NOAA Technical Memorandum NMFS-NWFSC-109

# Technical background for an Integrated Ecosystem Assessment of the California Current

## Groundfish, Salmon, Green Sturgeon, and Ecosystem Health

April 2011

**U.S. DEPARTMENT OF COMMERCE**
**National Oceanic and Atmospheric Administration**
National Marine Fisheries Service

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**Groundfish, Salmon, Green Sturgeon, and Ecosystem Health**

Edited by Phillip S. Levin and Franklin B. Schwing[1]

From contributions by the editors and Cameron H. Ainsworth, Kelly S. Andrews, Steven J. Bograd,[1] Merrick Burden,[2] Shallin Busch, William Cheung,[3] John Dunne,[4] Tessa B. Francis, Elizabeth A. Fulton,[5] Churchill B. Grimes,[6] Elliott L. Hazen,[1] Peter J. Horne, David Huff,[7] Isaac C. Kaplan, Steve T. Lindley,[6] Thomas Okey,[8] Jameal F. Samhouri, Isaac D. Schroeder,[1] William J. Sydeman,[9] Sarah A. Thompson,[9] Nick Tolimieri, Brian K. Wells,[6] and Gregory D. Williams

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

[1]Southwest Fisheries Science Center
1352 Lighthouse Avenue
Pacific Grove, California 93950

[2]Pacific Fishery Management Council
7700 Northeast Ambassador Place, Suite 101
Portland, Oregon 97220

[3]University of East Anglia
School of Environmental Sciences
Norwich, United Kingdom NR4 7TJ

[4]Geophysical Fluid Dynamics Laboratory
Princeton University Forrestal Campus
201 Forrestal Road
Princeton, New Jersey 08540

[5]CSIRO
Castray Esplanade
Hobart, Tasmania 7000, Australia

[6]Southwest Fisheries Science Center
110 Shaffer Road
Santa Cruz, California 95060

[7]University of California Santa Cruz
100 Shaffer Road
Santa Cruz, California 95060

[8]University of British Columbia
2329 West Mall
Vancouver, British Columbia V6T 1Z4

[9]Farallon Institute
P.O. Box 750756
Petaluma, California 94952

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# Executive Summary

Understanding marine systems and the processes that drive them is the first step to ensuring healthy oceans for the future. The National Marine Fisheries Service (NMFS) is developing an Integrated Ecosystem Assessment (IEA) tool to synthesize and analyze science knowledge and present it in a manner that informs management decisions. It will help resource managers understand the status and health of the oceans and how various management actions might influence those factors. It will inform an ecosystem-based management (EBM) approach. This technical memorandum provides an overview of this evolving tool and the results of the pilot 2010 IEA for the California Current.

Spanning nearly 3,000 km of latitude from Vancouver Island, British Columbia, to Baja California, Mexico, the California Current Large Marine Ecosystem (CCLME) is a large, dynamic, and spatially heterogeneous marine environment in the eastern North Pacific Ocean along the west coast of North America. Based on physical and biological attributes, the CCLME can be divided into three distinct subecosystems:

- Southern British Columbia, Washington, and Oregon to Cape Blanco;
- Cape Blanco, southern Oregon, to Point Conception, California; and
- Southern California (south of Point Conception) and Baja California.

## What are IEA and EBM?

IEA is a formal synthesis and quantitative analysis of all relevant scientific information—biological, geological, physical, economic, and social—in relation to ecosystem management objectives. The goal of an IEA is to fully understand the web of interactions in an ecosystem and forecast how changing environmental conditions and management actions affect the status of the ecosystem.

IEAs are a tool, a product, and a process. They are a tool that uses statistical analysis and ecosystem modeling to integrate a range of social, economic, and natural science data and information. They are a product for managers and stakeholders who rely on scientific support for policy and decision making, as well as for scientists who want to enhance their understanding of ecosystem dynamics. Finally, IEAs are a process that begins with involvement of stakeholders to address critical management and policy questions, moves to a quantitative assessment of ecosystem health, and concludes with an evaluation of management options. Through the tenets of adaptive management, the process reaches full circle to trigger an update of the assessment.

To this end, IEAs follow a four-step process:

- Scoping: Identify management objectives, articulate the ecosystem to be assessed, identify ecosystem attributes of concerns, and identify stressors relevant to the ecosystem being examined.
- Indicator development: Researchers must develop and test indicators that reflect the ecosystem attributes and stressors specified in the scoping process. Specific indicators are dictated by the problem at hand and must be linked objectively to decision criteria.
- Risk Analysis: The goal of risk analysis is to fully explore the susceptibility of an indicator to natural or human threats, as well as the ability of the indictor to return to its previous state after being perturbed.
- Evaluation: Evaluate the potential different management strategies to influence the status of ecosystem components of management concern or the drivers and pressures that affect these ecosystem components.

EBM is an integrated approach to management that considers the entire ecosystem, including humans. EBM differs from management approaches that focus on a single species, sector, activity, or concern by considering the cumulative impacts of different sectors on the whole ecosystem. The primary goal of EBM is to maintain an ecosystem in a healthy, productive, and resilient condition. The primary goal of the California Current IEA is to inform the implementation of EBM by melding diverse ecosystem components into a single, dynamic fabric that allows for coordinated evaluations of the status of the CCLME.

## EBM Drivers, Pressures, and Components in the California Current

A comprehensive IEA of the California Current is an enormous undertaking. The IEA team's approach to complete this daunting task was to systematically decompose the California Current into a series of ecosystem drivers, pressures, and components that are of keen interest to resource managers, policy makers, researchers, and the public. Working with regional managers, the team then selected a limited set of EBM drivers, pressures, and components to use in the initial phase of the California Current IEA.

Researchers created a lengthy list of drivers and pressures. Drivers are defined as factors that result in pressures that cause changes in the ecosystem. Both natural and anthropogenic factors such as climate variability and human population size were considered. While human driving forces can often be assessed and controlled, natural environmental changes cannot be controlled but must be accounted for in management decisions. The IEA team binned drivers and pressures into 11 broad categories: shipping, freshwater habitat issues, coastal zone development, fishing, invasive species, naval exercises, aquaculture, energy development, marine habitat disturbance, oil spills, and climate change.

A component is defined as any biological, physical, or human dimension that policy makers, managers, or citizens are trying to manage or conserve. For the purpose of the 2010 California Current IEA, researchers binned these components into seven categories:

- Wild fisheries, an EBM component centered on the condition of fishery stocks included in the coastal pelagic species, highly migratory species, groundfish, and salmon fishery management plans.

- Seafood, distinct from fisheries, an EBM component focused on the consistent delivery of plentiful, safe seafood. This overlaps with the wild fisheries EBM, but includes aquaculture and production hatcheries and focuses less on the health of the wild stocks and more on the provisioning of food for human consumption.
- Protected resources, species legally designated as protected (e.g., Marine Mammal Protection Act, Migratory Bird Treaty Act, Endangered Species Act).
- Habitat, including biogenic and abiotic habitats both on the seafloor and in the water column.
- Ecosystem health, referring to the structure and function of marine and coastal ecosystems and ecological communities.
- Vibrant coastal communities, including social, economic, and cultural well-being and human health as it is tied to the marine environment.
- Scientific knowledge and education, a distinct EBM goal of many agencies to provide unique opportunities for scientific research and education.

## California Current IEA–2010 Findings

The ultimate aim of the California Current IEA is to fully understand the web of interactions that links drivers and pressures to EBM components and to forecast how changing environmental conditions and management actions affect the status of the ecosystem. For 2010, the IEA team chose four aspects of the suite of components: groundfish (representing fisheries), salmon (representing protected resources), green sturgeon (*Acipenser medirostris*), and ecosystem health. The IEA team 1) selected a limited set of scientifically credible indicators for attributes of each component listed below, 2) reported on status and trends of these indicators, and 3) explored how management options might affect the indicators through a management strategy evaluation process.

### Groundfish

Groundfish are generally defined as a community of fishes which are closely associated with the ocean bottom, such as the rockfishes (Scorpaenidae), flatfishes (Pleuronectidae and Bothidae), sculpins (Cottidae), Pacific hake (*Merluccius productus*), and sablefish (*Anoplopoma fimbria*). Groundfish vary across a wide range of trophic levels and inhabit all types of habitats (e.g., rocky, sandy, muddy, kelp) from the intertidal zone to the abyss. This community of fishes constitutes a large biomass in the CCLME and provides the economic engine for coastal communities in Washington, Oregon, and California.

The two attributes selected for this component were population size and population condition. From the eight indicators in the top quartile of indicators for population size, we propose to use these three as indicators: abundance of groundfish (numbers) in large-scale bottom trawl surveys, population growth rate, and number of species below their management thresholds. From the five indicators in the top quartile for population condition, we propose to use these two as indicators: age structure of populations and spatial structure of populations.

Data for monitoring groundfish trends comes mainly from the U.S. West Coast bottom trawl surveys of groundfish resources conducted by the Alaska Fisheries Science Center and the Northwest Fisheries Science Center. Analyses examined a subset of 14 species representing different functional groups of fishes from various habitats and trophic guilds. Key findings include the following:

- Population size (the number of individuals per square kilometer in a trawl survey) is a useful indicator of trends in the population and is also a metric of conservation importance that is easy to understand in the policy arena.
- Size structure of a population is an indicator of population condition. The mean size of all species caught in fishery-independent surveys, fishery-dependent surveys, or landings is a simple indicator to evaluate the overall effects of fishing on an ecosystem. Size-based metrics respond to fishing impacts because body size determines the vulnerability of individuals, populations, and communities.
- The spatial structure of a population is a measure of a species' geographic range and distribution. Changes in spatial distribution can be caused by responses to climate or exploitation, so further research is necessary to disentangle the causes. Several species showed changes in spatial distribution in 2009 relative to the full time series.

## Salmon

Two salmon species along the CCLME make up the vast proportion of salmon abundance: Chinook salmon (*Oncorhynchus tshawytscha*) and coho salmon (*O. kisutch*). Salmon spawn in freshwater where their eggs and juveniles spend up to a year before migrating to sea. Ocean conditions at the time of sea entry are extremely important to the survival and ultimate abundance of fish in the fishery and the spawning population. Chinook salmon make up one of the most valuable and prized fisheries along the CCLME.

The two attributes selected for the salmon component were population size and population condition. For population size, we identified, evaluated, and propose these three indicators: spawning escapement, population growth rate, and hatchery contribution. For population condition, we also identified, evaluated, and propose three indicators: age structure, spatial stock structure, and size at age.

Data for monitoring salmon trends comes mainly from Northwest Fisheries Science Center and Southwest Fisheries Science Center trawl surveys, as well as estimates of catch and spawning numbers from state and federal agencies. For the 2010 CCLME IEA, the team emphasized 2 of the approximately 50 genetically distinct groups of West Coast salmon and steelhead (*Oncorhynchus mykiss*). Roughly half of those groups have been listed as endangered or threatened under the Endangered Species Act. In future years, the CCLME IEA will be expanded to include assessments of as many West Coast salmon groups as data allows. Initial findings include the following.

Sacramento River fall-run Chinook salmon abundance has varied over the years with greatest abundance in 1988, 1995, and 2002. As a result of decreased fishing pressures, the spawning abundance has had an increasing trend, though the values have plummeted since 2002, attributed in part to poor ocean conditions. There was also a near complete reproductive failure for the 2004 and 2005 broodyears, resulting in exceptionally low numbers of spawners for the fall-run California Chinook salmon in 2007–2009. By comparison, the Klamath River Chinook salmon fall-run population appears to have similarly variable abundance over the last 30 years with peak abundances occurring during 1986, 1995, and 2000–2003. Unlike Sacramento River fall-run Chinook salmon, the spawning abundance time series for the Klamath River fall-run Chinook salmon demonstrates no particular trend.

The behavioral characteristics of hatchery fall-run Chinook are relatively homogenized. Therefore, if hatchery production overwhelms natural production, there is a risk of stock collapse much like that observed for the Sacramento River fall-run Chinook salmon. The proportion of Sacramento River fall-run Chinook salmon spawning in hatcheries has increased to its greatest values during the last 5 years. Fall-run Chinook salmon from the Klamath River did not experience any particular trend in hatchery contribution.

Sacramento River and Klamath River fall-run Chinook salmon population growth rates do not show the same trends. The Sacramento River fall-run Chinook salmon population has shown an average 15% decline in population growth rate over the last 10 years, with an exceptional 48% decline in the last 5 years. Sacramento winter-run and spring-run Chinook salmon have also experienced precipitous declines in growth rates over the last 5 years (38% and 61% respectively). Unlike the Sacramento River fall-run Chinook salmon, Klamath River fall-run Chinook salmon did not experience any particular trend in growth rates over the last 5 to 10 years. Instead, growth rate was relatively stable but punctuated by extremely productive years.

The Sacramento River Chinook salmon stocks lack age-specific data to evaluate age structure of the population. For Klamath River Chinook, examination of the proportional contribution of each age to spawning stock demonstrates that the largest fraction of the spawning population is age-3 and age-4 fish and there has been a declining fraction of age-2 spawners. However, the negative trend for age-2 fish seems to be driven in large part by a few extraordinary years. Chinook salmon age structure appears relatively stable across the last 30 years; no trends are apparent in the age structure. However, this evaluation of Klamath River Chinook salmon should not be extrapolated to Sacramento River Chinook salmon. It is likely that Chinook salmon from the Sacramento River did demonstrate a change in age structure in recent years due to several consecutive years of poor early survival.

## Green Sturgeon

Green sturgeon are long-lived, slow growing fish. Along the Pacific coast are two distinct stocks: a northern stock from the Rogue and Klamath rivers and a southern stock from the Sacramento River. Generally, little is known about the biology, abundance, or condition of these stocks. Much like salmon, green sturgeon spawn in freshwater. Critical habitat required to complete the life cycle of green sturgeons has been identified as the shelf waters from Monterey Bay, California, to Vancouver Island, British Columbia, as well as the rivers and estuaries associated with spawning and rearing.

The two attributes selected for the green sturgeon component were population size and population condition. Compared to groundfish and salmon, green sturgeon have been little studied until quite recently and indicators are in the early stages of development. In light of the kinds of data that have been and are now beginning to be collected, just a few indicators relevant to green sturgeon will be possible to estimate. For population size, we identified, evaluated, and propose two indicators: spawning escapement and juvenile abundance. For population condition, we also identified, evaluated, and propose two indicators: age structure and spatial structure of stocks.

## Ecosystem Health

Just as the task of a physician is to assess and maintain the health of an individual, resource managers are charged with assessing and maintaining or restoring ecosystem health. In reality, however, disturbances, catastrophes, and large-scale abiotic forcing create situations where ecosystems are seldom near equilibrium. Thus assessing and managing ecosystem health is more complex than this simple analogy. Even so, we use the term ecosystem health because it has become part of the EBM lexicon, resonates with stakeholders and the general public, and is familiar and salient in the policy arena.

To measure the health of the CCLME ecosystem for this 2010 IEA, the team selected two key attributes representing the structure and function of the CCLME: community composition (structure) and energetics and material flows (function). From the 18 indicators in the top quartile for community composition, we propose these four indicators: zooplankton species biomass anomalies, taxonomic distinctness (average and variation), top predator biomass, and seabird annual reproductive output. From the three indicators in the top quartile for energetics and material flows, we propose to use these two: chlorophyll *a* (chl *a*) and inorganic nutrient levels (phosphate, nitrate, silicate). The suite of indicators was then used to evaluate the status of each ecosystem health attribute. Key findings include the following:

- Removing top predators from an ecosystem may result in a trophic cascade in which prey species increase in numbers because they are released from predatory control. Data collected by the West Coast bottom trawl surveys indicate that top predator biomass has declined sharply across the entire data set from 2003 to 2009.
- In the CCLME, the diversity of groundfish within the West Coast bottom trawl surveys has declined substantially over the last 5-year sampling period (2005–2009). This suggests a change in the community composition of groundfish across the CCLME.
- Over the last 5 years, the Northern Zooplankton Index, which measures whether zooplankton species from northern waters are more or less common than normal off the Oregon coast, shows an increasing trend, suggesting positive conditions at the base of the food web because northern species are typically rich in fats and other nutrients.
- In the CCLME, there is a high degree of spatial variation in chl *a*, which is an important metric of marine food webs values. Spatial patterns show chl *a* values are greater near the coast, particularly in estuaries such as San Francisco Bay, Puget Sound, and the mouth of the Columbia River. In 2010 several locations had low levels of chl *a* during the summer, and some locations have showed a declining trend in chl *a* during the summer over the past 5 years.

# Ecosystem Risk Assessment

A key aspect of implementing an IEA is risk analysis. A risk analysis evaluates the chance within a time frame of an event with adverse consequences. In the context of the California Current IEA, a risk analysis should evaluate the risk to indicators posed by human activities and natural processes. Adverse consequences or undesirable states for the indicators can be defined by reference to the ecosystem goals established by policy makers.

For the purpose of assessment, risk is often broken down into likelihood and consequence components. In the general risk literature, likelihood is the probability of an event's occurrence and consequence is the conditional probability of an adverse result should the event occur. In ecotoxicological studies, risk is described based on the response of an organism (or population, community, etc.) to different levels of exposure to a stressor. A stressor is an element of a system that precipitates an unwanted outcome; it can be natural or human induced. The exposure-response framework is convenient for evaluating risk due to chronic and persistent conditions faced by the subject of the risk analysis. In an effort to embrace the move toward ecosystem-based fisheries management, fisheries scientists have recently adopted another risk analysis framework, called productivity-susceptibility analysis or PSA. The goal of a PSA is to determine the vulnerability of different fish stocks to current fisheries management practices.

In this technical memorandum, we borrow elements from exposure-response and PSA risk analyses to assess the risk to ecosystem components (e.g., species, habitats, etc.) posed by stressors associated with different human activities. Here we focus on common human activities that in particular circumstances could lead to adverse consequences for different ecosystem components. For instance, human activities like aquaculture and shipping, which offer a variety of benefits to people, can be associated with stressors for some ecosystem components. Examples of stressors potentially associated with aquaculture and shipping include nutrient inputs and noise pollution.

For our ecosystem risk assessment, we adopt elements of the exposure-response framework widely used in ecotoxicology and expand it to include stressors other than toxic contaminants. We borrow heavily from the PSA framework but broaden the approach so that it is applicable for human activities beyond fishing. The result is a first-order risk analysis that integrates understanding of the extent or likely extent of exposure of different ecosystem components to the same stressor, and of an individual ecosystem component to different stressors, with an estimate of likely responses. We illustrate this approach using a case study of marine food web indicator species in Puget Sound, Washington.

We quantified risk to ecosystem components caused by stressors associated with human activities using a modified version of PSA. This approach is a type of risk ranking method that relies on qualitative estimates of likelihood and consequence to estimate risk, but can use quantitative information when it is available. We defined risk in a two-dimensional space created by susceptibility and consequence axes. The criteria we used were modified from a catalog of approximately 80 possibilities. The goal was to arrive at a list of criteria that at once provided for complementarity and parsimony, did not lead to high sensitivity of either axis to a single criterion, described risk inherent to individual species due to ecological and social factors, and revealed how the risk to each species varied among stressors.

The susceptibility criteria we selected include spatial, temporal, and management factors that describe the degree of exposure or likelihood of exposure of each species to a stressor or stressors. The consequence criteria we selected include resistance and recovery factors that describe the potential response of each species to a stressor or stressors. In addition to determining a score for each susceptibility and consequence criterion, we also assigned a data quality rating.

To demonstrate this ecosystem-based approach to risk assessment, we focused on stressors created by three human activities: coastal development, industry, and fishing. The stressors associated with these activities that we explicitly consider include shoreline armoring and overwater structures, point source pollution by toxic contaminants, and overharvesting, respectively.

Results showed that all of the Puget Sound food web indicator species are susceptible to stressors associated with coastal development, although there were differences in consequence due to variation among the species in their use of nearshore habitats. Like shoreline armoring and overwater structures resulting from coastal development, toxic contaminant point source pollution associated with industrial activity generally increased the susceptibility of Puget Sound indicator species. However, unlike risk due to coastal development, industry also increased the consequence scores for many species as well, suggesting that point source pollution from toxic contaminants is a ubiquitous threat to the Puget Sound food web. Under current management policies, overharvest associated with fishing poses less of a risk than coastal development or industry to most of the indicator species. Most species showed reduced susceptibility with little change in the consequence scores; however, some species, such as Chinook salmon and Pacific herring (*Clupea pallasii*), remained at relatively high risk due to fishing even under current fisheries management regulations.

We thus outlined a generic and flexible approach to ecosystem-based risk analysis and used Puget Sound marine food web indicator species to demonstrate the versatility of the approach. Though we focused on the entire Puget Sound, a convenient feature of this framework is that it is scalable. That is, the risk analysis could be repeated with a focus on larger (e.g., entire California Current, decadal processes) or smaller (e.g., subregions within Puget Sound, seasons) spatial and temporal scales. Similarly, criteria could be redesigned to include those that incorporate information about historical management practices or the likely zone of influence of different stressors. In addition, the approach can be adapted for ecosystem components beyond indicator species, including habitats, community indices, and other endpoints (e.g., water quantity or quality).

## Management Strategy Evaluation

In 2010 the IEA team worked with fishery managers at NMFS's regional offices and staff at national marine sanctuaries to conduct a proof of concept test using IEA findings to evaluate management scenarios. Specifically, they examined the influence of broad fishery management options on groundfish and ecosystem health using the Atlantis ecosystem model.

## California Current Atlantis Model

The California Current Atlantis Model (CCAM) is a decision support tool used in the California Current IEA that is built on the Atlantis ecosystem modeling framework. Worldwide, 13 Atlantis models are in use and several others are in development. The U.N. Food and Agriculture Organization recently named Atlantis the best ecosystem model available for marine resource management. CCAM simulates the ecosystem and allows researchers to forecast the ecosystem impacts of a wide range of human activities (e.g., fishing, pollution) or natural perturbations (e.g., climate variability). CCAM divides the coast into discrete spatial units so that evaluation of spatial management options is available.

Just as ecosystems are comprised of many smaller interrelated processes and nested ecosystems, the CCAM is made up of many submodels representing ecosystem dynamics. These submodels simulate oceanographic processes, biogeochemical factors driving primary production, and food web relations among species groups. CCAM simulates an area from Point Conception, California, north to the U.S.-Canada border, and from the shoreline west to a depth of 2,400 m. The area is divided into 82 regions, each consisting of up to 7 depth layers.

The core of CCAM is an ecological module that follows nutrients through 62 species groups in the system (5 bacteria/detritus, 8 plankton/algae, 14 invertebrate, 35 vertebrate). This module simulates feeding relationships and ecological processes including consumption, production, migration, predation, recruitment, habitat dependence, and mortality. The ecological processes are repeated in each of the depth layers within each region. An oceanographic model simulates fluxes of water and nutrients driven by temperature and salinity. CCAM represents persistent oceanographic processes such as a latitudinal stratification of salinity and temperature and ocean circulation. A human impacts submodel currently simulates multiple fishing fleets. This module considers both target and nontarget species, bycatch, and habitat effects. The economic consequences of different management scenarios are evaluated at the fleet level using information about potential revenue, costs, and fishing effort dynamics.

Using the CCAM in the 2010 IEA, the team explored status quo management as well as 20-year projections of several gear switching and spatial management scenarios. These scenarios involved changes to rockfish conservation areas, essential fish habitat, the amount of trawling relative to other gears, and overall levels of fishing effort, both within Monterey Bay National Marine Sanctuary and coast wide.

The team evaluated the scenarios based on ecological and economic performance. For groundfish, performance metrics included biomass, age structure, and population trends of harvested groundfish and unharvested species. For ecosystem health, performance metrics included zooplankton abundance, primary production, top predators, and the number of juvenile seabirds.

## Preliminary Outcomes of Alternative Management Scenario Evaluation

Of the scenarios that involved large-scale management changes, no single scenario maximized all performance metrics. Any policy choice would involve trade-offs between stakeholder groups and policy goals. When judged at a coast-wide scale, large management changes were needed to substantially change performance from status quo. When spatial management was imposed in specific areas, such as the Monterey Bay sanctuary, any coast-wide impacts that did occur tended to involve local interactions that were difficult to predict based solely on fishing patterns. On the other hand, if performance of scenarios were measured at the local scale (i.e., only within the sanctuary), local gear shift and spatial managements options did lead to increases in ecosystem function and health and landed value. Economic costs within the sanctuary that were associated with some of the improvements in ecological performance were highest when the management actions only involved the sanctuary, and were minimal when the management action occurred at a coast-wide scale. This exercise demonstrates the value of IEA information and management strategy evaluation in illuminating the trade-offs in management options.

## Future Plans

As new information, analytical techniques, and management needs arise, the California Current IEA will be refined, expanded, and improved. In the near term, scientists and members of the IEA team plan to collect and incorporate additional data, identify and test new ecosystem indicators, develop new analytical methods, and enhance risk assessments. In future years, the IEA team will conduct additional strategy evaluations based on input collected through stakeholder and partner scoping. Future plans include expanding coverage of drivers and pressures to include analyses of the effects of fishing, wave energy projects, habitat alteration, water quality, and climate, and adding particularly compelling groups (e.g., forage fishes within the wild fisheries component) to the list of EBM components.

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# Abbreviations and Acronyms

| | |
|---|---|
| AFSC | Alaska Fisheries Science Center |
| AvTD | average taxonomic distinctness |
| CalCOFI | California Coastal Oceanic Fisheries Investigative (reports) |
| CCAM | California Current Atlantis Model |
| CCLME | California Current Large Marine Ecosystem |
| chl *a* | chlorophyll *a* |
| CPUE | catch per unit of effort |
| CTD | conductivity temperature depth |
| CUI | Cumulative Upwelling Index |
| CVI | Central Valley Index |
| EBM | ecosystem-based management |
| EFH | essential fish habitat |
| ENSO | El Niño Southern Oscillation |
| EwE | Ecopath with Ecosim |
| GAM | generalized additive model |
| GFDL | Geophysical Fluid Dynamics Laboratory |
| GLOBEC | U.S. Global Ocean Ecosystems Dynamics |
| IEA | integrated ecosystem assessment |
| IFQ | individual fishing quota |
| IUCN | International Union for the Conservation of Nature |
| MAR | multivariate autoregressive |
| MBNMS | Monterey Bay National Marine Sanctuary |
| MEI | Multivariate ENSO Index |
| MLPA | Marine Life Protection Act (California) |
| MPA | marine protected area |
| MRFSS | Marine Recreational Fisheries Statistics Survey |
| MSE | management strategy evaluation |
| MSFCMA | Magnuson-Stevens Fishery Conservation and Management Act |
| MWMAR | moving window multivariate autoregressive |
| NDBC | National Data Buoy Center |
| NMFS | National Marine Fisheries Service |
| NMS | national marine sanctuary |
| NOI | Northern Oscillation Index |
| NPGO | North Pacific Gyre Oscillation |
| NPP | net primary production |
| NWFSC | Northwest Fisheries Science Center |
| OPI | Oregon Production Index |
| ORHAB | Olympic region harmful algal bloom |
| PacFIN | Pacific Fisheries Information Network |
| PAH | polycyclic aromatic hydrocarbon |

| | |
|---|---|
| PBDE | polybrominated diphenyl ether |
| PCB | polychlorinated biphenyl |
| PCGFMP | Pacific Coast Groundfish Fishery Management Plan |
| PDO | Pacific decadal oscillation |
| PFMC | Pacific Fishery Management Council |
| PISCO | Partnership for Interdisciplinary Studies of Coastal Oceans |
| POM | particulate organic matter |
| POP | persistent organic pollutant |
| PRBO | Point Reyes Bird Observatory |
| PSA | productivity-susceptibility analysis |
| PSP | Puget Sound Partnership |
| RCA | rockfish conservation area |
| ROV | remotely operated vehicle |
| SST | sea surface temperature |
| SWFSC | Southwest Fisheries Science Center |
| TD | taxonomic distinctness |
| VarTD | variation in taxonomic distinctness |
| WCGTS | West Coast Groundfish Trawl Survey |
| WTP | willingness-to-pay |

# Introduction: An Incremental Approach to the California Current Integrated Ecosystem Assessment

## The California Current Ecosystem

The California Current Large Marine Ecosystem (CCLME) is a large, dynamic, and spatially heterogeneous marine environment in the eastern North Pacific Ocean off the west coast of North America (Duda and Sherman 2002). It spans nearly 3,000 km of latitude from Vancouver Island, British Columbia, Canada, to Baja California, Mexico (Figure 1). Several major physical oceanographic processes, linked to variability in the atmospheric pressure cells that force winds and circulation, determine ecosystem structure, function, and services. From an oceanographic perspective, the CCLME is under influence from the northern and western Pacific and tropical eastern North Pacific. These processes result in local effects of coastal upwelling and basin-scale subarctic and subtropical water mass intrusions.

The California Current is the primary driver of oceanographic variability in the system and is a year-round equatorward flow extending from the continental shelf break to approximately 1,000 km offshore, with strongest speeds at the surface and extending to at least 500 m depth (Hickey 1989). It carries cooler, fresher, and nutrient-rich water equatorward. A narrow, weaker surface poleward flow along the coast is known as the California Countercurrent south of Point Conception and the Davidson Current north of Point Conception. Another narrow but deeper poleward flow, the California Undercurrent, extends the length of the coast along the continental slope. Maximum current speed is usually from summer to early fall for the California Current and California Undercurrent, and in winter for the California Countercurrent and Davidson Current. The CCLME is largely a wind-driven system, with little freshwater input except from the Columbia River.

Three major estuaries—San Francisco Bay, Columbia River, and Puget Sound—contribute significantly to local economies. Coastal upwelling, El Niño, and decadal-scale climate forcing result in highly variable productivity in the region and consequently increased variability in many fisheries (Bakun 1993, Aquarone and Adams 2008). In the northern and middle ecoregions of the CCLME, fishery resources include invertebrate populations, especially in nearshore waters, groundfish populations along the continental shelf, and migratory pelagic species such as salmon (*Oncorhynchus* spp.), Pacific sardine (*Sardinops sagax*), Pacific hake (*Merluccius productus*), and Pacific herring (*Clupea pallasii*). At the southern end, northern anchovy (*Engraulis mordax*) and market squid (*Loligo opalescens*) are important. The CCLME also supports large and diverse seabird and marine mammal populations.

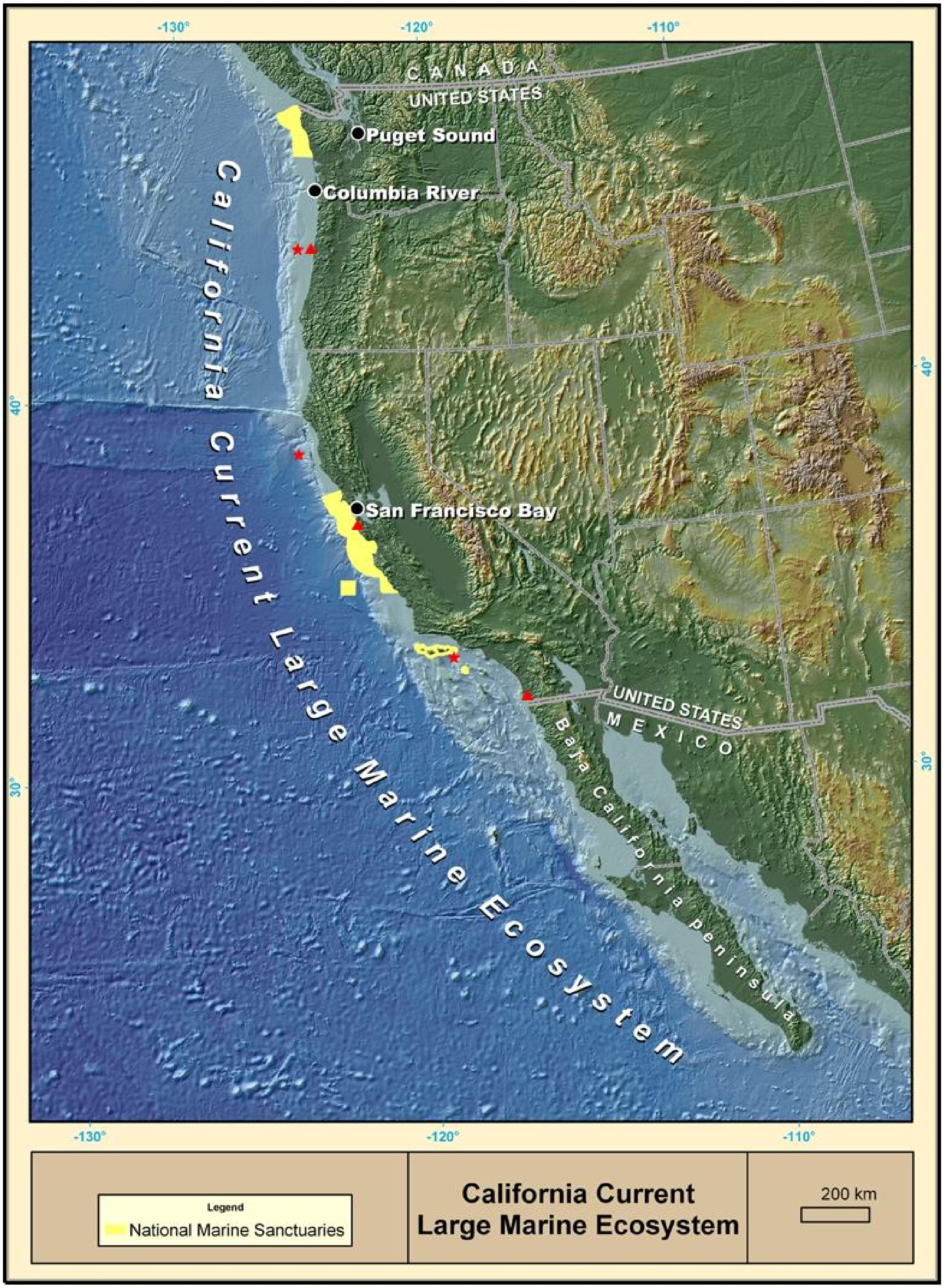



Figure 1. Map of the CCLME. National marine sanctuaries (NMSs) for the U.S. West Coast include (from north to south) Olympic Coast, Gulf of the Farallones, Cordell Bank, Monterey Bay, and the Channel Islands. Sea level measurement locations chosen for this report are represented by red triangles. NDBC buoys collecting sea surface temperatures and meridional wind time series are indicated by red stars. (Map by Blake Feist, NWFSC.)

The California Current is formed as the eastern leg of the North Pacific Gyre. The intensity of transport in the California Current is not well-known, but probably varies by season, year, and decade. It fluctuates in part relative to the position and strength of the North Pacific Current/West Wind Drift, which traverses the subarctic North Pacific Ocean and bifurcates from British Columbia to northern Oregon into the Alaska and California currents. While Washington and southern British Columbia may be considered a transition zone, we define the northern boundary of the CCLME as the northern tip of Vancouver Island, British Columbia, due to frequent upwelling along this section of the coastline in spring and summer (Allen et al. 2001, Yen et al. 2005). Based on physical and biological attributes, Parrish et al. (1981) subdivided the CCLME into three distinct subecosystems:

- Southern British Columbia, Washington, and Oregon to Cape Blanco;
- Cape Blanco, southern Oregon, to Point Conception, California; and
- Southern California (below Point Conception) and Baja California.

## What is an Integrated Ecosystem Assessment?

NOAA defines an ecosystem as a "geographically specified system of organisms (including humans), the environment, and the processes that control its dynamics" NOAA further defines the environment as "the biological, chemical, physical, and social conditions that surround organisms" (Murawski and Matlock 2006).

An ecosystem management approach is one that provides a comprehensive framework for marine, coastal, and Great Lakes resource decision making. Integrated ecosystem assessments (IEAs) are a critical science support element enabling ecosystem-based management (EBM) strategies. An IEA is a formal synthesis and quantitative analysis of information on relevant natural and socioeconomic factors in relation to specified ecosystem management goals. It involves and informs citizens, industry representatives, scientists, resource managers, and policy makers through formal processes to contribute to attaining the goals of EBM.

An IEA uses approaches that determine the probability that ecological or socioeconomic properties of systems will move beyond or return to within acceptable limits as defined by management objectives. An IEA must provide an efficient, transparent means of summarizing the status of ecosystem components, screening and prioritizing potential risks, and evaluating alternative management strategies against a backdrop of environmental conditions. To this end, IEAs follow four steps:

- Scoping: Identify management objectives, articulate the ecosystem to be assessed, identify ecosystem attributes of concerns, and identify stressors relevant to the ecosystem being examined.
- Indicator development: Researchers must develop and test indicators that reflect the ecosystem attributes and stressors specified in the scoping process. Specific indicators are dictated by the problem at hand and must be linked objectively to decision criteria.
- Risk Analysis: The goal of risk analysis is to fully explore the susceptibility of an indicator to natural or human threats, as well as the ability of the indicator to return to its previous state after being perturbed.

- Evaluation: Evaluate the potential different management strategies to influence the status of ecosystem components of management concern or the drivers and pressures that affect these ecosystem components.

Further description of IEAs can be found in Levin et al. (2008, 2009).

# Scope of this Report

The primary goal of the California Current IEA is to inform the implementation of EBM by melding diverse ecosystem components into a single, dynamic fabric that allows for coordinated evaluations of the status of the California Current ecosystem. We also aim to involve and inform a wide variety of stakeholders and agencies that rely on science support for EBM, and to integrate information collected by NOAA and other federal agencies, states, nongovernmental organizations, and academic institutions. The essence of IEAs is to inform the management of diverse, potentially conflicting ocean-use sectors. As such, a successful California Current IEA must encompass a variety of management objectives, consider a wide range of natural drivers and human activities, and forecast the delivery of ecosystem goods and services under a multiplicity of scenarios.

A full IEA of the California Current is thus a massive undertaking. Our approach to the task of completing this IEA was to systematically decompose the California Current into a series of ecosystem pressures and components that are of keen interest to resource managers, policy makers, and the public. Working with regional managers, we then selected a limited set of pressures and components that we could address in the initial phase of the IEA.

Participants in this exercise—members of the NOAA California Current IEA Team—were John Stein (program manager) and Phillip Levin (science lead), Northwest Fisheries Science Center (NWFSC); Frank Schwing and Brian Wells (science leads), Southwest Fisheries Science Center (SWFSC); Kathi Lefebvre, NWFSC; Yvonne deReynier, National Marine Fisheries Service (NMFS) Northwest Regional Office; Rikki Dunsmore, Monterey Bay National Marine Sanctuary; Churchill Grimes, SWFSC; Joshua Lindsay, Shelby Mendez, and Elizabeth Petras, NMFS Southwest Regional Office; Rondi Robison, NOAA MPA (marine protected area) Center; and Lisa Wooninck, National Marine Sanctuary West Coast Regional Office. Below we present the outcome of this dialogue.

# EBM Drivers, Pressures, and Components in the California Current Ecosystem

A lengthy list of drivers and pressures was created. Here we define drivers as factors that result in pressures that in turn cause changes in the ecosystem. For the purposes of an IEA, natural and anthropogenic forcing factors are considered. An example of the former is climate variability and the latter include factors such as human population size in the coastal zone and associated coastal development, and demand for seafood. In principle, human driving forces can be assessed and controlled. Natural environmental changes cannot be controlled but must be accounted for in management. Pressures include factors such as coastal pollution, habitat loss and degradation, and fishing effort that can be mapped to specific drivers. For example, coastal development results in increased coastal armoring and the loss of associated intertidal habitat.

We binned drivers and pressures into 11 broad categories (Figure 2). We define EBM components as the biological, physical, or human dimension entities that policy makers, managers, or citizens are trying to manage or conserve. Expressed this way, the list of management concern targets is quite long; however, the IEA team grouped these into seven bins (Figure 2) defined as follows:

- Wild fisheries, an EBM component centered on the condition of fishery stocks included in the coastal pelagic species, highly migratory species, groundfish, and salmon fishery management plans.
- Seafood, distinct from fisheries, an EBM component focused on the consistent delivery of plentiful, safe seafood. This overlaps with the wild fisheries EBM, but includes aquaculture and production hatcheries and focuses less on the health of the wild stocks and more on the provisioning of food for human consumption.
- Protected resources, species legally designated as protected (e.g., Marine Mammal Protection Act, Migratory Bird Treaty Act, Endangered Species Act).
- Habitat, including biogenic and abiotic habitats on the seafloor and in the water column.
- Ecosystem health, referring to the structure and function of marine and coastal ecosystems and ecological communities.
- Vibrant coastal communities, including social, economic, and cultural well-being and human health as it is tied to the marine environment.
- Scientific knowledge and education, a distinct EBM goal of many agencies to provide unique opportunities for scientific research and education.

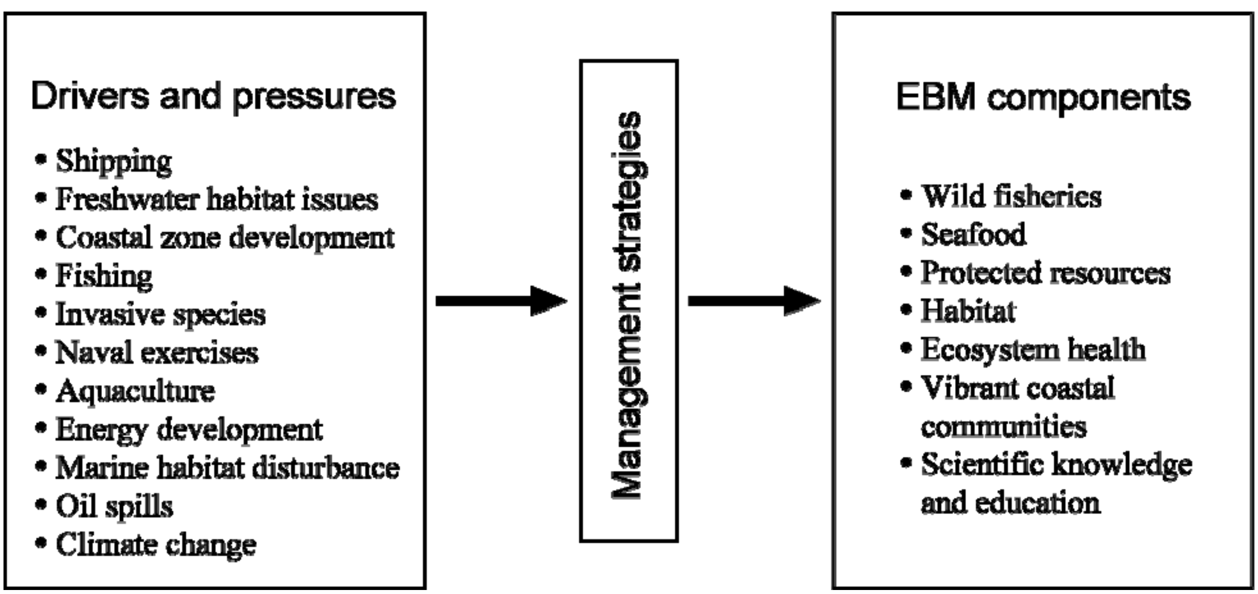



Figure 2. Conceptual diagram of the primary pressures and drivers affecting change in the primary EBM components of the CCLME as defined by the IEA team.

