydeman (Farallon Institute).

The positive density anomalies in recent years are surprising, given the recent and persistent warm conditions. (For example, sooty shearwaters increased despite their cold-water affinities.) These are abundance indicators of long-lived birds, however, and we may need condition indicators like diet, hatching rates, fledgling success, or others to fully understand recent seabird dynamics. To illustrate this, in each of the past several years, at least one seabird species has experienced a “wreck”—anomalously large numbers of dead birds washing up on beaches throughout much of the CCE (e.g., Cassin’s auklets in 2014 and common murres in 2015). In the summer of 2016, rhinoceros auklets (*Cerorhinca monocerata*) experienced a wreck, although it was largely confined to the Northern CCE (Harvey and Garfield 2017b).

Human Activities

Coastwide Landings by Major Fisheries

Data for fishery landings are current through 2015. Overall, total landings decreased over the last five years, driven mainly by steep declines in landings of Pacific hake, CPS, and crab in 2015 (Figure 22). Landings of groundfish (excluding hake) were historically low from 2011–15, while hake landings were highly variable. Landings of coastal pelagic fishes and market squid decreased over the last five years. Shrimp landings increased to historic highs, particularly from 2013–15, whereas crab declined sharply from a peak in 2013. Salmon landings were highly variable, while highly migratory species (HMS) landings were relatively consistent; both were within ±1 SD of historic averages. Recreational landings were historically low from 2004–15, and showed no recent trend. Total commercial fishery revenues (in adjusted 2015 dollars) have declined sharply since 2013, driven by declines in landings of crab, market squid, and hake (Harvey and Garfield 2017b). State-by-state commercial and recreational landings and revenue trends are summarized in Harvey and Garfield (2017b).

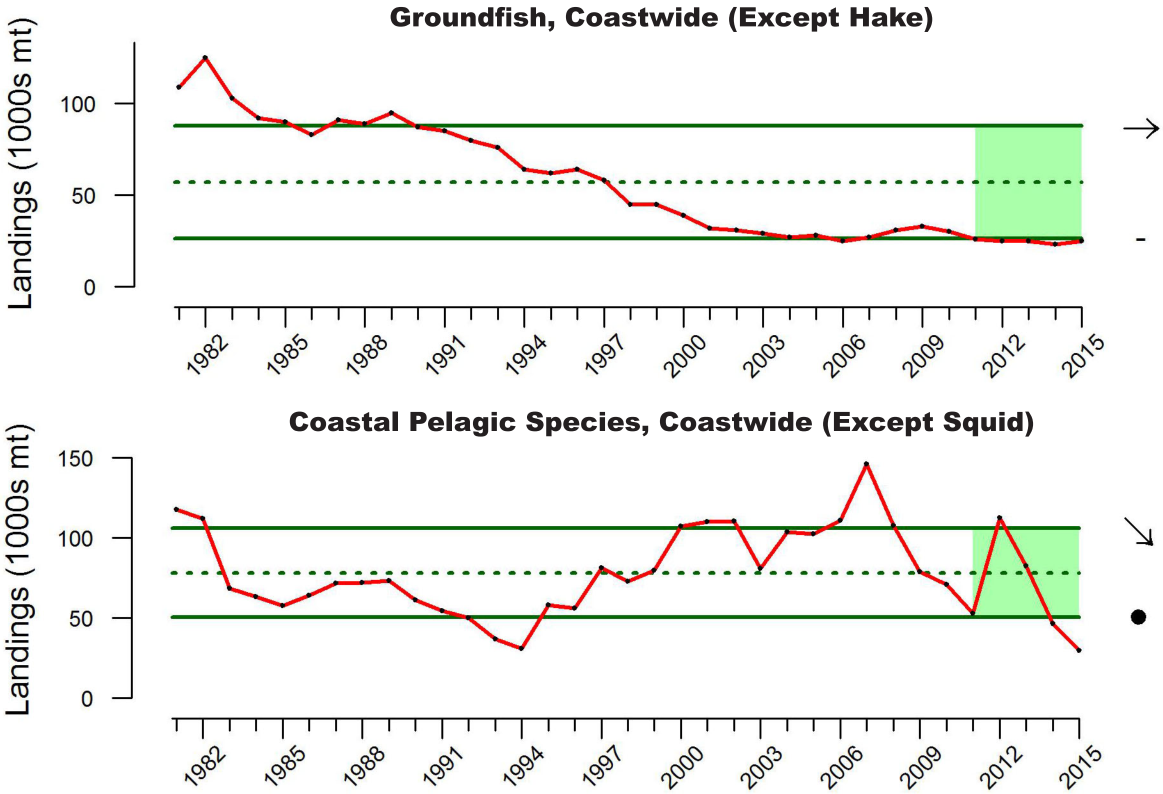


Figure 22. Annual landings of West Coast commercial and recreational fisheries, including total landings across all fisheries from 1981–2015. Lines and symbols are as in Figure 3a. Data for commercial landings are from PacFIN.[*] Data for recreational landings are from RecFIN.[†]

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[*] http://pacfin.psmfc.org/