## EBM Drivers, Pressures, and Components Addressed in the California Current IEA

The ultimate aim of the California Current IEA is to fully understand the web of interactions that links drivers and pressures to EBM components and to forecast how changing environmental conditions and management actions affect the status of EBM components. The IEA team decided to focus on climate as an important ecosystem driver. In the first year, the IEA team also focused on four aspects of the EBM components:

- Groundfish as an example of the wild fishery EBM component;
- Salmon as a group of species that is of interest as a protected resource, fisheries target, and an aspect of ecosystem health;
- Green sturgeon (*Acipenser medirostris*) as an example of a protected resource; and
- Ecosystem health.

The IEA team believed that given existing scientific tools and management needs, addressing these EBM components would have the greatest benefit to ongoing policy and management processes.

## Next Steps for the California Current IEA

This report is the first in a series of efforts to complete a full IEA of the California Current. In addition to improving analytical techniques and models and filling data gaps, the next iteration of the IEA will expand to include more ecosystem pressures and components. Specifically, in fiscal year 2011 the California Current IEA will add two EBM components: vibrant coastal communities and forage fish. In addition, the IEA will explicitly add wave energy power generation as an ecosystem pressure. In this document, we develop an approach to conduct an ecosystem risk assessment and apply this approach to a limited set of human activities and ecosystem components in the California Current. In subsequent years, this approach will be extended to include regions beyond the California Current. Finally, only a limited set of management strategy evaluations are presented here (see The Evaluation of Management Strategies section). In fiscal year 2011 thorough scoping will be conducted, which will allow scientists to analyze specific suites of well-vetted management strategies.

# Selecting and Evaluating Indicators for the California Current

## Selecting Ecosystem Indicators for the California Current

### What is an Ecosystem Indicator?

Ecosystem indicators are quantitative biological, chemical, physical, social, or economic measurements that serve as proxies of the conditions of attributes of natural and socioeconomic systems (e.g., Landres et al. 1988, Kurtz et al. 2001, EPA 2008, Fleishman and Murphy 2009). Ecosystem attributes are characteristics that define the structure, composition, and function of the ecosystem that are of scientific or management importance but insufficiently specific or logistically challenging to measure directly (Landres et al. 1988, Kurtz et al. 2001, EPA 2008, Fleishman and Murphy 2009). Thus indicators provide a practical means to judge changes in ecosystem attributes related to the achievement of management objectives. They can also be used for predicting ecosystem change and assessing risk.

Ecosystem indicators are often cast in the Driver-Pressure-State-Impact-Response (DPSIR) framework—an approach that has been broadly applied in environmental assessments of terrestrial and aquatic ecosystems, including NOAA's IEA (Levin et al. 2008). Drivers are factors that result in pressures that cause changes in the system. Natural and anthropogenic forcing factors are considered. An example of the former is climate conditions and examples of the latter include human population size in the coastal zone and associated coastal development, the desire for recreational opportunities, and so forth. In principle, human driving forces can be assessed and controlled, whereas natural environmental changes cannot be controlled but are accounted for in management.

Pressures are factors that cause changes in state or condition. They can be mapped to specific drivers. Examples include coastal pollution, habitat loss and degradation, and fishing. Coastal development results in increased coastal armoring and the degradation of associated nearshore habitat. State variables describe the condition of the ecosystem (including physical, chemical, and biotic factors). Impacts comprise measures of the effect of change in these state variables such as loss of biodiversity, declines in productivity and yield, etc. Impacts are measured with respect to management objectives and the risks associated with exceeding or returning to below these targets and limits.

Responses are the actions (regulatory and otherwise) taken in response to predicted impacts. Forcing factors under human control trigger management responses when target values are not met as indicated by risk assessments. Natural drivers may require adaptational response to minimize risk. For example, changes in climate conditions that in turn affect the basic productivity characteristics of a system may require changes in ecosystem reference points that reflect the shifting environmental states.

Ideally, indicators should be identified for each step of the DPSIR framework such that the full portfolio of indicators can be used to assess ecosystem condition as well as the processes and mechanisms that drive ecosystem health. State and impact indicators are preferable for identifying the seriousness of an environmental problem, but pressure and response indicators are needed to know how best to control the problem (Niemeijer and de Groot 2008). In 2010 we focused primarily on indicators of ecosystem state (EBM components), while future California Current IEA iterations will address and evaluate indicators of drivers and pressures. Indicators can be used as measurement endpoints for examining alternative management scenarios in ecosystem models (Appendix A) or in emerging analyses to predict or anticipate regime shifts (Appendix B).

## Specific Goals Will Determine the Suite of Indicators

It is a significant challenge to select a suite of indicators that accurately characterizes the ecosystem while also being relevant to policy concerns. A straightforward approach to overcoming this challenge is to employ a framework that explicitly links indicators to policy goals (Harwell et al. 1999, EPA 2002). This type of framework organizes indicators in logical and meaningful ways in order to assess progress towards policy goals. We use the framework established by Levin et al. (2010b) as guidance. Our framework begins with the set of seven EBM components (Figure 2). Each EBM component represents a discrete segment of the ecosystem that reflects societal goals or values and is relevant to the policy goals of NMFS. Each component is then characterized by key attributes, which describe fundamental aspects of each goal. Finally, we map indicators onto each key attribute. In this report, we focused on aspects of four ecosystem components: groundfish (wild fisheries component), salmon (wild fisheries and protected resources components), green sturgeon (*Acipenser medirostris*) (protected resources component), and ecosystem health (ecosystem health component).

### Groundfish

Groundfish are generally defined as a community of fishes that are closely associated with the ocean bottom. In the CCLME, some of the better known species include the rockfishes (Scorpaenidae), flatfishes (Pleuronectidae and Bothidae), sculpins (Cottidae), Pacific hake, sablefish (*Anoplopoma fimbria*), greenlings and lingcod (Hexagrammidae), skates (Rajidae), and benthic sharks (PFMC 2008a). Similar to most fishes, many groundfish species have a planktonic larval and young-of-year life history stage in which young fish inhabit surface waters and feed on a diet of zooplankton. After a few months in the plankton, most species settle to the bottom and remain there for the rest of their lives. Groundfish vary across a wide range of trophic levels and inhabit all types of habitats (e.g., rocky, sandy, muddy, kelp) from the intertidal zone to the abyss.

This community of fishes constitutes a large biomass in the CCLME and provides the economic engine for coastal communities in Washington, Oregon, and California. The Pacific Fishery Management Council (PFMC) manages a subset of groundfish species that are typically captured during fishing operations along the U.S. West Coast. Those species caught in the Pacific groundfish trawl fishery were worth approximately $40 million in 2009 (NOAA press release 2010). Thus understanding how groundfish populations fare over time is of great interest to ecosystem managers and the coastal communities that derive much of their wealth from this assemblage of fishes.

### Salmon

Two species make up the vast proportion of salmon abundance within the CCLME: Chinook salmon (*Oncorhynchus tshawytscha*) and coho salmon (*O. kisutch*) (Healy 1991). Salmon spawn in freshwater where their eggs and juveniles spend up to a year before migrating to sea. Ocean conditions at the time of sea entry are extremely important to the survival and ultimate abundance of fish in the fishery and the spawning population (Pearcy 1992, Beamish and Mahnken 2001). Chinook salmon generally spend 2–5 years at sea before returning to their natal stream to spawn (Quinn 2005). Coho spend approximately 1.5 years at sea (Sandercock 1991, Beamish et al. 2004).

Chinook salmon make up one of the most valuable and prized fisheries within the CCLME. For example, in 2004 and 2005 there were 5 million and 7.1 million pounds of Chinook salmon landed in California, respectively valued at $12.8 million and $17.8 million (Lindley et al. 2009a). Additionally, the associated economic benefits from the fisheries are great. During 2008 and 2009 a population collapse of Chinook salmon and the poor status of many West Coast coho salmon populations necessitated the closure of the salmon fishery in California waters (Lindley et al. 2009b). This translated to more than $200 million in losses and a U.S. Congressional appropriation of $170 million for disaster relief (Lindley et al. 2009b).

### Green sturgeon

Green sturgeon are long-lived, slow growing fish with a K-selected life history (MacArthur and Wilson 1967, Moyle 2002). Mature females can reach lengths of more than 2 m and do not mature until at least 15 years old (Adams et al. 2002). Along the coast are two distinct stocks: a northern stock from the Rogue and Klamath rivers and a southern stock from the Sacramento River (Adams et al. 2002). Generally, little is known about the biology, abundance, or condition of these stocks. Much like salmon, green sturgeon spawn in freshwater where juveniles can reside for up to 4 years (Adams et al. 2002). Once juveniles migrate to sea, they can undertake extensive migrations along the Pacific coast (Adams et al. 2002). Critical habitat required to complete the life cycle of green sturgeons has been identified as the shelf waters from Monterey Bay, California, to Vancouver Island, British Columbia, as well as the river and estuarine waters of rivers associated with spawning and rearing (50 CFR Part 226).

Based on trends in historical fisheries, during which catches indicated a much greater abundance than currently observed and extensive degradation of freshwater habitats, NMFS listed the southern stock as threatened (Adams et al. 2007).

### Ecosystem health

Rapport et al. (1985) suggested that the responses of stressed ecosystems were analogous to the behavior of individual organisms. Just as the task of a physician is to assess and maintain the health of an individual, resource managers are charged with assessing and, when necessary, restoring ecosystem health. This analogy is rooted in the organismic theory of ecology advocated by F. E. Clements more than 100 years ago, and is centered on the notion that ecosystems are homeostatic and stable, with unique equilibria (De Leo and Levin 1997). In reality, however, disturbances, catastrophes, and large-scale abiotic forcing create situations where ecosystems are seldom near equilibrium. Indeed, ecosystems are not "superorganisms"—they are open and dynamic with loosely defined assemblages of species (Levin 1992). Consequently, simplistic analogies to human health break down in the face of the complexities of the nonequilibrial dynamics of many ecological systems (Orians and Policansky 2009). Even so, the term "ecosystem health" has become part of the EBM lexicon and resonates with stakeholders and the general public (Orians and Policansky 2009). In addition ecosystem health is peppered throughout the literature on ecosystem indicators. Thus while we acknowledge the flaws and limitations of the term, we use it here because it is familiar and salient in the policy arena. In the CCLME application, ecosystem health is defined specifically by the key attributes described below.

## Key Attributes of EBM Components

Key attributes are ecological characteristics that specifically describe some relevant aspect of each EBM component. They are characteristic of the health and functioning of each EBM component, and they provide a clear and direct link between the indicators and components. For each of the first three components (groundfish, salmon, and green sturgeon), we identified the same key attributes (Levin et al. 2010b): population size and population condition. For the component ecosystem health, we identified and focused on two key attributes: community composition, and energetics and material flows (Table 1).

### Groundfish, salmon, and green sturgeon

**Population size**—Monitoring population size in terms of total number or total biomass is important for management and societal interests. For example, abundance estimates are used to track the status of threatened and endangered species and help determine whether a species is recovering or declining. Accurate population biomass estimates of targeted fisheries species are used to assess stock viability and determine the number of fish that can be sustainably harvested from a region. While population size can be used to assess population viability, more accurate

Table 1. Selected key attributes for each goal. Relevant measures describe what each attribute means (e.g., population size is represented by the number of individuals in a population or the total biomass).

| Goal | Key attribute | Relevant measures |
|---|---|---|
| Groundfish, salmon, and green sturgeon | Population size | Number of individuals or total biomass, population dynamics |
| | Population condition | Measures of population or organism condition including: age structure, population structure, phenotypic diversity, genetic diversity, organism condition |
| Ecosystem health | Community composition | Ecosystem structure: species diversity, trophic diversity, functional redundancy, response diversity |
| | Energetics and material flows | Ecosystem function: primary production, nutrient flow/cycling |

predictions of viability can be obtained by including the mechanisms responsible for the dynamics of the population. Population dynamics thus provide a predictive framework to evaluate the combined effect of multiple mechanisms of population regulation (e.g., birth and death rates, immigration, and emigration) to evaluate changes in abundance through time.

**Population condition**—Whereas the preceding attribute is concerned with measures of population size, there are instances when the health of the population may be of interest. For example, monitoring changes in population condition may presage an effect on population size or provide insight into long-term population viability. The dynamics of many populations are better understood through knowledge of population conditions such as organism condition, age structure, genetic diversity, phenotypic diversity, and population structure. Impaired condition of any or all of these subcategories indicates biological resources at risk. In addition, monitoring changes in population condition can be used to infer changes in environmental conditions.

### Ecosystem health

**Community composition**—This attribute represents the structure of the ecosystem, describing the individual components and the relative extent of their potential interactions. Our definition of community composition includes species diversity, trophic level diversity, functional group redundancy, and response diversity. Species diversity encompasses species richness or the number of species in the ecosystem, and species evenness or how individuals or biomass are distributed among species within the ecosystem (Pimm 1984). Trophic diversity refers to the relative abundance or biomass of different primary producers and consumers within the ecosystem (EPA 2002). Consumers include herbivores, carnivores or predators, omnivores, and scavengers. Functional redundancy refers to the number of species characterized by traits that contribute to a specific ecosystem function, whereas response diversity describes how functionally similar species respond differently to disturbance (Laliberte and Legendre 2010). For example, an ecosystem containing several species of herbivores would be considered to have high functional redundancy with respect to the ecosystem function of grazing, but only if those herbivorous species responded differently to the same perturbation (e.g., trawling) would the food web be considered to have high response diversity.

**Energetics and material flows**—This attribute represents ecosystem function and includes ecological processes such as primary production and nutrient cycling, in addition to flows of organic and inorganic matter throughout an ecosystem. Primary productivity is the capture and conversion of energy from sunlight into organic matter by autotrophs, and provides the fuel fundamental to all other trophic transfers throughout the ecosystem. Material flows, or the cycling of organic matter and inorganic nutrients (e.g., nitrogen, phosphorus), describe the efficiency with which an ecosystem maintains its structure and function.

# Evaluating Potential Indicators for the California Current: Groundfish and Ecosystem Health

## Initial Selection of Indicators

There are numerous publications that cite indicators of species and ecosystem health in marine systems. For this report, we generally relied on several core references from the literature (Jennings and Kaiser 1998, Link et al. 2002, Rochet and Trenkel 2003, Fulton et al. 2005, Jennings 2005, Jennings and Dulvy 2005, Link 2005, Shin et al. 2005, Samhouri et al. 2009, Sydeman and Thompson 2010) to develop an initial list of potential indicators for each of the key attributes for two of the four EBM components: West Coast groundfish and ecosystem health. In many cases, indicators identified in the literature were chosen by the authors based on expert opinion or based on the context of the researchers' expertise. For example, many reviews of marine ecosystem indicators are put into the context of fisheries (e.g., Fulton et al. 2005, Link 2005) and ask the question: Which indicators reflect changes in the population as a result of fishing pressure? The approach we describe throughout this section to select and evaluate indicators for groundfish and ecosystem health could also be applied to the other EBM components.

During reviews of the literature, we identified 125 indicators for the key attributes of the groundfish and ecosystem health components. Indicators of population size are rather obvious, including estimates of abundance in numbers or biomass and estimates of population growth rate. Indicators of population condition vary widely in the literature and are generally dependent on the taxa of interest. Physiological measurements, such as cortisol and vitellogenin levels, and measurements of body growth and size/age structure are often related to the condition of populations via size-related fecundity processes, while measurements of genetic diversity and spatial structure of a population are often cited as measures of resilience in populations against perturbations such as fishing pressure or climate change. Indicators of community composition include community level metrics such as taxonomic diversity and ratios between different foraging guilds. Community composition indicators also include population level trends and conditions across a wide variety of taxa such as marine mammals, seabirds, and zooplankton. Indicators of energetics and material flows primarily examine the base of the food web and the cycling of nutrients that supply the basis for phytoplankton growth.

## Evaluation Framework

We follow the evaluation framework established by Levin et al. (2010b). We divide indicator criteria into three categories: primary considerations, data considerations, and other considerations. Ecosystem indicators should do more than simply document the decline or recovery of species or ecosystem health; they must also provide information that is meaningful to resource managers and policy makers (Orians and Policansky 2009). Because indicators serve as the primary vehicle for communicating ecosystem status to stakeholders, resource managers, and policy makers, they may be critical to the policy success of EBM efforts, where policy success can be measured by the relevance of laws, regulations, and governance institutions to ecosystem goals (Olsen 2003). Advances in public policy and improvements in management outcomes are most likely if indicators carry significant ecological information and resonate with the public (Levin et al. 2010a).

### Primary considerations

Primary considerations are essential criteria that should be fulfilled by an indicator in order for it to provide scientifically useful information about the status of the ecosystem in relation to the key attribute of the defined goals. They are:

1. Theoretically sound: Scientific, peer-reviewed findings should demonstrate that indicators can act as reliable surrogates for ecosystem attributes.
2. Relevant to management concerns: Indicators should provide information related to specific management goals and strategies.
3. Predictably responsive and sufficiently sensitive to changes in specific ecosystem attributes: Indicators should respond unambiguously to variation in the ecosystem attribute(s) they are intended to measure, in a theoretically or empirically expected direction.
4. Predictably responsive and sufficiently sensitive to changes in specific management actions or pressures: Management actions or other human-induced pressures should cause detectable changes in the indicators, in a theoretically or empirically expected direction, and it should be possible to distinguish the effects of other factors on the response.
5. Linkable to scientifically defined reference points and progress targets: It should be possible to link indicator values to quantitative or qualitative reference points and target reference points, which imply positive progress toward ecosystem goals.

### Data considerations

Data considerations relate to the actual measurement of the indicator. Criteria are listed separately to highlight ecosystem indicators that meet all or most of the primary considerations, but for which data are currently unavailable. They are:

1. Concrete and numerical: Indicators should be directly measureable. Quantitative measurements are preferred over qualitative, categorical measurements, which in turn are preferred over expert opinions and professional judgments.
2. Historical data or information available: Indicators should be supported by existing data to facilitate current status evaluation (relative to historic levels) and interpretation of future trends.
3. Operationally simple: The methods for sampling, measuring, processing, and analyzing the indicator data should be technically feasible.
4. Broad spatial coverage: Ideally, data for each indicator should be available across a broad range of the California Current.
5. Continuous time series: Indicators should have been sampled on multiple occasions, preferably without substantial time gaps between sampling.
6. Spatial and temporal variation understood: Diel, seasonal, annual, and decadal variability in the indicators should ideally be understood, as should spatial heterogeneity and patchiness in indicator values.
7. High signal-to-noise ratio: It should be possible to estimate measurement and process uncertainty associated with each indicator, and to ensure that variability in indicator values does not prevent detection of significant changes.

## Other considerations

Other considerations are meant to incorporate nonscientific information into the indicator evaluation process. Criteria may be important but not essential for indicator performance. They are:

1. Understood by the public and policy makers: Indicators should be simple to interpret, easy to communicate, and public understanding should be consistent with technical definitions.
2. Historically reported: Indicators already perceived by the public and policy makers as reliable and meaningful should be preferred over novel indicators.
3. Cost-effective: Sampling, measuring, processing, and analyzing the indicator data should make effective use of limited financial resources.
4. Anticipatory or leading indicator: A subset of indicators should signal changes in ecosystem attributes before they occur, ideally with sufficient lead time to allow for a management response.
5. Lagging indicator: Reveals evidence of a failure in or to the attribute.
6. Regionally, nationally, and internationally compatible: Indicators should be comparable to those used in other geographic locations, in order to contextualize ecosystem status and changes in status.

Each indicator was evaluated independently according to these 18 criteria by examining peer-reviewed publications and reports. The result is a matrix of indicators and criteria that contains specific references and notes in each cell, which summarize the literature support for each indicator against the criteria. This matrix can be easily reevaluated and updated as new information becomes available.

# Results of Indicator Evaluations

The results of our evaluation of each indicator are summarized in the tables included in this section. Following the framework outlined above, we organized the results of the evaluation by EBM component (i.e., groundfish, salmon, green sturgeon, and ecosystem health).

## Evaluation of groundfish indicators

We evaluated a total of 46 indicators of the two key attributes: population size and population condition. In general, the indicators that were evaluated scored well against the primary considerations criteria; however, when indicators performed poorly, it was generally because data were not available at large spatial scales or across long time series.

**Population size**—We first evaluated three primary indicators that are obvious and well established—numbers of individuals, total biomass of the population, and population growth rate. These indicators performed well across all three evaluation criteria categories and are supported as indicators of population size by all of our primary literature resources (e.g., Fulton et al. 2005, Link 2005, etc.). However, the ability of scientists and managers to measure the abundance or growth rate of any population of groundfish over time relies on surveys that are performed to collect data. Thus we decided to evaluate data sets in the CCLME that measure the abundance or biomass of groundfish populations over time (fishery dependent and fishery independent). This resulted in an evaluation of the strengths and weaknesses of various data sources that estimate the size of groundfish populations. We identified and evaluated a total of 29 potential indicators of population size in the CCLME, summarized in Table 2.

In general, data sources that relied on fishery-dependent data (e.g., commercial landings numbers, total harvest biomass) did not perform well against the primary considerations evaluation criteria. For example, recreational landings data are generally collected at docks and only include individuals and species that are kept by fishers. Thus these data are highly biased by fisher behavior in what species are targeted and what species or individuals they retain. When fishery-independent indicators did not perform well, it was generally because these data sources focused on a very narrow range of species (e.g., hake acoustic surveys) due to gear selectivity (e.g., International Pacific Halibut Commission longline surveys) or because the surveys did not occur at large spatial scales or over long time scales (e.g., NWFSC's hook-and-line surveys, scuba surveys). Interestingly, "local ecological knowledge" scored well in the primary considerations categories, but these interviews of people's memories simply do not exist for most of the CCLME. One attempt in Puget Sound by Beaudreau and Levin (in prep.) has shown a correlation between abundance trends of marine species derived from interviews with fishers and divers and scientifically collected survey data.

**Population condition**—We identified and evaluated 17 potential indicators (Table 3) for groundfish. Indicators related to age structure, fecundity, or spatial structure of populations generally scored well in the primary considerations categories. Many condition indicators did not score well in the data considerations categories because there is simply little data available across the entire CCLME or data do not exist at multiple periods through time. For example, age at maturity and genetic diversity score high in primary considerations, but there are few examples from a limited number of species in which these data have been collected or processed. Collecting the data (e.g., gonads or fin clips) is relatively easy to do during bottom trawl surveys, but processing the samples can be expensive and taxing for current staff levels.

### Evaluation of ecosystem health indicators

We evaluated indicators of the two key attributes: 1) community composition and 2) energetics and material flows. The support in the literature for these indicators varied widely under all evaluation categories.

**Community composition**—We identified and evaluated 69 potential indicators of overall ecosystem health across a wide variety of taxa and foraging guilds (Table 4). Indicators that scored well under primary considerations generally included species or foraging guild trends and abundance. Many functional group ratios have been identified by modeling exercises as good indicators of diversity and total biomass in the system. A common theme for many indicators was that they performed poorly for the criteria "responds predictably and is sufficiently sensitive to changes in a specific ecosystem attribute." This is because changes in species' or foraging guilds' trends and abundance will influence community composition and ecosystem structure, but changes in community composition may not be reflected in any one species or foraging guild. Moreover, it is conceivable that many of the foraging guild ratio

Table 2. Summary of groundfish population size indicator evaluations. The numerical value under each of the considerations represents the number of evaluation criteria supported by peer-reviewed literature. For example, California Coastal Oceanic Fisheries Investigative (CalCOFI) egg/larvae abundance reporting has peer-reviewed literature supporting two out of five primary considerations criteria.

| **Indicator** | **Primary consider-ations (5)** | **Data consider-ations (7)** | **Other consider-ations (6)** | **Summary comments** |
|---|---|---|---|---|
| Biomass | 5 | 7 | 4 | While biomass for each species is an obvious indicator for individual species, aggregate groundfish biomass is not necessarily indicative of the state of the entire groundfish community due to changes in a few large components of the community. |
| Numbers | 5 | 7 | 4 | Similar comment as for biomass above. |
| Population growth rate | 4 | 5 | 5 | Theoretically sound and can be calculated at numerous spatial and temporal scales as data sets can be integrated. |
| Number of groups below management thresholds | 3 | 5 | 5 | Good snapshot of species trends over time, but only 30 of 90 managed groundfish species are assessed. |
| Stock assessment biomass | 5 | 7 | 5 | Stock assessments perform well for data-rich species. Similar to above, only 30 of 90 groundfish species are assessed. |
| Bottom trawl survey biomass | 5 | 7 | 3 | Multiple surveys have occurred, but these surveys have been integrated to provide large-scale time series data from 1980 to 2010. |
| Bottom trawl survey numbers | 5 | 7 | 3 | Multiple surveys have occurred, but these surveys have been integrated to provide large-scale time series data from 1980 to 2010. |
| Hake acoustic survey biomass | 4 | 5 | 3 | Effective indicator for the most abundant groundfish species in the CCLME, but may not reflect trends of other species. Survey is not reliable when Humboldt squid are present. |
| Hake acoustic survey numbers | 4 | 0 | 0 | Acoustic surveys generally calculate biomass, not numbers. |
| Prerecruit survey biomass | 3 | 3 | 3 | The survey provides data on a limited number of species centered around San Francisco. |
| Prerecruit survey numbers | 3 | 3 | 3 | Similar comment as above. |
| Hook-and-line survey biomass | 5 | 3 | 3 | Survey is limited in spatial scale, but provides biomass estimates in untrawlable habitats in the Channel Islands, California. |
| Hook-and-line survey numbers | 5 | 3 | 3 | Similar comment as above. |
| PISCO scuba surveys biomass | 5 | 0 | 0 | Scuba surveys do not provide actual data on biomass. |
| PISCO scuba surveys numbers | 5 | 4 | 3 | Scuba surveys are limited in spatial scale and highly variable for cryptic species. |

Table 2 continued. Summary of groundfish population size indicator evaluations. The numerical value that appears under each of the considerations represents the number of evaluation criteria supported by peer-reviewed literature. For example, CalCOFI egg/larvae abundance reporting has peer-reviewed literature supporting two out of five primary considerations criteria.

| **Indicator** | **Primary consider-ations (5)** | **Data consider-ations (7)** | **Other consider-ations (6)** | **Summary comments** |
|---|---|---|---|---|
| National Park Service kelp monitoring survey biomass | 5 | 0 | 0 | Similar comment as for PISCO scuba surveys biomass above. |
| National Park Service kelp monitoring survey numbers | 5 | 4 | 3 | Similar comment as for PISCO scuba surveys numbers above. |
| IPHC longline survey biomass | 4 | 2 | 3 | International Pacific Halibut Commission (IPHC) longline surveys are useful for a small number of species. |
| IPHC longline survey numbers | 4 | 2 | 3 | Similar comment as above. |
| CalCOFI egg/larvae abundance | 2 | 3 | 3 | Survey is most effective for coastal pelagic species. The survey does not collect enough information on most groundfish species. In addition, species identification of larval rockfish requires DNA techniques. |
| Pot surveys biomass | 1 | 1 | 3 | Variation in behavior of fish biases these passive survey methods. Survey no longer occurs. |
| Pot surveys numbers | 1 | 1 | 3 | Similar comment as above. |
| Commercial landings biomass | 1 | 3 | 1 | Fishery-dependent data biased toward fisher behavior, fleet dynamics, and management restrictions. Only economically valuable species. |
| Commercial landings numbers | 1 | 2 | 1 | Similar comment as above. |
| Recreational landings biomass | 1 | 3 | 1 | Similar comment as above. |
| Recreational landings numbers | 1 | 3 | 1 | Similar comment as above. |
| Total harvest biomass, catch per unit effort | 1 | 4 | 1 | Similar comment as above. |
| Bycatch abundance | 0 | 5 | 4 | Levels of bycatch are heavily influenced by fisher behavior and management restrictions. |
| Local ecological knowledge | 4 | 1 | 4 | Theoretically sound, but limited data throughout the CCLME. |

Table 3. Summary of groundfish population condition indicator evaluations. The numerical value that appears under each of the considerations represents the number of evaluation criteria supported by peer-reviewed literature. For example, Cortisol/vitellogenin has peer-reviewed literature supporting two out of five primary considerations criteria.

| **Indicator** | **Primary considerations (5)** | **Data considerations (7)** | **Other considerations (6)** | **Summary comments** |
|---|---|---|---|---|
| Age structure of populations | 5 | 7 | 4 | Strongly supported by the literature in most criteria. |
| Size structure of populations | 0 | 5 | 4 | Size structure from catch data generally biased by gear selectivity and catchability. |
| Center of distribution (latitudinal or depth changes) | 2 | 5 | 5 | Distributional shifts tend to suggest a pressure is acting on the population (i.e., fishing or climate). |
| Genetic diversity of populations | 5 | 2 | 2 | Scores well in primary considerations, but there is an overall lack of data for most groundfish species at multiple points in time. |
| Age at maturity | 5 | 1 | 3 | Similar comment as above. |
| Size at maturity | 3 | 2 | 2 | Similar comment as above. |
| Diet of groundfish | 0 | 1 | 1 | Prey is highly variable and there are few species with enough data over time and space to understand differences. |
| Larval abundance | 2 | 3 | 2 | Abundance of larvae most likely driven by oceanographic conditions and may not be reflective of the condition of specific populations. |
| Parasitic load | 3 | 1 | 0 | Theoretically sound, but little data for most species. |
| Condition factor (K) | 3 | 5 | 2 | Theoretically sound as condition of fish is directly related to growth and fecundity, but this is generally not described—data limited to species which have both individual length and weight measured during surveys. |
| Cortisol/vitellogenin | 2 | 1 | 1 | May be related to condition, but changes in the attribute are not likely to vary with this indicator at any scale but the very smallest. |
| Disease (liver and gall bladder) | 2 | 1 | 1 | Similar comment as above. |
| Fecundity | 5 | 1 | 2 | Scores well in primary considerations, but there is an overall lack of data available for most species across time and space. |
| Body growth | 2 | 5 | 5 | Typically, age is calculated from otoliths collected during bottom trawl surveys, but growth could also be measured with these samples. |
| Spatial structure of population | 5 | 5 | 4 | Theoretically sound and data are available for many species, but stocks are generally assessed at the scale of the entire coast. |
| Mean length of species | 5 | 1 | 5 | Lengths measured for many species, but there may be limited data on unassessed species. |
| Rebuilding timeline | 3 | 7 | 5 | Available for overfished species. Most species stop declining, but some have not increased. |

Table 4. Summary of ecosystem health: Community composition indicator evaluations. The numerical value that appears under each of the considerations represents the number of evaluation criteria supported by peer-reviewed literature. For example, area of live, hard coral has peer-reviewed literature supporting four out of five primary considerations criteria.

| Guild | Indicator | Primary consider-ations (5) | Data consider-ations (7) | Other consider-ations (6) | Summary comments |
|---|---|---|---|---|---|
| Marine mammals | Cetacean species status and trends | 3 | 2 | 3 | Theoretically sound sentinel species, but high variability in data; low sample size and numerous coverage gaps; slow population response rate. |
| | Pinniped abundance and population trends | 3 | 4 | 3 | See above, although surveys at breeding grounds and haul-out sites facilitate population estimates. |
| | Pinniped biomass | 3 | 4 | 2 | See above. |
| | Pinniped annual reproductive performance | 4 | 4 | 4 | Strong link to nutritional stress, contaminants, and disease; incomplete pup counts for some species, but long time series for others. |
| | Pinniped contaminant load | 3 | 3 | 2 | Theoretically sound, but problems due to high migratory patterns, limited spatial and temporal replication, high analysis costs, and lagged response. |
| | Pinniped diet (fatty acids, stable isotopes) | 2 | 4 | 2 | Reflects broad status of food supply, variety of methods can discern variable scales of feeding, high sampling replication and effort required. |
| | Pinniped stress hormones | 0 | 2 | 1 | Integrative measure of stress, but difficult to differentiate cause and effect; baseline information needed to discern normal variation, data generally lacking across species' ranges. |
| | Pinniped disease, death, mortality, bycatch | 2 | 4 | 4 | Theoretically valid and increasingly well studied; often difficult to attribute cause to changes in pinniped mortalities; mortality database maintained by the U.S. Geological Survey's National Wildlife Health Center since 1971. |
| | Integrative marine mammal index (multivariate) | 2 | 1 | 3 | Can be used to show predictable responses to stressors, type of data in the index affect interpretability, unlikely to correlate specific cause with effect, data requirements high. |
| Key fish groups | Forage fish biomass; species status and trends | 3 | 0 | 5 | Changes in a single group may or may not be indicative of entire community. Most forage fish data are fishery dependent but new surveys are coming on-line. |
| | Groundfish status and trends | 3 | 7 | 5 | Similar to comment above except that ample data are available for species and individuals susceptible to bottom trawling. |

Table 4 continued. Summary of ecosystem health: Community composition indicator evaluations. The numerical value that appears under each of the considerations represents the number of evaluation criteria supported by peer-reviewed literature. For example, area of live, hard coral has peer-reviewed literature supporting four out of five primary considerations criteria.

| Guild | Indicator | Primary consider-ations (5) | Data consider-ations (7) | Other consider-ations (6) | Summary comments |
|---|---|---|---|---|---|
| Key fish groups (cont.) | Flatfish biomass | 3 | 7 | 5 | Changes in a single group may or may not be indicative of the entire community. Ample data are available for species and individuals susceptible to bottom trawling. |
| | Zooplanktivorous fish biomass | 3 | 0 | 5 | Identified as the best indicator of total biomass in marine systems during modeling exercises, but data for many species will be limited (see forage fish biomass). |
| | Piscivorous fish biomass | 3 | 1 | 5 | Changes in a single group may or may not be indicative of the entire community. Data for many species may be limited to fishery-dependent data. |
| | Roundfish biomass | 3 | 7 | 5 | Identified as a significant indicator for nine ecosystem attributes in modeling exercises. |
| | Demersal fish biomass | 3 | 7 | 5 | Changes in a single group may or may not be indicative of the entire community, but data are generally available. |
| | Pelagic fish biomass | 3 | 0 | 5 | Changes may indicate predatory release of prey populations or insufficient forage base, but changes in a single group may not be indicative of the entire community. |
| | Rockfish biomass | 3 | 7 | 5 | Changes in a single group may or may not be indicative of the entire community, but data are available for many rockfish species. |
| | Juvenile rockfish index | 3 | 6 | 4 | Can be useful in forecasting year-class strength and reflect trends in adult biomass, used frequently in stock recruitment models, historical but spatially limited data available for CCLME. |
| | Juvenile hake abundance | 3 | 6 | 4 | See juvenile rockfish abundance above. |
| Salmon | Salmon smolt-to-adult survival rate | 5 | 7 | 2 | Related to dominant modes acting over the coastal region, extensive historical records, perhaps best as a retrospective (lagging) indicator of historic ocean conditions. |
| | Salmon adult escapement | 3 | 5 | 3 | Highly influenced by ocean conditions; large extensive historic database, but difficult to discern cause and effect; lagging indicator. |

Table 4 continued. Summary of ecosystem health: Community composition indicator evaluations. The numerical value that appears under each of the considerations represents the number of evaluation criteria supported by peer-reviewed literature. For example, area of live, hard coral has peer-reviewed literature supporting four out of five primary considerations criteria.

| Guild | Indicator | Primary consider-ations (5) | Data consider-ations (7) | Other consider-ations (6) | Summary comments |
|---|---|---|---|---|---|
| Seabirds | Marine seabird species status and trends | 2 | 3 | 3 | Easily enumerated top consumers, difficult to attribute change to particular causes, often respond to environmental change or management actions, better indicator at years to decades. |
| | Seabird biomass | 2 | 4 | 2 | Primarily used in food web models, not highly sensitive, changes likely occur at same rate as populations, few locations where this is monitored. |
| | Seabird annual reproductive performance | 4 | 5 | 4 | Strong correlation between breeding success, food availability, and large scale indices of ocean climate; expensive and time consuming; long-term data sets available along Pacific coast. |
| | Seabird contaminant load | 0 | 4 | 1 | See pinniped contaminant load above. |
| | Seabird diet (fatty acids, stable isotopes) | 4 | 2 | 2 | See pinniped diet above. |
| | Seabird stress hormones | 0 | 2 | 1 | See pinniped stress hormones above. |
| | Seabird disease, death, mortality, bycatch | 2 | 5 | 5 | See pinniped disease, death, mortality, bycatch above. |
| | Integrative seabird index (multivariate) | 2 | 2 | 3 | See integrative marine mammal index above. |
| | Marine shorebird species status and trends | 2 | 3 | 2 | Provide information on coastal and shoreline habitat; often slow to respond to environmental change or management actions, but difficult to attribute cause and effect; some monitoring data available, but unpublished. |
| Reptiles | Sea turtle status and trends | 2 | 1 | 3 | Widely dispersed, nonprominent member of CCLME; difficult to monitor population trends, except adult females during nesting events; slow to respond to environmental change or management actions, and attribute cause and effect; limited spatial extent. |
| Shellfish and invertebrates | Jellyfish biomass, status and trends | 4 | 3 | 2 | Indicator of trophic energy transfer and pelagic community composition, abundance can be linked to human activities, no existing reference condition, historical data in CCLME are limited, no evidence to suggest as leading indicator. |

Table 4 continued. Summary of ecosystem health: Community composition indicator evaluations. The numerical value that appears under each of the considerations represents the number of evaluation criteria supported by peer-reviewed literature. For example, area of live, hard coral has peer-reviewed literature supporting four out of five primary considerations criteria.

| **Guild** | **Indicator** | **Primary consider-ations (5)** | **Data consider-ations (7)** | **Other consider-ations (6)** | **Summary comments** |
|---|---|---|---|---|---|
| Shellfish and invertebrates (cont.) | Squid, Humboldt | 1 | 2 | 2 | Range expansion correlated with reduction in top predators; possibly indicates shifts in climate regimes, ocean circulation, and ecosystem-wide food webs; data minimal and of limited spatial and temporal scale. |
| | Crustaceans: catch and survey trends; larval surveys | 4 | 5 | 4 | Attributed to climate induced changes in water column temperature and fishing; indicative of community regime shift (high trophic level groundfish to low trophic level crustaceans); zooplankton data sets provide good record of larval abundance for estimating spawning stocks. |
| | Coastal oyster condition index | | | | Incomplete. |
| | Shellfish status, trends | | | | Incomplete. |
| | Benthic invertebrate biomass | 4 | 2 | 2 | Correlates well with ecosystem health and responds to fishing pressure; some databases available, although depth strata and sampling design not readily apparent; gradual change should show major community reorganization. |
| Zooplankton | Zooplankton abundance and biomass | 4 | 7 | 5 | Base of food web, fundamental component of CCLME, correlated with regime shift and climate change, can be used to estimate thresholds, several ongoing long-term data sets. |
| | Copepod species ratio (cold vs. warm) or zooplankton species biomass anomalies) | 5 | 7 | 5 | Reflect modifications in water masses, currents, or atmospheric forcing; respond rapidly to climate variability; some taxa reflect influence of different water types on ecosystem structure; data availability as above. |
| | Euphausid biomass and richness | 5 | 2 | 3 | Indicator of plankton biomass changes, critical link in marine food web, low counts and high patchiness in samples may increase variability, data availability as above. |

Table 4 continued. Summary of ecosystem health: Community composition indicator evaluations. The numerical value that appears under each of the considerations represents the number of evaluation criteria supported by peer-reviewed literature. For example, area of live, hard coral has peer-reviewed literature supporting four out of five primary considerations criteria.

| Guild | Indicator | Primary consider-ations (5) | Data consider-ations (7) | Other consider-ations (6) | Summary comments |
|---|---|---|---|---|---|
| Diversity indices | Biodiversity index (Hurlbert's delta) | 4 | 7 | 3 | Reflects taxonomic evenness; calculated from abundance estimates; change detectable with latitude and depth at large scales; natural and baseline levels of evenness may vary; significance of certain types of change not known; data available from groundfish, zooplankton, and benthic invertebrate surveys. |
| | Slope of log (biomass) vs. trophic level–Simpson Diversity Index | 4 | 6 | 1 | Theoretically sound, calculated from abundance estimates; difficulty linking diversity indices to targets or reference points; for data availability see Hurlbert's biodiversity index above. |
| | Marine mammal diversity–Shannon Diversity | 4 | 5 | 2 | Measures taxonomic richness and evenness, community stability related to higher diversity, difficulty linking diversity indices to targets or reference points, for data availability see Hurlbert's biodiversity index above. |
| | Adult sablefish biomass (indicator of diversity)–Shannon Diversity | 4 | 7 | 4 | Theoretically correlated with community diversity in British Columbia ecosystem during modeling exercises; for data availability, see groundfish biomass trends and stock assessments above. |
| | Detritivore biomass (indicator of diversity)–Shannon Diversity | 4 | 3 | 1 | See above; for data availability, see benthic invertebrate population trends above. |
| | Taxonomic distinctness (average and variation in) | 3 | 6 | 3 | Uses species lists, not abundance data; minimal data requirements allows integration of data sets, use of historical data, and data of varying quality; for data availability see Hurlbert's biodiversity index above. |
| | Number of threatened species (IUCN A1 criteria as modified by Dulvy et al. 2006) | 4 | 7 | 3 | Composite indicator based on weighted average of species threat, criteria somewhat arbitrary, linking index to targets or reference points is difficult, data available and numerical. |
| Functional groups | Top predator biomass (trophic level > 4.0) | 5 | 2 | 4 | Top predator removal typically results in trophic cascades. Data available for many groundfish and seabird top predators, but data for sharks and marine mammals are less reliable. |

Table 4 continued. Summary of ecosystem health: Community composition indicator evaluations. The numerical value that appears under each of the considerations represents the number of evaluation criteria supported by peer-reviewed literature. For example, area of live, hard coral has peer-reviewed literature supporting four out of five primary considerations criteria.

| **Guild** | **Indicator** | **Primary consider-ations (5)** | **Data consider-ations (7)** | **Other consider-ations (6)** | **Summary comments** |
|---|---|---|---|---|---|
| Functional groups (cont.) | Invertivore biomass | 2 | 7 | 2 | Correlated with several measures of diversity and total biomass in modeling exercises, but variation in community composition may not be detected by variation in this functional group alone. |
| | Detritivore biomass | 3 | 7 | 2 | Similar comment as above. |
| | Herbivore biomass | 3 | 7 | 2 | Similar comment as above. |
| | Scavenger biomass | 4 | 7 | 2 | Some evidence that disturbances, such as fishing activities, induce chronic increases in scavenger populations, but changes in this one functional group may (or may not) be indicative of the entire community. |
| Functional group ratios | Forage fish and jellyfish biomass ratio | 3 | 2 | 1 | Highly correlated with diversity measures and mean trophic level in modeling exercises. Data limited for both groups and ratios of functional groups are not easily understood indicators. |
| | Piscivorous and Zooplanktivorous fish biomass ratio | 3 | 0 | 2 | Highly correlated with diversity measures in modeling exercises, but how many species have data available is unknown. |
| | Pelagic and demersal fish biomass ratio | 3 | 1 | 2 | Appears to be a proxy for differential impact of nutrients on the pelagic and benthic food webs based on modeling exercises. |
| | Zooplankton and phytoplankton biomass ratio | 2 | 1 | 1 | Highly correlated with measures of diversity and mean trophic level in modeling exercises, but data are particularly limited for phytoplankton, although proxies such as chl *a* have been used. |
| | Rockfish and flatfish biomass ratio | 2 | 7 | 1 | Highly correlated with measures of diversity and total biomass in modeling exercises. |
| | Invertivore and herbivore biomass ratio | 3 | 7 | 1 | Similar to comment above. |
| | Finfish and crustacean biomass ratio | 3 | 7 | 1 | Indicative of community regime shift in several systems from high trophic level groundfish to a low trophic level, crustacean-dominated system; see comments above under crustacean and groundfish biomass and survey trends for data availability. |
| Fishery catch | Trophic level of catch (mean biomass) | 2 | 1 | 1 | Shortcomings associated with typical catch-based data; size-based indicators are better because they do not require diet data, are less error prone, and more easily collected. |

Table 4 continued. Summary of ecosystem health: Community composition indicator evaluations. The numerical value that appears under each of the considerations represents the number of evaluation criteria supported by peer-reviewed literature. For example, area of live, hard coral has peer-reviewed literature supporting four out of five primary considerations criteria.

| Guild | Indicator | Primary consider-ations (5) | Data consider-ations (7) | Other consider-ations (6) | Summary comments |
|---|---|---|---|---|---|
| Fishery catch (cont.) | Proportion noncommercial species (unfished groups) | 5 | 4 | 3 | Modeling results show response to variation in fishing pressure and correlation with ecosystem attributes, one of the more sensitive indicators of changes in species composition. |
| | Total catch and landings of target species | 1 | 4 | 2 | Considered good indicator of fishing effects but poor indicator of marine ecosystem performance, primarily a function of fishing effort and a poor approximation of production, landings can be misleading in assessments ecosystems. |
| | Total fishery removals of all species (including bycatch) | 1 | 3 | 2 | See above, bycatch data often not recorded. |
| | Total fishery removals of all species | 2 | 6 | 3 | See above. |
| | Mean length, all species | 4 | 1 | 5 | Useful and simple indicator to evaluate effects of fishery removals, but may not be observable over short-term monitoring data sets. |
| | Slope size spectrum, all species | 2 | 1 | 2 | Good indicator of fishing effects, models show change is predictable and consistent, unclear what attributes it would act as an indicator for besides general ecosystem health, thresholds unclear, size data sparse for some species. |
| Habitat species | Kelp forest coverage | 4 | 5 | 5 | Kelp forests occur at small scales compared to the entire California Current, so overall ecosystem structure may not be tied to kelp coverage, but these are important habitats for recruitment of important species. |
| | Area of live, hard coral | 4 | 2 | 2 | Similar comment as above. Data on spatial extent of coral cover are limited. |

indicators (e.g., piscivorous to zooplanktivorous fish ratio) could have scientifically defined reference points and progress targets, but these ratios may not be easily understood by the public and policy makers for establishing management targets. These evaluations suggest that multivariate indicators may be more indicative of changes in ecosystem structure. Changes in many of these community-level metrics cannot be observed in short-term monitoring sets and may be more useful at longer management time scales (Nicholson and Jennings 2004).