[†] http://www.recfin.org/

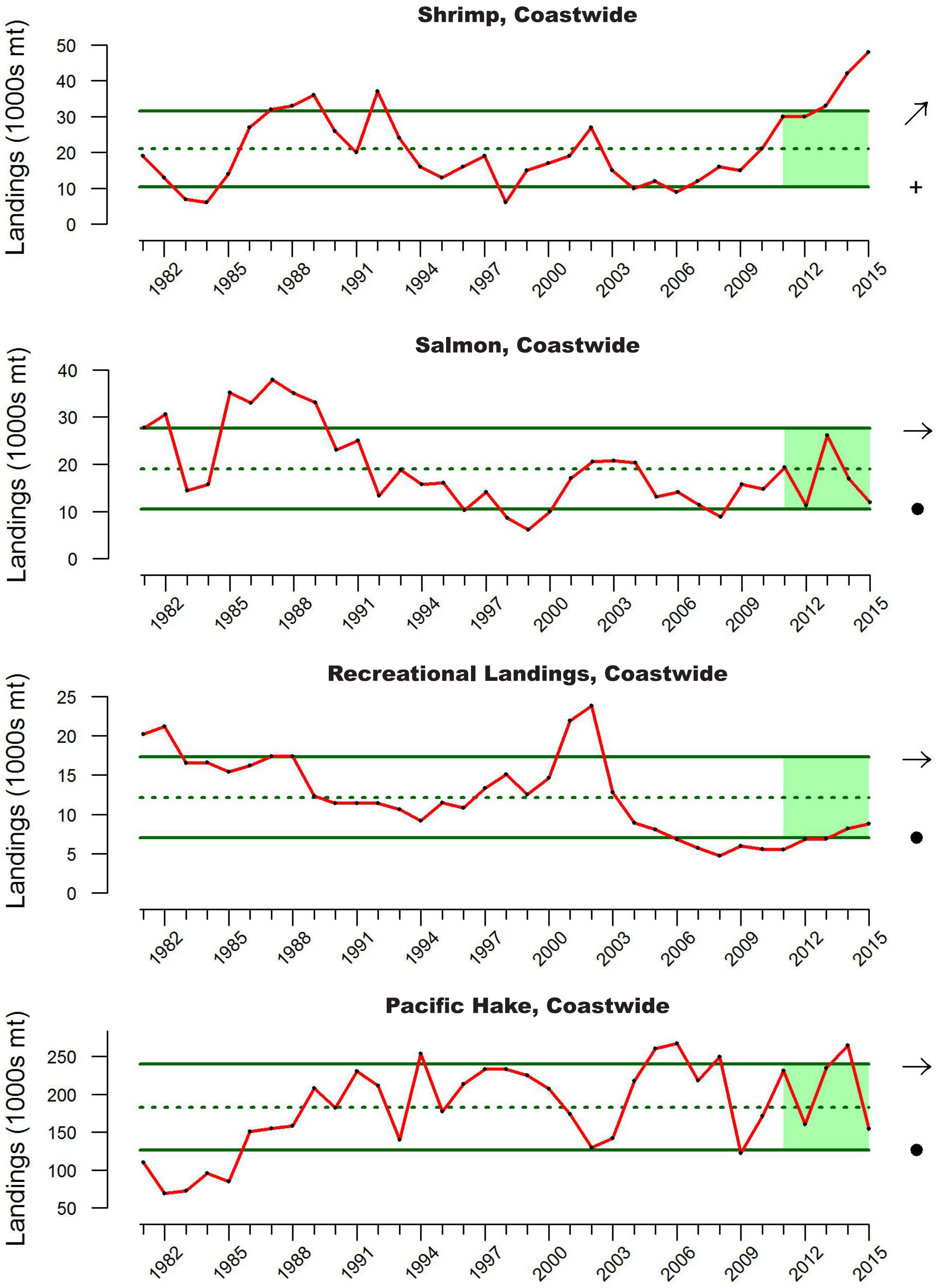

Figure 22 (continued). Annual landings of West Coast commercial and recreational fisheries, including total landings across all fisheries from 1981–2015. Lines and symbols are as in Figure 3a. Data for commercial landings are from PacFIN. Data for recreational landings are from RecFIN.

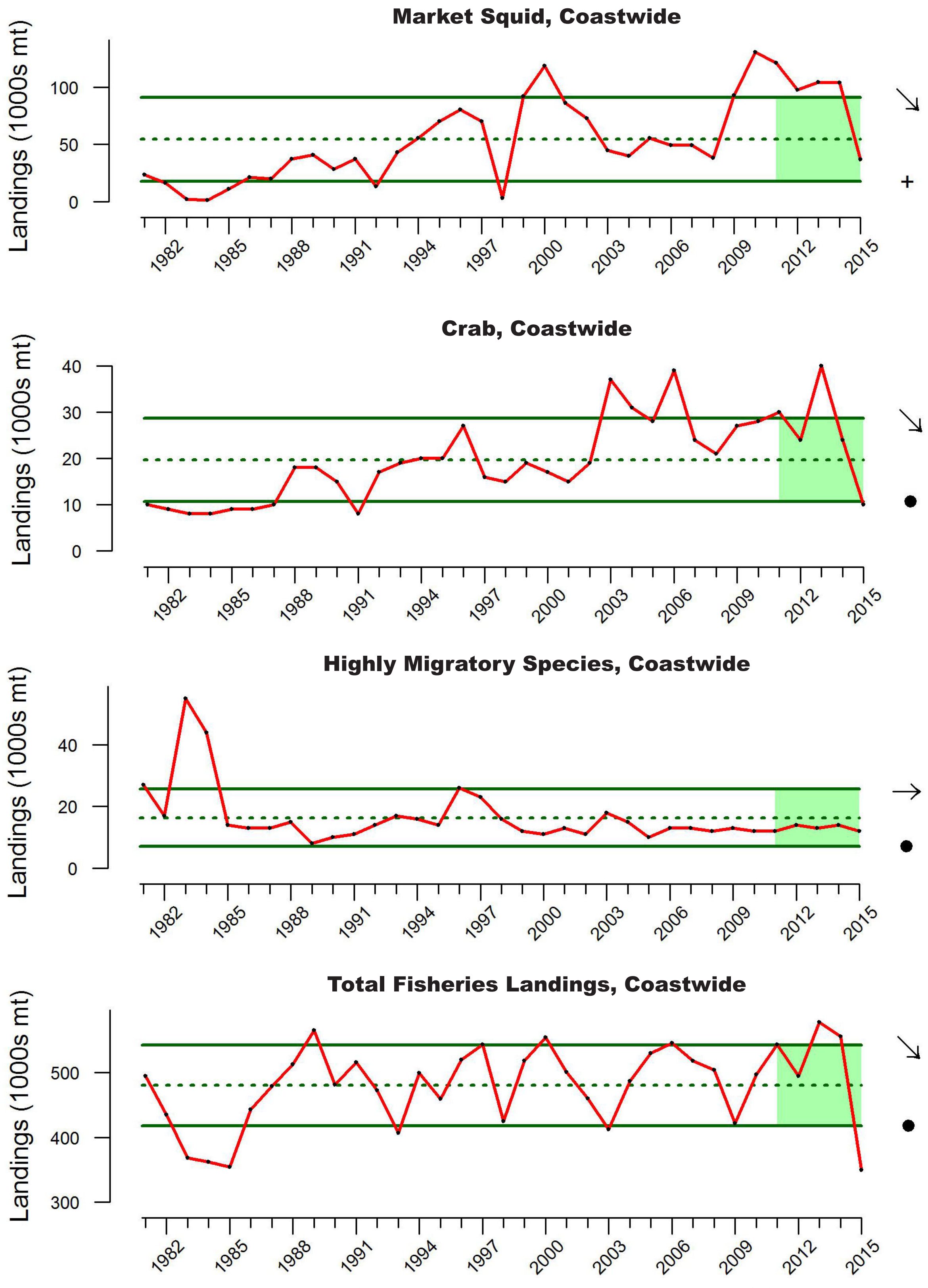

Figure 22 (continued). Annual landings of West Coast commercial and recreational fisheries, including total landings across all fisheries from 1981–2015. Lines and symbols are as in Figure 3a. Data for commercial landings are from PacFIN. Data for recreational landings are from RecFIN.