Population trends of large-bodied, long-lived, or high trophic–level vertebrates (e.g., cetaceans, pinnipeds, sea turtles, or seabirds) were consistently considered poor indicators of ecosystem condition because of the inherent low variability of their life history characteristics, which limited their ability to serve as an early warning (i.e., leading indicator) of impacts, as well as the associated difficulty in attributing change to particular causes or interpreting the spatial extent of trends (Hilty and Merenlender 2000, Holmes et al. 2007). Indicators related to fishery removal (e.g., total catch or total harvested biomass) also performed poorly because landings were often poorly correlated with marine population trends due to fleet behavior and dynamics, targeting and behavior of the fishermen, and bias from misreporting (Hilborn and Walters 1992, Watson and Pauly 2001, Rochet and Trenkel 2003, de Mutsert et al. 2008).

**Energetics and material flows**—We identified and evaluated 10 potential indicators for the CCLME (Table 5). In general, there was wide disparity between indicators that met both primary and data considerations and those that did not. Most indicators that were theoretically sound, relevant to management, and predictably responsive tended to meet many of our data criteria (e.g., chlorophyll *a* [chl *a*], inorganic nutrient levels), whereas those that did not meet many of the primary criteria also fell short with regard to data considerations (e.g., oxidation rates, respiration rates). Exceptions to this rule included indicators that were: 1) not necessarily well characterized or understood in ocean upwelling systems (e.g., nitrogen fixation rates), 2) difficult to measure directly due to methodological difficulties (e.g., microbial decomposition rates), or 3) recognized as important but poorly characterized by data sets at large spatial scales or over long time series (e.g., phytoplankton biomass and particulate organic matter [POM] levels).

Inorganic nutrient levels and proxies for primary productivity such as chl *a* concentration are the most widely available indicators for energy and material flows in the California Current. Remote-sensing data are a valuable source of this information, though other, labor-intensive approaches are available for obtaining spatially explicit and finely resolved understanding of primary productivity as well (e.g., plankton tows). Biogeochemical approaches for measuring carbon cycling rates are well developed and theoretically sound, but such data are not widely available and can be quite expensive to obtain. Modeling efforts (e.g., Ecopath with Ecosim) currently provide a useful tool for estimating the magnitude of secondary production and pathways of energy flows and carbon cycling throughout the food web, but more detailed data collection is needed to validate many of the inherent model assumptions. Making up for this deficiency will require detailed, broad-scale studies of how different species interact with the physical and chemical oceanography of the CCLME to affect processes such as nitrogen fixation, carbon sequestration, and microbial decomposition. Nevertheless, we suggest the evaluation of additional indicators of energy and material flows in the future.

Table 5. Summary of ecosystem health: Energetics and material flows indicator evaluations. The numerical value under each consideration represents the number of evaluation criteria supported by peer-reviewed literature. For example, microbial decomposition/respiration rate has peer-reviewed literature supporting two out of five primary considerations criteria.

| Indicator | Primary consider-ations (5) | Data consider-ations (7) | Other consider-ations (6) | Summary comments |
|---|---|---|---|---|
| Phytoplankton biomass | 4 | 1 | 2 | Good indicator of pelagic ecosystems and hydroclimatic forcing, few long-term time series that identify phytoplankton species. |
| Chl a | 4 | 5 | 3 | Good indicator of phytoplankton biomass and amount of energy fueling the ecosystem, satellite remotely sensed chlorophyll concentration data available system wide. |
| Nitrogen fixation rate, nitrification/denitrification rate, $^{15}N$ ratios | 1 | 3 | 0 | May indicate vigor or resilience of an ecosystem, although the CCLME is an upwelling system characterized by nutrient limitation; scientific understanding of ocean N fixation lacking. |
| Inorganic nutrient levels: dissolved inorganic nitrogen, silicate, phosphate, iron | 4 | 3 | 5 | Strongly linked to upwelling events, which drive system productivity and control production; poorly characterized in space and time, except intensive sampling at individual regions. |
| Stratification: temperature, salinity; thermocline depth | 0 | 0 | 0 | Thought to limit nutrient exchange and be source of decadal regime shift, little evidence in scientific literature that it acts as good indicator. |
| Oxidation rate | 0 | 0 | 0 | Little evidence in scientific literature that oxidation rates act as good ecosystem indicator. |
| Microbial decomposition/ respiration rate | 2 | 0 | 1 | Good indicator of ecosystem stress; however, not routinely measured directly; very limited global database (<1,700 samples); most measurements from shallow, euphotic zone during spring. |
| Respiration rate | 2 | 1 | 1 | Captures the overall state or maturity of an ecosystem, although too few samples collected worldwide to determine spatial and temporal variability; methods have precision limitations. |
| Number of cycles (carbon) | 5 | 5 | 3 | Carbon cycling decreases as ecosystem stress increases, can be estimated using mass balance models. |
| POM, dissolved organic carbon | 0 | 3 | 0 | Little evidence in scientific literature that POM acts as good ecosystem indicator; however, high POM usually linked to hypoxia and dead zones; poorly characterized in CCLME. |

## Scoring Indicators

The matrix of ecosystem indicators and indicator evaluation criteria provides the basis for scoring the relative support in the literature for each indicator (Levin et al. 2010b). For each cell in the evaluation matrix, we assigned a literature-support value of 1.0, 0.5, or 0.0 depending on whether there was support in the literature for the indicator, the literature was ambiguous, or there was no support in the literature for the indicator, respectively. However, scoring indicators also requires careful consideration of the relative importance of evaluation criteria. The importance of the criteria will certainly vary depending on the context within which the indicators are used and the people using them. Thus scoring requires that managers and scientists work together to weight criteria. Failure to weight criteria is, of course, a decision to weight all criteria equally.

To determine the weightings for each of the evaluation criteria, we asked 15 regional resource managers, policy analysts, and scientists to rate how important each of the evaluation criteria was to them. Approximately one-third of the responses came from each profession category. We asked each person to indicate how strongly they agree or disagree with the following statement about each of the evaluation criteria: "I feel this criterion is of high importance when ranking indicators for use in the California Current IEA." Each person then assigned one of the following ratings to each criterion: strongly disagree, disagree, neutral, agree, or strongly agree. Each rating was assigned a value between 0 and 1, where strongly disagree equals 0, disagree equals 0.25, neutral equals 0.5, agree equals 0.75, and strongly agree equals 1.0. We then calculated the percentage of responses for each rating for each criterion. The percentages were multiplied by the assigned value for each rating, then summed across each criterion and divided by 100. This provided an average weighting for each criterion (Table 6). We used the distribution of average weightings and calculated the quartiles for this distribution. We assigned each criterion to the quartile into which its average fell. For example, the average weighting for "historically reported" (under the other considerations category) was 0.39 and that value was in the lowest quartile of the distribution, so this criterion received a weighting of 0.25.

For each cell, the literature-support value was multiplied by the weighting for the respective criterion, then summed across each indicator. This score was used as the final score for each indicator. For each key attribute of each EBM component, we calculated the quartiles for the distribution of scores for each indicator. Indicators that scored in the top quartile (top 25%) for each attribute of each goal were considered to have good support in the literature as an indicator of the attribute they were evaluated against. We describe below the results of the evaluation for each indicator that scored in the top quartile.

## Indicators that Scored in the Top Quartile

### Groundfish

**Population size**—*Stock assessment biomass*. Stock assessment trends in spawning stock biomass are well established measures of the size of the many commercially important species and are subject to intense peer review. Assessments are tied directly to management efforts and provide quota levels for various fisheries. Changes in assessed populations reflect changes in the abundance of individuals collected in bottom trawl surveys. When management restrictions are

Table 6. Assignment of weightings to each criterion. Fifteen regional resource managers, policy analysts, and scientists were asked to indicate how strongly they agreed or disagreed with the following statement: "I feel this criterion is of high importance when ranking indicators for use in the California Current IEA." Values under each rating are the percentage of responses in favor of each. Weightings were averaged and each criterion assigned to the quartile in which its average weighting fell in the distribution.

| **Evaluation criteria** | **Strongly disagree** | **Disagree** | **Neutral** | **Agree** | **Strongly agree** | **Average weighting** | **Quartile of average weighting** |
|---|---|---|---|---|---|---|---|
| Historically reported | 6.7 | 40.0 | 47.0 | 6.7 | 0 | 0.39 | 0.25 |
| Operationally simple | 0.0 | 13.3 | 40.0 | 20.0 | 13 | 0.51 | 0.25 |
| Regionally, nationally, and internationally compatible | 0.0 | 13.0 | 67.0 | 20.0 | 0 | 0.52 | 0.25 |
| Theoretically sound | 0.0 | 0.0 | 13.3 | 40.0 | 20 | 0.57 | 0.50 |
| Anticipatory or leading indicator | 0.0 | 13.3 | 46.7 | 40.0 | 0 | 0.57 | 0.50 |
| Relevant to management concerns | 0.0 | 0.0 | 0.0 | 40.0 | 30 | 0.60 | 0.50 |
| Responds predictably and is sufficiently sensitive to changes in specific ecosystem attributes | 0.0 | 0.0 | 20.0 | 33.0 | 27 | 0.62 | 0.50 |
| Continuous time series | 0.0 | 6.7 | 47.0 | 33.3 | 13 | 0.63 | 0.50 |
| Numerical | 0.0 | 13.3 | 47.0 | 13.3 | 27 | 0.64 | 0.50 |
| Broad spatial coverage | 0.0 | 0.0 | 53.0 | 33.3 | 13 | 0.64 | 0.50 |
| Responds predictably and is sufficiently sensitive to changes in specific management actions or pressures | 0.0 | 6.7 | 13.3 | 60.0 | 13 | 0.66 | 0.75 |
| Cost-effective | 6.7 | 0.0 | 33.0 | 40.0 | 20 | 0.67 | 0.75 |
| Spatial and temporal variation understood | 0.0 | 0.0 | 27.0 | 73.3 | 0 | 0.68 | 0.75 |
| High signal-to-noise ratio | 0.0 | 13.3 | 33.0 | 13.3 | 40 | 0.70 | 0.75 |
| Concrete | 0.0 | 0.0 | 33.3 | 40.0 | 27 | 0.74 | 0.75 |
| Understood by the public and policy makers | 0.0 | 13.3 | 7.0 | 53.3 | 27 | 0.74 | 0.75 |
| Historical data or information available | 0.0 | 0.0 | 6.7 | 80.0 | 13 | 0.76 | 1.00 |
| Linkable to scientifically defined reference points and progress targets | 0.0 | 6.7 | 13.3 | 60.0 | 27 | 0.80 | 1.00 |

established, assessed populations generally stop declining. Many species begin to recover and experience population growth according to the assessments, but there are other species which appear to respond slowly to management actions (see Miller et al. 2009). Assessments provide two primary reference points for assessed species: B40 and B25. B40 is the level of spawning stock biomass at which stocks are considered at their optimal yield—40% of virgin spawning biomass. B25 is the level of spawning stock biomass at which stocks are overfished—25% of virgin spawning biomass. However, only 30 of 90-plus species within the Pacific Coast Groundfish Fishery Management Plan (PCGFMP) have been assessed and there are generally 200–300 species of fish detected each year in the West Coast Groundfish Trawl Survey (WCGTS) (e.g., Keller et al. 2008).

Stock assessments use data from multiple sources for various species, but the primary source of data is from the WCGTS. This survey contains data from the Alaska Fisheries Science Center's (AFSC) triennial bottom trawl survey from 1977 to 2004 and the Northwest Fisheries Science Center (NWFSC) annual bottom trawl survey from 1998 to 2010. These surveys have covered different spatial extents in the past, but the current survey is a random-stratified design by depth which samples across the entire U.S. West Coast from 50 to 1,280 m (Figure 3). Assessments use multiple data sources incorporating length frequencies, diet, age structure, and fecundity measures when available. Analyses used to generate time series data generally use the same stock assessment framework (Stock Synthesis version 3 in 2009, e.g., Stewart 2009). Assessments generally use multiple data sources across the range of each stock (e.g., Gertseva et al. 2009, Stewart et al. 2009); however, some species (i.e., cabezon [*Scorpaenichthys marmoratus*] and bocaccio [*Sebastes paucispinis*]) are only assessed in specific regions along the West Coast (Cope and Key 2009, Field et al. 2009).

The major findings of a stock assessment can be easily understood by the public and policy makers (i.e., these species are declining, these species are increasing, these species are overfished). Assessments are typically done on species that are worse off, thus assessments generally show declines that have already happened. Since assessments measure spawning biomass, it is generally an assessment of processes that have already taken place (i.e., spawning stocks in the past were fished or had bad years and now the current spawning biomass reflects those bad years), so this is generally a lagging indicator.

*Bottom trawl survey biomass.* The WCGTS is well established and has been developed with input by stock assessment scientists and through outside peer review during the PFMC process. The major objective of this survey is to provide fishery-independent data necessary to conduct formal stock assessments of fish species managed within the PCGFMP (e.g., Keller et al. 2008). Historically, this survey was performed triennially by the AFSC from 1977 to 2004. In its current format, the WCGTS survey has been conducted annually since 2003 by the NWFSC. Data are collected in trawlable habitats from the U.S.-Canada border to the U.S.-Mexico border between the months of May to October. Each trawl is 15 minutes in duration and total counts and aggregate weights by species are recorded for all species. Subsamples of targeted species (generally consisting of the 90 managed species) are randomly selected for individual measurements of length and weight, removal of age structures, and sex determination. In a typical year, approximately 600 trawls are successfully conducted, approximately 150,000 fish are individually measured for weight and length, and more than 20,000 have otoliths removed for aging (i.e., Keller et al. 2008). Other individuals are sampled for genetics, stomach

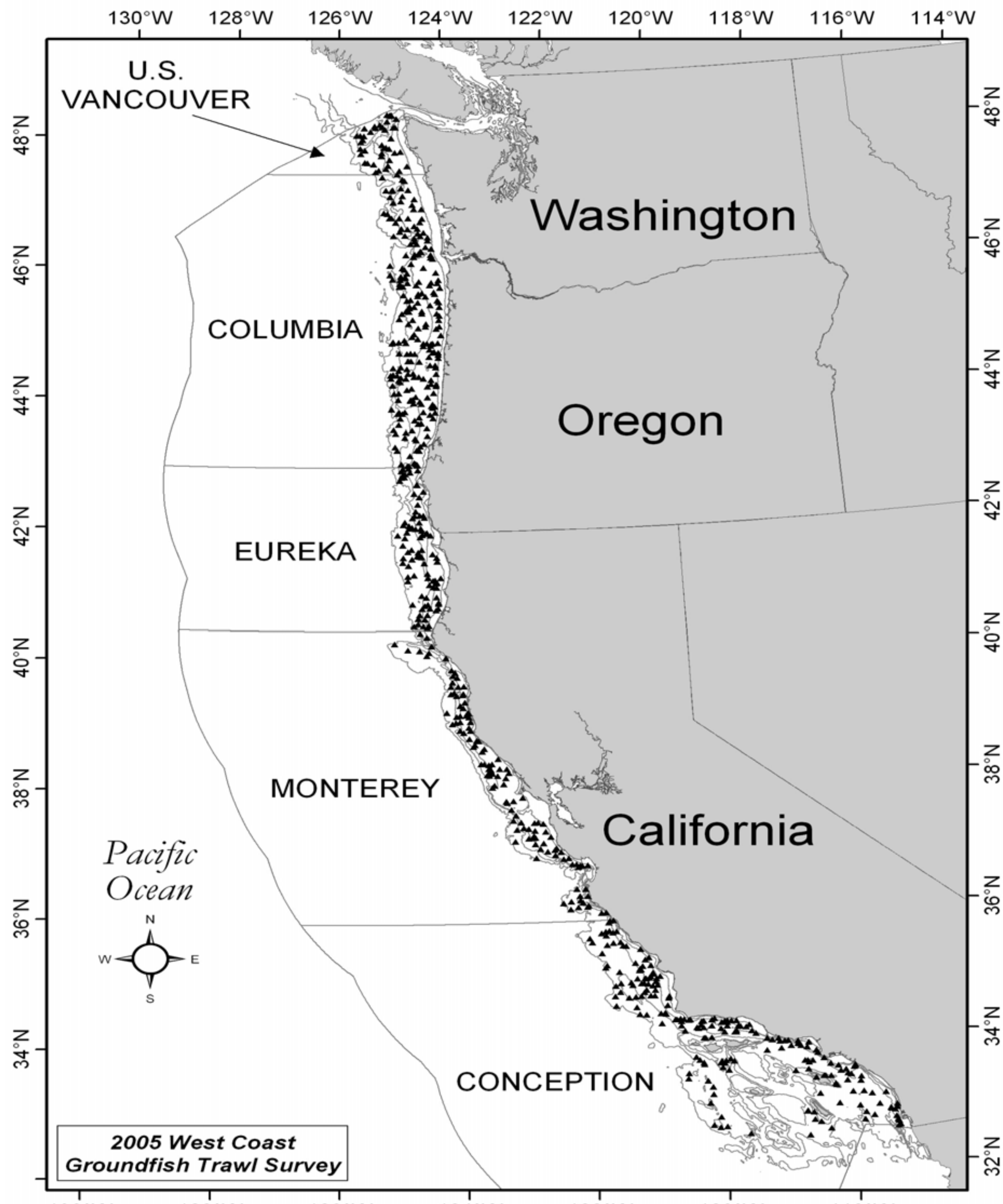



Figure 3. Example of the number and spatial extent of locations (triangles) surveyed by the West Coast groundfish trawl survey each year during 2003–2010. (Reprinted from Keller et al. 2008.)

contents, maturity level, and toxicology as special projects. These data are in a Fishery Resource Analysis and Monitoring Division database at NWFSC.

These data allow for estimates of density and biomass and evaluation of change in population size for many more species than are assessed through formal stock assessments (e.g., Levin et al. 2006). As noted, only 30 of the 90-plus managed species on the U.S. West Coast are formally assessed, while there are approximately 250 species or groups of fish detected each year during the WCGTS. One caveat to the bottom trawl survey is data will always be biased towards species that occupy trawlable habitats in depths 50–1,280 m and towards life history stages susceptible to the survey's trawl gear. Most small individuals, either young individuals or smaller species, are not captured by the bottom trawl survey because they are in shallower water as juveniles or they escape through the net mesh. Moreover, species that move into rockier and untrawlable habitats through life are not sampled at larger sizes in the bottom trawl survey. The bottom trawl survey is also not a good indicator of Pacific hake biomass, which is a more pelagic species and comprises the largest component of the groundfish population in the CCLME from a fisheries standpoint (Miller et al. 2009).

Estimates of biomass calculated from trawl surveys are easily understood by the public and have been used historically by policy makers for regulatory and legislative purposes. The estimates of abundance from the trawl survey are concurrent with the current abundance of the stock, but these estimates are a lagging indicator of what was happening to the stock several years ago (i.e., what were the conditions of the ecosystem that allowed recruitment to be good or bad, as many species aren't captured in the survey until they are 5–8 years old). Trawl surveys performed appropriately are compatible with other regional, national, or international surveys.

*Biomass.* Biomass is a standard measurement of population size and is cited voluminously in the indicator literature (e.g., Link et al. 2002, Fulton et al. 2005). Biomass is the metric calculated in formal stock assessments and the metric used for harvest rates of individual species in West Coast fisheries. However, an aggregate groundfish biomass is not necessarily indicative of the state of the groundfish community, because this information will be biased towards a few large components of the community. For example, Pacific hake is the most abundant groundfish species detected in the WCGTS and variation in this species will likely swamp detectable variation in the rest of the groundfish community. Thus any indicator of population size will need to identify species of interest or representatives of different functional groups to monitor changes over time. Alternatively, multivariate measurements of the groundfish community will need to be developed to detect meaningful changes in the population size of groundfish.

*Population growth rate.* Population growth rate is a standard metric for measuring changes in population size over time (e.g., Levin et al. 2006) and is a common metric in the indicator literature (Sibly and Hone 2002, Trenkel and Rochet 2003, Fulton et al. 2005). Population growth rate is not explicitly stated in formal stock assessments, but the metric is shown as spawning stock biomass over time. The growth rate of a population integrates the size of the spawning stock and the variability in recruitment of young fish. In many cases, population growth rate will increase with increases in spawning stock, but if recruitment is density independent or is limited by environmental conditions, this relationship will not hold true (Hilborn and Walters 1992). Sibly and Hone (2002) argue that "population growth rate is the key unifying variable linking the various facets of population ecology. The importance of population growth rate lies partly in its central role in forecasting future population trends; indeed if the form of density dependence were constant and known, then the future population dynamics could to some degree be predicted."

Data for calculating population growth rates for many groundfish species are available via the WCGTS. It is unknown at this point how many species have enough data to make this calculation. As an indicator, population growth rate will always be lagging due to timing of data availability and calculation of the indicator. Because most species are not collected by conventional trawl surveys until they are 5 to 8 years old, the most recent estimates of population growth will be measures of the environmental conditions since these individuals were born. Moreover, predictions from the model of population growth may suggest a trend, but environmental variation will always alter this prediction (Hilborn and Walters 1992).

Population growth rate is easily understood by the public and policy makers; species are increasing, decreasing, or remain constant. In the form of spawning stock biomass, this indicator has been used historically and is compatible with measurements of population size from other regions and nations.

*Hake acoustic survey biomass.* The Pacific hake integrated acoustic and trawl survey has been conducted since 1977 to assess the size and distribution of the population in the CCLME (Helser and Martell 2007, Helser et al. 2008). The joint survey between the United States and Canada has taken place in 1977, 1980, 1983, 1986, 1989, 1992, 1995, 1998, 2001, 2003, 2005, 2007, and 2009. The survey is generally conducted between June and August along the continental slope and shelf from Monterey, California (lat 35.7°N), to the Dixon Entrance in northern British Columbia (lat 54.8°N). During the survey, hydroacoustics are used to measure numbers (or biomass) and subsequent midwater trawls over the same location are used to collect length and age compositions.

This survey is a single species survey that does not provide adequate information for other groundfish species. In addition, massive northward movements of Humboldt squid (*Dosidicus gigas*) complicated the 2009 survey. Since it is very difficult to distinguish between Pacific hake and Humboldt squid with the current acoustic survey methodologies, changes in the spatial distribution and frequency of occurrence of Humboldt squid in the survey area may pose problems in the future.

Similar to the bottom trawl surveys, the acoustic survey produces data that are easily understood by the public, have been used historically, and are compatible with measurements used by other regions and nations.

*Number of groups below management thresholds.* A simple indicator of the status of assessed groundfish species is the number of species that are currently below various management thresholds. The Magnuson-Stevens Fishery Conservation and Management Act (MSFCMA) requires fishery conservation and management measures that prevent overfishing, while achieving optimum yield on a continuing basis (16 U.S.C. §1851a1). Overfishing occurs when the actual catch of a species exceeds the allowable catch for that species. The MSFCMA also requires that fishery management plans specify objective and measureable criteria for identifying when a fishery is overfished and contain conservation and management measures to prevent or end overfishing and rebuild the fishery (16 U.S.C. §1853a10). Under the PCGFMP, a species (or stock) is considered overfished when its current spawning stock biomass is assessed to be less than 25% of unfished spawning biomass. NMFS's national standard guidelines clarify that "overfished" relates to biomass of a stock or stock complex, while "overfishing" pertains to a rate or level of removal from a stock or stock complex (50 CFR 600.310(e)(2)). Estimates of spawning stock biomass and virgin biomass are calculated during the formal stock assessment analysis.

Data to measure the overfishing threshold is available for all stocks that have an identified allowable catch. Approximately 30 of the 90-plus managed groundfish species can be evaluated for the overfished threshold. However, data are likely available from the WCGTS to evaluate this threshold for other species.

The public can easily understand whether a species is above or below specific management thresholds and policy makers have used this indicator for regulatory and legislative purposes. Other nations have similar thresholds in their management frameworks (Gray et al. 2010).

**Population condition**—*Age structure of populations.* The longevity of many groundfish species allows them to allocate their reproductive output across many years. This strategy is particularly important when environmental conditions are unfavorable for survival of larvae or new recruits (Leaman and Beamish 1984, Berkeley et al. 2004a). In addition, there is growing support in the literature that older fish produce more fit eggs and larvae (Hislop 1988, Berkeley et al. 2004a, Wright and Gibb 2005, Sogard et al. 2008). This work suggests that older individuals may produce offspring that will survive and recruit to the population in higher proportions than offspring from younger individuals. This would be particularly true during years when environmental conditions were less than optimal. Thus populations with a truncated age structure (fewer older individuals) may have more difficulty sustaining current population levels. For many groundfish species, the largest and oldest individuals have been historically targeted and removed by fishing practices, which would suggest that many groundfish species have a truncated size (and age) structure from historical levels (Jennings and Blanchard 2004, Blanchard et al. 2005). Reference points have not been established for this indicator, but similar reference points have been suggested for the indicator mean size that would set reference points at the median size (age) of maturity.

The WCGTS collects otoliths for most managed species and age structure should be available for these species throughout the time series. Data for other species varies, but are typically limited to small spatial scales and to single estimates in time. The variability in age structure is not clearly understood across time and space in the CCLME for most species.

Fundamentally, the public can easily understand the importance of age structure to the success of fish populations—older individuals are generally larger and generally produce more and stronger offspring. Age structure is inherently used by policy makers because stock assessments use spawning stock biomass as the fundamental metric, which is related to the age of individuals when they mature.

*Rebuilding timeline.* For groundfish species in the PCGFMP, if a species population size is assessed to be less than 25% of its unfished spawning biomass, it is declared overfished and a rebuilding plan must be developed. A rebuilding plan establishes an allowable harvest rate that will enable the species to rebuild to its target spawning biomass (40% unfished spawning biomass) within an adequate period of time based on the minimum time of recovery, assuming no fishing (PFMC 2010a). The rebuilding timeline varies dramatically among species. For example, under current management harvest rates, cowcod (*Sebastes levis*) were predicted to rebuild by 2071, while widow rockfish (*Sebastes entomelas*) were predicted to rebuild by 2010 (PFMC 2010a). When management action is taken, such as reductions in harvest rate, most species stop declining, but the rate at which they rebuild varies (Miller et al. 2009). Rebuilding timelines are only developed for those species declared overfished, so there is a limited number with this information calculated. However, rebuilding timelines could be calculated from available data on other assessed species.

This indicator is relatively easy to understand by the public and policy makers. It is also easy to understand which species are having a difficult time rebounding from historical pressures.

*Spatial structure of populations.* The spatial structure is a measure of the geographic range and distribution of a species or stock. Most groundfish species in the PCGFMP are managed as a single stock, but there is mounting evidence that the genetic composition of recruits may be quite complicated spatially (Larson and Julian 1999, Berkeley et al. 2004b). Youngest recruits are found to have different genetic diversity and haplotypes from older year-classes or adults. This suggests that the geographic source of successful recruits may differ from year to year and that some populations may be reproductively isolated depending on oceanic conditions. Thus understanding how spatial structure may have changed over time may help our understanding of the connectivity of species across large spatial scales such as the CCLME. Distributional shifts are hypothesized to occur for either of two reasons—climatic or exploitation—but the difference is difficult to distinguish. Perry et al. (2005) showed large latitudinal shifts correlated with changes in temperature. Changes in depth distribution of groundfish assemblages have been found to be the result of changes in climate, while latitudinal shifts in distribution may be caused by either climate or exploitation (Fairweather et al. 2006, Coetzee et al. 2008, Dulvy et al. 2008).

As predicted, the geographic ranges of many overexploited species typically shrink, and stocks are concentrated into smaller regions following population declines (Atkinson et al. 1997, Garrison and Link 2000). Moreover, shrinking spatial distribution may limit the ability of a population to find suitable environmental conditions for offspring (Berkeley et al. 2004b). Some changes in species spatial distributions may even result in population extinctions (Thomas et al. 2004, Drinkwater 2005). Reference points for distributional shifts are not currently used and would be difficult to measure unless species were divided into distinct population segments and shifts away from one segment triggered management actions.

The WCGTS has collected data on the density and distribution of the CCLME groundfish assemblage for nearly 30 years. At this time, it is unknown whether shifts in the distribution of any species vary with changes in climate, exploitation, or changes in population condition.

In general, shifting or changing patterns of spatial distribution are easily understood by the public and policy makers. This type of information has been transmitted to the public in the past in the context of invasive species for terrestrial, freshwater, and marine systems. For example, the expanding geographic range of red lionfish (*Pterois volitans*) in the Caribbean may have started as a human introduction to the waters around Florida, but the subsequent movement to the rest of the Caribbean is clearly a spatial range expansion (Schofield 2009). The ability to detect spatial shifts in distribution or range is likely to occur at long time scales for noninvasive species, so spatial structure should be a lagging indicator of changes in the population condition.

*Mean size of all species.* The mean size (measured by length or weight) of all species caught in fishery-independent surveys, fishery-dependent surveys, or landings has been used to evaluate changes in an ecosystem (Link and Brodziak 2002, Link et al. 2002, Rochet and Trenkel 2003, Nicholson and Jennings 2004, Sala et al. 2004). A decrease in mean size is expected and has been observed in heavily fished systems (Haedrich and Barnes 1997, Levin et al. 2006, Methratta and Link 2006). However, the sensitivity of changes in mean size to environmental conditions is not well understood (Rochet and Trenkel 2003). One study suggests changes greater than 30% in mean length from one year to the next be set as a reference point (Link 2005), while another study suggests the reference point be set at the median length at maturity (Caddy and Mahon 1995).

In the WCGTS, subsamples of targeted species (up to 100 per trawl) are individually measured for length and weight. In order to monitor this indicator with fishery-independent data, all species would need to be sampled and measured in some fashion. However, this metric can be calculated using fisheries landings data (Link 2005), so historical data are available via Pacific Fisheries Information Network (PacFIN, http://pacfin.psmfc.org/).

This indicator is easily understood and is being used in other regional ecosystems (Link 2005). Similar to other indicators, mean size of all species is most likely to be a lagging indicator of the population condition because the size structure may be the result of environmental conditions acting on each individual since it was born.

*Age at maturity.* Population parameters such as age and size at maturity are adaptive traits and there is increasing support in the literature for rapid evolution of these life history characteristics (Haugen and Vøllestad 2001, Stockwell et al. 2003). As with the discussion of age structure as an indicator, significant changes in a population's age at maturity can signal extreme pressures that may have significant impact on a population's ability to sustain itself and ought to be cause for concern (Olsen et al. 2004). Declines in age-at-first-maturity have been commonly associated with compensatory responses to a reduction in population size (Trippel 1995, Berkeley et al. 2004b). There are multiple examples in which age at maturity has declined in heavily exploited groundfish populations such as Atlantic cod (*Gadus morhua*) (Beacham 1983a, Morgan et al. 1993), haddock (*Melanogrammus aeglefinus*) (Beacham 1983b), American plaice (*Hippoglossoides platessoides*) (Trippel 1995), and community-wide measurements (Greenstreet and Rogers 2006). In most studies, age at maturity declined during periods of exploitation, as evolutionary theory would predict, but striped bass (*Morone saxatilis*) in coastal Rhode Island showed a 15% increase in age at maturity over a 46-year period (Berlinsky et al. 1995). Olsen et al. (2004) provide a framework for Atlantic cod reference points that would provide managers with early warning signals about changes in this indicator.

Estimates of age at maturity exist for most managed groundfish species, but sampling generally occurred across short temporal scales (Gunderson et al. 1980, Echeverria 1987, see references within Love et al. 2002, Thompson and Hannah 2010). There are a few examples of multiple studies that measured age at maturity at various points in time at different locations within the CCLME, for example, canary rockfish (*Sebastes pinniger*) from California, Oregon, Washington, and British Columbia at various times between 1960 and 1982 (Phillips 1964, Westrheim 1975, Gunderson et al. 1980, Echeverria 1987). Age structures (otoliths, dorsal spines, and fin rays) are collected from targeted species during the WCGTS and gonads are collected as special projects from time to time. However, most groundfish are in need of new data on maturity and fecundity relationships, because methods have been inconsistent across studies and there are few examples of estimates over time (Stewart 2008).

Age at maturity is an easy indicator to understand for the public and policy makers, but this indicator has not been used because of the general lack of data over time for most species.

### Ecosystem health

**Community composition**—*Zooplankton species biomass anomaly.* Zooplankton time series provide some of the best opportunities to understand marine ecosystem responses to climate change because zooplankton are the foundation of the ocean food web, linking oceanographic conditions and primary production to upper trophic levels and fueling the delivery of ocean ecosystem services. Zooplankton life cycles are short (on the order of weeks to a year) and populations have the potential to respond to and reflect event-scale and seasonal changes in environmental conditions (Hooff and Peterson 2006). Moreover, many zooplankton taxa are known to be indicator species whose presence or absence may represent the relative influence of different water types on ecosystem structure. Thus zooplankton may serve as sentinel taxa that reflect changes in marine ecosystems by providing early indications of a biological response to climate variability and are often used as an indicator to detect climate change or regime shifts (Hooff and Peterson 2006, Mackas et al. 2006, Peterson 2009). Finally, zooplankton are abundant and can be quantified by relatively simple and comparable sampling methods and, because few are fished, most population changes can be attributed to environmental causes (Mackas and Beaugrand 2010). As such, they may prove useful as a leading indicator of what may happen to regional commercial fish stocks several years later (Mackas et al. 2007, Peterson et al. unpubl. manuscr.).

All along the California Current, anomalies in zooplankton species composition shifts have been correlated with regional climate patterns (Mackas et al. 2006). For example, off the Oregon coast zooplankton indices have been developed based on the affinities of copepods for different water types: those with cold water and those with warm water affinities (Peterson et al. unpubl. manuscr.). The cold water group usually dominates the coastal zooplankton community during the summer (typically May through September) upwelling season, whereas the warm water group usually dominates during winter, although this pattern is altered during summers with El Niño events or when the Pacific Decadal Oscillation (PDO) is in a positive (warm) phase. Perhaps the most significant aspect of the copepod index is that two of the cold water species, *Calanus marshallae* and *Pseudocalanus mimus*, are lipid-rich species. Therefore, an index of northern copepod biomass may also index the amount of wax esters and fatty acids being fixed in the food chain, compounds which appear to be essential for many pelagic fishes if they are to grow and survive through the winter successfully.

Several long-term zooplankton monitoring programs, representing seven subregions spanning the entire CCLME from Baja California to Vancouver Island, now provide zooplankton time series of various lengths from 1969 to the present. Although differences in processing and sampling zooplankton time series introduce a variety of biases that often prevent comparisons between data sets, many major questions can still be answered because an individual data set can be presented and analyzed as a time series of log-scale anomalies relative to the local long-term-average seasonal climatology. Anomalies are primarily used to separate interannual variability from the often large annual seasonal cycle of zooplankton stock size (Mackas and Beaugrand 2010). The specific species associated with these anomalies vary regionally, but can generally be classified as resident versus nonresident species. Regional anomalies can be combined into a single index using multivariate techniques (e.g., principal component analysis) in similar fashion to the calculation of regional climate indices, such as the Multivariate El Niño Southern Oscillation (ENSO) Index (Wolter and Timlin 1993). This index can then be tested for use as a leading indicator of regional climate signals, such as ENSO or PDO, using existing time series from the last 20 years, during which time the California Current saw at least two major climate regime shifts.

*Zooplankton abundance and biomass.* As noted above, zooplankton time series provide some of the best opportunities to understand marine ecosystem responses to climate change. As an important link at the base of the pelagic food web, they are considered a fundamental component in the CCLME (Brand et al. 2007, Horne et al. 2010, Sydeman and Thompson 2010). Because the biomass of planktivorous fish is inversely related to zooplankton biomass, which in turn is inversely related to phytoplankton biomass, zooplankton may prove useful as a leading indicator of what may happen to regional commercial fish stocks several years later (Sherman 1994, Mackas et al. 2007, Mackas and Beaugrand 2010, Peterson et al. unpubl. manuscr.). Zooplankton biomass declines have been correlated with warming of surface waters (Roemmich and McGowan 1995, Sydeman and Thompson 2010) and used to detect regime shifts (Hare and Mantua 2000). However, for time series observations of ecosystem state variables such as biomasses or chemical concentrations, standard deviations may increase, variance may shift to lower frequencies in the variance spectrum, and return rates in response to disturbance may decrease prior to a change (Carpenter et al. 2008).