Gear Contact with Seafloor

Benthic marine species, communities, and habitats can be disturbed by natural processes as well as by human activities (e.g., bottom contact fishing, mining, or dredging). The impacts of fishing likely differ by gear and by habitat type, with hard, mixed, and biogenic habitats needing longer to recover than soft sediments.

We compiled estimates of coastwide distances affected by bottom-contact gear from 1999–2015. Estimates from 2002–15 include bottom trawl and fixed gear, while 1999–2002 includes only bottom trawl data. We calculated trawling distances based on set and haul-back points, and fixed gear distances based on set and retrieval locations of pot, trap, and longline gear. We weighted distances by gear and habitat type, according to sensitivity values described in Table A3a.2 of the 2013 PFMC Groundfish Essential Fish Habitat Synthesis Report[7] (available online only). Gear contact with the seafloor was at historically low levels over the most recent five-year period (Figure 23). The dominant source of seafloor-gear interaction was bottom trawl contact with soft sediments on the shelf and upper slope of the Northern CCE (Harvey and Garfield 2017b). There is uncertainty in the estimation of bottom contact among fixed gear types (e.g., longline vs. pot and trap gear), but this uncertainty is minor compared to the signal from bottom trawl gear.

Figure 23. Cumulative weighted distance of fishing gear contact with bottom habitat across the entire CCE, 1999–2015. Lines, colors, and symbols are as in Figure 3a. Data for total benthic habitat distance disturbed by bottom-contact fishing gears were provided by Mr. Jon McVeigh (NOAA). Weightings for benthic habitat sensitivity values come from PFMC's Pacific Coast Groundfish 5-Year Review of Essential Fish Habitat.

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[7] http://www.pcouncil.org/wp-content/uploads/D6b_SUP_NMFS_SYNTH2_APPENDICES_ELECTRIC_ONLY_APR2013BB.pdf

Aquaculture and Seafood Production

Aquaculture activities satisfy some of the demands for seafood and may be related to benefits (e.g., water filtration by bivalves, nutrition, income, or employment) or impacts (e.g., habitat conversion, waste discharge, or species introductions). Shellfish aquaculture production in the CCE has been at historically high levels in recent years (updated through 2014 as of this report), and finfish aquaculture (exclusively Atlantic salmon [*Salmo salar*]) has been near the upper limits of historical averages (Figure 24). Demand for seafood products is increasingly being met by aquaculture, and may be influencing the increases in production.

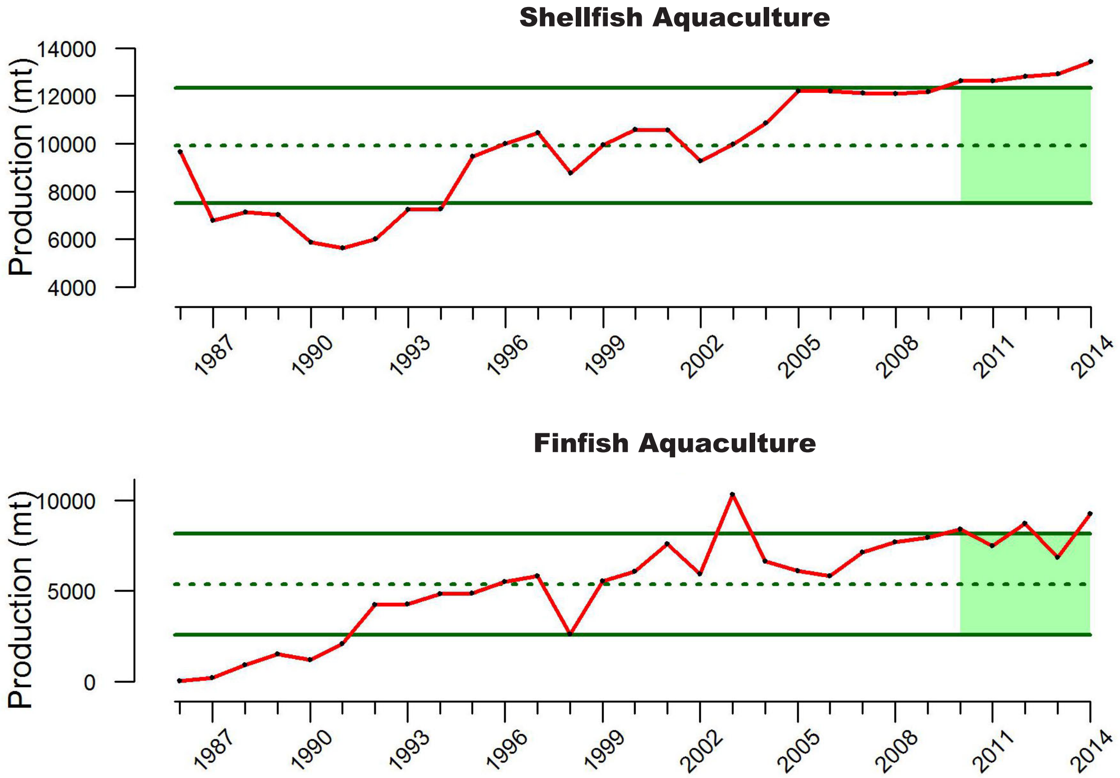

Figure 24. Aquaculture production of shellfish (clams, mussels, oysters) and finfish (Atlantic salmon) in CCE waters. Lines, colors, and symbols are as in Figure 3a. Shellfish aquaculture production data are from the Washington Department of Fish and Wildlife, the Oregon Department of Agriculture, and the California Department of Fish and Game. The only marine net-pen finfish aquaculture operations in the CCE occur in Washington State, and data came from the Washington Department of Fish and Wildlife.

Seafood demand in the U.S. was relatively constant from 2011–15, and had largely recovered from declines late in the previous decade (Figure 25). The recent average total consumption was above historical averages, while per-capita demand was within the historic range. With total demand already at historically high levels, increasing populations, and recommendations in U.S. Dietary Guidelines to increase seafood intake, total demand for seafood products seems likely to continue to increase for the next several years.

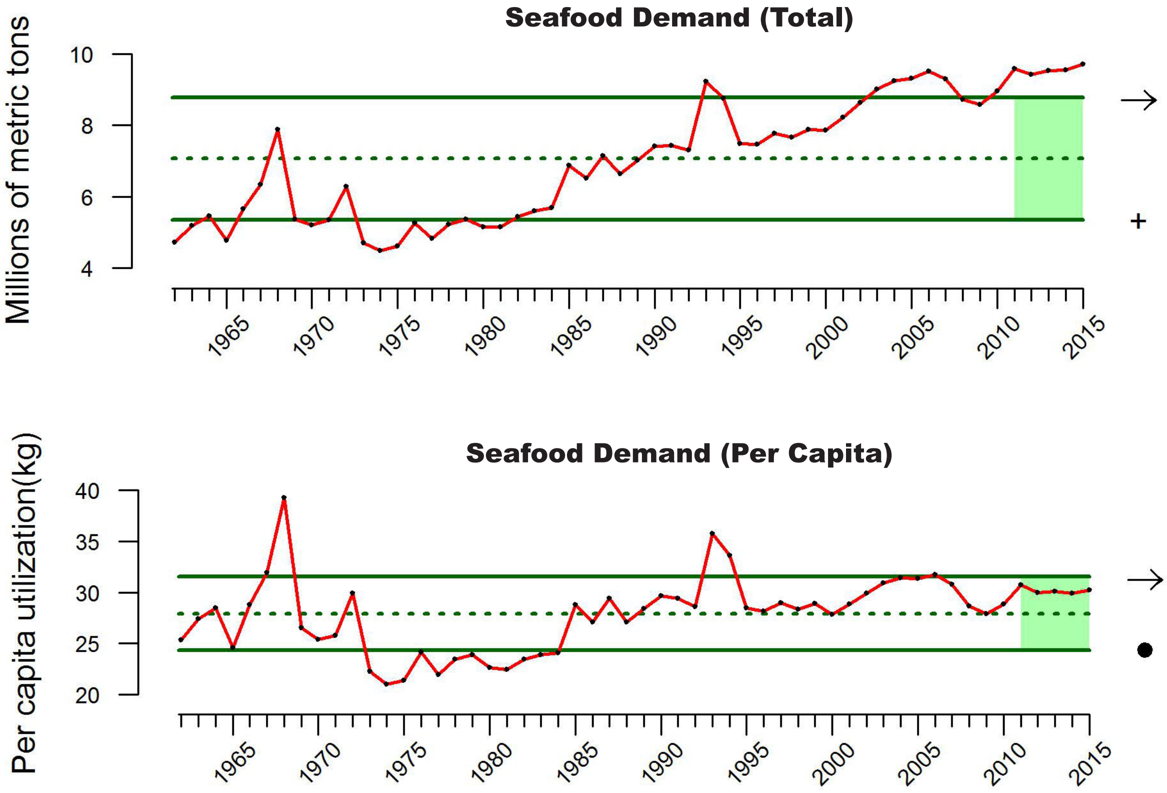

Figure 25. a) Total and b) per-capita use of fisheries products in the U.S., 1962–2015. Lines, colors, and symbols are as in Figure 3a. Data for total (imported and domestic) edible and inedible seafood consumption are from NOAA's Fisheries of the United States* annual reports describing the utilization of fisheries products.

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* http://www.st.nmfs.noaa.gov/st1/publications.html

Human Wellbeing

Social Vulnerability

Coastal community vulnerability indices are generalized socioeconomic vulnerability metrics for communities involved in commercial fishing. To assess social vulnerability in fishery-dependent communities, we use community-level social data, port-level fish ticket data, and a factor analysis approach to generate composite social vulnerability and commercial fishing indices for 1,139 coastal communities. The Community Social Vulnerability Index (CSVI; Jepson and Colburn 2013) is derived from social vulnerability data (demographics, personal disruption, poverty, housing characteristics, housing disruption, labor force structure, natural resource labor force, etc.). The fishing dependence composite index is based on commercial fishing engagement in a community (including fishery landings, revenues, permits, and processing) and commercial fishing reliance (per-capita enagagement). Figure 26 shows both indices for 25 highly fishing-dependent communities in five regions of the West Coast. Scores are relative to the entire CCE; for example, in 2014, the commercial fishing dependence of Moss Landing was ~33 SD greater than the average community. State-level summaries of CSVI scores are summarized elsewhere (Harvey and Garfield 2017b).

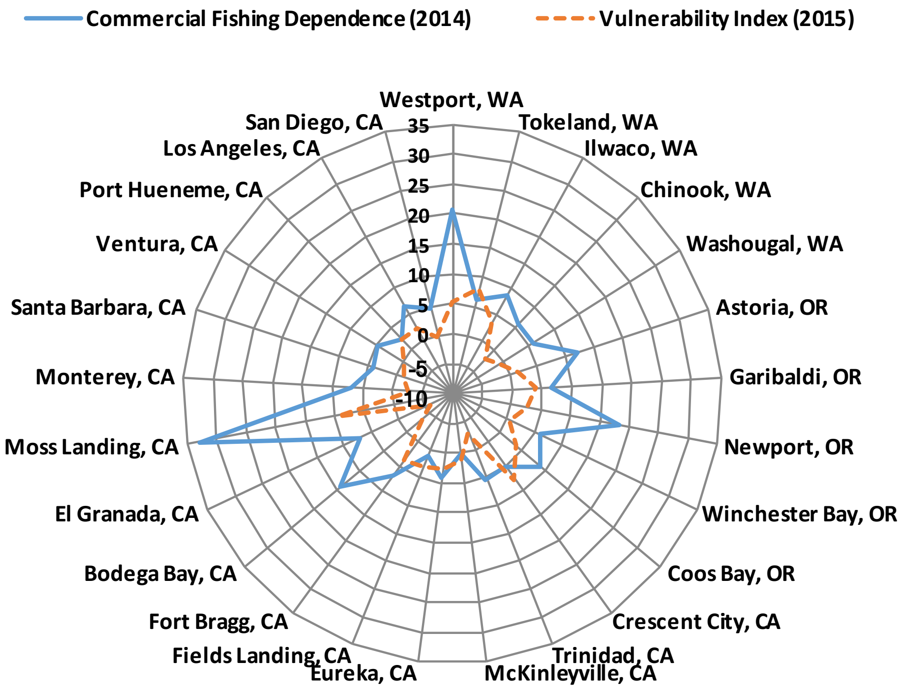

Figure 26. Commercial fishing dependence in 2014 (solid) and social vulnerability index in 2015 (dashed) for the five most fishing-dependent communities in Washington, Oregon, and northern, central, and southern California, expressed as standard deviations relative to all CCE communities. Shaded region is ≤1 SD. Fishery dependence and community social vulnerability index (CSVI) data were provided by Dr. Karma Norman (NOAA) and were derived from the U.S. Census Bureau,[*] the American Community Survey (ACS),[†] and PacFIN.