The feeding effect of pink salmon (*Oncorhynchus gorbuscha*) has been shown to control summer macrozooplankton and phytoplankton biomass in the subarctic North Pacific (Shiomoto et al. 1997). Trophic cascade theory holds that reductions in harvest of zooplanktivorous fish would ultimately result in lower biomass of zooplankton, but it is unclear whether this has been demonstrated in the field for large marine systems (Pace et al. 1999). There are a number of (up to seven) long-term zooplankton biomass time series that have been maintained throughout various regions of the CCLME (Hooff and Peterson 2006, Mackas and Beaugrand 2010); one of the oldest of these data sets is the California Cooperative Oceanic Fisheries Investigative (CalCOFI) reports time series, which has been collected since 1956 (McClatchie et al. 2009). In freshwater systems, zooplankton biomass has been used as a leading indicator of trophic cascades.

*Demersal fish biomass and trends (groundfish).* The groundfish community of the CCLME consists of approximately 250 species or groups of fish (as detected in the WCGTS). This assemblage forms a large component of the ecosystem; thus changes in the status and trends of this group will impact the community composition of the ecosystem. Testing for changes in population size using individual species or groups of species has been used to assess community change using a variety of statistical approaches (e.g., Heessen and Daan 1996, Haedrich and Barnes 1997, McClanahan et al. 2010). In simulations of six northeast Pacific Ocean food web models, demersal fish biomass was significantly correlated with 9 of 22 different ecosystem attributes and was the best indicator (out of 27 candidate indicators) of total respiration/total biomass in the ecosystem and the best indicator of mean trophic level (Samhouri et al. 2009). However, changes in the attribute community composition may be a result of changes in various assemblages of fish, but a change (or no change) in a single group of fish may not be indicative of the ecosystem as a whole. Fisheries-based reference points include B40 (target level where production is predicted to be greatest) and B25 (overfished). These single-species reference points could be adapted to be used for assemblages of fish such as groundfish. Alternatively, Link (2005) describes a framework of reference points that could be applied to most any indicator.

Fishery-independent data (see Groundfish, Population size, *Bottom trawl survey biomass* subsection above) is available for all groundfish species susceptible to bottom trawling across the U.S. portion of the CCLME since 1977. There are also data available at smaller spatial scales and various temporal scales in untrawlable habitats from submersibles, remotely operated vehicles (ROVs), and the NWFSC hook-and-line surveys. All surveys have been incorporated into the stock assessment process for managed species. Temporal variability and spatial heterogeneity are not completely understood for this indicator at this time, but the data are available to perform these analyses.

The public can easily understand the concept of groundfish and whether groundfish are trending up or trending down. In addition, policy makers have already used this type of information for regulatory and legislative purposes. Detecting changes in the biomass of groundfish would likely be measured against long-term averages, so unless dramatic changes are observed, groundfish biomass will be a lagging indicator of changes in community composition. Moreover, groundfish have been a common assemblage to measure worldwide when trying to understand the structure of ecosystems or the consequences of pressures such as fishing or climate change (Link et al. 2002, Dulvy et al. 2006, Levin et al. 2006).

*Flatfish biomass.* There are approximately 24 species of flatfish detected in the WCGTS. Changes in flatfish biomass, particularly increases, are indicative of heavily fished ecosystems (Pauly 1979, Kaiser and Ramsay 1997, Hall 1999, Link 2005). In simulations of 6 northeast Pacific Ocean food web models, flatfish biomass was significantly correlated with 12 of 22 different ecosystem attributes and was the best indicator (out of 27 candidate indicators) of the ecosystem reorganization index (Samhouri et al. 2009). Detectable changes in the attribute community composition may be a result of changes in various assemblages of fish, but a change (or no change) in a single group of fish may not be indicative of the ecosystem as a whole. Fisheries-based reference points include B40 (target level where production is predicted to be greatest) and B25 (overfished). These single-species reference points could be adapted for use with assemblages of fish such as flatfish. Alternatively, Link (2005) describes a framework of reference points that could be applied to most any indicator.

Fishery-independent data (see Groundfish, Population size, *Bottom trawl survey biomass* subsection above) are available for all groundfish species susceptible to bottom trawling across the U.S. portion of the CCLME since 1977. There are also data available at smaller spatial scales and at various temporal scales in untrawlable habitats from submersibles, ROVs, and the NWFSC hook-and-line surveys. All surveys have been incorporated into the stock assessment process for managed species. Temporal variability and spatial heterogeneity is not completely understood for this indicator at this time, but the data are available to perform these analyses.

The public can easily understand whether flatfish populations are trending up or down and policy makers have used this type of information for regulatory and legislative purposes. Detecting changes in the biomass of flatfish would likely be measured against long-term averages, so unless dramatic changes are observed, flatfish biomass will be a lagging indicator of changes in community composition. Monitoring flatfish biomass is consistently performed in other regions of the United States and in other nations because they have been shown to respond to exploitation (Pauly 1979, Kaiser and Ramsay 1997, Hall 1999, Link 2005).

*Roundfish biomass.* There are approximately 103 species of roundfish detected in the WCGTS. We define roundfish similarly to Samhouri et al. (2009), as species in the following families: Anoplopomatidae, Cottidae, Gadidae, Hexagrammidae, Macrouridae, Merlucciidae, and Scorpaenidae. In simulations of 6 northeast Pacific Ocean food web models, roundfish biomass was significantly correlated with 9 of 22 different ecosystem attributes; however, roundfish biomass was not the best indicator (out of 27 candidate indicators) of any one ecosystem attribute (Samhouri et al. 2009). Detectable changes in the attribute community composition may be a result of changes in various assemblages of fish, but a change (or no change) in a single group of fish may not be indicative of the ecosystem as a whole. Fisheries-based reference points include B40 (target level where production is predicted to be greatest) and B25 (overfished). These single-species reference points could be adapted for use with assemblages of fish such as roundfish. Alternatively, Link (2005) describes a framework of reference points that could be applied to most any indicator.

Fishery-independent data (see Groundfish, Population size, *Bottom trawl survey biomass* subsection above) are available for all roundfish species susceptible to bottom trawling across the U.S. portion of the CCLME since 1977. There are also data available at smaller spatial scales and at various temporal scales in untrawlable habitats from submersibles, ROVs, and the NWFSC hook-and-line surveys. All surveys have been incorporated into the stock assessment process for managed species. Temporal variability and spatial heterogeneity is not completely understood for this indicator at this time, but the data are available to perform these analyses.

The public can easily understand whether roundfish populations are trending up or down and policy makers have used this type of information for regulatory and legislative purposes. Detecting changes in the biomass of roundfish would likely be measured against long-term averages, so unless dramatic changes are observed, roundfish biomass will be a lagging indicator of changes in community composition. Monitoring roundfish biomass is consistently performed in other regions of the United States and in other nations.

*Rockfish biomass.* There are approximately 61 species of rockfish detected in the WCGTS. Rockfish are of conservation concern because they are generally targeted or captured as bycatch in several West Coast fisheries. Rockfish are long-lived species, often exceeding 50 years (Love et al. 2002). Rockfish also grow slowly and mature relatively late compared to other fishes. This life history strategy helps rockfish populations persist through poor environmental conditions. However, this strategy also inhibits their ability to recover from high levels of exploitation. Rockfish occupy a broad range of habitat and trophic roles. In simulations of 6 northeast Pacific Ocean food web models, rockfish biomass was significantly correlated with 9 of 22 different ecosystem attributes and was the best indicator (out of 27 candidate indicators) of the piscivorous fish reorganization index (Samhouri et al. 2009). Detectable changes in the attribute community composition may be a result of changes in various assemblages of fish, but a change (or no change) in a single group of fish may not be indicative of the ecosystem as a whole. Fisheries-based reference points include B40 (target level where production is predicted to be greatest) and B25 (overfished). These single-species reference points could be adapted for use with assemblages of fish such as rockfish. Alternatively, Link (2005) describes a framework of reference points that could be applied to most any indicator.

Fishery-independent data (see Groundfish, Population size, *Bottom trawl survey biomass* subsection above) are available since 1977 for all rockfish species susceptible to bottom trawling across the U.S. portion of the CCLME. There are also data available at smaller spatial scales and at various temporal scales in untrawlable habitats from submersibles, ROVs, and the NWFSC hook-and-line surveys. All surveys have been incorporated into the stock assessment process for managed species. Temporal variability and spatial heterogeneity are not completely understood for this indicator at this time, but the data are available to perform these analyses.

The public can easily understand whether rockfish populations are trending up or down and policy makers have used this type of information for regulatory and legislative purposes. Detecting changes in the biomass of rockfish would likely be measured against long-term averages, so unless dramatic changes are observed, rockfish biomass will be a lagging indicator of changes in community composition. Monitoring assemblages such as rockfish is consistently performed in other regions of the United States and in other nations.

*Adult sablefish biomass* (correlation to Shannon Diversity Index). Theoretical modeling results have been used to show that some ecosystem structural (e.g., diversity) attributes can be related to thresholds in the level of human-induced pressure. In particular, a marine ecosystem model for British Columbia was used to show that sablefish density is positively correlated with Shannon Diversity, suggesting that changing levels of fishing on a particular species may produce substantial improvements toward protecting ecosystem goals based on this structural attribute (Samhouri et al. 2010). The model also describes how to incorporate uncertainty into the estimation of utility thresholds and their value in the context of understanding EBM trade-offs. These modeling results may be equally applicable to the CCLME because of many similarities between these ecosystems. The value of this indicator is predicated not only on the correlation between sablefish biomass and ecosystem diversity, but also on how well each of these independent indicators meet individual evaluation considerations.

With regard to biodiversity, Shannon Diversity is a measure that incorporates both richness (the number of different species within a system) and evenness (the number of individuals of each species within a system). The correlation between diversity and ecosystem function (productivity and stability) has been reviewed recently for terrestrial and marine systems, suggesting that the relationship is complex but communities are more stable at higher richness (Hooper et al. 2005, Stachowicz et al. 2007). In general, populations can be more variable but community level processes are more stable at higher diversity (i.e., the biomass of species A and species B may fluctuate, but A + B tends to be stable). Linking diversity indices to targets or reference points is difficult, and the significance of certain types of change is not known for biodiversity indices (Link 2005, Dulvy et al. 2006). Furthermore, the general public tends to have a basic understanding and positive impression toward biodiversity as it relates to ecosystem health (Thompson and Starzomski 2007). Species richness has been shown to decrease with fishing, although these results appear largely related to trawling and dredging on benthic invertebrates (Gaspar et al. 2009, Reiss et al. 2009).

Shannon Diversity indices can be used with a variety of existing survey data: groundfish trawl surveys (Weinberg et al. 2002, Keller et al. 2008), reef fish surveys conducted by trained divers (REEF 2008), invertebrates from benthic grabs conducted by the EPA Environmental Monitoring and Assessment Program's National Coastal Assessment (http://www.epa.gov/emap/index.html), and a variety of seabird and marine mammal surveys (Barlow and Forney 2007, Carretta et al. 2007, McClatchie et al. 2009, Ainley and Hyrenbach 2010). For their biomass, sablefish have a wide distribution, and populations are managed and evaluated on the west coast of North America using stock assessments that are calculated from abundance estimates (Keller et al. 2008, PFMC 2008b). Increased fishing pressure leads to lower sablefish biomass and populations have been shown to vary with decadal-scale climate regimes (King et al. 2000, 2001). Bioenergetics models have also been used to examine the effects of temperature change on sablefish, but not specifically with regard to changes in biomass or population size (Harvey 2009).

*Coho salmon smolt-to-adult survival rate.* The salmon smolt-to-adult survival rate is considered a good indicator of the state of the CCLME because salmon populations are highly influenced by ocean conditions, and coho salmon marine survival in particular is significantly and independently related to the dominant modes acting over the coastal region in the periods when the coho first enter the ocean (Koslow et al. 2002, Logerwell et al. 2003, Scheuerell and Williams 2005, Peterson et al. unpubl. manuscr.). Furthermore, salmon are of high commercial, recreational, and cultural importance along much of the Pacific coast, and therefore have high relevance in the delivery of ocean ecosystem services to the region (NRC 1996). Strong coupling has been demonstrated between smolt-to-adult survival and ocean upwelling in the spring and fall, suggesting management policies directed at conserving salmon need to explicitly address the important role of the ocean in driving future salmon survival (Scheuerell and Williams 2005). Furthermore, the salmon smolt-to-adult survival rate may affect management as it relates to using ocean conditions to determine best release date of hatchery fish.

The Oregon Production Index (OPI), defined as the percent of smolt-to-adult returns for coho salmon in Oregon, is currently one of several time series considered useful ecosystem indicators within the California Current region (Peterson et al. unpubl. manuscr., Sydeman and Thompson 2010). This data set is temporally extensive and comprehensive for the central CCLME (PFMC 2010b). However, it is considered a lagging or retrospective indicator of ocean conditions due to the protracted life cycle of salmon (Scheuerell and Williams 2005, Peterson et al. unpubl. manuscr.).

*Biodiversity index*. Hurlbert's delta is a measure of taxonomic evenness that, when applied to abundance estimates from a particular ecological community, estimates the probability of two individuals in a sample being different species (Hurlbert 1971). It has a clear, concise ecological interpretation and has been applied as an indicator for detecting the impact of fishing on a fish community (Trenkel and Rochet 2003). Linking diversity indices to targets or reference points is difficult, and the significance of certain types of change is not known for biodiversity indices (Link 2005, Dulvy et al. 2006). Hurlbert's delta measure has been applied in measuring detectable spatial variation with depth and latitude at large scales and, although temporal patterns may be unknown, could be calculated from historical data (Tolimieri 2007). It can also be used to detect changes in community composition after change has occurred, although natural and baseline levels of taxonomic evenness may vary so much that absolute values may not be comparable in terms of thresholds.

Other studies have shown biodiversity trends in the Bering Sea correlate with regime shifts (Hoff 2006). The same approach could be applied to a variety of existing survey data: groundfish trawl surveys (Weinberg et al. 2002, Keller et al. 2008), reef fish surveys conducted by trained divers (REEF 2008), invertebrates from benthic grabs conducted by the EPA EMAP National Coastal Assessment (http://www.epa.gov/emap/index.html), and a variety of seabird and marine mammal surveys (Barlow and Forney 2007, Carretta et al. 2007, McClatchie et al. 2009, Ainley and Hyrenbach 2010).

*Proportion of noncommercial species.* The proportion of noncommercial species in groundfish survey data has been shown to be strongly related to 12 attributes of ecosystem health, based on modeling results from numerous systems (Samhouri et al. 2009). It has been used as one of the more sensitive indicators for detecting the impacts of fishing on fish communities, with a coefficient of variation around 20% for either biomass or abundance (Trenkel and Rochet 2003). Modeling results show the proportion of noncommercial species responds to variation in fishing pressure and correlates to ecosystem attributes (Samhouri et al. 2009). If this indicator is monitored, gradual change should be detected prior to major community reorganization (i.e., leading indicator). Data for this indicator include a limited number of time series with good spatial coverage: Marine Recreational Fisheries Statistics Survey (MRFSS 1980–2003) data for nontrawl species (http://www.recfin.org/) and data from the observer program (bycatch species) (Bellman et al. 2009).

*Juvenile rockfish abundance indices.* Indices of larval or juvenile fish abundance can be good indicators of adult biomass and often play a useful role in stock recruitment models that forecast year-class strength (Bailey and Spring 1992, Ralston and Howard 1995). Long-term trends in larval abundance can reflect trends in adult biomass, whereas short-term fluctuations are likely related to episodes of high or low reproductive output or geographic shifts due to animal movement (Hsieh et al. 2005). Larval fish surveys from CalCOFI reports have provided some of the first empirical evidence to show that fishing increases variability in the abundance of exploited populations, even after accounting for life history effects, ecological traits, phylogeny, and a changing environment (Hsieh et al. 2006). Rockfish and hake both have significant commercial and recreational importance and play an important role in the delivery of a variety of ocean ecosystem services to the region.

Larval fish surveys have been conducted over the central California coastal region since 1983, with a 2004 expansion of the survey area to the U.S.-Mexico border (Brodeur et al. 2003, Sakuma et al. 2007, Helser and Martell 2007), and therefore have limited spatial coverage within the CCLME. A juvenile rockfish index is currently used as 1 of 20 time series considered useful ecosystem indicators within the CCLME (Sydeman and Thompson 2010). Larval fish abundance indices have been used as ecosystem indicators in other regions, such as the North Sea (Frederiksen et al. 2006).

*Juvenile hake abundance.* See *Juvenile rockfish abundance indices* subsection above.

*Crustacean survey trends.* Crustaceans are a prominent component of the CCLME and contribute to the delivery of several important ecosystem services in the region through commercially and recreationally important fisheries (Fogarty and Botsford 2006). They also comprise several important predatory and scavenger groups in existing CCLME models (Brand et al. 2007). They are highly responsive to top-down effects in the food web, and predatory finfish abundance may be a negative indicator for invertebrate fishery productivity (Caddy 2004). For instance, shrimp biomass has been strongly negatively related to cod biomass in the North Atlantic Ocean, showing that changes in predator populations can have strong effects on prey populations in oceanic food webs (Worm and Myers 2003). Fishing effects may exacerbate these patterns: the Gulf of Maine shifted from a high trophic level, groundfish-dominated, system to a low trophic level, crustacean-dominated system during the 1980s to 1990s (Zhang and Chen 2007).

As a group, crustaceans are often found low in the food web, are highly fecund, and may be sensitive to bottom-up effects; therefore, indicators measuring plankton productivity, turbidity, oxygen levels, and eutrophication should be useful in predicting the typically large variations in recruitment success that drive these fisheries (Caddy 2004). Climate change manifested in water column temperature also has an effect on lower trophic levels of boreal marine ecosystems, and changes in crustacean recruitment patterns may be one of the first indicators of community regime shift (Zheng and Kruse 2000). For instance, declines in several species of pandalid shrimp and other community effects in the Gulf of Alaska have been attributed to climate induced changes in water column temperature (Anderson 2000). Pandalid shrimp surveys are also used as indicators of Pacific Ocean conditions off British Columbia (DFO 2009). The abundance of decapod larvae in the plankton also appears to be positively correlated to changes in North Sea sea surface temperature (SST) (Kirby et al. 2009).

For the most part, data availability for this group is relatively good. Zooplankton time series are spatially and temporally extensive (Mackas et al. 2007, McClatchie et al. 2009), and crustacean larval surveys represent a long established means of estimating the spawning stocks of decapods (Kirby et al. 2009). Harvest data records are fairly extensive through PacFIN (though biased by typical catch issues) and some aspects of the ongoing West Coast groundfish surveys may be useful in deciphering abundance/biomass patterns (Keller et al. 2008).

*Kelp forest coverage.* Kelp forests are ecologically and economically important, as they are the foundational structure for diverse communities in most coastal waters of the CCLME (Dayton 1985, Graham 2004). The persistence of many biologically and commercially important species of algae, invertebrates, fish, and marine mammals are directly coupled to the production of energy from kelp (Foster and Schiel 1985, Steneck et al. 2002). Kelp forests may also serve functional roles in cycling carbon between coastal marine, littoral (Polis and Hurd 1996, Dugan et al. 2003), and continental shelf (Harrold et al. 1998, Vetter and Dayton 1999) ecosystems. Most kelp forests exist in waters less than 60 m deep, so at the scale of the CCLME community composition may not be tied to the abundance of kelp, but because of its importance as essential fish habitat for many species of concern, including young-of-year (Carr 1991), understanding the temporal variation and spatial heterogeneity (Jones 1992, Bustamante and Branch 1996) of kelp forest coverage in the CCLME may be a useful indicator of ecosystem structure. Following the framework of Link (2005), reference points related to percent change in aerial coverage of kelp could be established.

The density and distribution of kelp forests have been measured historically in numerous ways. Many historical data sets include scuba diving surveys (e.g., Partnership for Interdisciplinary Studies of Coastal Oceans [PISCO] at http://www.piscoweb.org/, U.S. National Park Service at http://www.nps.gov/chis/contacts.htm), but these are generally over small spatial and short temporal scales. Recent advances in satellite and infrared photography have allowed researchers to measure areal canopy cover and biomass of kelp along much of the U.S. West Coast (Deysher 1993, Cavanaugh et al. 2010).

Kelp forest coverage is easily understood by the public and has been used by policy makers to develop guidelines related to provisions of the marine statistical area on the identification of essential fish habitat (16 USC §1855b). Changes in kelp forest coverage affect recruitment of invertebrates and other species (e.g., Carr 1991), such that kelp forest coverage could anticipate recruitment of older life stages into the bottom trawl surveys or into the fishery; thus kelp forest coverage could be a leading indicator for the community composition of the CCLME.

*Number of threatened species.* This is a composite indicator based on a weighted average of species threat, as determined by the International Union for the Conservation of Nature (IUCN 2008), which may be different from those considered threatened under the U.S. Endangered Species or Marine Mammal Protection acts. This is essentially a richness survey, and although the relationship between richness and function is complex, communities appear to be more stable at higher richness (Stachowicz et al. 2007).

Richness can influence stability and productivity in two ways: sampling/selection effect or compensatory effect (Stachowicz et al. 2007). Under the sampling effect, higher richness leads to a greater chance of highly productive species being present. This type of relationship is not considered a real richness effect by some, but more of a compositional or keystone species effect. Under the compensatory effect, higher production or stability occurs in two ways: via resource complementarity, where more species occupy more niches and better utilize all resources (e.g., different type of nitrogen), and facilitation, where some species combinations do better. However, it is not always clear how to relate species richness or other diversity measures to reference points or targets (Hooper et al. 2005, Link 2005), although some authors have provided a rationale to manage for biodiversity as an approach to EBM (Palumbi et al. 2009).

Species richness has been shown to decrease with fishing, although these results appear largely related to trawling and dredging on benthic invertebrates (Gaspar et al. 2009, Reiss et al. 2009). The weighting criteria for this indicator are somewhat arbitrary and linking the index to targets or reference points is difficult; however, data are readily available and numerical. The same approach used by the IUCN could be applied to a variety of existing survey data: groundfish trawl surveys (Weinberg et al. 2002, Keller et al. 2008), reef fish surveys conducted by trained divers (REEF 2008), and a variety of seabird and marine mammal surveys (Gislason et al. 2000, Dulvy et al. 2006, McClatchie et al. 2009).

*Taxonomic distinctness.* Measures of community diversity are directly indicative of ecosystem structure and can be used to test for effects of environmental pressures on various communities (Gaspar et al. 2009, Reiss et al. 2009). In general, communities are considered more stable at higher measures of diversity (Stachowicz et al. 2007). Taxonomic distinctness (TD) is a measure of diversity based on the relatedness of species in a sample and incorporates the evolutionary history of ecosystem constituents. For example, a sample with two rockfish of different species would be considered less taxonomically distinct or diverse than a sample with one rockfish and one flatfish.

Average taxonomic distinctness (AvTD) is the mean of all species-to-species distances through a taxonomic classification tree for all species pairs within a sample and represents the taxonomic breadth of the sample. Gristina et al. (2006) found lower TD in trawled versus untrawled habitats and TD was higher in marine reserves versus fished areas (Stobart et al. 2009). Variation in taxonomic distinctness (VarTD) is the variation in branch lengths among all species pairs (not the variance of AvTD among samples) and is a measure of the irregularities and divergences in the distribution of branch lengths within a sample. Latitudinal and depth related variation in AvTD and VarTD on the West Coast are described by Tolimieri and Anderson (2010). Defining reference points for measurements of diversity is difficult (Link 2005, Dulvy et al. 2006).

Both indices are appealing because they are based on presence/absence data and, unlike many biodiversity measures, neither is affected by the number of species or the sampling effort. In the present case, these properties allow one to compare the bottom trawl survey data from the AFSC and NWFSC as evidenced by the close agreement in AvTD and VarTD values for 2004 (see EBM Component, Ecosystem Health subsection). Data are available to investigate TD for intertidal invertebrates from 2002 to 2010 (PISCO at http://www.piscoweb.org/) and zooplankton across various regions of the CCLME for varying periods of time (e.g., NWFSC, Newport Line, CalCOFI survey). Other data sets are also available at smaller spatial and temporal scales (e.g., National Park Service kelp forest monitoring program in the Channel Islands). Many of these data sets will need to be combined to investigate trends in TD over time across the entire scale of the CCLME. Statistical tools have been developed that take into account the uncertainty associated with multiple data sets so they can be combined (Drake et al. 2010).

Trends in TD and the fundamental idea of diversity are easily understood by the public and policy makers. Increases or decreases in TD would certainly be a lagging indicator of changes in ecosystem structure.

*Scavenger biomass.* Scavengers play significant roles in the ecosystem by recycling dead and decomposing organic matter back into the food web. However, human interference in the marine ecosystem has likely increased the abundance and number of species that forage on carrion (Britton and Morton 1994). For example, many fishing operations discard dead bycatch to the ocean floor or damage organisms on the seabed during bottom fishing operations (Ramsay et al. 1998). Scavenger population increases may be related to these types of fishing activities (Britton and Morton 1994, Ramsay et al. 1998, Demestre et al. 2000). Scavengers are typically defined by the proportion of carrion or detritus in a species' diet.

When evaluating this indicator, we use the definition of scavenger used in the Atlantis ecosystem models for the California Current (Brand et al. 2007, Horne et al. 2010). In these models, scavengers include all large crabs, large demersal sharks, grenadiers, deposit feeders (i.e., isopods and amphipods), and carnivorous infauna such as polychaetes. Detectable changes in the attribute community composition may be a result of changes in various foraging guilds, but a change (or no change) in a single guild may not be indicative of the ecosystem as a whole. Fisheries-based reference points include B40 (target level where production is predicted to be greatest) and B25 (overfished). These single-species reference points could be adapted and used for foraging guilds such as scavengers. Alternatively, Link (2005) describes a framework of reference points that could be applied to most any indicator.

Fishery-independent data (see Groundfish, Population size, *Bottom trawl survey biomass* subsection above) are available since 1977 for all scavenger species susceptible to bottom trawling across the U.S. portion of the CCLME. There are also data available at smaller spatial scales and at various temporal scales in untrawlable habitats from submersible, ROV, and the NWFSC hook-and-line surveys. Fishery-dependent data for crab species are available in the PacFIN database (http://pacfin.psmfc.org/). Some species of the scavenger guild, such as isopods, amphipods, and polychaetes, will need new surveys to quantify these components. Benthic grab samples are commonly used to quantify benthic infauna, but it may be difficult to perform this type of survey at the scale of the CCLME at necessary temporal scales. Moreover, quantifying a value for many foraging guilds will require quantitative analyses to combine data sets which collect data using very different methods. For example, bottom trawl surveys, longline surveys, and benthic grab samples will need to be combined at various spatial and temporal sampling scales to quantify the biomass of grenadiers, crabs, large demersal sharks, and deposit feeders.

The public can easily understand whether a foraging guild, such as scavengers, is trending up or down, but this particular indicator may be less attractive to the public than more charismatic groups (i.e., marine mammals or sharks). Detecting changes in the biomass of scavengers would likely be measured against long-term averages, so unless dramatic changes are observed, scavenger biomass will be a lagging indicator of changes in community composition. Monitoring foraging guilds such as scavengers has been performed in other regions of the United States (Link and Almeida 2002) and in other nations (Demestre et al. 2000, Greenstreet and Rogers 2000).

**Energetics and material flows**—*Number of cycles.* Carbon cycling, or the flow of energy within an ecosystem, has increasingly been estimated in the CCLME and elsewhere using mass-balance models (e.g., Atlantis and EcoSim) (Christensen and Walters 2004, Fulton et al. 2005, Brand et al. 2007, Horne et al. 2010). One ecosystem indicator that has been measured with the aid of these models is the number of cycles inherent in a particular system (Baird et al. 1991). From a theoretical standpoint, carbon cycling should decrease predictably as ecosystem stress increases, stability decreases, and the system becomes more open to carbon inputs and removals (i.e., as internal cycling is reduced) (Odum 1985, Link 2005, Gaichas et al. 2009, Samhouri et al. 2010). Carbon cycling is therefore highly relevant to various human activities, such as fishing, where biomass is removed from a system, or climate change, where carbon sequestration decreases. The number of carbon cycles in a system should respond predictably to management actions such as fishing closures where cycling should increase as top predators rebuild.

The modeling approach itself, though subject to a number of large assumptions, is operationally simple and robust to a variety of data issues, allowing historical simulations over a broad spatial range. It is also increasingly used by policy makers as a cost effective tool to predict and anticipate management actions and valuable as a comparative tool between other ecosystems and historic states (Baird et al. 1991, Fulton et al. 2005, Gaichas et al. 2009, Samhouri et al. 2010). Model calibration itself involves substantial preparation and trial and error, and there are numerous uncertainties and assumptions associated with estimating biomass of various trophic groups using incomplete survey or census data (Hill and Wheeler 2002).

*Inorganic nutrient levels (phosphate, nitrate, silicate).* The availability of inorganic nutrients in the euphotic zone acts as a control on biological production in the California Current ecosystem (McGowan et al. 2003). In general, the open waters of the CCLME are nutrient limited, with nutrient pulses characterized by upwelling events and to a lesser degree, river plumes (Hill and Wheeler 2002). Therefore, anomalies in nutrient levels or periodicity represent a leading indicator of changing upwelling patterns, hydrographic and flow alterations, climate change, or regime shifts that effect subsequent patterns of biological production. Although eutrophication is not common in the open waters of the CCLME, increased nutrient turnover and decreased cycling frequently appear in stressed ecosystems, and together result in accumulation of nutrients which, like unused production, may be lost from the system (Odum 1985).

The eutrophication of estuaries and coastal seas is one of the best-documented and best-understood consequences of human-altered nutrient cycling; consequently, nutrient levels are often the focus in water quality monitoring programs. However, altered nutrient levels have not performed strongly as an indicator of fishing in ecosystem simulation models (Fulton et al. 2005). Nevertheless, alterations to the global nitrogen cycle have caused changes in the composition and functioning of estuarine and nearshore ecosystems and contributed to long-term declines in coastal marine fisheries (Vitousek et al. 1997). At the same time, some nearshore species (e.g., bull kelp [*Nereocystis luetkeana*]) in the California Current may be especially sensitive to episodic events that limit intrusion of deep, cooler, nutrient-rich waters from offshore (McGowan et al. 2003).

For offshore regions, nutrient levels in the upper layers of the water column have generally been poorly characterized in space and time (Hill and Wheeler 2002). Some notable exceptions to this pattern include intensive sampling at individual regions: the southern California Current via the CalCOFI report program (McClatchie et al. 2009) and portions of the northern California Current via U.S. Global Ocean Ecosystems Dynamics (GLOBEC) cruises. Most nutrient levels (nitrate, phosphate, silicate) are characterized in the CalCOFI region from 1984 to present based on concentration anomalies in the mixed layer depth (McClatchie et al. 2009). In notable contrast to offshore regions, nutrient concentrations in nearshore regions of the California Current have been more or less continuously measured in many rivers, estuaries, beaches, and other drinking water supplies for decades; some examples include Washington State's Olympic Region Harmful Algal Bloom (ORHAB) program and the Monterey Bay National Marine Sanctuary Program.

*Chlorophyll a.* Chl *a* can be used as an indicator of phytoplankton biomass, which itself is a good indicator of the amount of energy fueling the ecosystem (Falkowski and Kiefer 1985, Cole and Cloern 1987, Polovina et al. 2001, Edwards and Richardson 2004, Fulton et al. 2005). The amount of primary productivity, measured as total chlorophyll per unit area (mg $m^{-3}$), has been recognized as an important aspect of the marine food web, and chl *a* values are used to estimate phytoplankton biomass for mass-balance models of the CCLME (Falkowski and Kiefer 1985, Brand et al. 2007, Horne et al. 2010). Chl *a* has been shown to respond predictably to reductions or increases in nutrient inputs (eutrophication). It should be possible to identify time-specific and location-specific limit reference points for upwelling or transition fronts, although the relationship between reflectance and phytoplankton biomass must be derived before this can be accomplished.

Chl *a* has been used to provide basic data for CCLME ecosystem model building and calibration based on values from GLOBEC sampling cruises between 1997 and 2004 and CalCOFI cruises from 2000 to 2004 (Brand et al. 2007). Satellite remotely sensed chl *a* concentration (mg $m^{-3}$) data can be obtained at minimal cost from the Sea-viewing Wide Field-of-View Sensor (SeaWiFS at http://oceancolor.gsfc.nasa.gov/SeaWiFS/) to derive broad-scale coverage of values over the CCLME (Polovina and Howell 2005) or at smaller regional scales (Sydeman and Thompson 2010). Phytoplankton color, a visual index of chlorophyll derived from continuous plankton recorder surveys (http://www.sahfos.ac.uk/about-us/cpr-survey/the-cpr-survey.aspx), can also be used to show intensity and seasonal extent of chl *a* (Edwards and Richardson 2004). Some species or subsets of species of phytoplankton that affect chl *a* concentration can serve as an indicator of change in phytoplankton biomass, but physical measurements of upwelling intensity may provide a better leading indicator.

# Evaluating Potential Indicators for the California Current: Salmon and Green Sturgeon

## Initial Selection of Indicators

The selection of indicators for salmon and green sturgeon in the CCLME did not replicate the comprehensive literature-based evaluation used for groundfish and ecosystem health. Rather, the initial indicator list was compiled and refined based on the expertise of biologists currently studying these species. Future versions of the IEA will seek to expand the indicator vetting process for these species to enhance its transparency and comprehensiveness.

## Salmon

**Population size**—For population size, we evaluated three primary indicators: 1) spawning escapement, 2) population growth rate, and 3) hatchery contribution. These indicators are supported by all of our primary literature resources (e.g., Lindley et al. 2007, Lindley et al. 2009b, PFMC 2010a). Each of these three indicators was chosen based on length of time series, quality of data, managerial usefulness, and their representation of important life history characteristics and population viability.

*Spawning escapement.* Estimates of spawning escapement are extremely important to salmon management. Ultimately, management is designed to meet escapement goals such that the population remains viable (for ESA-listed populations) or near the biomass that produces maximum recruitment (for stocks covered by a fisheries management plan). If the number of spawners falls too low, whether due to overfishing or natural mortality, the fishery could be closed as it was in 2008 and 2009.

*Population growth rate.* Calculated as the proportional change in abundance between successive years, population growth rate is an indication of the population's resilience. In addition, growth rate can act as a warning of critical abundance trends that can be used for determining future directions in management. Also, the viability of a population is dependent in part on maintaining life history diversity in the population.

*Hatchery contribution.* Hatchery production is a relatively homogeneous life history type relative to naturally produced populations. If natural production is reduced, the population can be at risk during periods of increased environmental variability (Lindley et al. 2007).

**Population condition**—For the attribute population condition, we identified and evaluated three potential indicators: 1) age structure, 2) spatial stock structure of stocks, and 3) size at age. These indicators are supported as indicators of population condition by our primary literature resources (e.g., Lindley et al. 2007, Lindley et al. 2009b, PFMC 2010a). Each of the three indicators was chosen based on length of time series, quality of data, managerial usefulness, and their representation of important life history characteristics and population viability.

*Age structure.* A diverse age structure is important to improve the population viability. Larger, older Chinook salmon produce more and larger eggs (Healey and Heard 1983). Therefore, they produce a brood that may contribute proportionally more to the later spawning population than broods from younger, smaller fish. However, the diversity of ages including younger fish is important to accommodate variability in the environment. If mortality on any given cohort is great, there is benefit to having younger spawners. This bet hedging is a critical aspect of Chinook salmon that allow it to naturally mitigate year-to-year environmental variability (Heath et al. 1999).

*Spatial stock structure.* Maintaining a metapopulation is critical to improving population viability. The limited connectivity between subpopulations allows each to act somewhat asynchronously. Therefore, the collapse of one subpopulation may not affect, in any dramatic manner, the viability of another subpopulation. Further, the subpopulation that experienced the collapse can be rebuilt by the limited connections it has with the remaining subpopulations. In the event that bridges between subpopulations are fragmented, the chance of extirpation is great, such has happened with the construction of dams across the California Central Valley (Schick and Lindley 2007).

*Size at age.* Size at age is an easily measured indicator of the growing conditions of populations that may be related to population growth rate. Also, management is designed to use average size at age to set size limits in the fishery. Therefore, variations in size at age can lead to variations in the age structure of the catch year-to-year, which could translate to changes in the age structure of the population at large.

## Green Sturgeon

**Population size**—Compared to groundfish and salmon, green sturgeon have been little studied until quite recently and indicators are in the early stages of development. In light of the kinds of data that have been and are now beginning to be collected, just a few indicators relevant to green sturgeon will be possible to estimate. These include: 1) abundance of mature individuals in spawning rivers, 2) the catch of juvenile sturgeon in fish traps at large water diversions, and 3) the distribution in time and space of adult and subadult green sturgeon in rivers, estuaries, and the coastal ocean.

*Abundance of mature individuals.* Abundance is being estimated systematically for the first time in 2010, using sonar and underwater video to count green sturgeon in their summer holding pools on the Sacramento, Klamath, and Rogue rivers. Over time, these surveys can be repeated to generate estimates of population growth rate.

*Catch of juveniles.* Catch of juvenile green sturgeon in fish traps at large water diversions is available for the past several decades, and will likely be available for some time in the future until a planned major reorganization of water infrastructure in California's Central Valley radically alters the hydrology and operation of the pumping plants (Scheiff et al. 2001, LHC 2010). Catches at these pumping plants may be an index of recruitment to the population, although the factors affecting the sampling performance of these pumps are unknown.

**Population condition**—Two indicators of population condition will be evaluated: 1) age structure and 2) spatial structure of subpopulations.

*Age structure.* Green sturgeon population age structure will be evaluated as an indicator of population condition in 2011.

*Spatial structure of subpopulations.* Tagging studies of green sturgeon conducted by the SWFSC and NWFSC have collected a large amount of data on habitat associations and movement of green sturgeon within and among the coastal Pacific Ocean, spawning rivers, and estuaries of nonnatal rivers. These data are being used to create dynamic models of green sturgeon distribution. A spawning river model for the Sacramento River has been completed (Mora et al. 2009) and a marine distribution model is in development.

## Top Indicators

### Salmon

**Population size**—*Spawning escapement.* Spawning escapement is the metric used to determine the allowable catch of salmon at sea and in-river. Therefore, these estimates are subject to extensive review (PFMC 2010c). In addition, the data have a record of more than 30 years. Variability in spawning escapement values represents changes in fisheries as well and changes in production and natural mortality. For Central Valley and Klamath River Chinook salmon populations, estimates of fishery catches can be added to escapement estimates to achieve estimates of total abundance (e.g., Sacramento Index) which is ultimately a measure of production. Specifically, total abundance is estimated a year in advance of the fish returning to spawn. The difference between total abundance and minimum spawning escapement thresholds is considered available to catch. In 2008 and 2009, these estimates indicated there were not enough fish available to open the fishery; therefore, fishing was closed for California coastal and inland waters.

*Population growth rate.* Not directly used in fishery management, population growth rate can be used to inform managers regarding population trends. The summed value of escapement and total catch offers reliable and peer-reviewed estimates of abundance between years (PFMC 2010c). Simply, growth rate can be estimated as the change in these values over time. Growth rate estimates have become critical recently when questions of resilience and population recovery are paramount. Furthermore, population growth rate estimates are an important component of status reviews conducted under the ESA (Good et al. 2005) and are a major component of viability criteria for Central Valley winter and spring Chinook (Lindley et al. 2007).

*Hatchery contribution.* Not directly used in fishery management, hatchery contribution is a component of viability criteria for Central Valley winter and spring Chinook salmon (Lindley et al. 2007). Recent declines in the abundance of fall-run Chinook stocks have required a reevaluation of how a more diverse wild and hatchery population structure could have improved resiliency to environmental perturbations (Lindley et al. 2009b). The estimates of hatchery contribution used here are considered to be underestimates, as they do not account for straying of hatchery fish from the hatcheries. Hatchery release locations are often great distances from the hatcheries themselves (e.g., directly into the estuary); therefore, natal homing of the later spawning salmon is compromised. Such concerns are confirmed by Barnett-Johnson (2007) wherein otolith chemistry and microstructure were used to determine that the hatchery contribution to the California coastal fishery may be as great as approximately 90%. Unfortunately, the time series of otolith data sets is too short to yield useful indicators in an IEA assessment. California has embarked on a constant fractional marking program that will allow robust estimation of hatchery contribution rates to fisheries and natural escapement areas, with such data to become available in the near future.

**Population condition**—*Age structure.* Age structure is considered in the management of Klamath River Chinook salmon populations (Farr and Kern 2005). Appropriate tagging of hatchery fish enables cohort reconstructions. The age structure represents the amount of mixing between cohorts and a wide age distribution is preferred so the population can remain viable if recruitment of any given cohort is compromised (e.g., 2004 and 2005 broodyears). Therefore, a diverse age structure is appreciated by managers as an indication of the population's resiliency (Farr and Kern 2005). Changes in age structure indicate variability across cohorts that could relate to variability in production, fisheries, and natural mortality.

Unfortunately, age structure cannot be determined for Central Valley stocks, as standardized proportional tagging and in-river surveys are only now being implemented.

The age structure of coho salmon is less of a concern, as the vast majority of cohorts practice the same life history such that the age structure of the population remains relatively stable. However, trends in early maturation of males (jack rates) are available. Some degree of early maturation is important to maintain mixing between cohorts. Females typically represent a very small proportion of the early maturing fish.

*Spatial structure.* Spatial structure of subpopulations is considered largely in management of the freshwater systems used by salmon. For instance, rebuilding the spatial structure of Central Valley and Klamath River salmon is a critical aspect of habitat rehabilitation and dam removal considerations. Improving salmon metapopulation dynamics and genetic diversity will increase the resiliency of the fish to environmental perturbations in freshwater and ocean arenas (Schick and Lindley 2007, Lindley et al. 2009b).

*Size at age.* Management is designed to use average size at age to set size limits in the fishery. Therefore, variations in size at age can lead to variations in the age structure of the catch year-to-year, which could translate to changes in the age structure of the population at large.

Size at age indicates variability in the growth of salmon from a cohort and can indicate conditions experienced at sea (Wells et al. 2006, Wells et al. 2007, Wells et al. 2008). There are large, coded-wire tag data sets that can be used to estimate the size at age of fish captured at sea and on the spawning grounds. These data have been successfully used in the past by Wells et al. (2006) to demonstrate how large-scale factors (e.g., ENSO and PDO) affect size at age. These tagging data sets go back more than 30 years.