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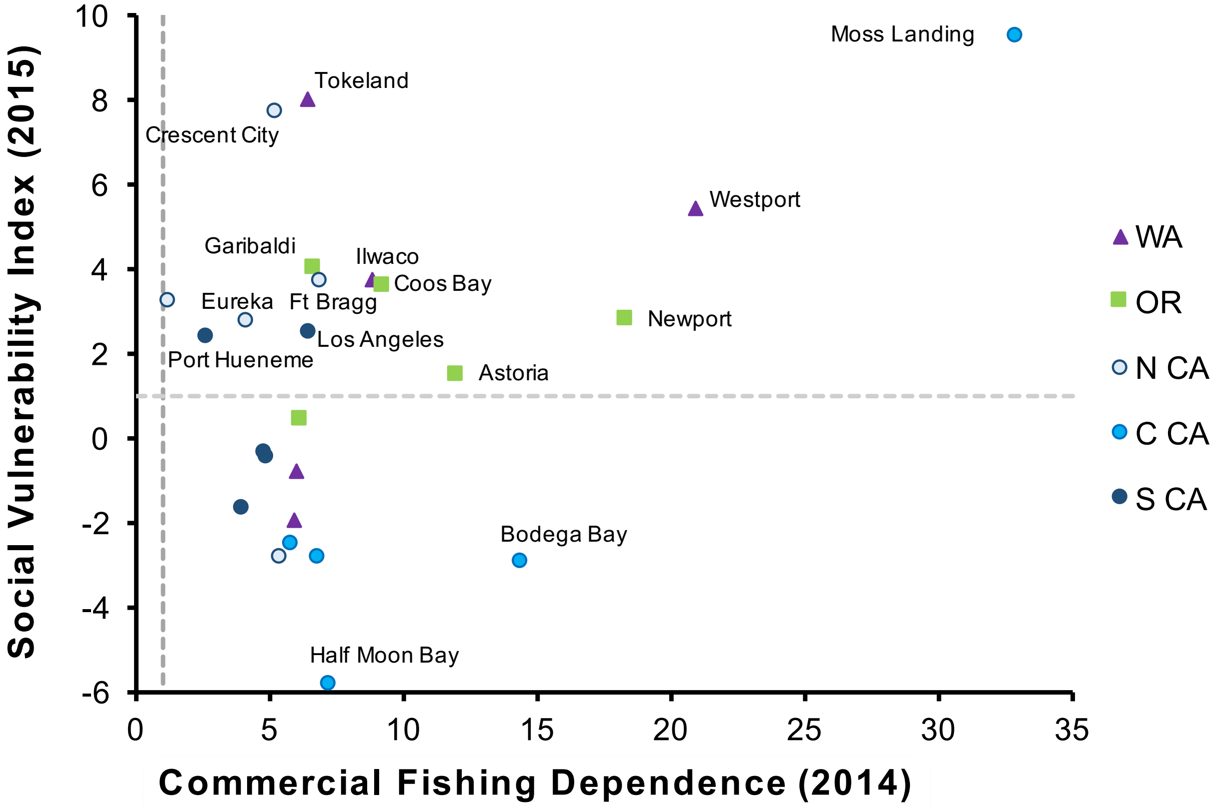
[*] http://www.census.gov/

[†] https://www.census.gov/programs-surveys/acs/

Figure 27 shows the two indices in x–y space, allowing us to readily identify fishing-dependent communities with high social vulnerability. Of note are communities like Moss Landing and Westport, which have relatively high commercial fishing dependence (~33 and 21 SD above average) and also a high CSVI (~10 and 5 SD above average). Communities that are strong outliers in both indices may be particularly socioeconomically vulnerable to a downturn in commercial fishing. Exogenous shocks of a management- or ecosystem-related nature may produce especially high individual and community-level social stress in these communities.



time periods as in Figure 26, but as x–y data color-coded by region. Dashed lines indicate 1 SD above the coastwide means, i.e., communities above and right of the two dashed lines have significantly greater social vulnerability and commercial fishing dependence than average communities in the CCE. Fishery dependence and community social vulnerability index (CSVI) data were provided by Dr. Karma Norman (NOAA) and were derived from the U.S. Census Bureau, the American Community Survey (ACS), and PacFIN.

Fleet Diversity Indices

Catches and prices from many fisheries exhibit high interannual variability, leading to high variability in fishers' income. Variability in annual revenue can be reduced by diversifying fishing activities across multiple fisheries or regions (Kasperski and Holland 2013). There may be good reasons for individuals to specialize, however, including reduced costs or greater efficiency. Thus, while diversification may reduce income variation, it does not necessarily promote higher average profitability. We measure diversification with the Effective Shannon Index (ESI). ESI = 1 when revenues are all from a single species group and region. It increases both as revenues are spread across *more* fisheries and as revenues are spread more *evenly* across fisheries. The index has an intuitive meaning: ESI = 2 if fishery revenues are spread evenly across 2 fisheries; ESI = 3 if revenues are spread evenly across 3 fisheries; and so on. If revenue is not evenly distributed across multiple fisheries, the ESI value is lower than the number of fisheries.

As of 2015, the fleet of vessels fishing on the U.S. West Coast and in Alaska was less diverse on average than at any point in the preceding 35 years (Figure 28). Between 2014 and 2015, some categories of vessels showed a small increase in ESI, while others decreased, but absolute changes were minor. The only vessel class to change by >2 SD was vessels 81–125 ft in length, for which ESI increased by about 5%; this change apparently was due to nonparticipation of some less-diversified vessels from West Coast fisheries in 2015. The long-term decrease in ESI from 1981–2015 was due both to entry and exit of vessels and changes for individual vessels. Over time, less-diversified vessels have been more likely to exit, which increases average diversification. However, vessels that remain in the fishery have also become less diversified since at least the mid-1990s, and newer entrants have generally been less diversified than earlier entrants. The overall result is a moderate decline in ESI since the mid-1990s or earlier for most vessel groupings. Notwithstanding these average trends, there are wide ranges of diversification levels and strategies within, as well as across, vessel classes, and some vessels remain highly diversified. It should be noted that increases in diversification from one year to the next may not always indicate an improvement in conditions for the fishing fleet. For example, if a class of vessels was heavily dependent on a single target species with highly variable revenues, such as Dungeness crab (*Metacarcinus magister*), an overall decline in the Dungeness crab fishery might cause ESI to increase. Also, an increase in ESI may be due to the exit of less-diversified vessels. Additional break-downs of diversification are provided in Harvey and Garfield (2017b).