### Green sturgeon

Top indicators of green sturgeon will be evaluated and selected in 2011.

## Suite of Indicators for the California Current

Based on the selection, evaluation, and ranking described in the previous subsections, we provide a framework for identifying a suite of indicators to evaluate the current status of the CCLME relative to historical conditions. This IEA report evaluates indicators for a subset of the seven EBM components. Due to the ultimate number of indicators that will be identified, evaluated, and selected for each of seven EBM components, we decided to limit each key attribute of each component to between two and four indicators.

## Complementarity of Indicators

For the EBM components groundfish and ecosystem health, we used complementarity to narrow the list of top-ranked indicators for each key attribute. We compared highly ranked indicators across key attributes and EBM components and selected indicators that complemented each other in either the taxa or processes they represented. For example, many fish functional groups ranked highly as indicators of ecosystem health, but because many of these groups were also highly ranked indicators of groundfish, we did not select them for ecosystem health. Below we describe the full suite of indicators chosen for each key attribute of each EBM component and discuss the final selection process.

### Groundfish

**Population size**—From the eight indicators in the top quartile for population size, we propose to use these three as indicators for population size of groundfish in the CCLME:

- Abundance of groundfish (numbers) in large-scale bottom trawl surveys
- Population growth rate
- Number of species below management thresholds

We chose to use numerical abundance of groundfish in bottom trawl surveys because whole-population stock assessments (another indicator in the top quartile) already exist and supply estimates of population size in spawning stock biomass. Abundance in numbers provides another useful indicator of trends in the population. Numbers of individuals in a population are also a metric of conservation importance and easy to understand in the policy arena. We did not choose hake acoustic survey biomass because it is limited to monitoring hake, while hake numbers can be monitored for trends in the bottom trawl survey. We chose number of species below management thresholds because it is an easy measure of species or stocks that have typically been doing poorly in the past, but we recognize that documents (Miller et al. 2009) already exist that communicate this information. Thus this indicator may not be necessary in a final status report of the CCLME.

**Population condition**—From the five indicators in the top quartile for population condition, we propose to use these two as indicators for population condition of groundfish in the CCLME:

- Age structure of populations
- Spatial structure of populations

These indicators were two of the top three indicators evaluated. We did not choose rebuilding timeline as one of the final indicators because it is only available for species which have been formally considered overfished; thus it is only useful for a small number of species that are already in poor shape. Using age structure accounts for many of the ecological processes that would affect age at maturity, so we felt age at maturity could be eliminated from the final suite. However, due to time constraints for this report, we have been unable to analyze age structure data for the groundfish community. Therefore, we have substituted size structure of populations as a proxy for age structure. This indicator was not in the top quartile for population condition, but it was the top-ranked indicator in the second quartile and missed the top quartile by 0.03

points.  Because we are including size structure of populations in this iteration of the IEA, we decided it would be redundant to include mean length of species.

*Size structure of populations.*  The mean size of all species caught in either fishery-independent surveys, fishery-dependent surveys, or landings is thought to be a useful and simple indicator to evaluate the overall effects of fishing (e.g., changes in rates of mortality) on an ecosystem (Fulton et al. 2005, Link 2005, Coll et al. 2009).  Size-based metrics respond to fishing impacts because body size determines the vulnerability of individuals, populations, and communities (Jennings and Dulvy 2005).  Others contend, however, that there are very few examples where length-based analysis leads to useful management advice, in part because of the need for age and gear selectivity information, and because size related changes in distribution will influence data (Hilborn and Walters 1992).  Size-based metrics are thought to better support medium-term rather than year-to-year management evaluation, because they are unlikely to be appropriate for detecting responses to management action on time scales less than 5 years, and the response to management action often cannot be quantitatively interpreted for contributing causal factors without extensive additional research (Jennings and Dulvy 2005).

Fish population size structure has been linked to scientifically defined reference points or progress targets.  Some have based these on a decline in mean size of greater than 30% (warning or precautionary threshold) or greater than 50% (limiting reference point), the latter of which was chosen because it corresponds to an observed doubling in the time series of length after fishing has decreased (Link 2005).  Others suggest that practical issues currently preclude the development and adoption of firm reference points for size-based indicators, although an appropriate target would be a reference direction that is consistent with a decline in the overall human impacts of fishing on the community, and thereby on the ecosystem (Jennings and Dulvy 2005).

The principal attraction of size-based metrics is the widespread availability of species size and abundance data collected during ongoing monitoring programs (Jennings and Dulvy 2005).  In the North Pacific, trawl survey data have been collected since 1998 under the annual/triennial groundfish surveys (Keller et al. 2008), where up to 100 length measurements, sex determinations, and individual weights, and up to 25 age structures continue to be collected per haul for key species, and more recently for all groundfish species of management concern. These surveys encompass a broad range of depths (55 to 1,280 m) and a vast geographic range from Cape Flattery, Washington, (lat 48°10′N) to the U.S.-Mexico border (lat 32°30′N).  There are well recognized gear-selectivity issues associated with size data (Hilborn and Walters 1992) and ideally indicators should be calculated for size classes that are well selected by the gear. Fish population size structure has been used as an indicator in a variety of other ecosystems, including the Celtic Sea (Blanchard et al. 2005), northeastern U.S. continental shelf (Link and Brodziak 2002), and eastern Bering Sea (AFSC 2009).

### Salmon

**Population size**—We identified, evaluated, and propose these three indicators for salmon in the CCLME:

- Spawning escapement

- Population growth rate
- Hatchery contribution

These indicators are supported by all of our primary literature resources (e.g., Lindley et al. 2009b, PFMC 2010a). Each indicator was chosen based on length of time series, quality of data, managerial usefulness, and their representation of important life history characteristics and population viability.

**Population condition**—We identified, evaluated, and propose these three indicators for salmon in the CCLME:

- Age structure
- Spatial stock structure
- Size at age

These indicators are supported as indicators of population condition by all of our primary literature resources (e.g., Lindley et al. 2007, Lindley et al. 2009b, PFMC 2010a). Each indicator was chosen based on length of times series, quality of data, managerial usefulness, and their representation of important life history characteristics and population viability.

### Green sturgeon

**Population size**—We identified, evaluated, and propose these two indicators for green sturgeon in the CCLME:

- Spawning escapement
- Juvenile abundance

These indicators are supported by primary literature resources (e.g., Adams et al. 2007).

**Population condition**—We identified, evaluated, and propose these two indicators for green sturgeon in the CCLME:

- Age structure
- Spatial structure of stocks

These indicators are supported as indicators of population size primary literature resources (e.g., Adams et al. 2007).

### Ecosystem health

**Community composition**—From the 18 indicators in the top quartile for community composition, we propose to use these four as indicators in the CCLME:

- Zooplankton species biomass anomalies
- Taxonomic distinctness (average and variation)
- Top predator biomass

- Seabird annual reproductive output

We selected two indicators (zooplankton species biomass anomalies and taxonomic distinctness) from the top quartile of the community composition attribute to represent ecosystem health in the CCLME, as well as two indicators (seabird annual reproductive performance and top predator biomass) that did not initially score in the top quartile (yet were in the top 30th percentile), but complemented the suite.

Two zooplankton indicators scored highest during the evaluation process: zooplankton species biomass anomalies and zooplankton abundance/biomass. We selected zooplankton species biomass anomaly over zooplankton biomass because of the relative benefits associated with having sentinel taxa guide indicator performance. Of the four diversity indices in the top quartile (adult sablefish biomass, Hurlbert's delta, IUCN number of threatened species, and taxonomic distinctness), we selected taxonomic distinctness for two reasons: 1) adult sablefish biomass and IUCN number of threatened species are correlates of diversity, but not actual measures of diversity, and 2) taxonomic distinctness has minimal data requirements that allow the integration of data sets, use of historical data, and data sets of varying quality.

We decided to exclude many of the groundfish-based indicators from the community composition attribute due to their inherent overlap with the groundfish component. We also passed over the salmon smolt-adult survival rate indicator for a similar reason, related to the salmon goal. Many of the groundfish indicators (groundfish status and trends, flatfish biomass, roundfish biomass, demersal fish biomass, rockfish biomass, proportion of noncommercial species, juvenile rockfish, and hake abundance) scored particularly well in part because of their strength regarding data considerations.

To supplement the suite of indicators that best characterized ecosystem structure, we added two indicators that focused on upper trophic levels of the CCLME: seabird annual reproductive performance and top predator biomass. Each indicator scored just below the top quartile (score = 8.1, top quartile = 8.25); thus there is good support in the literature for these indicators. In addition, our initial inventory of seabird colony monitoring programs underestimated the availability of long-term time series spanning the CCLME, which led us to reevaluate the potential utility of this indicator and its inclusion in the final suite. We describe the full evaluation of each indicator below.

*Top predator biomass.* The role of top predators in marine ecosystems has been the subject of numerous high-profile studies (e.g., Pauly et al. 1998, Myers and Worm 2003), while top predators are also of great societal interest (e.g., great white sharks [*Carcharodon carcharias*] and killer whales [*Orcinus orca*]). Typically, removing top predators from an ecosystem results in a trophic cascade (Strong 1992) in which populations of prey species increase in numbers because they are released from predatory control (e.g., Estes and Duggins 1995, Estes et al. 1998, Ward and Myers 2005). In many instances, this process cascades to the lowest trophic levels: phytoplankton (Frank et al. 2005, Casini et al. 2008). When top predators are able to rebuild (due to regulatory or management actions), prey species are once again controlled and the composition of the community reverts back to the initial state (e.g., otters, urchins, and kelp, Estes and Duggins 1995). Reference points for this indicator are easily defined and Link (2005) describes potential reference levels.

During the evaluation of this indicator, we defined top predator as any species with a trophic level equal to or greater than 4.0. Thus top predators span many taxa and may be monitored for estimates of biomass using various methods. Data for groundfish species are available from 1977 to 2010 in the WCGTS (see Groundfish, Population size, *Stock assessment biomass* subsection above). Time series data for marine mammals are available for a limited number of species from multiple sources which generally report numbers of individuals (Carretta et al. 2010). Fishery-independent time series data for benthic and pelagic sharks generally do not exist (except for spiny dogfish [*Squalus acanthias*]) and the fishery-dependent data are generally inadequate for formal stock assessments. Commercial landings data are available for a few species in the CCLME and might provide some insight into coarse trends over time with all the caveats of fishery-dependent data implied (see Hilborn and Walters 1992). The SWFSC performs an annual juvenile longline survey that typically catches shortfin mako (*Isurus oxyrinchus*) and blue sharks (*Prionace glauca*) with the occasional thresher shark (*Alopias vulpinus*).

The abundance and trends of top predators are easy to understand and are usually of interest to the public and policy makers. Due to the potential for trophic cascades with declines in top predator biomass (e.g. Estes and Duggins 1995, Estes et al. 1998, Ward and Myers 2005), this could be a leading indicator for changes in overall community composition of the CCLME.

*Seabird annual reproductive output.* Seabirds have frequently been identified as good indicators of the health and status of marine ecosystems because they are sensitive to variations in food supply and relatively easy to observe (Furness and Camphuysen 1997, Frederiksen et al. 2007, Piatt et al. 2007). Seabird reproductive performance tends to be a useful indicator of ecosystem conditions because it integrates useful information throughout the initiation of egg-laying through chick-rearing each year. As a result, seabird breeding failures often provide an early indicator of declines to marine forage fish populations, and related demographic parameters, such as seabird production and population trends, have been correlated with large scale indices of ocean climate, such as temperature or the Southern Oscillation Index (Sydeman et al. 2001, Montevecchi 2007, Piatt et al. 2007).

Costs for conducting long-term seabird colony monitoring programs are high. As a result, there are only a handful of seabird colony sites along the Pacific coast with long-term monitoring programs in place. Fortunately, the spatial scale of existing colony monitoring projects ranges from British Columbia to Southern California (including the Washington and Oregon coasts) and the monitoring often focuses on similar species. The availability of this information is highly variable, ranging from highly accessible, Web-based tables (e.g., Point Reyes Bird Observatory [PRBO] and Columbia River estuary) to currently inaccessible. Some recent projects have used these data sets as indicators of ecosystem condition (Sydeman and Thompson 2010), but the reliability of any individual parameter (e.g., breeding success of a particular species at one site) may also be affected by other drivers (e.g., local predation) (Frederiksen et al. 2007). However, a multivariate approach (Frederiksen et al. 2007) may be used to integrate data sets from a variety of species (both piscivorous and zooplanktivorous) from all of the long-term seabird colony monitoring programs along the Pacific coast. This combined index would use the breeding performance of a variety of seabird species along the Pacific coast as a general indicator of the health of the CCLME, in terms of providing sufficient food for breeding seabirds to raise their young. It is expected that the availability of data sets will improve as this index is developed and disseminated.

**Energetics and material flows**—From the three indicators in the top quartile for energetics and material flows, we propose to use these two in the CCLME:

- Chl a
- Inorganic nutrient levels (phosphate, nitrate, silicate)

Both indicators not only scored well with regard to our evaluation considerations, but also can be used in the near term with readily available data to evaluate drivers that affect fundamental processes. Number of cycles, a third indicator that describes carbon cycling, also scored in the top quartile and holds promise for inclusion in the near future as existing mass-balance models (Brand et al. 2007, Horne et al. 2010) are further developed, tested, and validated.

## Future Criteria

In future iterations of the California Current IEA, we propose to include other formal criteria during the ranking of potential indicators to quantify the quality of science supporting each indicator during the evaluation process. Although not completely developed, these criteria will categorize the literature cited as: 1) peer-reviewed literature, 2) government document, or 3) gray literature. These categories of literature will be given a rating value between 0 and 1. In addition, peer-reviewed literature will receive an additional rating based on the impact factor of the publishing journal. These values will be summed, averaged, multiplied by the weighting of each criterion, and summed across each indicator to produce a score for the quality of science supporting each indicator.

# Status of the California Current Ecosystem: Major EBM Components

## Introduction

Our main findings are:

- The variability of seasonal upwelling onset (for example late upwelling in 2005) led to the collapse of Sacramento River fall-run Chinook salmon, Oregon coho, and Cassin's auklets (*Ptychoramphus aleuticus*) in the Gulf of the Farallones. Cumulative interactions between climate change and fishing pressure have resulted in severe CCLME salmon population declines, potentially resulting in severe societal costs in recent years.
- Groundfish assemblages on the west coast have shown changes in abundance (number per $km^2$) and assemblage structure from 2005 to 2009. Seventeen species were chosen to represent broad functional groups. More than half (10 of 17) of the groundfish species examined declined in abundance, while 5 showed no trend and only 2 increased. Shannon Diversity and top predator biomass of groundfish assemblages have also declined over this period.

Below we present time series of indicators associated with each of our EBM components. For primary producers, we present annual winter and summer time series while mid and upper trophic species are examined on an annual basis. For a summary of data sets included in this report, see Appendix C. Analyses of groundfish and ecosystem health were repeated for each of four NMSs north of Point Conception and these results are presented in Appendix D.

## EBM Component: Central California Salmon

Pacific salmon are among the most culturally important and economically valuable commercially fished species in the CCLME. Significant fluctuations in salmon abundances and marine survival occurred throughout the CCLME during 2003–2008, leading to a number of dramatic management actions. Chinook and coho salmon that emigrate from rivers from California to Oregon reside in coastal waters for a period of time before migrating up the coast. It is in these coastal waters that the greatest mortality occurs. A poor environment can lead to reduced early growth and ultimately poor survival and recruitment to the spawning stock (Beamish and Mahnken 2001, Beamish et al. 2004, Wells et al. 2008).

Coho salmon hatchery returns (OPI) were below average in 2005 and 2006 (Figure 4), pointing to poor ocean conditions in 2004 and 2005, the years of ocean entry. These years, though demonstrating reduced returns, were not as poor as during the mid-1990s (Peterson and Schwing 2003). Juvenile coho salmon growth off the west coast of Vancouver Island in 2005 was the lowest on record since 1998 (DFO 2006).

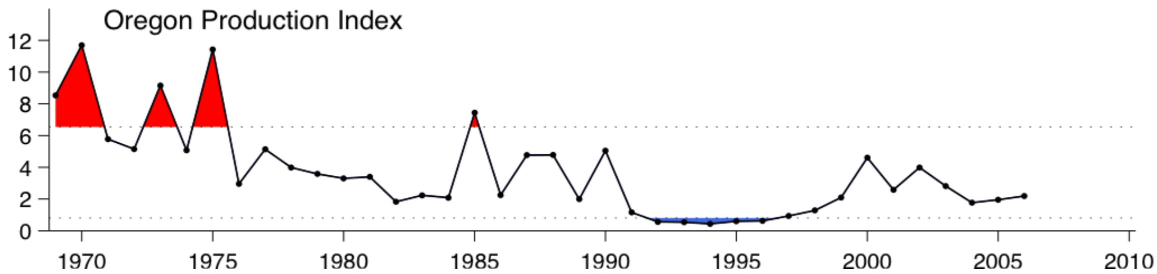



Figure 4. Coho salmon percent, smolt-adult return, 1970–2006. Dashed lines reflect 1 SD above and below the long-term mean.

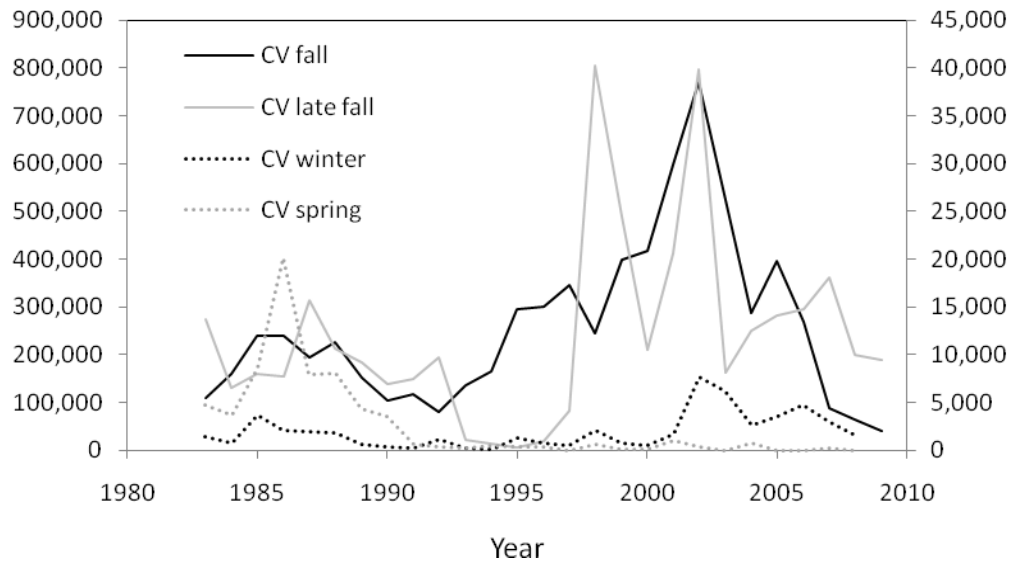
## Key Attribute: Population Size

### Indicator: Spawning escapement

There are four temporally segregated Chinook salmon runs in the Central Valley. Such diversity in life history buffers Chinook salmon against environmental variability. However anthropogenic impacts have resulted in an unnaturally large contribution of a fall run and three less productive runs (Lindley et al. 2009b). Estimates of Central Valley spawning escapement are used to set fishery limits to ensure that spawner numbers remain high enough for populations to remain viable.

Chinook salmon fall escapement had an increasing trend, though the values have plummeted since 2002 (Figure 5). There was also a near complete reproductive failure for the 2004 and 2005 brood years (Figure 5). As a result, there were exceptionally low adult returns to fall-run California Central Valley in 2007–2008. The fall-run Chinook salmon collapse may have been caused by climatic conditions that produced little food in the ocean (e.g., delayed upwelling in the ocean-entry year 2005) combined with a reliance on a hatchery-reared homogeneous salmon population instead of a varied wild salmon population (Lindley et al. 2009a). The Central Valley late fall-run population also experienced peak escapement in the early 2000s, but has not demonstrated the same decline experienced by the fall-run population. The Central Valley winter-run population actually had the highest escapement values in the most recent years. Finally, the Central Valley spring-run population experienced its greatest returns in the mid-1980s and has since remained relatively flat.

This asynchrony in population escapement trends indicates that the populations are likely exposed to different environmental or management forces. In fact, two of these populations are threatened or endangered (spring and winter run) and, therefore, attempts are made to avoid catches in the fishery. However, it is also important to recognize that variability in the timing of spawning, emigration, and distribution could have an effect on the ultimate production of the stocks as well, which could result in the asynchrony shown here. Unlike Central Valley populations, the Klamath River fall-run population appears to have variable spawning escapement over the last 30 years with no particular trend apparent (Figure 5). However, there does appear to be an episode to the Klamath escapement values likely related to large-scale oceanographic conditions (e.g., ENSO).



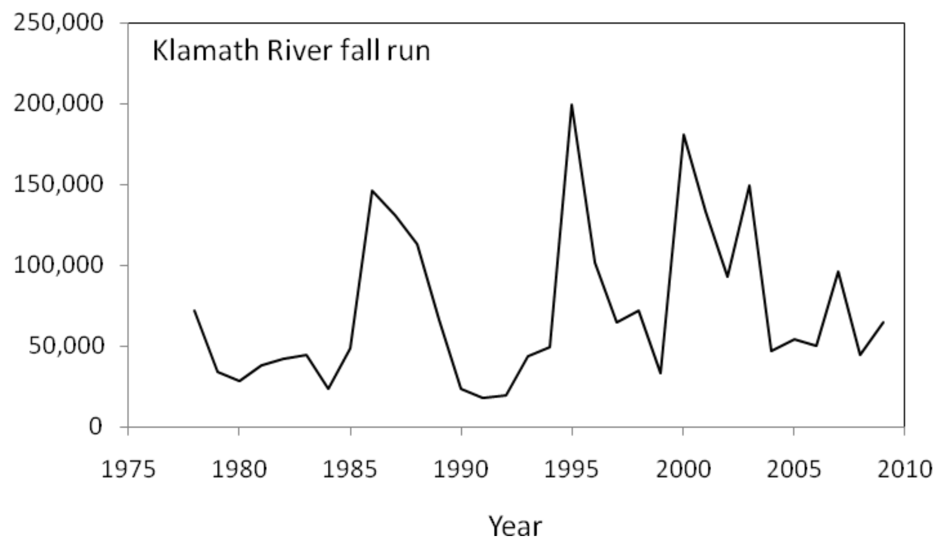




Figure 5. Spawning escapement for Central Valley (CV) populations and Klamath River fall-run populations of Chinook salmon. Data represent total returns to spawning grounds (hatchery plus natural). For the CV, fall run Chinook are plotted on the left primary vertical axis and the other stocks are plotted on the right vertical axis.

A primary goal will be to determine the natural and managerial forces driving variability within and between Chinook salmon populations from the Klamath and Sacramento rivers. Such information will help improve the utility of a spawning escapement index toward evaluating the health of both populations.

**Indicator: Population growth rate**

The Sacramento River fall-run Chinook salmon population has shown an average 15% decline in growth rate over the last 10 years with an exceptional 48% decline in the last 5 years (Figure 6), which could make recovery slow. Not shown in Figure 6, Sacramento winter-run and

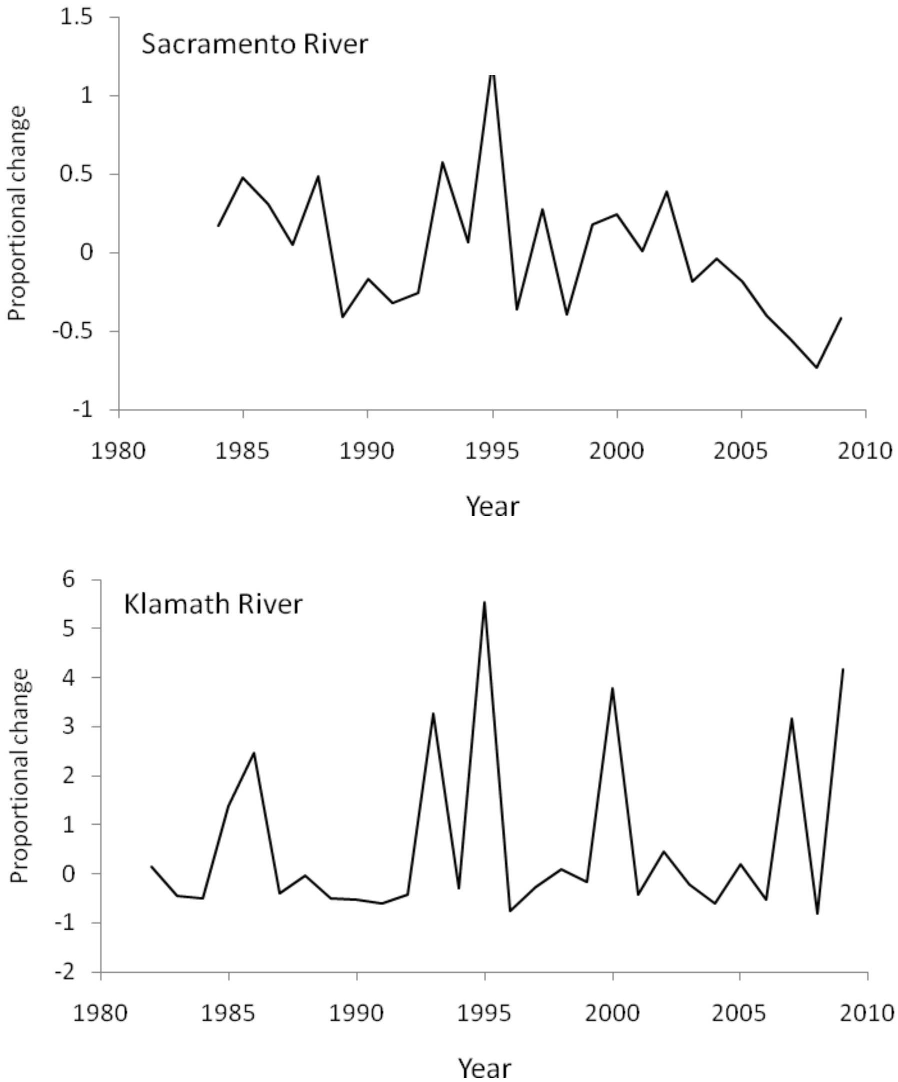



Figure 6. Population growth rates for Sacramento River fall-run Chinook salmon (the largest component of the Central Valley Chinook fall runs) and Klamath River fall-run Chinook salmon. The growth rate for the Sacramento River fall run was calculated as the proportional change in the Sacramento Index between successive years. The Sacramento Index represents the ocean abundance of age-3 fish calculated by summing later harvest and escapement values. The growth rate of the Klamath River fall run was calculated based on the ocean abundance of age-3 Klamath River fall-run fish.

spring-run Chinook salmon have also experienced precipitous declines in growth rates over the last 5 years (38% and 61%, respectively). Unlike the Sacramento River Chinook salmon, Klamath River fall-run Chinook salmon did not experience any particularly dramatic trend in growth rates over the last 5 to 10 years (Figure 6). Instead, growth rate was relatively stable but punctuated by extremely productive years. It is likely these bumps in growth rate are corrections following poor productivity years, such as during the 1983 and 1998 ENSO events. These differences between Sacramento River and Klamath River populations may be caused by a combination of managerial or environmental differences experienced by the fish.

As with the future direction for improving the spawning escapement index, a future goal will be to determine the forces driving variability within and between Chinook salmon populations from the Klamath and Sacramento rivers. Such information will help improve the utility of a growth rate index toward evaluating the health of the both populations.

### Indicator: Hatchery contribution

Population viability is dependent in part on maintaining life history diversity in the population. Hatchery production is a relatively homogeneous life history type relative to naturally produced populations. If natural production is reduced, the population can be at risk during periods of increased environmental variability. In recent years, the contribution of hatchery fish to the population has increased substantially. That the number of hatchery fish produced has remained relatively stable indicates that the remaining natural spawners have diminished. Therefore the natural population is at increased risk (Lindley et al. 2007). The proportion of fall-run Chinook salmon spawning in hatcheries, a corollary to the actual contribution of hatchery fish to the population, has increased dramatically in the Central Valley over the last 5 years (Figure 7). Such an increase is indicative of a diminished production of natural populations and could indicate constriction of life history diversity. Fall-run Chinook salmon from the Klamath River did not experience any particular trend over the years and recently have not demonstrated an increase in the hatchery contribution (Figure 7).

The methodology used here to estimate hatchery contribution is flawed. Specifically, it simply calculates the proportion of fish that spawn at hatcheries with no consideration to straying rates. Therefore, it likely underestimates the contribution of hatchery fish. Improvements to the index could come from using genetic sampling, otolith chemistry, and systematic proportional tagging of hatchery fish.

## Key Attribute: Population Condition

### Indicator: Age structure

A diverse age structure is important to improve the viability of a population. Larger, older Chinook salmon produce more and larger eggs. Therefore, they produce a brood which may contribute proportionally more to the later spawning population than broods from younger, smaller fish. However, the diversity of ages, including younger fish, is important to accommodate variability in the environment. If mortality on any given cohort is great, there is benefit to having younger spawners. This bet hedging is a critical aspect of Chinook salmon populations that allows them to naturally mitigate year-to-year environmental variability.

While Central Valley Chinook salmon stocks lack age-specific data to evaluate age structure of the population, the Klamath River fall run has sufficient data. Examination of the proportional contribution of each age to the spawning stock demonstrates that the largest fraction of the spawning population is age-3 and age-4 fish (Figure 8). In addition, there has been a declining fraction of age-2 spawning over the years. However, little should be made of this negative trend, as it seems to be driven in large part by a few extraordinary years. Overall, no recent trends are apparent in the age structure of Klamath River Chinook salmon and it actually appears relatively stable across the last 30 years. This evaluation of Klamath River Chinook

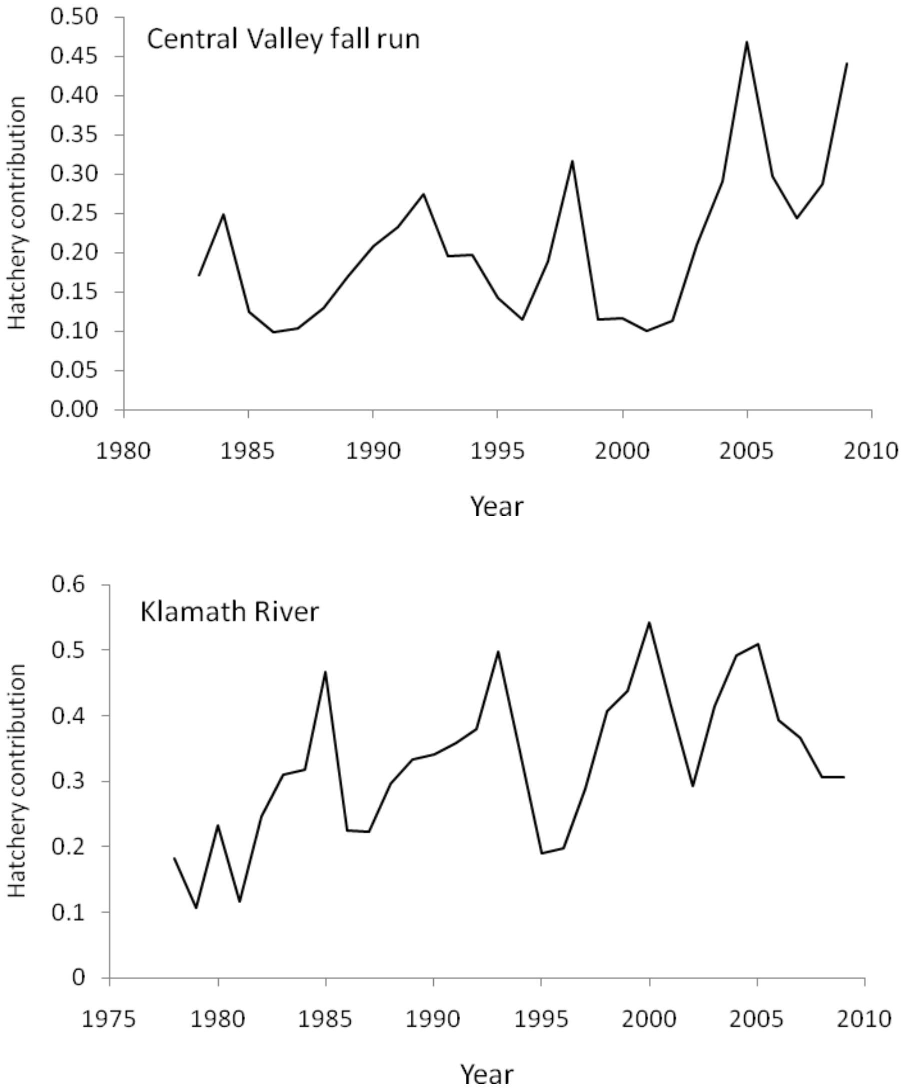
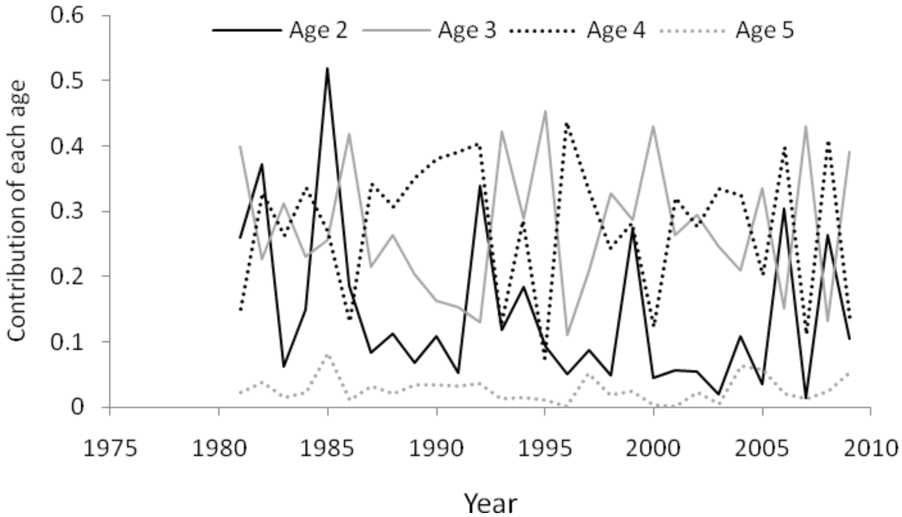



Figure 7. Proportions of Chinook salmon from the Central Valley fall-run and Klamath River fall-run populations that spawned in hatcheries. This is only an index of hatchery contribution, as estimates of hatchery fish spawning in natural areas are not available.

salmon should not be extrapolated to Central Valley Chinook salmon. As indicated in nearly every example shown here, the Central Valley Chinook populations seem not to correlate to the Klamath River population with any regularity. It is likely that fish from the Central Valley did demonstrate a change in age structure in recent years. Specifically, 2005–2008 represented consistently poor conditions; therefore, the age structure of a 3-year cohort was less likely to mitigate this lower frequency environmental event. With the recent implementation of standardized proportional tagging of hatchery fish, better estimates of age structure variability will become available for Central Valley Chinook salmon.



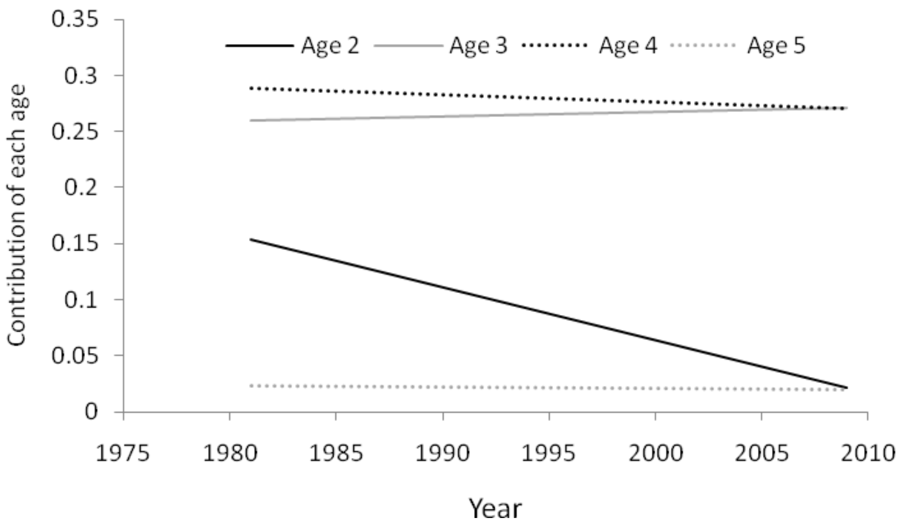




Figure 8. Time series of run size estimates for each age of returning Klamath River fall-run Chinook salmon in given years are in the upper plot. Specifically, this figure represents the age structure of the Klamath River fall-run population during any given year. As indicated by the lower plot, there was only a trend in the age-2 group; namely, the proportion of fish returning to spawn at age 2 has declined. However, examination of the time series (upper plot) shows that the trend is likely derived from a few years (e.g., 1982 and 1985) that represented enormous numbers of age-2 fish returns.

### Indicator: Spatial stock structure

A more comprehensive evaluation of the spatial structure of central California salmon stocks will be completed in 2011.

### Indicator: Size at age

A more comprehensive evaluation of size at age for central California salmon will be completed in 2011.

# EBM Component: Sturgeon

Generally, little data are available on the abundance or condition of green sturgeon populations, yet the southern stock is considered likely to become an endangered species in the foreseeable future. This concern is based on the drastic reduction of spawning habitat above Shasta Dam on the Sacramento River and Oroville Dam on the Feather River, California (Adams et al. 2007). There has also been a large decline in the number of juveniles entrained in water diversion projects, indicating a reduction in the production of the populations. The northern population is not currently considered to be in danger of extinction (Adams et al. 2007).

## Key Attribute: Population Size

### Indicator: Spawning escapement

Spawning abundance was estimated systematically for the first time in 2010, using sonar and underwater video to count green sturgeon in their summer holding pools on the Sacramento, Klamath, and Rogue rivers. Over time, these surveys can be repeated to generate estimates of population growth rate.

### Indicator: Juvenile abundance

Catch of juvenile green sturgeon in fish traps at large water diversions is available for the past several decades and will likely be available for some time in the future, until a planned major reorganization of water infrastructure in California's Central Valley radically alters the hydrology and operation of pumping plants. The number of Sacramento River sturgeon juveniles captured at water diversions has dropped, indicating reduced production of the population. Catches at these pumping plants may be an index of recruitment to the population, although the factors affecting the sampling performance of these pumps are unknown.

## Key Attribute: Population Condition

### Indicator: Age structure

This will be completed in a future IEA.

### Indicator: Spatial structure

Tagging studies of green sturgeon conducted by SWFSC and NWFSC have collected a large amount of data on the habitat associations and movement of green sturgeon within and among the coastal Pacific Ocean, spawning rivers, and estuaries of nonnatal rivers. These data are being used to create dynamic models of green sturgeon distribution. A spawning river model for the Sacramento River has been completed (Mora et al. 2009) and a marine distribution model is in development.

# EBM Component: Groundfishes

Because of their ecological importance and high value as recreational and commercial fisheries, groundfish are an important component of the California Current ecosystem. Time series of groundfish catch expressed as number of fish $km^{-2}$ provide indicators of changes in abundance. Time series of size distribution provide indicators of changes in population structure (e.g., many young fish or more older fish). Changes in spatial distribution can indicate responses to climate or localized fishing effects.

The combined data from the AFSC triennial and NWFSC annual trawl surveys (see Table 7 through Table 10 for trawl survey characteristics, net details, triennial survey effort, and annual survey effort, respectively) contained more than 349 taxa identifiable to species—far too many to present here. For each of the groundfish indicators below, a subset of 17 species was chosen for analysis and presentation (Table 11). These species represent the most common species from each of the 17 functional groups used in the Horne et al. (2010) ecosystem model of the California Current. Thus the 17 groundfish that we cover are representative of groups of fish from different habitats and trophic guilds. These 17 species comprise about 80% of the total number of species captured.

## Key Attribute: Population Size

Groundfish number was selected as the sole indicator for groundfish population size. Time series of groundfish abundance follow a standard format with additional statistical information presented on each figure. The triennial and NWFSC data were not combined because of differences in survey design (see Appendix C).