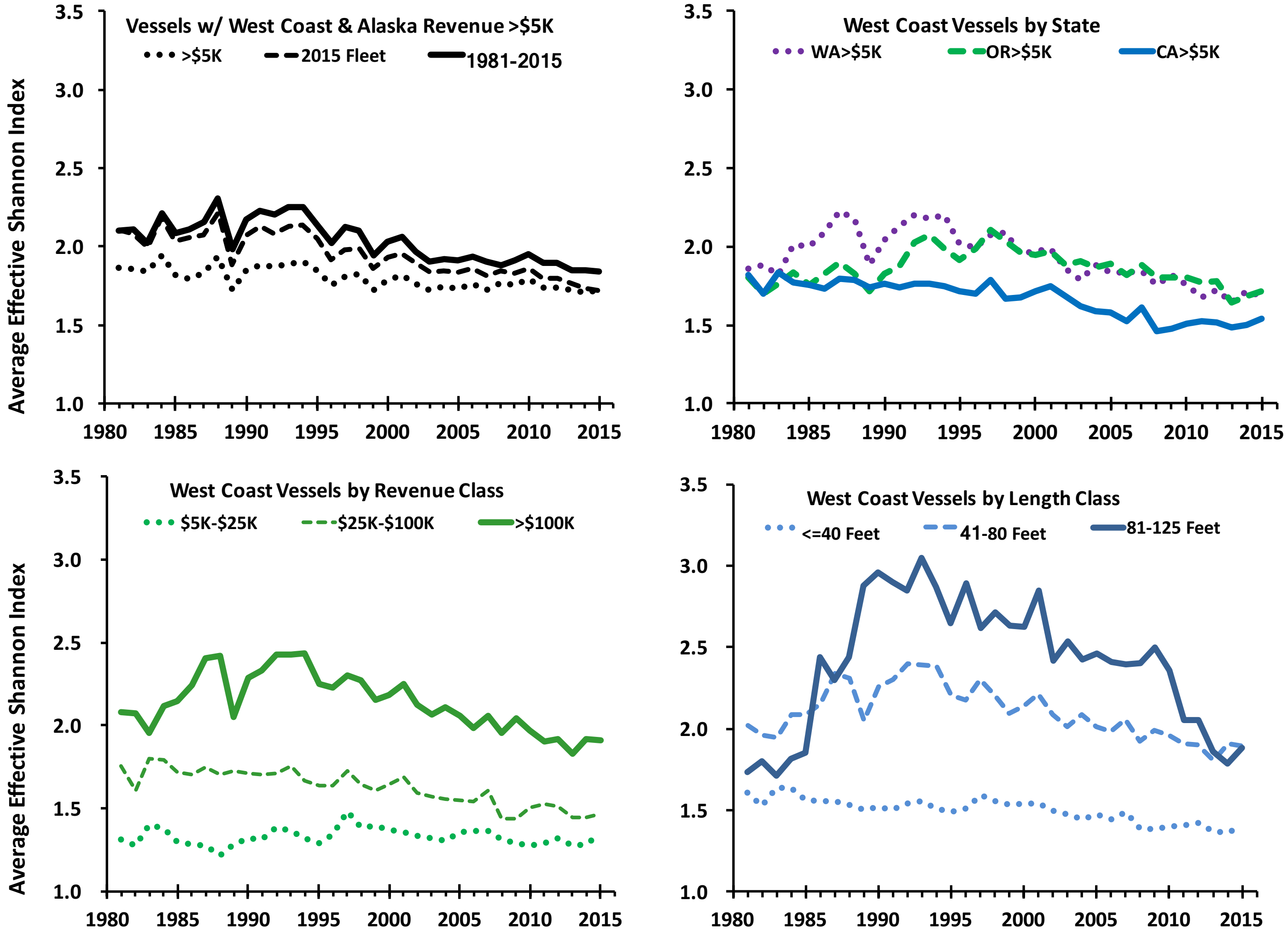


Figure 28. Average fishing vessel diversification for U.S. West Coast and Alaskan fishing vessels with over $5K in average revenues (top left) and for vessels in the 2015 West Coast Fleet, broken out by state (top right), average gross revenue (bottom left), and vessel length (bottom right). Fishery diversification estimates were provided by Dr. Dan Holland and Dr. Stephen Kasperski (NOAA).

CCIEA Team Recommendations for Future Research in the CCE

In March 2015, the PFMC approved FEP Initiative 2, "Coordinated Ecosystem Indicator Review," by which the PFMC, advisory bodies, the public, and the CCIEA team would work jointly to refine the indicators in the annual CCIEA Ecosystem Status Report to better meet PFMC objectives. The Initiative was implemented by an ad-hoc Ecosystem Working Group (EWG). (See PFMC's Decision Summary Document.[8])

As part of the FEP Initiative 2 process, the EWG asked the CCIEA team to summarize their research recommendations in the 2017 ecosystem status report. The six recommendations below reflect our collective assessment of science products that a) we believe are important, b) we could provide to the PFMC in a reasonable time frame (e.g., 1–3 years, including technical review by the SSCES), c) should support regional implementation of the NOAA EBFM Policy and Road Map,[9] and d) would provide added value to the indicators as they relate to management of FMP stocks and protected species.

1. Continue an ongoing scoping process between the PFMC and the CCIEA.

The CCIEA team recognizes the necessity to partner directly with the PFMC on these research recommendations, in order for them to be effective and directly applicable to management. We greatly appreciated the time and effort the PFMC committed to scoping these indicators under FEP Initiative 2. An ongoing scoping process could give the CCIEA team clear direction on PFMC needs, and give the PFMC a clear sense of CCIEA capabilities and capacity. Therefore:

- The Research Recommendations below are based on our current work and interests, but we would appreciate an opportunity to further scope CCIEA work with the PFMC and its advisory bodies, to ensure that our work is aligned with the PFMC's ecosystem science needs.

2. Continue making improvements to indicator analysis.

The CCIEA team benefited greatly from working with the EWG on FEP Initiative 2, and from the complementary support of the SSCES in providing technical review of CCIEA indicators and activities. The CCIEA team recommends that this partnership continue, with emphasis on:

- Continued refining of the existing indicators in this report, to better meet PFMC needs.
- Identifying and prioritizing indicator gaps, such as CPS, HMS, groundfish, diet information, chlorophyll, harmful algal blooms, and socioeconomic data from underreported communities.
- Using MARSS models to estimate trends in our indicators, separate from the observation error inherent in field sampling.
- Analyzing time series to 1) determine if threshold relationships exist between stressors and indicators, thus informing risk assessments, and 2) to detect early-warning indicators of major shifts in ecosystem structure or function.