Ten of 17 species showed declines during the 2005–2009 period that were greater than 1 SD of the NWFSC time series for said species (Figure 9 through Figure 12). These species include: Pacific hake, stripetail rockfish (*Sebastes saxicola*) (small shallow rockfishes), Dover

Table 7. Characteristics of the triennial and NWFSC groundfish trawl surveys. (Data courtesy of Melissa Haltuch, NWFSC.)

| | **Triennial survey** | **NWFSC survey** |
|---|---|---|
| Time extent | 1977–2004 | 1998–present |
| 1977 not used | Shelf added in 2003 | |
| Vessel | Alaska class commercial vessels, 65–147 m | West Coast groundfish commercial vessels, 65–93 m |
| Survey design | Line transect survey, random trawls on same lines | Stratified random survey |
| Survey timing | 1980–1992 later | Consistent |
| | 1995–2004 earlier | |
| Depth and range | Varies over time, 55–336 m, 55–500 m, lat 36.8°N, lat 34.5°N, excludes Point Conception | Consistent, 55–1,280 m since 2003, lat 32.5°N to lat 48.17°N, includes Point Conception |

Table 8. Comparison of net characteristics for the triennial and NWFSC groundfish trawl surveys. (Data courtesy of Melissa Haltuch, NWFSC.)

| **Triennial survey** | **NWFSC survey** |
|---|---|
| High opening Nor'Eastern trawl | 4 panel Aberdeen style trawl |
| 76.2 m net to doors | 62.5 m net to doors |
| Roller gear (37.4 m footrope) | Continuous disk footrope (32.5 m) |
| Bare wire bottom bridles | 20.3 cm disk partway into bridles |
| 1.8 m × 2.7 m V-door | 1.5′ × 2.1′ V-door |
| 12.7 cm mesh, 8.9 cm codend, 3.2 cm liner | 13.9 cm mesh, 12.7 cm codend, 3.8 cm liner |
| 30 minute tow | 15 minute tow |
| 3.0 knot towing speed | 2.2 knot towing speed |
| Little or no mud cloud between doors and net due to lack of disks in wings (little herding) | Mud cloud between doors and net due to disks in wings (enhanced herding) |
| Strong avoidance of rocky areas | Able to tow closer to rocky areas |

Table 9. Distribution of survey effort for the AFSC triennial survey among latitudes and years. (Data courtesy of Mark Wilkins, AFSC.)

| **Latitude** | **1980** | **1983** | **1986** | **1989** | **1992** | **1995** | **1998** | **2001** | **2004** |
|---|---|---|---|---|---|---|---|---|---|
| 34 | — | — | — | 14 | 13 | 12 | 12 | 12 | 13 |
| 35 | — | — | — | 22 | 11 | 15 | 16 | 16 | 12 |
| 36 | 6 | 6 | 2 | 12 | 10 | 11 | 11 | 12 | 9 |
| 37 | 27 | 26 | 27 | 58 | 53 | 32 | 33 | 32 | 26 |
| 38 | 25 | 23 | 26 | 31 | 29 | 33 | 32 | 32 | 20 |
| 39 | 13 | 13 | 14 | 18 | 16 | 17 | 18 | 17 | 16 |
| 40 | 12 | 12 | 10 | 14 | 14 | 15 | 16 | 16 | 14 |
| 41 | 16 | 18 | 15 | 23 | 23 | 23 | 23 | 23 | 20 |
| 42 | 10 | 33 | 8 | 22 | 20 | 20 | 21 | 22 | 17 |
| 43 | 77 | 82 | 38 | 25 | 28 | 27 | 30 | 29 | 27 |
| 44 | 66 | 79 | 46 | 45 | 46 | 41 | 44 | 43 | 36 |
| 45 | 21 | 27 | 34 | 67 | 66 | 38 | 39 | 39 | 33 |
| 46 | 82 | 86 | 54 | 46 | 47 | 32 | 31 | 33 | 26 |
| 47 | 35 | 48 | 105 | 37 | 32 | 28 | 29 | 27 | 29 |
| 48 | 50 | 90 | 127 | 74 | 73 | 55 | 66 | 51 | 17 |

sole (*Microstomus pacificus*), rex sole (*Glyptocephalus zachirus*) (small flatfishes), chilipepper (*Sebastes goodei*) (midwater rockfishes), spiny dogfish (small demersal sharks), shortbelly rockfish (*Sebastes jordani*), white croaker (*Genyonemus lineatus*) (miscellaeneous nearshore demersal fishes), canary rockfish, and longnose skate (*Raja rhina*) (skates and rays). Five species had stable population trends over the 5-year period: sablefish, redstripe rockfish (*Sebastes proriger*) (shallow large rockfishes), splitnose rockfish (*Sebastes diploproa*) (deep small rockfishes), darkblotched rockfish (*S. crameri*) (deep large rockfish), and yelloweye rockfish (*S. ruberrimus*). Only lingcod (*Ophiodon elongatus*) (representing large demersal predators) and arrowtooth flounder (*Atheresthes stomias*) (large flat fishes) increased.

Table 10. Distribution of trawl effort for the annual NWFSC survey. (Data courtesy of Beth Horness, NWFSC.)

| Latitude | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 |
|---|---|---|---|---|---|---|---|
| 34 | 30 | 28 | 41 | 24 | 33 | 31 | 41 |
| 35 | 12 | 12 | 11 | 9 | 17 | 12 | 18 |
| 36 | 7 | 8 | 14 | 9 | 10 | 13 | 6 |
| 37 | 18 | 21 | 27 | 22 | 20 | 28 | 36 |
| 38 | 18 | 25 | 29 | 25 | 25 | 26 | 25 |
| 39 | 11 | 13 | 19 | 16 | 5 | 17 | 8 |
| 40 | 13 | 5 | 14 | 9 | 14 | 4 | 8 |
| 41 | 20 | 9 | 19 | 8 | 14 | 12 | 20 |
| 42 | 28 | 15 | 21 | 21 | 16 | 20 | 16 |
| 43 | 10 | 17 | 30 | 36 | 31 | 17 | 25 |
| 44 | 18 | 32 | 46 | 39 | 39 | 47 | 39 |
| 45 | 18 | 22 | 26 | 39 | 44 | 31 | 34 |
| 46 | 15 | 24 | 27 | 23 | 32 | 24 | 27 |
| 47 | 33 | 21 | 19 | 20 | 29 | 31 | 28 |
| 48 | 38 | 23 | 21 | 16 | 20 | 15 | 18 |

Table 11. Groundfish functional groups and representative species (from Horne et al. 2010).

| Functional group | Representative species | Scientific name |
|---|---|---|
| Hake | Pacific hake | *Merluccius productus* |
| Shallow small rockfish | Stripetail rockfish | *Sebastes saxicola* |
| Sablefish | Sablefish | *Anoplopoma fimbria* |
| Dover sole | Dover sole | *Microstomus pacificus* |
| Shallow large rockfish | Redstripe rockfish | *Sebastes proriger* |
| Deep small rockfish | Splitnose rockfish | *Sebastes diploproa* |
| Small flatfish | Rex sole | *Glyptocephalus zachirus* |
| Midwater rockfish | Chilipepper rockfish | *Sebastes goodei* |
| Small demersal sharks | Spiny dogfish | *Squalus acanthias* |
| Shortbelly rockfish | Shortbelly rockfish | *Sebastes jordani* |
| Large flatfish | Arrowtooth flounder | *Atheresthes stomias* |
| Deep large rockfish | Darkblotched rockfish | *Sebastes crameri* |
| Misc. nearshore demersal fish | White croaker | *Genyonemus lineatus* |
| Canary rockfish | Canary rockfish | *Sebastes pinniger* |
| Large demersal predators | Lingcod | *Ophiodon elongatus* |
| Skates and rays | Longnose skate | *Raja rhina* |
| Yelloweye rockfish | Yelloweye rockfish | *Sebastes ruberrimus* |

Over longer periods, however, some species show different trends. For example, while currently stable, sablefish populations clearly declined from 2003 to the 2009 survey. For chilipepper rockfish, the 5-year trend showed a decrease in numbers per square kilometer, but the final 3 years of the trend appear to have stabilized.

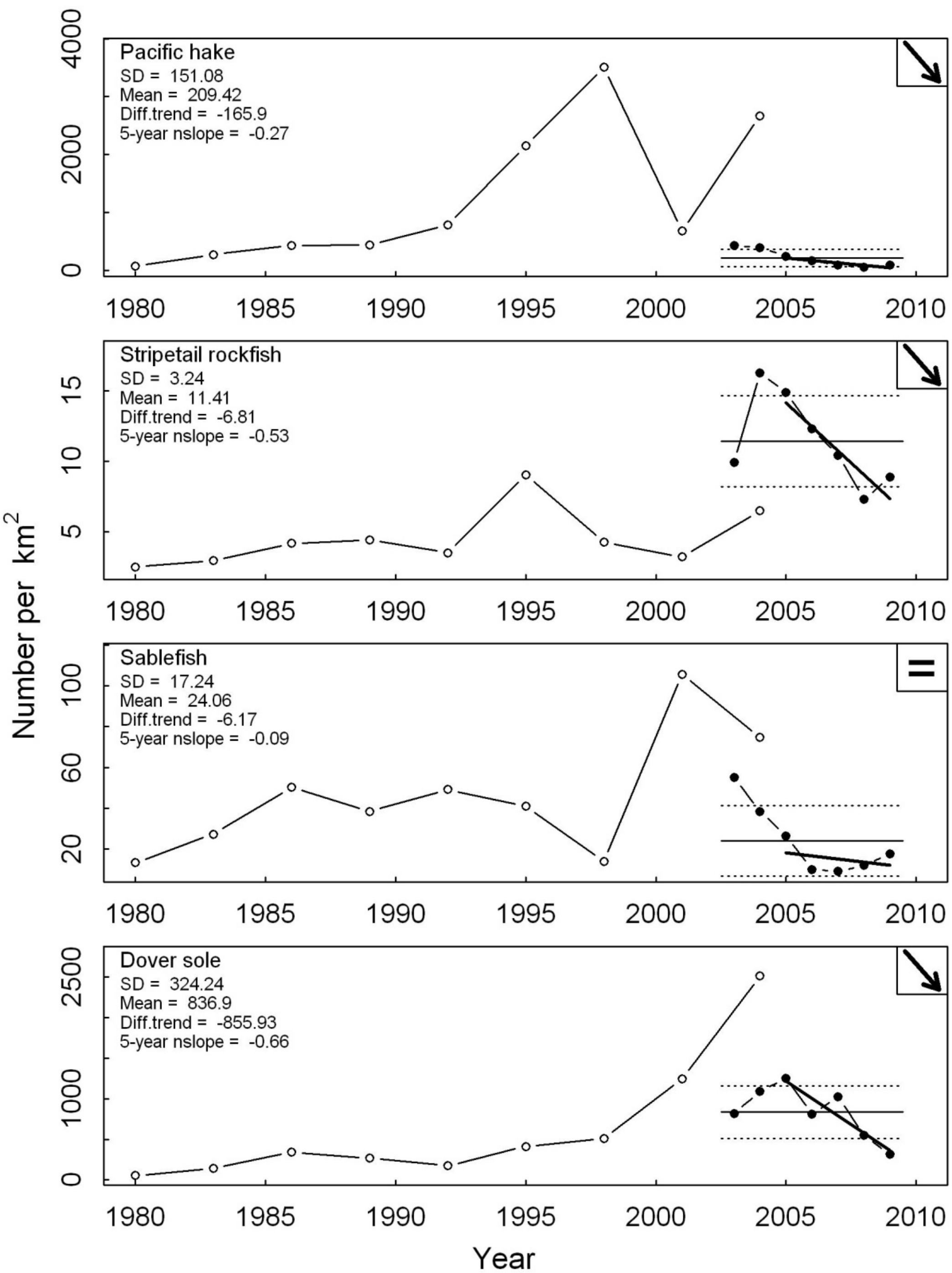



Figure 9. Catch per unit effort (CPUE) (number per $km^2$) for four groundfishes from 1980 to 2009 for the triennial trawl survey (open circles, data courtesy of Mark Wilkins, AFSC) and the NWFSC trawl survey (closed circle, data courtesy of Beth Horness, NWFSC). Mean and SD are the mean and standard deviation of the NWFSC time series, Diff.trend is the absolute change in the predicted trend over 5 years, and 5-year nslope is the slope of normalized data for comparison across species. The solid line is the mean for the 7-year NWFSC data. Dotted lines are ±1 SD. The trend line (thick black) is the 5-year trend. Symbols in the upper right indicate whether the 5-year trend decreased or showed no change relative to 1 SD of NWFSC data.

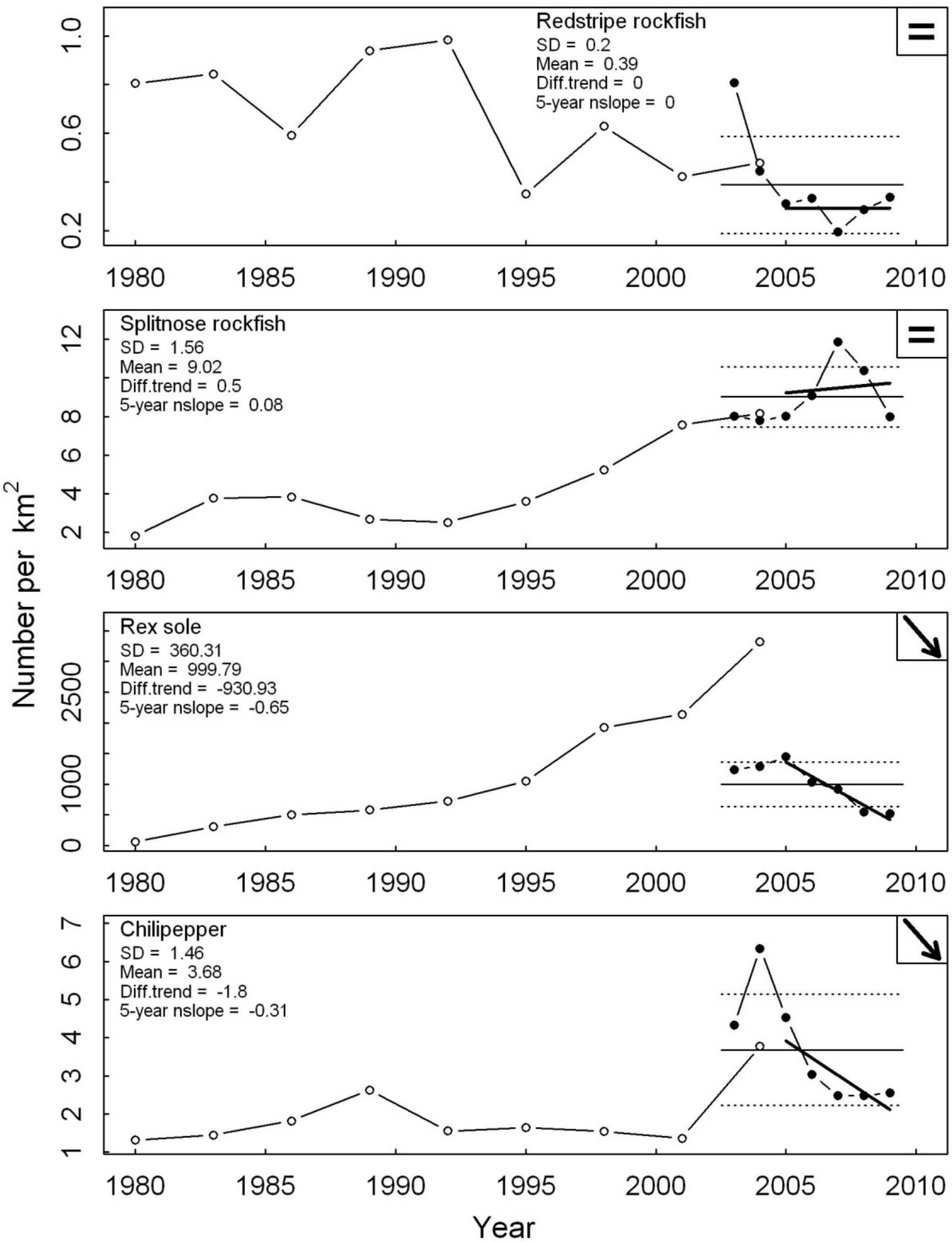



Figure 10. CPUE (number per km$^2$) for four groundfishes from 1980 to 2009 for the triennial trawl survey (open circles, data courtesy of Mark Wilkins, AFSC) and the NWFSC trawl survey (closed circle, data courtesy of Beth Horness, NWFSC). Mean and SD are the mean and standard deviation of the NWFSC time series, Diff.trend is the absolute change in the predicted trend over five years, 5-year nslope is the slope of normalized data for comparison across species. The solid line is the mean for the 7-year NWFSC data. Dotted lines are ±1 SD. The trend line (thick black) is the 5-year trend. Symbols in the upper right indicate whether the 5-year trend decreased or showed no change relative to 1 SD of NWFSC data. Data are the year effect from the GAM model and not absolute estimates of abundance.

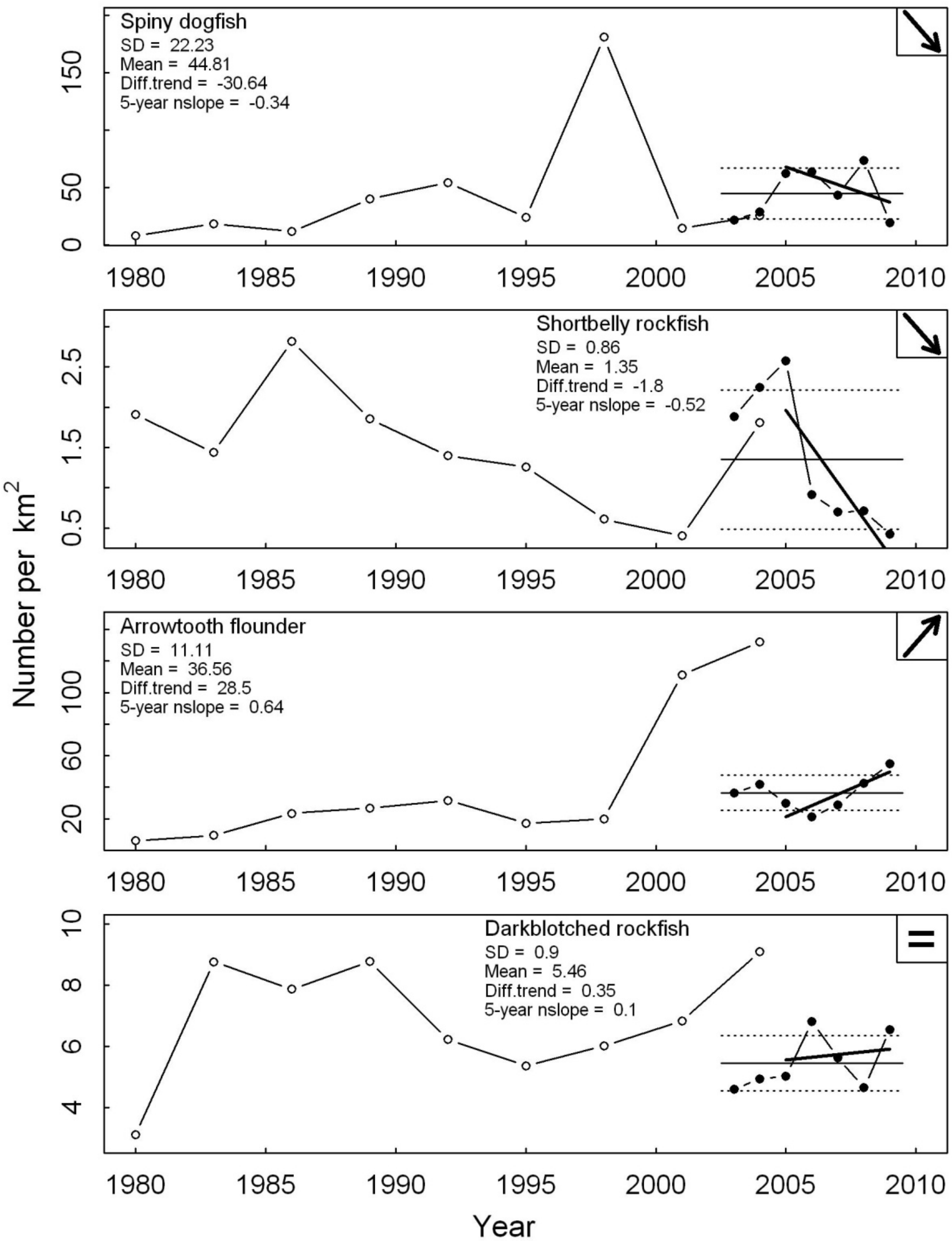



Figure 11. CPUE (number per km$^2$) for four groundfishes from 1980 to 2009 for the triennial trawl survey (open circles, data courtesy of Mark Wilkins, AFSC) and the NWFSC trawl survey (closed circle, data courtesy of Beth Horness, NWFSC). Mean and SD are the mean and standard deviation of the NWFSC time series, Diff.trend is the absolute change in the predicted trend over 5 years, 5-year nslope is the slope of normalized data for comparison across species. The solid line is the mean for the 7-year NWFSC data. Dotted lines are ±1 SD. The trend line (thick black) is the 5-year trend. Symbols in the upper right indicate whether the 5-year trend increased, decreased, or showed no change relative to 1 SD of NWFSC data. Data are the year effect from the GAM model and not absolute estimates of abundance.

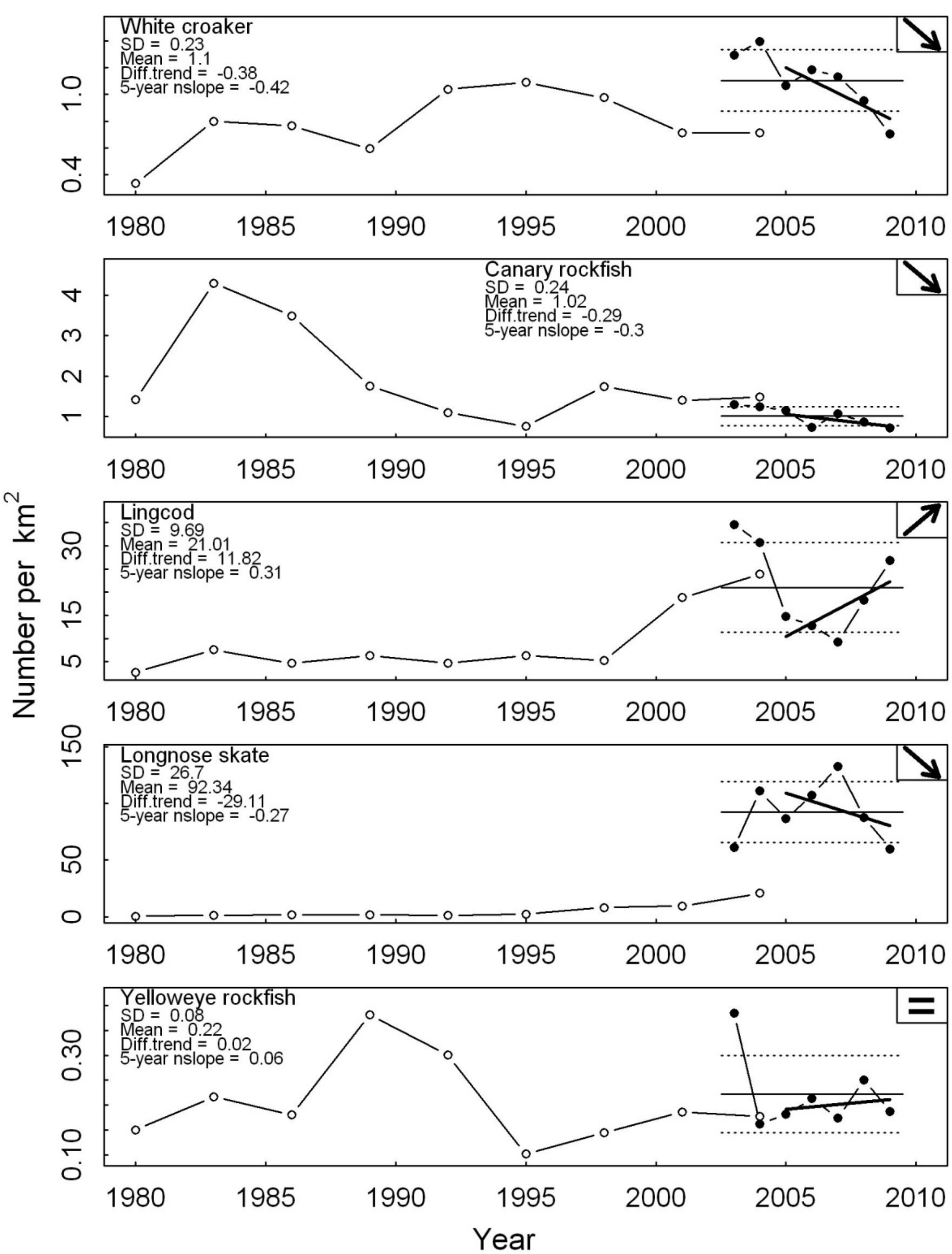



Figure 12. CPUE (number per km$^2$) for five groundfishes from 1980 to 2009 for the triennial trawl survey (open circles, data courtesy of Mark Wilkins, AFSC) and the NWFSC trawl survey (closed circle, data courtesy of Beth Horness, NWFSC). Mean and SD are the mean and standard deviation of the NWFSC time series, Diff.trend is the absolute change in the predicted trend over 5 years, 5-year nslope is the slope of normalized data for comparison across species. The solid line is the mean for the 7-year NWFSC data. Dotted lines are ±1 SD. The trend line (thick black) is the 5-year trend. Symbols in the upper right indicate whether the 5-year trend increased, decreased, or showed no change relative to 1 SD of NWFSC data. Data are the year effect from the GAM model and not absolute estimates of abundance.

There are three areas for potential improvement of the current indicators: 1) integration of the AFSC and NWFSC surveys, 2) development of more species-specific statistical models, and 3) the development of composite indicators.

While there are important differences in the methodologies of the two trawl surveys, future work should examine the possibility of integrating the two time series. Approaches have been developed for the integration of time series of different quality (Drake et al. 2010). Several species showed similar estimates of number per square kilometer for the overlapping year of 2004. Others showed similar overall trends, although absolute numbers differed. This integration will need to be done carefully, since different net sizes and trawl speeds are likely sampling different components (size distributions) of the relevant populations.

In the present report, abundance estimates for all species were derived from the same relatively simple statistical model using data covering the same latitudinal and depth extents and were limited to the shelf and shallow slope (shallower than 350 m). To provide better abundance estimates, it may be fruitful to develop more complex statistical models tailored to individual species.

Many species (including those not presented here) showed similar trends. Therefore, future work could focus on developing composite metrics that combine information from multiple species into one or several time lines to simplify presentation.

## Key Attribute: Population Condition

### Indicator: Size structure

For each species, the quartiles were calculated for length of all individuals collected during the first year of each survey (triennial survey 1980, NWFSC survey 2003). In instances when there were less than 20 individuals of a species measured during a year, the first year in which there were more than 20 individuals was used.

A number of species showed changes in size structure (Figure 13 through Figure 16). For example, the proportion of small hake increased from 2003 to 2009. For chilipepper rockfish, the proportion of older individuals increased from 2003 to 2009. Taken in conjunction with the numbers trends above, chilipepper show an aging and declining population. Note also that results from the two surveys do not match well. This is to be expected for two reasons. First, differences in trawl methodology (net size, tow duration, tow speed) mean that the two surveys sampled different components of the population. Second, quartiles in each survey are calculated relative to the first year of the survey, and the precise size ranges likely differ.

Future work should investigate the possibility of combining the two data sets to give a better understanding of long-term changes in size structure and the mechanisms causing size shifts.

### Indicator: Spatial structure

Annual variation in the distribution of groundfishes was examined by comparing abundances (CPUE estimated as number per $km^2$) in 1° latitudinal bins at lat 34–48°N along the

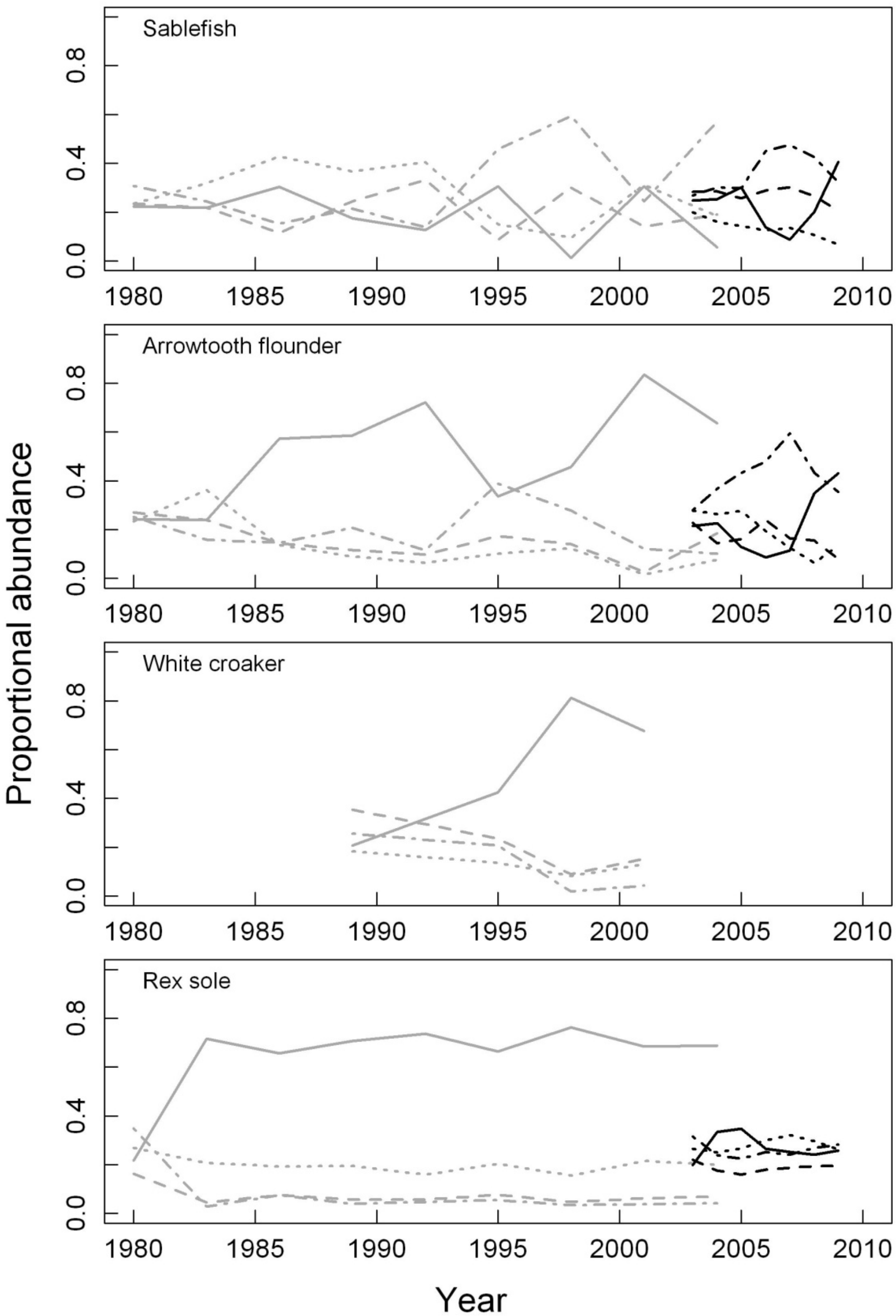



Figure 13. Size distribution for four groundfishes from 1980 to 2009. Plots show the proportion of fish in the first (solid), second (dashed), third (dotted), and fourth (dot-dash) quartiles. Gray lines are triennial survey data (courtesy of Mark Wilkins, AFSC), and black lines are NWFSC survey data (courtesy of Beth Horness, NWFSC). To show change in size structure through time, size cutoffs for the quartiles were established based on the first year in each time series (1980 and 2003). Subsequent years show proportion of fishes in those size classes.

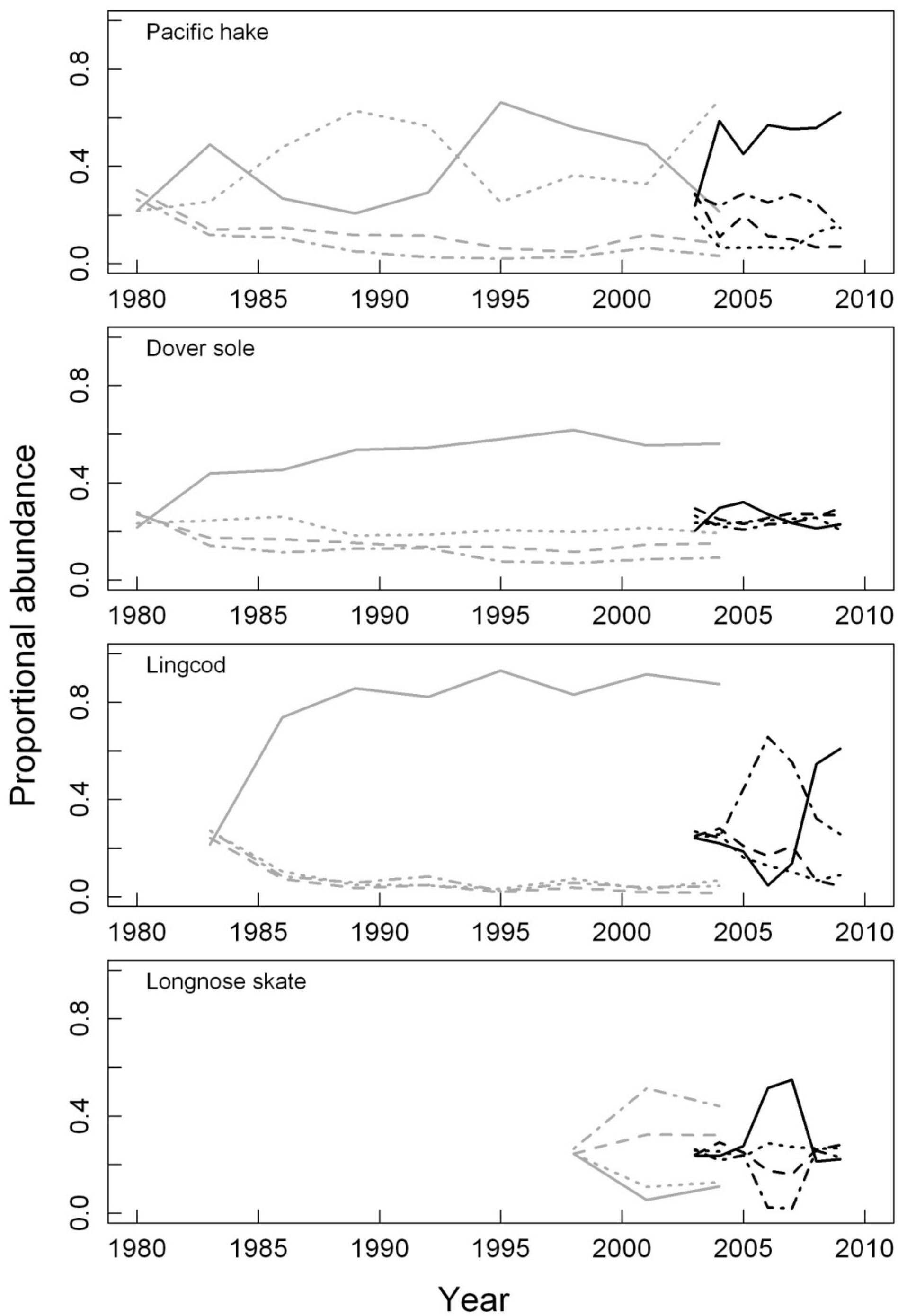



Figure 14. Size distribution for four groundfishes from 1980 to 2009. Plots show the proportion of fish in the first (solid), second (dashed), third (dotted), and fourth (dot-dash) quartiles. Gray lines are triennial survey data (courtesy of Mark Wilkins, AFSC), and black lines are NWFSC survey data (courtesy of Beth Horness, NWFSC). To show change in size structure through time, size cutoffs for the quartiles were established based on the first year in each time series (1980 and 2003). Subsequent years show proportion of fishes in those size classes.

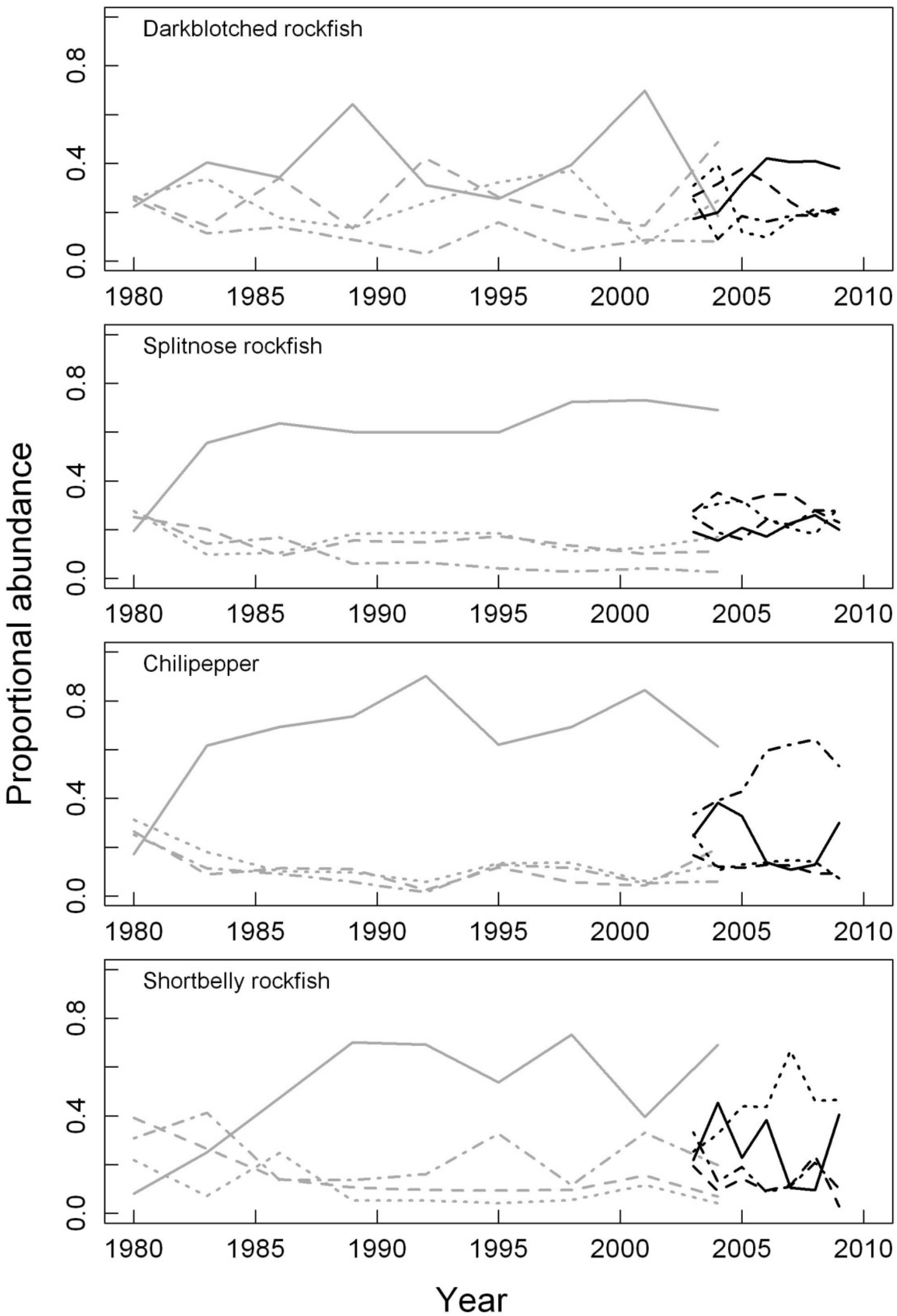



Figure 15. Size distribution for four groundfishes from 1980 to 2009. Plots show the proportion of fish in the first (solid), second (dashed), third (dotted), and fourth (dot-dash) quartiles. Gray lines are triennial survey data (courtesy of Mark Wilkins, AFSC), and black lines are NWFSC survey data (courtesy of Beth Horness, NWFSC). To show change in size structure through time, size cutoffs for the quartiles were established based on the first year in each time series (1980 and 2003). Subsequent years show proportion of fishes in those size classes.

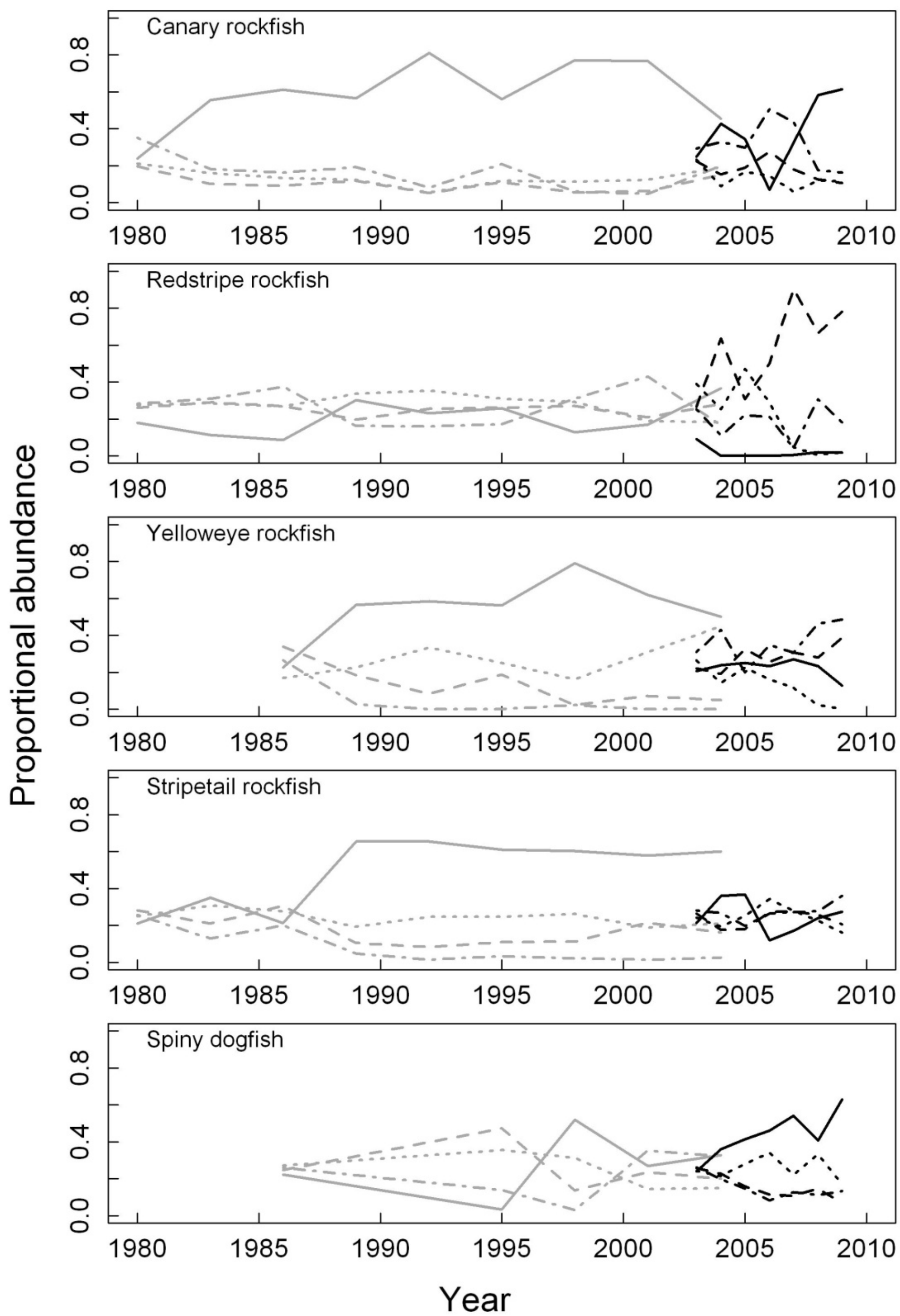



Figure 16. Size distribution for five groundfishes from 1980 to 2009. Plots show the proportion of fish in the first (solid), second (dashed), third (dotted), and fourth (dot-dash) quartiles. Gray lines are triennial survey data (courtesy of Mark Wilkins, AFSC), and black lines are NWFSC survey data (courtesy of Beth Horness, NWFSC). To show change in size structure through time, size cutoffs for the quartiles were established based on the first year in each time series (1980 and 2003). Subsequent years show proportion of fishes in those size classes.

West Coast. The data selection in terms of latitude and depth ranges followed that use in groundfish numbers above.

As with groundfish numbers, results for both the triennial and NWFSC surveys are presented on the same figures. However, given differences between the two surveys, they should not be directly compared. As such, trends are interpreted within time series. When examining triennial survey results, note that the 34° and 35°N latitude bins were not sampled from 1980 to 1986, so southern expansions (e.g., stripetail rockfish) into these latitudes in the triennial survey are not real.

Many species showed some variation in their spatial distributions through time (Figure 17 through Figure 20). For example in the triennial survey, Pacific hake show a northerly shift from 1980 to 1992 and a more bimodal distribution in 1995. In the NWFSC survey, hake are distributed to the north in 2003 but farther south in 2008, then back north in 2009. Spiny dogfish have also shown recent changes in distribution. Both surveys show a generally northern distribution through 2004, after which dogfish were more abundant in the southern half of the sampled range. Other species have shown relatively stable spatial distributions. Arrowtooth flounder maintained a northern distribution across both time series, although in the NWFSC surveys their relative abundance at midlatitudes has fluctuated. For example, rex sole were distributed primarily to the north across both time series.

There are two potential areas for improvement of present analyses. First, at present a relatively simple statistical approach standardized for all species was used to estimate the CPUE by latitude bin. Future improvements may seek to implement more complex estimation approaches (e.g., delta-generalized linear model) and tailor models to each indicator species. Second, the current presentation of spatial distribution is complex and difficult to interpret. It may be necessary to maintain a similar presentation to fully understand species distributions. However, it would be beneficial to produce a more simplified metric for each species that would be more easily visually interpreted. Integration of data sources and improved statistical approaches will improve the utility of this indicator.

## EBM Component: Ecosystem Health

As noted in the Selecting and Evaluating Indicators for the California Current section, the concept of ecosystem health is technically problematic, but the term has become part of EBM and thus we use it here. In our framework, ecosystem health is defined specifically by the key attributes we developed in that section.

Note on the figures that presentation of the time series of most indicators follows a standard format with additional statistical information displayed on each figure. When groundfish data were used, statistics pertain only to the NWFSC data because of differences in survey design (see Appendix C). In these cases, the relationship of the mean of the final 5 years of the time series was not compared to the mean of the NWFSC time series because the latter was only 7 years long.

Indicators of ecosystem health necessarily cover diverse taxa and require data from broad geographic areas. Time constraints prevented us acquiring and integrating data representing

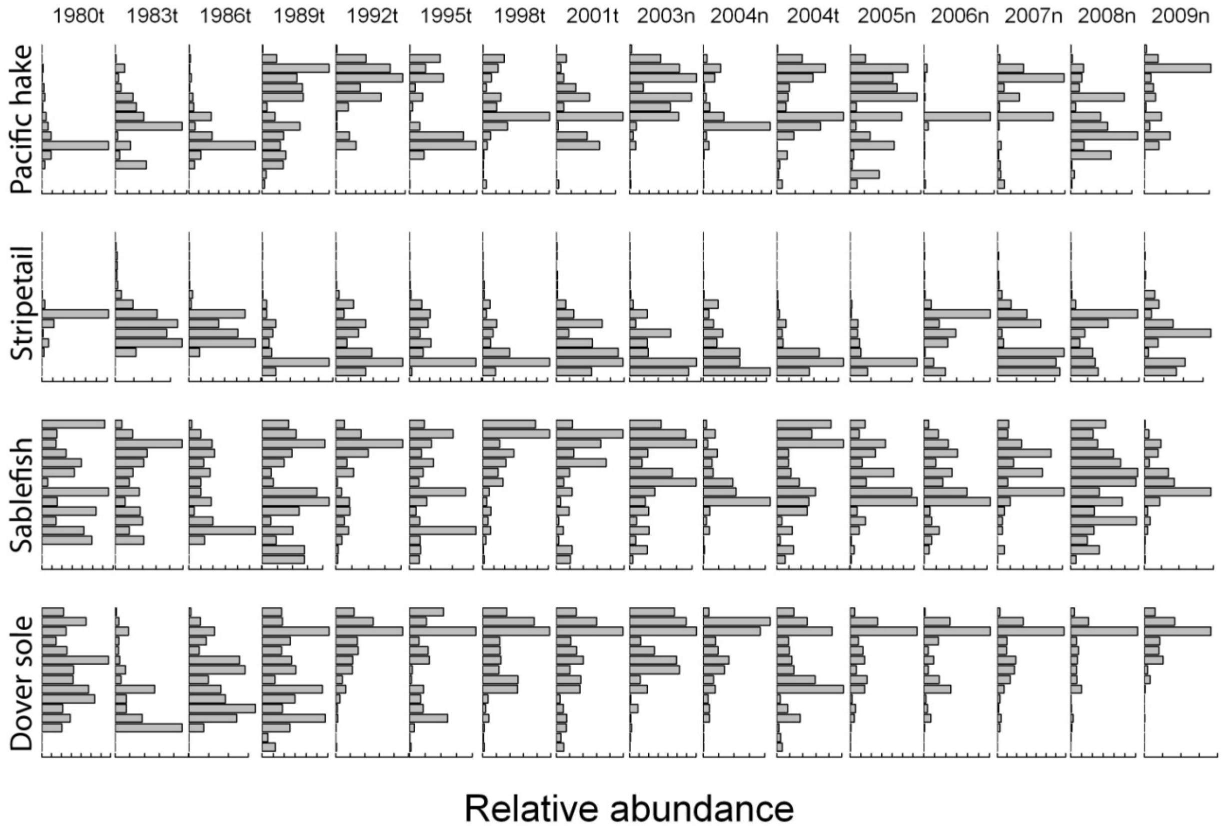



Figure 17. Spatial distribution of four groundfish from 1980 to 2009. Data are CPUE (number per $km^2$) presented in 10 latitude bins from lat 34°N (y-axis minimum) to lat 48°N (y-axis maximum). Data are relative within years and absolute values should not be compared across years as axes may vary. Letters following year headings indicate triennial (t, data courtesy of Mark Wilkins, AFSC) or NWFSC (n, data courtesy of Beth Horness, NWFSC) surveys. Due to difference between the two surveys, trends between the two should be made with caution. Both surveys were conducted in 2004.

some components of the ecosystem for this year's report. Throughout this section, we note crucial data gaps that will be filled in the coming year and incorporated into subsequent iterations of the California Current IEA.

## Key Attribute: Community Composition

### Indicator: Diversity

**Shannon Diversity**—The Shannon Diversity Index takes into account the number of species and the evenness of those species in a sample (Magurran 1988). The index increases with the addition of unique species or with more even representation of species (greater evenness).

Shannon Diversity ($log_e$) for West Coast groundfishes was estimated from the triennial survey and the NWFSC survey. A subset of the available data was used including trawls

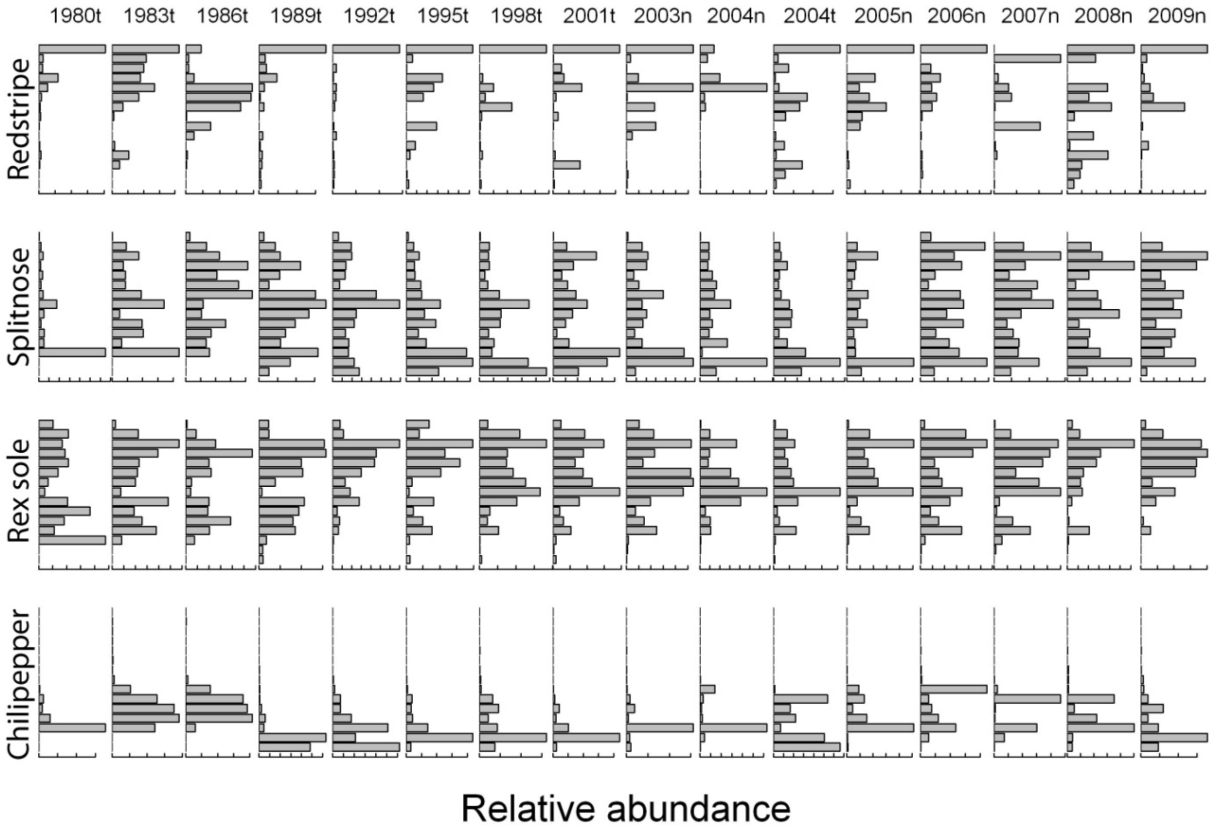



Figure 18. Spatial distribution of four groundfish from 1980 to 2009. Data are CPUE (number per $km^2$) presented in 10 latitude bins from lat 34°N (y-axis minimum) to lat 48°N (y-axis maximum). Data are relative within years and absolute values should not be compared across years as axes may vary. Letters following year headings indicate triennial (t, data courtesy of Mark Wilkins, AFSC) or NWFSC (n, data courtesy of Beth Horness, NWFSC) surveys. Due to difference between the two surveys, trends between the two should be made with caution. Both surveys were conducted in 2004.

between 50–350 m and 34–38°N latitude. AFSC data included the years 1980–2004 (every third year), while NWFSC data included 2003–2009 data. See Appendix C for further details.

The 5-year trend for Shannon Diversity showed a decrease from 2005 to 2009 (Figure 21), indicating some change in assemblage structure for West Coast groundfishes. Notably the 2009 estimate was similar to the 2003 value, suggesting a return to an earlier state. Future monitoring will need to determine whether Shannon Diversity continues to decline or levels off.

Estimates of Shannon Diversity are not easily comparable between the triennial data and the NWFSC data. Shannon Diversity in 2004 was higher in the NWFSC surveys than in the triennial surveys.

**Taxonomic distinctness**—TD is a diversity metric that quantifies the relatedness of species in a sample based on the distance between species pairs in a taxonomic tree (see

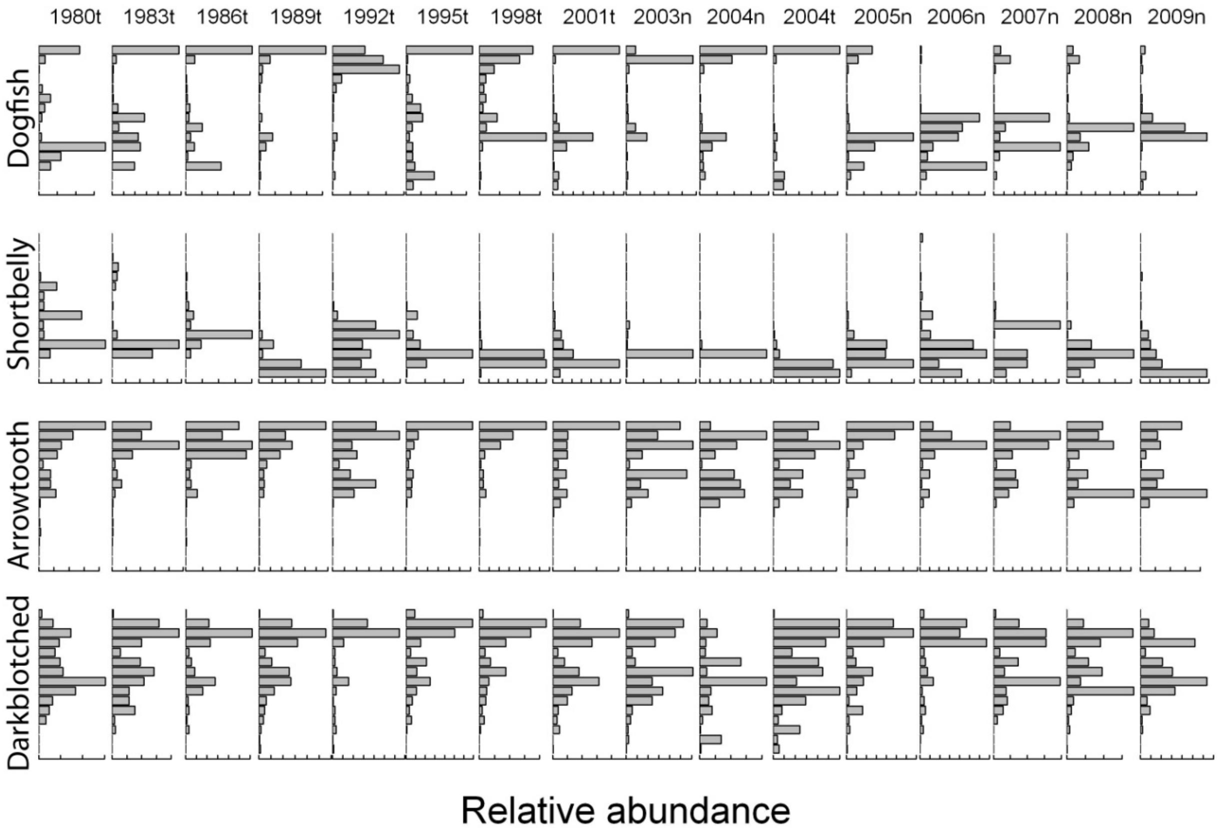



Figure 19. Spatial distribution of four groundfish from 1980 to 2009. Data are CPUE (number per $km^2$) presented in 10 latitude bins from lat 34°N (y-axis minimum) to lat 48°N (y-axis maximum). Data are relative within years and absolute values should not be compared across years as axes may vary. Letters following year headings indicate triennial (t, data courtesy of Mark Wilkins, AFSC) or NWFSC (n, data courtesy of Beth Horness, NWFSC) surveys. Due to difference between the two surveys, trends between the two should be made with caution. Both surveys were conducted in 2004.

Appendix C). Changes in TD indicate changes in the deeper evolutionary makeup of the community, not just the number or evenness of species in a system. High AvTD values indicate low relatedness of species or taxa in the sample. VarTD is a measure of the regularity of branch lengths within the taxonomic tree for that sample, not the variance of AvTD among samples. See Appendix C for more details.

AvTD and VarTD (Clarke and Warwick 1998a, Clarke and Warwick 2001b) for West Coast groundfishes were estimated from the triennal survey and the NWFSC trawl survey (see Appendix C for further details). A subset of the available data was used: trawls between 50–350 m and 34–38°N latitude. Triennial data included the years 1980–2004 (every third year), while NWFSC data included 2003–2009 data. Yearly estimates were derived separately for each time series.

AvTD (Figure 22) increased slightly but steadily from 1980 to 1998. The trend over the last 5 years of the NWFSC time series was for a decline in AvTD, but this decline was based

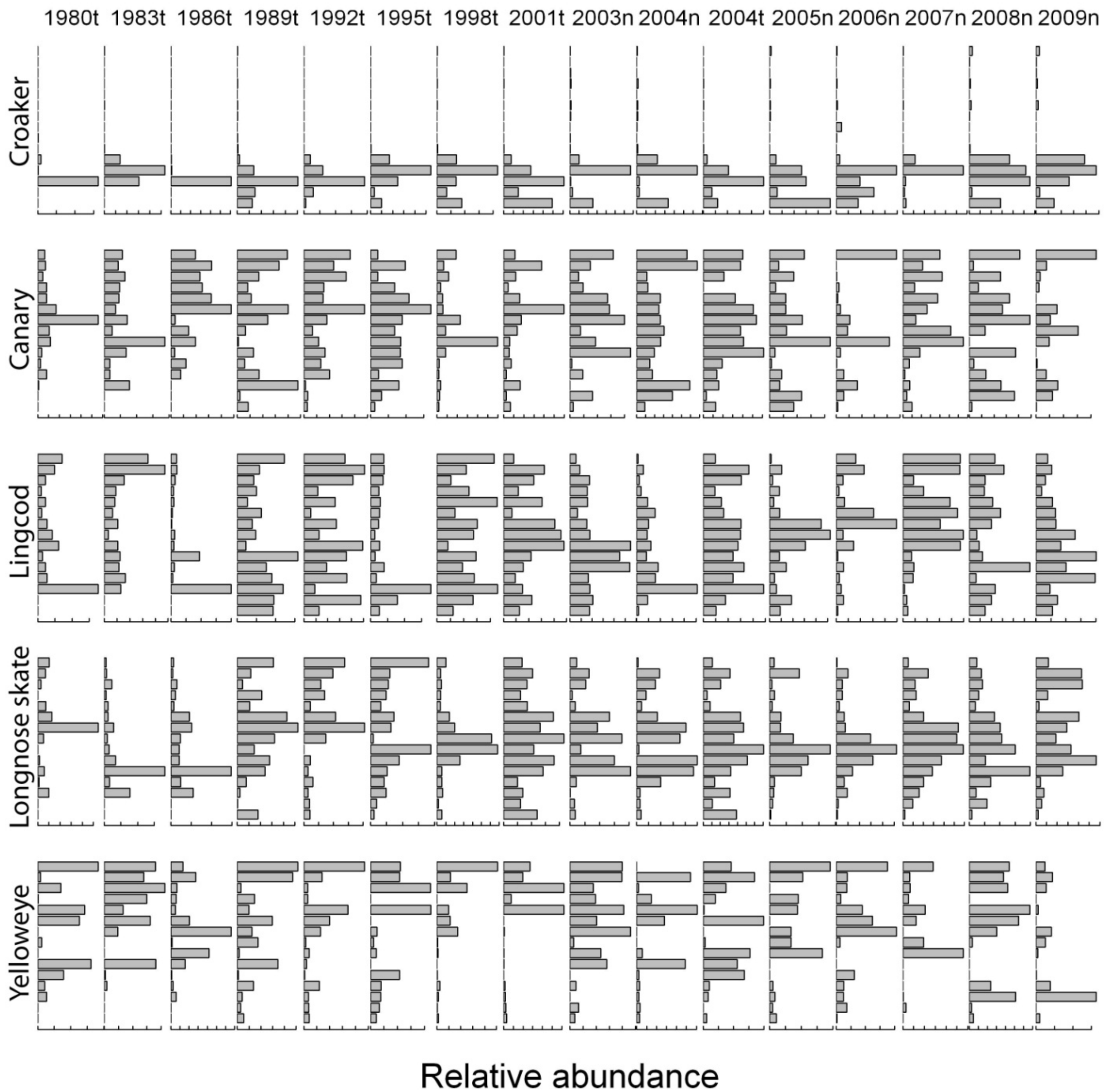



Figure 20. Spatial distribution of five groundfish from 1980 to 2009. Data are CPUE (number per $km^2$) presented in 10 latitude bins from lat 34°N (y-axis minimum) to lat 48°N (y-axis maximum). Data are relative within years and absolute values should not be compared across years as axes may vary. Letters following year headings indicate triennial (t, data courtesy of Mark Wilkins, AFSC) or NWFSC (n, data courtesy of Beth Horness, NWFSC) surveys. Due to difference between the two surveys, trends between the two should be made with caution. Both surveys were conducted in 2004.

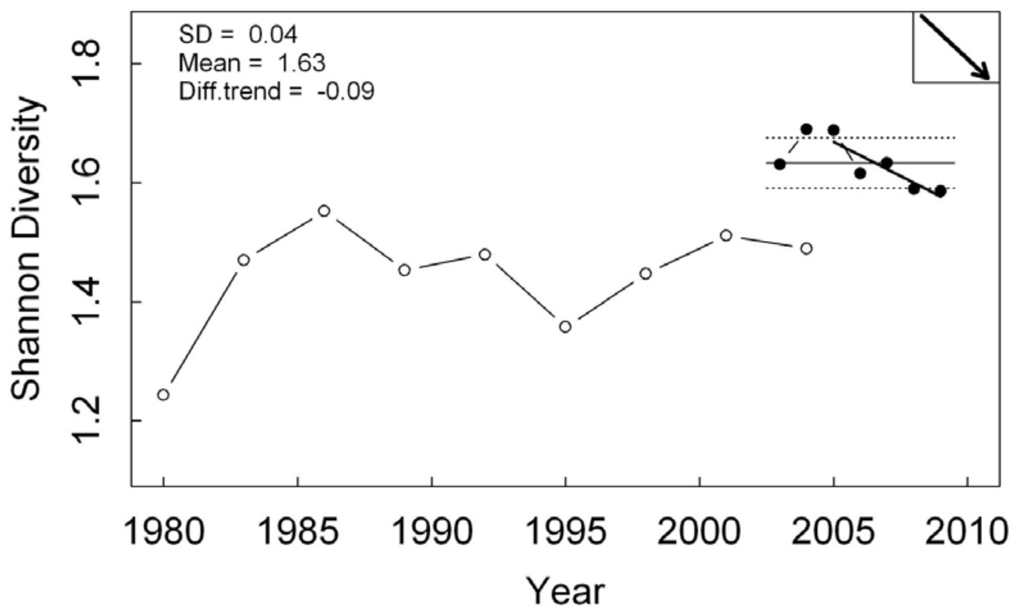



Figure 21. Annual mean Shannon Diversity for lat 34–48°N and 50–350 m bottom depth. Open circles show yearly averages calculated from triennial trawl survey (data courtesy of Mark Wilkins, AFSC). Closed circles show results for the NWFSC trawl survey (data courtesy of Beth Horness, NWFSC). Mean and SD are the mean and standard deviation of the NWFSC time series, Diff.trend is the absolute change in the predicted trend over 5 years. The solid line is the mean for the NWFSC data. Dotted lines are ±1 SD. The trend line (thick black) is the 5-year trend. Symbol in the upper right indicates that the 5-year trend decreased relative to 1 SD of NWFSC data. Data are the year effect from the GAM model and not absolute estimates of diversity.

largely on one data point. VarTD (Figure 22) showed an overall increase from the early 1990s, but the 5-year trend is presently stable.

TD of zooplankton in the California Current was largely stable over the last 5 years except during the winter (Figure 23 and Figure 24). Winter values during the last 5 years have trended up for AvTD. For both metrics, the 5-year mean was within 1 SD of the long-term mean in all cases.

The trend in TD indicates that the structure of the groundfish assemblage has changed since 1980 to some degree. Caution should be used in interpreting the results and further investigation of the data is necessary to fully understand the significance of the change. Higher diversity (usually measured as richness but here measured as AvTD) is generally considered good because of biodiversity-ecosystem function relationships (Stachowicz et al. 2007). However, the West Coast groundfish assemblage contains many closely related rockfishes (*Sebastes*), which leads to low AvTD values and high VarTD (Tolimieri and Anderson 2010). A reduction in the frequency of occurrence of rockfishes would cause the reverse trend—an increase in AvTD, as the species present would be less related, and a decrease in VarTD, as branch lengths between species became more regular.

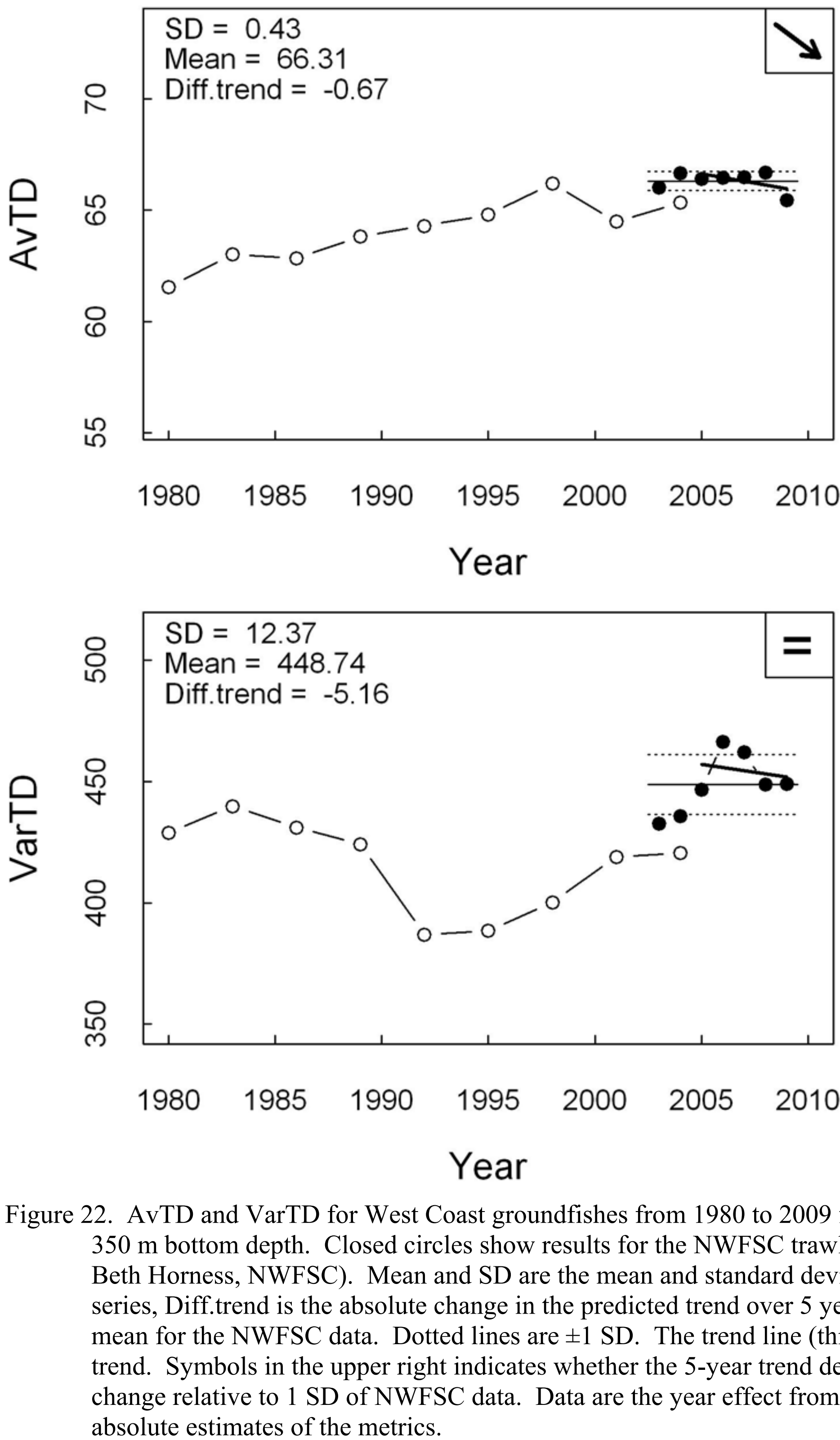



Figure 22. AvTD and VarTD for West Coast groundfishes from 1980 to 2009 for lat 34–48°N and 50–350 m bottom depth. Closed circles show results for the NWFSC trawl survey (data courtesy of Beth Horness, NWFSC). Mean and SD are the mean and standard deviation of the NWFSC time series, Diff.trend is the absolute change in the predicted trend over 5 years. The solid line is the mean for the NWFSC data. Dotted lines are ±1 SD. The trend line (thick black) is the 5-year trend. Symbols in the upper right indicates whether the 5-year trend decreased or showed no change relative to 1 SD of NWFSC data. Data are the year effect from the GAM model and not absolute estimates of the metrics.

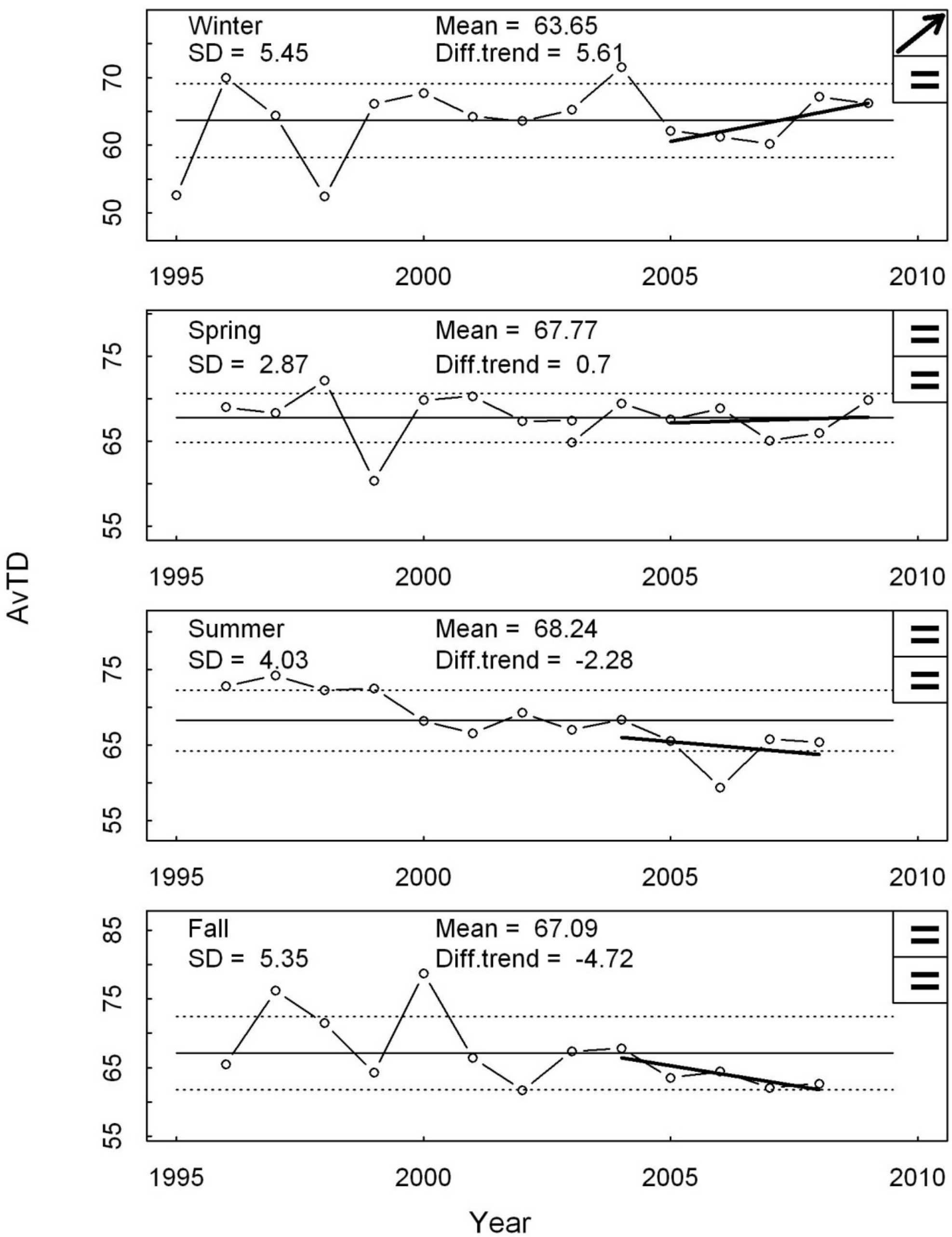



Figure 23. AvTD of California Current zooplankton from 1996 to 2008 in four seasons. Mean and SD are the mean and standard deviation of the NWFSC time series, Diff.trend is the absolute change in the predicted trend over 5 years. Dotted lines are ±1 SD. The trend line (thick black) is the 5-year trend. Symbols in the upper right box indicate whether the 5-year trend increased or showed no change relative to 1 SD of NWFSC data. Symbols in the lower right box indicate that the 5-year mean showed no change relative to the long-term mean. Data are the year effect from the GAM model and not absolute estimates of the metrics.

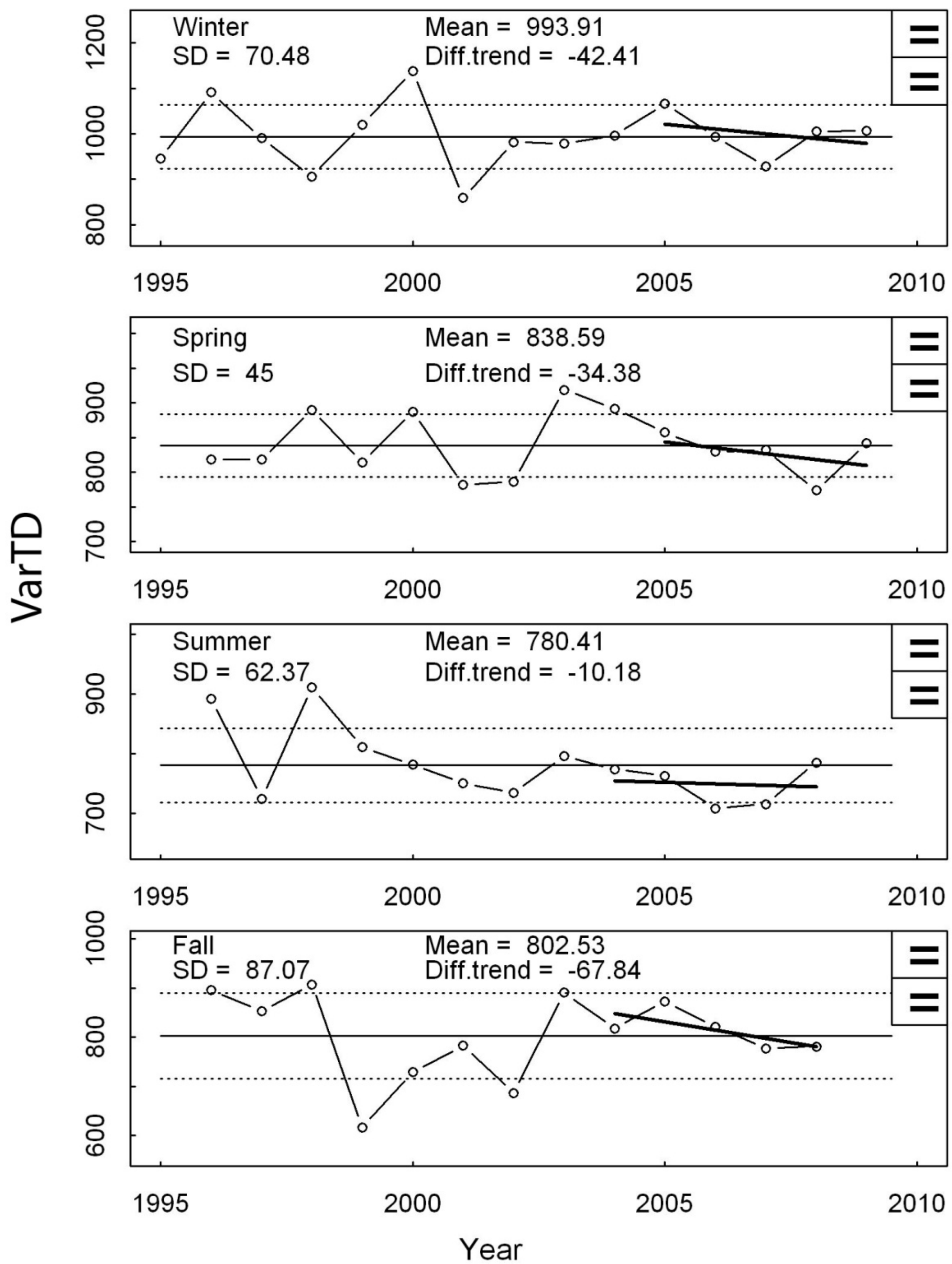



Figure 24. VarTD of California Current zooplankton from 1996 to 2008 in four seasons. Mean and SD are the mean and standard deviation of the NWFSC time series, Diff.trend is the absolute change in the predicted trend over 5 years. Dotted lines are ±1 SD. The trend line (thick black) is the 5-year trend. Symbols in the upper right box indicate that the 5-year trend showed no change relative to 1 SD of NWFSC data. Symbols in the lower right box indicate that the 5-year mean showed no change relative to the long-term mean. Data are the year effect from the GAM model and not absolute estimates of the metrics.

**Indicator: Seabird reproduction indices**

While there are a handful of seabird colonies with long-term monitoring programs in place (Appendix C), no single coast-wide indicator has been developed. Future work will endeavor to develop a coast-wide seabird reproductive index based on a multivariate approach (Frederiksen et al. 2007) that integrates data sets from a variety of long-term seabird colony monitoring programs along the Pacific coast.

**Indicator: The northern copepod biomass anomaly**

The northern copepod biomass anomaly measures whether copepod species from northern waters are more or less common than normal off the Oregon coast. It is responsive to climate effects such as El Niño or PDO. The anomaly indicates change in the structure of the zooplankton community. Importantly, because northern species of copepods are lipid rich, a high value of the northern copepod index is suggestive of good feeding conditions at the base of the food web and may help to predict changes in fish populations (Beamish and Mahnken 2001).

Over the last 5 years (2005–2009), the northern copepod anomaly has followed an increasing trend (Figure 25), although the 5-year mean is within 1 SD of the long-term mean for the time series. This increasing trend suggests the increasing prevalence of cold water copepods in the system. This increase may be temporary, however, as the overall time series suggests long-term cycling.

Several long-term zooplankton monitoring programs, representing seven subregions spanning the entire California Current system from Baja California to Vancouver Island, now provide zooplankton time series of various lengths from 1969 to the present. Although differences in processing and sampling zooplankton time series introduce a variety of biases that often prevent comparisons between data sets, many major questions can still be answered, because an individual data set can be presented and analyzed as a time series of log-scale anomalies relative to the local long-term average seasonal climatology. Anomalies are primarily used to separate interannual variability from the often large annual seasonal cycle of zooplankton stock size (Mackas and Beaugrand 2010).

The specific species associated with these anomalies vary regionally, but can generally be classified as resident versus nonresident species. Here we propose to combine these regional anomalies into a single index that can be used to represent coast-wide responses of zooplankton communities to regional climate signals. This coast-wide zooplankton index indicator will combine regionally specific community composition anomalies into a single index using multivariate techniques (i.e., principal component analysis) in similar fashion to the calculation of regional climate indices, such as the MEI (Wolter and Timlin 1993). This index can then be tested for use as a leading indicator of regional climate signals, such as ENSO or PDO, using existing time series from the last 20 years, during which time the California Current saw at least two major climate regime shifts.

**Indicator: Top predator biomass**

Data sources, data selection, and statistical procedures follow those for the estimation of groundfish numbers (see Evaluating Potential Indicators for the California Current: Groundfish

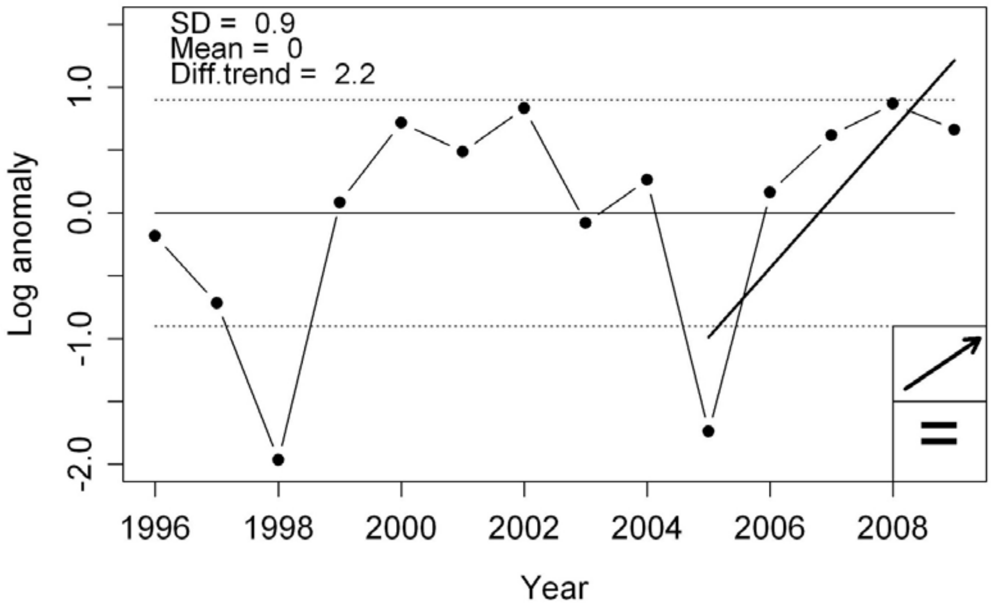



Figure 25. The northern copepod anomaly off Oregon from 1996 to 2009. Biomass values are mg carbon $m^{-3}$ in log10. Values above zero indicate a higher than normal abundance of northern copepod species. Symbol in the upper right box indicates that the 5-year trend increased relative to 1 SD of the long-term mean. Symbol in the lower right box indicates that the 5-year mean showed no change relative to the long-term mean. (Data courtesy of Bill Peterson, NWFSC.)

and Ecosystem Health subsection above and Appendix C). While similar generalized additive models (GAMs) were used to produce annual means, top predator data were transformed (log(x+0.1)) prior to analysis.