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[8] http://www.pcouncil.org/wp-content/uploads/2015/03/0315decisions.pdf

[9] https://www.st.nmfs.noaa.gov/ecosystems/ebfm/creating-an-ebfm-management-policy

3. Assess the dynamics of fisheries adaptation to short-term climate variability.

The CCE is highly variable, driven by annual or decadal variations such as El Niño events, PDO shifts, and marine heat waves. The livelihoods of fishers in the CCE are heavily influenced by such variability. As fishers attempt to adapt to variability by switching among fisheries, their actions impact other fishers and fishing communities, and may actively influence ecosystem dynamics. This project will investigate how fisheries management and fishers' fishing strategies combine to affect social and ecological resilience to the short-term climate variability inherent to the CCE. We plan to:

- Analyze how productivity of key species varies with climate/ocean conditions.
- Survey CCE fishers to determine motivations for fishery participation, and use the data from the survey and fish tickets to fit statistical models of individual fishing participation choices.
- Construct an integrated model of several CCE fisheries (e.g., salmon, Dungeness crab, albacore [*Thunnus alalunga*], groundfish, and shrimp) that determines participation and effort in each fishery.
- Model how climate variability affects fisheries both directly, via environmental effects, and indirectly, via participation decisions, and explore what types of fishing portfolios, for individuals or ports, result in lower variation in income and higher quality of life.

4. Assess the vulnerability of communities at sea to long-term climate change.

Long-term climate change has already shifted distributions of marine species in the CCE, but the socioecological impacts of climate change on fishing communities over the next several decades are difficult to anticipate. A major challenge remains in linking vulnerability to predicted long-term changes in the marine seascape upon which each community depends, particularly because both target species and fleets from different ports form spatially and temporally dynamic "communities at sea" (e.g., Colburn et al. 2016). We plan to:

- Develop a composite index of vulnerability for each community at sea as a function of its exposure (changes in target species biomass) and sensitivity (dependence on each target species) to long-term climate change.
- Assess each community at sea's adaptive capacity (e.g., mobility and target switching).
- Set up Environmental Competency Groups throughout the CCE, so that scientists, fishers, and managers can together interrogate information about climate vulnerabilities and impacts, co-develop adaptation strategies, and proactively reveal barriers to adaptation.

5. Explore implementing Dynamic Ocean Management to reduce bycatch in HMS fisheries.

Traditional management measures for bycatch reduction are static in space and time, despite the fact that both marine species and human users rely on dynamic environmental features. Dynamic Ocean Management (DOM) offers an ecosystem-based management approach toward addressing these dynamic issues (Lewison et al. 2015). We define DOM as management of marine systems that can change in space and time with the shifting nature of the ocean and its users. We are exploring DOM for HMS, specifically to maximize swordfish (*Xiphias gladius*) catch in the California drift gillnet fishery while minimizing bycatch of key species including leatherback sea turtles (*Dermochelys* *coriacea*), blue sharks (*Prionace glauca*), and California sea lions; we will extend this to include marine mammals that are hard-cap species, i.e., species that are protected such that capture of a specific number will result in a fishery closure for the rest of the season. Our approach is to:

- Use species-specific bycatch risk profiles to create risk–reward ratios for swordfish vessels.
- Track spatiotemporal changes in risk ratios as a function of management strategies and dynamic environmental conditions in the area of the drift gillnet fishery.

6. Assess the ecological and economic impacts of ocean acidification.

The CCE is characterized by upwelling of deep, cold, nutrient-rich waters that support fish stocks and the human communities that rely on them, but that also make the area particularly at risk of OA. The CCIEA team is leading focused research to identify the species, fisheries, FMPs, and ports most vulnerable to OA. Specifically, we will:

- Apply an Atlantis ecosystem model, which was formally reviewed by a PFMC Methodology Review Panel and the Center for Independent Experts in July 2014, and presented to the full PFMC in November 2014 (Kaplan and Marshall 2016).
- Link the Atlantis model to 1) ensembles of future scenarios for OA, warming, and species range shifts, and 2) updated information about species exposure and sensitivity to OA.
- Identify FMPs, ecoregions, and ports most likely affected by OA, warming, and subsequent range shifts, including both direct and indirect (e.g., food web) effects and impacts on coastal economies, as explored by Marshall et al. (2017).
- Consider impacts on FMPs that result from changes in prey productivity, for instance impacts on rebuilding rockfish stocks.

Conclusions

Conditions in the CCE in 2016–17 suggest a transitional period from several years of anomalously warm temperatures, below-average precipitation, and poor coastal productivity into conditions more representative of long-term averages. Some species already appear to be responding to this shift, although the extent of species responses will require many years to understand: the CCE is a species-rich system, and the many species have developed a wide range of adaptations to deal with the highly variable environmental conditions that characterize the California Current. Some of these adaptations may manifest themselves quickly, but many species in the CCE have highly protracted life histories, which could result in lag times before the environmental effects are known. Many species are also highly mobile or migratory, making it difficult to monitor them and track their responses in real time. Finally, we simply do not fully understand the relationships between many species and their environment, particularly when their environment experiences such extreme anomalies as observed in the California Current from 2013–16.

The CCIEA team will collaborate with colleagues in NOAA and partner agencies and institutions to determine if, in fact, the recent anomalous conditions have resulted in negative impacts on forage species, salmon, and higher predators. We are likely to find unanticipated responses, such as the large numbers of YOY groundfish observed in 2015–16 that suggest favorable conditions for early life stages of those species despite environmental and lower trophic-level indicators to the contrary. We will also continue to study linkages between these dynamics and the equally dynamic human communities that rely on California Current marine resources.

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Appendix:
Authors and Affiliations

Dr. Chris Harvey
Conservation Biology Division
Northwest Fisheries Science Center
2725 Montlake Boulevard East
Seattle, Washington 98112

Dr. Newell (Toby) Garfield
Environmental Research Division
Southwest Fisheries Science Center
8501 La Jolla Shores Drive
La Jolla, California 92037

Mr. Gregory Williams
Pacific States Marine Fisheries Commission
206 Southeast Spokane Street, Suite 100
Portland, Oregon 97202
and
Conservation Biology Division
Northwest Fisheries Science Center
2725 Montlake Boulevard East
Seattle, Washington 98112

Mr. Kelly Andrews
Conservation Biology Division
Northwest Fisheries Science Center
2725 Montlake Boulevard East
Seattle, Washington 98112

Dr. Caren Barceló
College of Earth, Ocean, & Atmospheric Sciences
Oregon State University
104 CEOAS Administration Building
Corvallis, Oregon 97331

Ms. Katie Barnas
Conservation Biology Division
Northwest Fisheries Science Center
2725 Montlake Boulevard East
Seattle, Washington 98112

Dr. Steven Bograd
Environmental Research Division
Monterey Research Station
Southwest Fisheries Science Center
99 Pacific Street, Suite 255A
Monterey, California 93940
and
Institute of Marine Sciences
University of California, Santa Cruz
1156 High Street
Santa Cruz, California 95064

Dr. Richard Brodeur
Fish Ecology Division
Newport Research Station
Northwest Fisheries Science Center
2032 Southeast OSU Drive
Newport, Oregon 97365

Dr. Brian Burke
Fish Ecology Division
Northwest Fisheries Science Center
2725 Montlake Boulevard East
Seattle, Washington 98112

Dr. Jason Cope
Fishery Resource Analysis & Monitoring Division
Northwest Fisheries Science Center
2725 Montlake Boulevard East
Seattle, Washington 98112

Ms. Lynn deWitt
Environmental Research Division
Santa Cruz Research Station
Southwest Fisheries Science Center
110 McAllister Way
Santa Cruz, California 95060

Dr. John Field
Fisheries Ecology Division
Santa Cruz Research Station
Southwest Fisheries Science Center
110 McAllister Way
Santa Cruz, California 95060

Ms. Jennifer Fisher
Cooperative Institute for Marine Resources Studies
Hatfield Marine Science Center
Oregon State University
2030 Southeast Marine Science Drive
Newport, Oregon 97365
and
Fish Ecology Division
Newport Research Station
Northwest Fisheries Science Center
2032 Southeast OSU Drive
Newport, Oregon 97365

Dr. Correigh Greene
Fish Ecology Division
Northwest Fisheries Science Center
2725 Montlake Boulevard East
Seattle, Washington 98112

Dr. Thomas Good
Conservation Biology Division
Northwest Fisheries Science Center
2725 Montlake Boulevard East
Seattle, Washington 98112

Dr. Elliott Hazen
Environmental Research Division
Monterey Research Station
Southwest Fisheries Science Center
99 Pacific Street, Suite 255A
Monterey, California 93940
and
Institute of Marine Sciences
University of California, Santa Cruz
1156 High Street
Santa Cruz, California 95064

Dr. Daniel Holland
Conservation Biology Division
Northwest Fisheries Science Center
2725 Montlake Boulevard East
Seattle, Washington 98112

Dr. Michael Jacox
Environmental Research Division
Monterey Research Station
Southwest Fisheries Science Center
99 Pacific Street, Suite 255A
Monterey, California 93940

Dr. Stephen Kasperski
Resource Ecology & Fisheries Management Division
Alaska Fisheries Science Center
7600 Sand Point Way Northeast
Seattle, Washington 98115

Ms. Su Kim
Office of the Science Director
Northwest Fisheries Science Center
2725 Montlake Boulevard East
Seattle, Washington 98112

Dr. Andrew Leising
Environmental Research Division
Monterey Research Station
Southwest Fisheries Science Center
99 Pacific Street, Suite 255A
Monterey, California 93940

Dr. Sharon Melin
Marine Mammal Laboratory
Alaska Fisheries Science Center
7600 Sand Point Way Northeast
Seattle, Washington 98115

Ms. Cheryl Morgan
Cooperative Institute for Marine Resources Studies
Hatfield Marine Science Center
Oregon State University
2030 Southeast Marine Science Drive
Newport, Oregon 97365
and
Fish Ecology Division
Newport Research Station
Northwest Fisheries Science Center
2032 Southeast OSU Drive
Newport, Oregon 97365

Dr. Stuart Munsch
Ocean Associates
Under contract to Fish Ecology Division
Northwest Fisheries Science Center
2725 Montlake Boulevard East
Seattle, Washington 98112

Dr. Karma Norman
Conservation Biology Division
Northwest Fisheries Science Center
2725 Montlake Boulevard East
Seattle, Washington 98112

Dr. William T. Peterson
Fish Ecology Division
Newport Research Station
Northwest Fisheries Science Center
2032 Southeast OSU Drive
Newport, Oregon 97365

Dr. Melissa Poe
Washington Sea Grant
University of Washington
3716 Brooklyn Avenue Northeast
Seattle, Washington 98105
and
Conservation Biology Division
Northwest Fisheries Science Center
2725 Montlake Boulevard East
Seattle, Washington 98112

Dr. Jameal Samhouri
Conservation Biology Division
Northwest Fisheries Science Center
2725 Montlake Boulevard East
Seattle, Washington 98112

Dr. Isaac Schroeder
Institute of Marine Sciences
University of California, Santa Cruz
1156 High Street
Santa Cruz, California 95064
and
Environmental Research Division
Monterey Research Station
Southwest Fisheries Science Center
99 Pacific Street, Suite 255A
Monterey, California 93940

Dr. William Sydeman
Farallon Institute
101 H Street, Suite Q
Petaluma, California 94952

Dr. Julie Thayer
Farallon Institute
101 H Street, Suite Q
Petaluma, California 94952

Dr. Andrew Thompson
Fisheries Resources Division
Southwest Fisheries Science Center
8501 La Jolla Shores Drive
La Jolla, California 92037

Dr. Nick Tolimieri
Conservation Biology Division
Northwest Fisheries Science Center
2725 Montlake Boulevard East
Seattle, Washington 98112

Ms. Anna Varney
Pacific States Marine Fisheries Commission
206 Southeast Spokane Street, Suite 100
Portland, Oregon 97202
and
Conservation Biology Division
Northwest Fisheries Science Center
2725 Montlake Boulevard East
Seattle, Washington 98112

Dr. Brian Wells
Fisheries Ecology Division
Santa Cruz Research Station
Southwest Fisheries Science Center
110 McAllister Way
Santa Cruz, California 95060

Dr. Thomas Williams
Fisheries Ecology Division
Santa Cruz Research Station
Southwest Fisheries Science Center
110 McAllister Way
Santa Cruz, California 95060

Dr. Jeannette Zamon
Fish Ecology Division
Point Adams Research Station
520 Heceta Place
Hammond, Oregon 97121

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