Top predator biomass (kg per $km^2$) per trawl for groundfishes was calculated by summing the biomass of all groundfish species listed in FishBase.org with trophic levels of 4.0 or higher (Table 12). Top predator biomass declined from 2003 to 2009 (Figure 26) by more than 2 SD of the full NWFSC time series. Over the last 5 years, biomass has continued to decline by more than 1 SD of the full NWFSC time series.

Time constraints prevented us from collating and analyzing appropriate data for other apex predators. Future efforts will expand this indicator so that it includes a breadth of top predator species.

## Key Attribute: Energetics and Material Flows

### Indicator: Nutrient levels

In developed nearshore regions of the California Current, nutrient concentrations have been more or less continuously measured for decades in many rivers, estuaries, beaches, and other drinking water supplies. In contrast for offshore regions, nutrient levels in the upper layers of the water column have generally been poorly characterized in space and time (Hill and Wheeler 2002). Some exceptions to this pattern include intensive sampling at individual regions:

Table 12. Species used in the estimation of top predator biomass. Trophic level from FishBase.org.

| Common name | Scientific name | Trophic level |
|---|---|---|
| Giant grenadier | *Albatrossia pectoralis* | 4.3 |
| Longnose lancetfish | *Alepisaurus ferox* | 4.1 |
| Thresher shark | *Alopias vulpinus* | 4.5 |
| Fangtooth | *Anoplogaster cornuta* | 4.0 |
| North Pacific daggertooth | *Anotopterus nikparini* | 4.5 |
| Black scabbardfish | *Aphanopus carbo* | 4.5 |
| Arrowtooth flounder | *Atheresthes stomias* | 4.3 |
| Javelin spookfish | *Bathylychnops exilis* | 4.1 |
| Deepsea skate | *Bathyraja abyssicola* | 4.0 |
| Aleutian skate | *B. aleutica* | 4.1 |
| White skate | *B. spinosissima* | 4.0 |
| Roughtail skate | *B. trachura* | 4.0 |
| Northern pearleye | *Benthalbella dentata* | 4.5 |
| Pacific pomfret | *Brama japonica* | 4.4 |
| Manefish | *Caristius macropus* | 4.2 |
| Can-opener smoothdream | *Chaenophryne longiceps* | 4.1 |
| Pacific viperfish | *Chauliodus macouni* | 4.1 |
| Black swallower | *Chiasmodon niger* | 4.2 |
| Spotted cusk-eel | *Chilara taylori* | 4.1 |
| Filamented grenadier | *Coryphaenoides filifer* | 4.5 |
| Triplewart sea devil | *Cryptopsaras couesii* | 4.5 |
| Petrale sole | *Eopsetta jordani* | 4.1 |
| Pacific hagfish | *Eptatretus stoutii* | 4.2 |
| Umbrellamouth gulper | *Eurypharynx pelecanoides* | 4.1 |
| Pacific cod | *Gadus macrocephalus* | 4.0 |
| Soupfin shark | *Galeorhinus galeus* | 4.2 |
| Whipnose | *Gigantactis vanhoeffeni* | 4.5 |
| Sixgill shark | *Hexanchus griseus* | 4.3 |
| Pacific halibut | *Hippoglossus stenolepis* | 4.1 |
| Ragfish | *Icosteus aenigmaticus* | 4.5 |
| Smooth stargazer | *Kathetostoma averruncus* | 4.3 |
| Pacific lamprey | *Lampetra tridentata* | 4.5 |
| Pacific scabbardfish | *Lepidopus fitchi* | 4.1 |
| Slender barracudina | *Lestidiops ringens* | 4.1 |
| Shortfin eelpout | *Lycodes brevipes* | 4.0 |
| Duckbill barracudina | *Magnisudis atlantica* | 4.1 |
| Softhead grenadier | *Malacocephalus laevis* | 4.2 |
| Common blackdevil | *Melanocetus johnsonii* | 4.1 |
| Pacific hake | *Merluccius productus* | 4.3 |
| Ocean sunfish | *Mola mola* | 4.0 |
| Sailfin sculpin | *Nautichthys oculofasciatus* | 4.1 |
| Glowingfish | *Neoscopelus macrolepidotus* | 4.2 |
| California grenadier | *Nezumia stelgidolepis* | 4.4 |
| Pink salmon | *Oncorhynchus gorbuscha* | 4.2 |
| Coho salmon | *O. kisutch* | 4.2 |
| Chinook salmon | *O. tshawytscha* | 4.4 |
| [No common name] | *Oneirodes thompsoni* | 4.2 |
| Lingcod | *Ophiodon elongatus* | 4.3 |

Table 12 continued. Species used in the estimation of top predator biomass. Trophic level from FishBase.org.

| **Common name** | **Scientific name** | **Trophic level** |
|---|---|---|
| California halibut | *Paralichthys californicus* | 4.5 |
| Pacific pompano | *Peprilus simillimus* | 4.1 |
| [No common name] | *Photonectes margarita* | 4.0 |
| Plainfin midshipman | *Porichthys notatus* | 4.0 |
| Blue shark | *Prionace glauca* | 4.2 |
| Pacific sand sole | *Psettichthys melanostictus* | 4.1 |
| Brown rockfish | *Sebastes auriculatus* | 4.0 |
| Copper rockfish | *S. caurinus* | 4.1 |
| Yellowtail rockfish | *S. flavidus* | 4.1 |
| Black rockfish | *S. melanops* | 4.4 |
| Yelloweye rockfish | *S. ruberrimus* | 4.4 |
| Pacific sleeper shark | *Somniosus pacificus* | 4.3 |
| Spiny dogfish | *Squalus acanthias* | 4.3 |
| Pacific angel shark | *Squatina californica* | 4.1 |
| Blackbelly dragonfish | *Stomias atriventer* | 4.0 |
| California lizardfish | *Synodus lucioceps* | 4.5 |
| Longfin dragonfish | *Tactostoma macropus* | 4.2 |
| Pacific electric ray | *Torpedo californica* | 4.5 |

the southern California Current via the CalCOFI program (Figure 27 through Figure 29, McClatchie et al. 2009) and portions of the northern California Current via GLOBEC cruises.

Most nutrient levels (nitrate, phosphate, silicate) are characterized in the CalCOFI region from 1984 to present based on concentration anomalies in the mixed layer depth, calculated using a density criterion set either to 12 m or to the halfway point between the 2 sampling depths where the gradient first reaches values larger than 0.002 per million, whichever is larger. Annual averages and the climatological mean are also graphed (McClatchie et al. 2009).

Preliminary comparisons are shown between existing nearshore (e.g., Washington State's ORHAB program, Monterey Bay National Marine Sanctuary Program) and offshore sampling programs by presenting data on seasonal averages (January-March = Win; April-June = Spr; July-September = Sum; October-December = Fall) of three nutrient levels (nitrate, phosphate, silicate) in the surface 5 m of the water column.

Future iterations of this indicator will seek to standardize these values using concentration anomalies in the mixing layer relative to annual and climatological means for each region.

### Indicator: Chlorophyll *a*

High values of chl *a* levels indicate increased abundance of primary producers at the water surface. Satellite chl *a* values since 2002 were low in 2005 at locations B and C and in 2009 at locations A and B. In winter 2010, they were above 1 SD for all three locations (Figure 30). In the summers of 2003 and 2004, there were peaks at locations B and C, respectively.

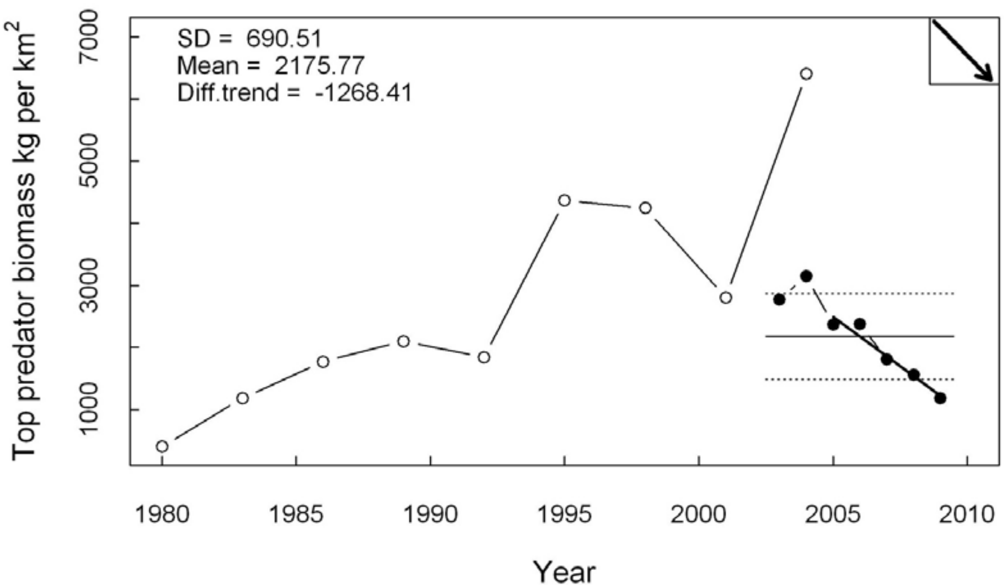



Figure 26. Top predator biomass. Closed circles show results for the NWFSC trawl survey (data courtesy of Beth Horness, NWFSC). Mean and SD are the mean and standard deviation of the NWFSC time series, Diff.trend is the absolute change in the predicted trend over 5 years. The solid line is the mean for the NWFSC data. Dotted lines are ±1 SD. The trend line (thick black) is the 5-year trend. Symbol in the upper right indicates that the 5-year trend decreased relative to 1 SD of NWFSC data. Data were log(x+0.1) transformed prior to analysis and back-transformed for presentation. Data are the year effect from the GAM model and not absolute estimates of abundance.

Chl *a* values at all three locations were low in 2010 and showed a decline over the past 5 years at locations B and C. Spatial patterns show chl *a* greater near the coast particularly in estuaries such as San Francisco Bay, Puget Sound, and the Columbia River mouth. Overall chl *a* values were greater in summer than winter.

In the past several years, surface chlorophyll concentrations in Monterey Bay have been anomalously high (Kahru and Mitchell 2008, Kahru et al. 2009), consistent with the PDO shift in late 1998 and subsequent cooler state of the CCLME (Peterson and Schwing 2003, Chavez et al. 2003). Surface chlorophyll concentrations on the Oregon continental shelf have also been high in recent years, with summer averages nearly double values from 1997 to 2000 (Figure 30).

## EBM Component: Forage Fish

This EBM component will be developed for the 2011 report. We have included existing data on trends below as a precursor to more thorough treatment in FY2011.

Most mesopelagic fishes decreased in abundance during cool phases of the PDO and increased during warm phases from CalCOFI data up to 2002 (Hsieh et al. 2005, 2009). Because these species are not commercially fished and are highly linked to primary productivity, they can serve as a potential proxy for tracking changes in environmental forcing that could cascade through the pelagic food web. Market squid in the southern ecoregion were below normal in

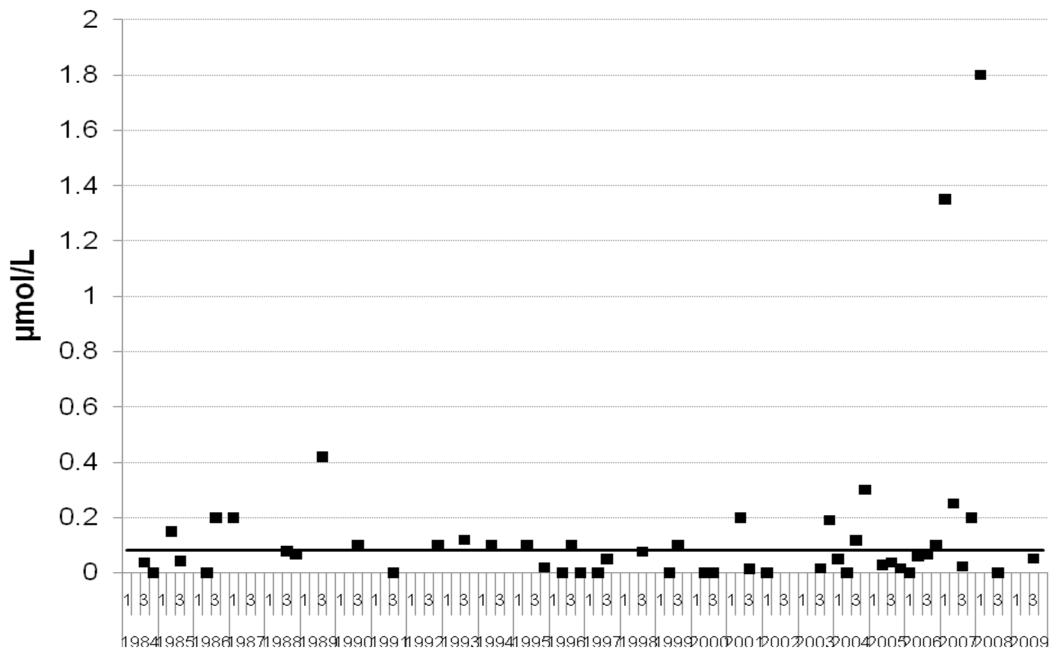



Figure 27. Mean nitrate ($NO_3$) concentrations (µmol/L) by season (1 = Win = Jan–Mar; 2 = Spr = Apr–Jun; 3 = Sum = Jul–Sep; 4 = Fall = Oct–Dec), from 1984 to 2009 at depths less than 6 m. Long-term mean indicated by the thick horizontal line. Geographic range encompasses station grid 66.7 (CalCOFI north) through grid 136.7 (IMECOCAL–Baja California). Data accessible in the CCE LTER data repository supported by the Division of Ocean Sciences, NSF Grant OCE-0417616. Data set 82: Conductivity temperature depth bottle data–Survey cruise data set (CalCOFI–SIO).

2005 and 2006, as evidenced by both landing data and California sea lion (*Zalophus californianus*) diets (Figure 31).

Of the key coastal species, northern anchovy is often characterized as being favored during cool periods and Pacific sardine during warm periods (Chavez et al. 2003). However, it has been a cool period for the past 5 years and the abundance of sardine larvae has remained relatively high, but anchovy abundance has remained low. Northern anchovy and Pacific sardine egg counts in spring (April) 2005 and 2006 were very low, especially in comparison with the 2001–2003 period (Bograd et al. 2010). The relative increases and decreases in anchovy versus sardine eggs between years may be attributed to temperature and upwelling (Lluch-Belda et al. 1991).

The composition of the forage fish community in 2005 and 2006 was most similar to that observed during the 1998 El Niño, with very low abundances of young-of-year groundfish and market squid, but with relatively high catch rates of anchovies and sardines. However, since 2006 the midwater trawl assemblage has trended back towards a species composition more characteristic of the cool, productive period of 2002. The abundance of juvenile age-0 rockfish (*Sebastes* spp.) was exceptionally low in 2005. Essentially, complete recruitment failure in the central ecoregion was observed (Bograd et al. 2010).

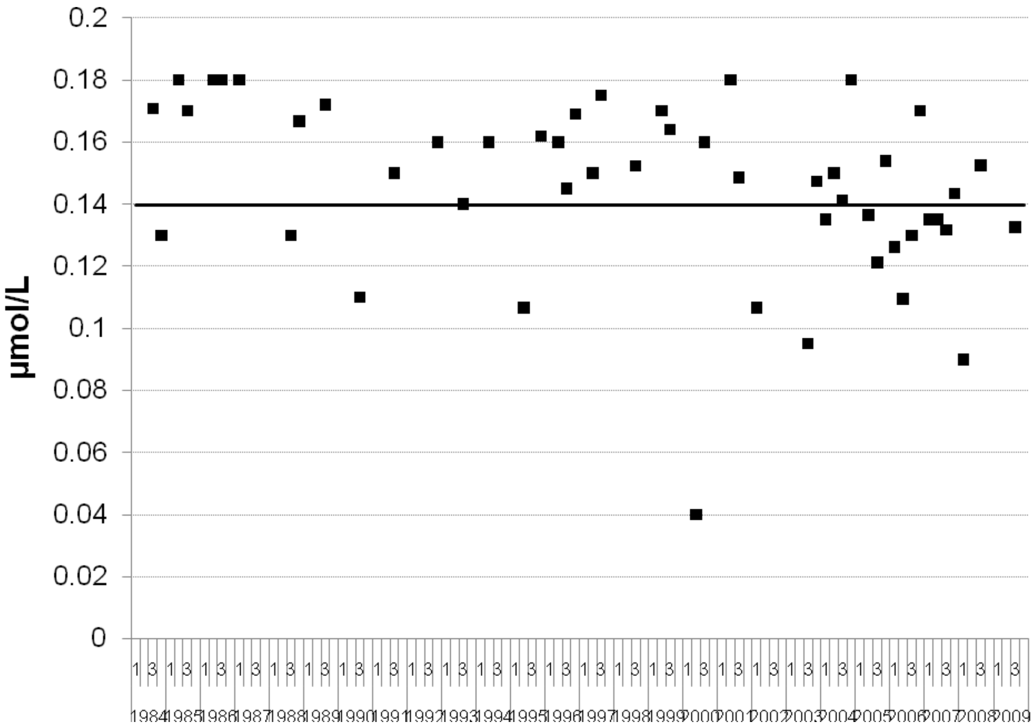



Figure 28. Mean phosphate ($PO_4$) concentrations (µmol/L) by season (1 = Win = Jan–Mar; 2 = Spr = Apr–Jun; 3 = Sum = Jul–Sep; 4 = Fall = Oct–Dec), from 1984 to 2009 at depths less than 6 m. Long-term mean indicated by a thick horizontal line. Geographic range encompasses station grid 66.7 (CalCOFI north) through grid 136.7 (IMECOCAL–Baja California). Data accessible in the CCE LTER data repository supported by the Division of Ocean Sciences, NSF Grant OCE-0417616. Data set 82: Conductivity temperature depth bottle data–Survey cruise data set (CalCOFI–SIO).

# EBM Component: Vibrant Coastal Communities

Work will commence on this EBM component in FY2011.

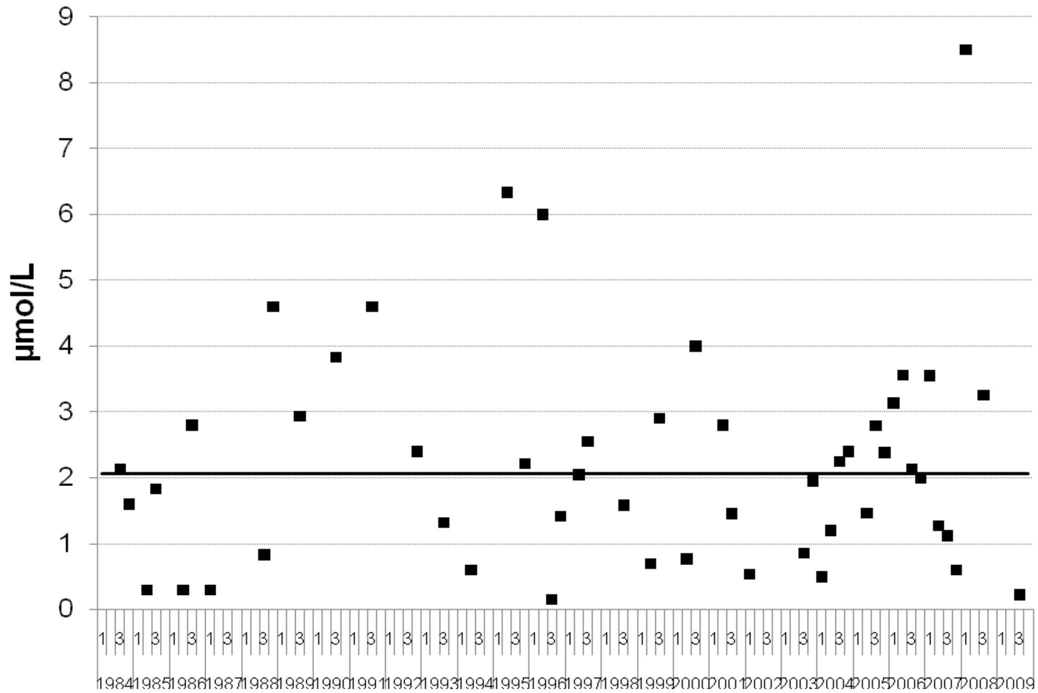



Figure 29. Mean silicate ($SiO_3$) concentrations (µmol/L) by season (1 = Win = Jan–Mar; 2 = Spr = Apr–Jun; 3 = Sum = Jul–Sep; 4 = Fall = Oct–Dec), from 1983 to 2009 at depths less than 6 m. Long-term mean indicated by a thick horizontal line. Geographic range encompasses station grid 66.7 (CalCOFI north) through grid 136.7 (IMECOCAL–Baja California). Data accessible in the CCE LTER data repository supported by the Division of Ocean Sciences, NSF Grant OCE-0417616. Data set 82: Conductivity temperature depth bottle data–Survey cruise data set (CalCOFI–SIO).

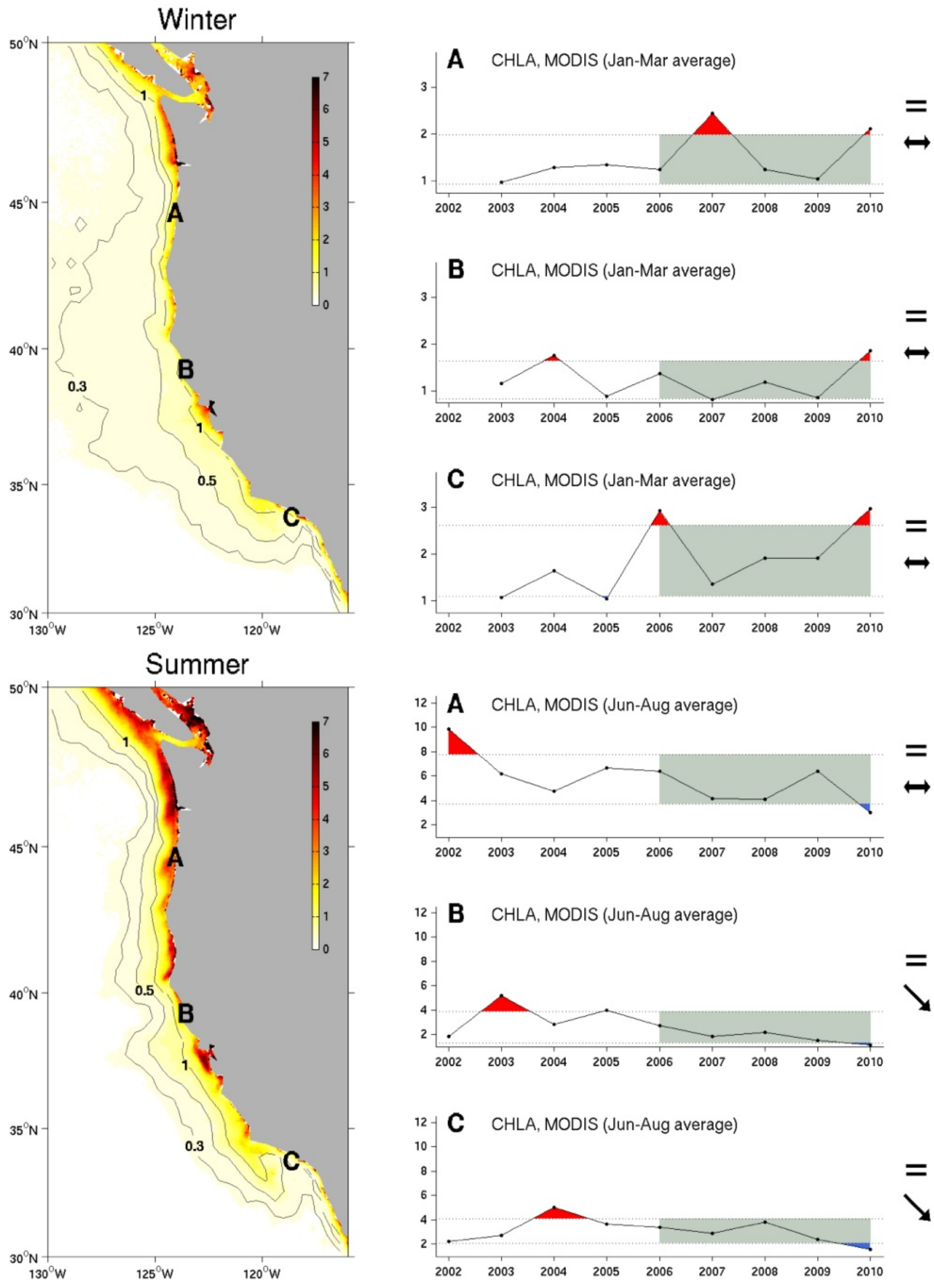



Figure 30. Winter and summer spatial means of SeaWiFS chl *a* (1999–2008) and MODIS chl *a* time series from NDBC buoys. The MODIS time series are area averages of 2 degree x 50 km boxes for north-south and east-west, respectively, and centered on locations A, B, and C. All values on the figures have units of milligrams per cubic meter. On the right side of each line chart, the equal sign indicates that the 2006–2010 mean is within the long-term SD; the down and horizontal arrows indicate whether the 2006–2010 trend is below or within 1 SD.

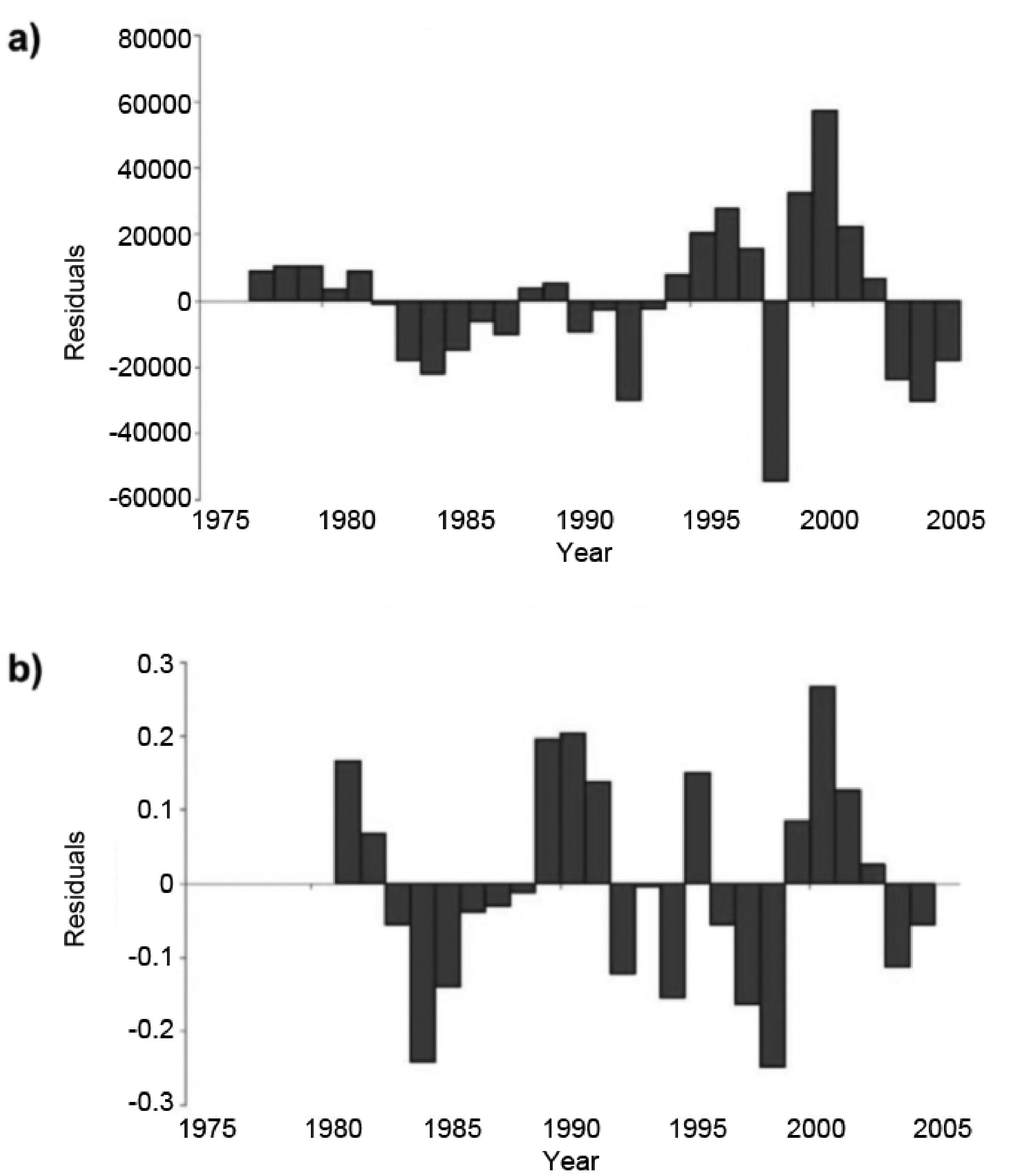



Figure 31. Market squid indices from landings data (panel a) and California sea lion diets (panel b). Note that the trend of increasing catch due to increasing fishing effort has been removed by quadratic regression. Bars represent residuals after detrending. (Catch data courtesy of Dale Sweetnam, California Department of Fish and Game, and marine mammal data courtesy of Mark Lowry, SWFSC.)

# Status of the California Current Ecosystem: Major EBM Drivers and Pressures

## Main Findings

- The CCLME is highly influenced by the southward flowing California Current. The CCLME is exhibiting natural interannual and multidecadal variability, but also undergoing changes in temperature, sea level, and upwelling consistent with anthropogenic global warming models. Time series correlations have confirmed that CCLME predator and prey populations are primarily driven by bottom-up physical oceanographic signals. Further understanding and incorporating the physical forcing in ecosystem models will improve our management of CCLME fisheries.
- Broad CCLME indices such as the North Pacific Gyre Oscillation (NPGO), PDO, MEI, Northern Oscillation Index (NOI), and the Cumulative Upwelling Index (CUI) have all shown an increasing trend over the past 50 years including increased interannual variability.
- Over the past 50 years, the CCLME shows general increasing trends in sea surface temperature in Monterey Bay, California, Newport, Oregon, and the Southern California Bight; sea level from Cape Flattery, San Francisco, and San Diego; and surface chl *a* throughout most of the CCLME.
- Long-term ocean time series have trended towards lower dissolved oxygen (DO) in the upper pycnocline, from Southern California to Oregon. Shoaling of the hypoxic boundary in parts of the CCLME may lead to habitat compression. Hypoxic events on continental shelf hypoxia have become more common off Oregon and can have lethal consequences for coastal benthic species.
- Over the past 5 years, intense upwelling was documented in 2006 to 2008. A cool phase since 1999 continued to be observed in both low PDO and high NPGO values. From late 2009 to early 2010, downwelling favorable conditions were dominant due to a short duration El Niño. The El Niño was quickly followed by increased offshore transport with La Niña conditions in summer of 2010. Resultant increased upwelling and productivity are likely to persist through mid-2011.

# EBM Driver and Pressure: Climate

## Physical Drivers and State Variables

### Large scale climate forcing

**PDO**—This is a low frequency signal in North Pacific sea surface temperatures that affects biological productivity in the Northeast Pacific. Cold (negative values of the PDO) eras are associated with enhanced productivity in the CCLME and vice versa. The PDO index (Figure 32) has been largely in a positive (i.e., warm California Current and Northeast Pacific) state since late 1977, resulting in warmer waters along the coast of the CCLME with negative periods from 1998 to 2002 and 2006 to 2008. Over the past 5 years, the winter index declined from 2005 to 2009 with a sharp increase in 2010. The summer index was more stable with a sharp trough in 2007.

**MEI**—The index describes ocean-atmosphere coupling in the equatorial Pacific. Positive (negative) values of the MEI represent El Niño (La Niña) conditions. El Niño conditions in the CCLME are associated with warmer surface water temperatures and weaker upwelling winds. The MEI also had an increasing trend, with more positive values since 1977 (Figure 32). Most recently, the MEI had a relatively strong negative value in the winter of 2008 indicating more productive, greater upwelling, La Niña conditions. The MEI switched to positive suggesting El Niño conditions in the beginning of 2010, which switched to a negative value in the summer of 2010. Projections indicate continued La Niña conditions through mid-2011.

**NPGO**—This is a low frequency signal in sea surface heights over the Northeast Pacific. Positive (negative) values of the NPGO are linked with increased (decreased) surface salinities, nutrients, and chl *a* values in the CCLME. Since 1975 there have been more extreme and longer duration events with positive NPGO values than earlier in the time series (Figure 32). Winter and summer trends were very similar with a broad low from 1991 to 1997 and a peak from 1998 to 2004. Since 2006 values have been increasing with one near 0.0 year in 2009.

**NOI**—This index of sea level pressure difference between the North Pacific High and Darwin, Australia, describes the strength of atmospheric forcing between the equatorial Pacific and the North Pacific, particularly in terms with ENSO. Positive (negative) values are associated with cooler (warmer) SST in biologically important regions of the CCLME. NOI was largely positive from 1950 to 1977, but switched to more negative values until 1998 (Figure 32). In the winter, NOI values were positive from 2006 to 2009 with a drop and overall negative trend in 2010. In summer 2010, NOI values became strongly positive, which should result in increased coastal upwelling in the California Current.

**CUI**—This is an index of the cumulative upwelling. Upwelling has been variable, with an apparent general increase in NOAA's west coast upwelling index (Schwing and Mendelssohn 1997). The 2005 upwelling season was unusual in terms of its initiation, duration, and intensity. In 2005 upwelling was delayed or interrupted and SSTs were approximately 2–6°C warmer than normal (GRL 2006). The situation in the southern ecoregion was different in both 2005 and 2006, as average upwelling and SST prevailed (Peterson et al. 2006). Other than a brief period

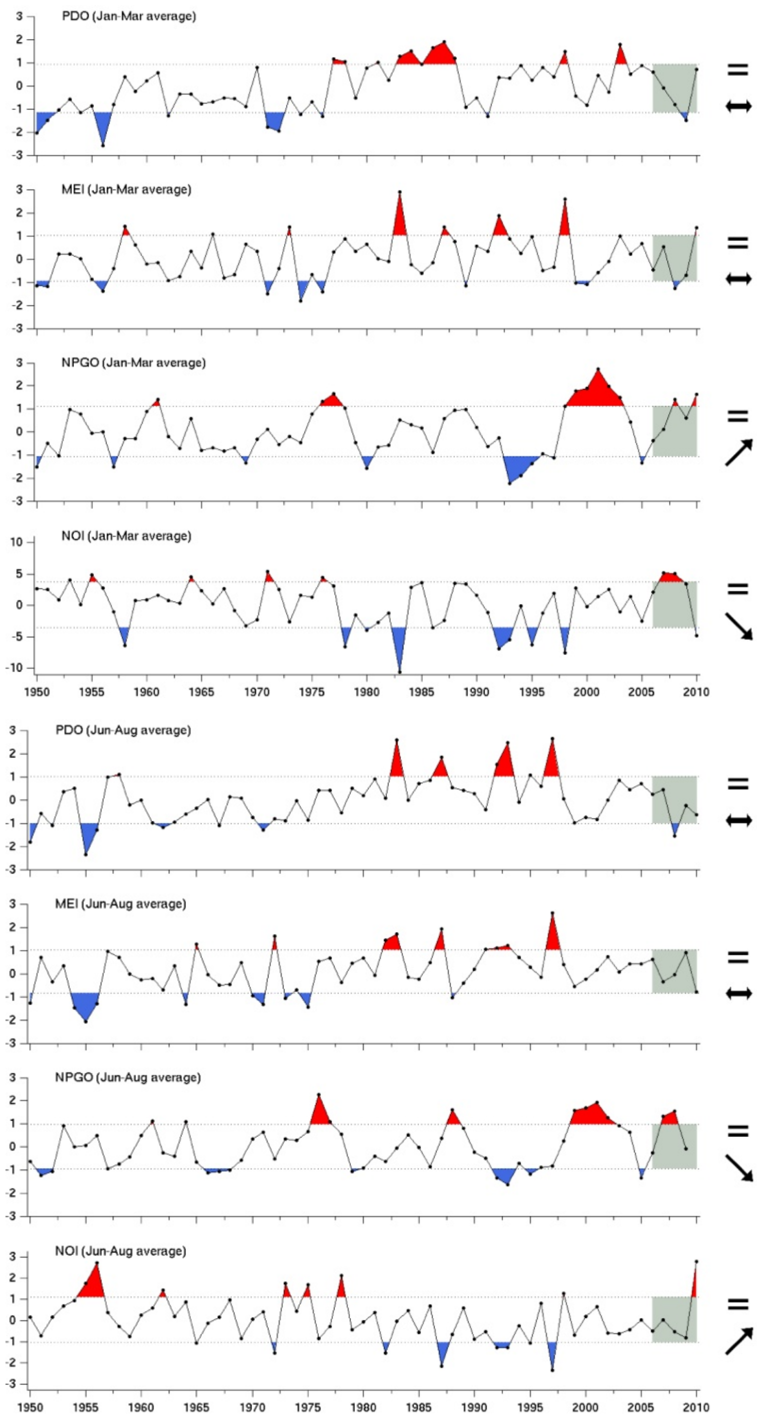



Figure 32. Winter (January-March) and summer (June-August) averages of PDO, MEI, NPGO, and NOI. Dashed lines reflect 1 SD above and below the long-term mean. Positive/negative PDO values indicate warm/cool eastern North Pacific SSTs. Positive/negative MEI values reflect El Niño/La Niña events. Positive/negative NPGO values indicate a strong/weak North Pacific Gyre and increased/decreased advective transport from the north into the CCLME. Positive/negative NOI values indicate a cooler/warmer SST in the biologically important regions of the CCLME. On the right side of each line chart, the equal sign indicates that the 2006–2010 mean is within the long-term SD; the up, down, and horizontal arrows indicate whether the 2006–2010 trend is above, below, or within 1 SD.

of weaker than normal upwelling in the summer of 2008, west coast upwelling has been increasing since the late summer of 2006 (Figure 33). Wind patterns in early 2009 reflect anomalously strong high pressure over the Northeast Pacific and very high upwelling while early to mid 2010 appears to be a below average upwelling year at lat 35–45°N.

### Large scale physical and biological conditions

**SST**—Cold upwelled water often results in high productivity but nutrient content depends on remotely forced state of the ocean, which can be indicated by large-scale climate indices (NPGO, PDO, MEI, and NOI). Negative NPGO, positive PDO, and positive MEI would act in concert to create an extremely warm, low-productivity regime in the CCLME. According to many long-term data sets, SSTs have increased by 0.5°C to 1.0°C over the past 50 years (IPCC 2007). SST from three NOAA National Data Buoy Center (NDBC) buoys showed highs in 1983 and 1998 corresponding with increased MEI values (Figure 34). North of Cape Mendocino (excluding buoy C), winter SST values showed a cool, productive period from 1999 to 2002, changing to a warm, relatively unproductive period from 2003 to 2006. South of Cape Blanco, buoys B and C show a declining trend in SST from 2006 to 2010. From 1999 to 2008, spatial patterns in winter SST show a zonal gradient from warm in the south to cold in the north. In the summer, upwelled waters result in cooler SSTs hugging the coast north of Cape Mendocino, while the Southern California Bight shows no appreciable cooling from upwelling.

**Winds**—Northerly winds in the CCLME result in offshore transport and upwelling of cold, nutrient rich water into the photic zone. In the winter, meridional (north/south) winds were consistently northward in 1998 and 2010, indicative of downwelling favorable conditions (positive MEI and NOI; Figure 35). In winter 2006, winds were also indicative of downwelling although less extreme than 1998 and 2010. In summer 2006 and winter 2007, there were highly favorable upwelling winds at the northern buoys (A and B). In summer 2010, upwelling favorable winds dominated all three buoys. Spatial patterns in winter winds show a change in a direction from upwelling favorable above lat 42°N to downwelling favorable south. A local maximum in northerly winds was between long 120 and 125°W and below lat 35°N. In the summer, the CCLME consists of entirely northerly winds with a peak at lat 39°N and long 124°W near buoy B.

**Sea level**—Sea level heights are used as proxies for nearshore surface current strength and direction. In the winter, sea levels are high due to the poleward flowing counter current (Davidson Current). With the onset of upwelling winds in the spring, sea levels lower and the current is directed equatorward; the equatorward flow is dominant in the spring and summer. Since 1950, there has been an increasing trend particularly until 1977 with subsequent higher interannual variability and more numerous positive anomalies (Figure 36). Over the past five winters, station 1 showed an increasing trend since 2006 while all three stations had high values in 2010. For the past five summers, sea level height has declined with 2010 a particularly low year.

**Hypoxia**—The northern CCLME has had increased continental shelf hypoxia and shoaling of the hypoxic boundary resulting from enhanced upwelling, primary production, and respiration. Severe and persistent anoxic events have had downstream effects on both demersal fish and benthic invertebrate communities off Oregon. For example, during a severe anoxic

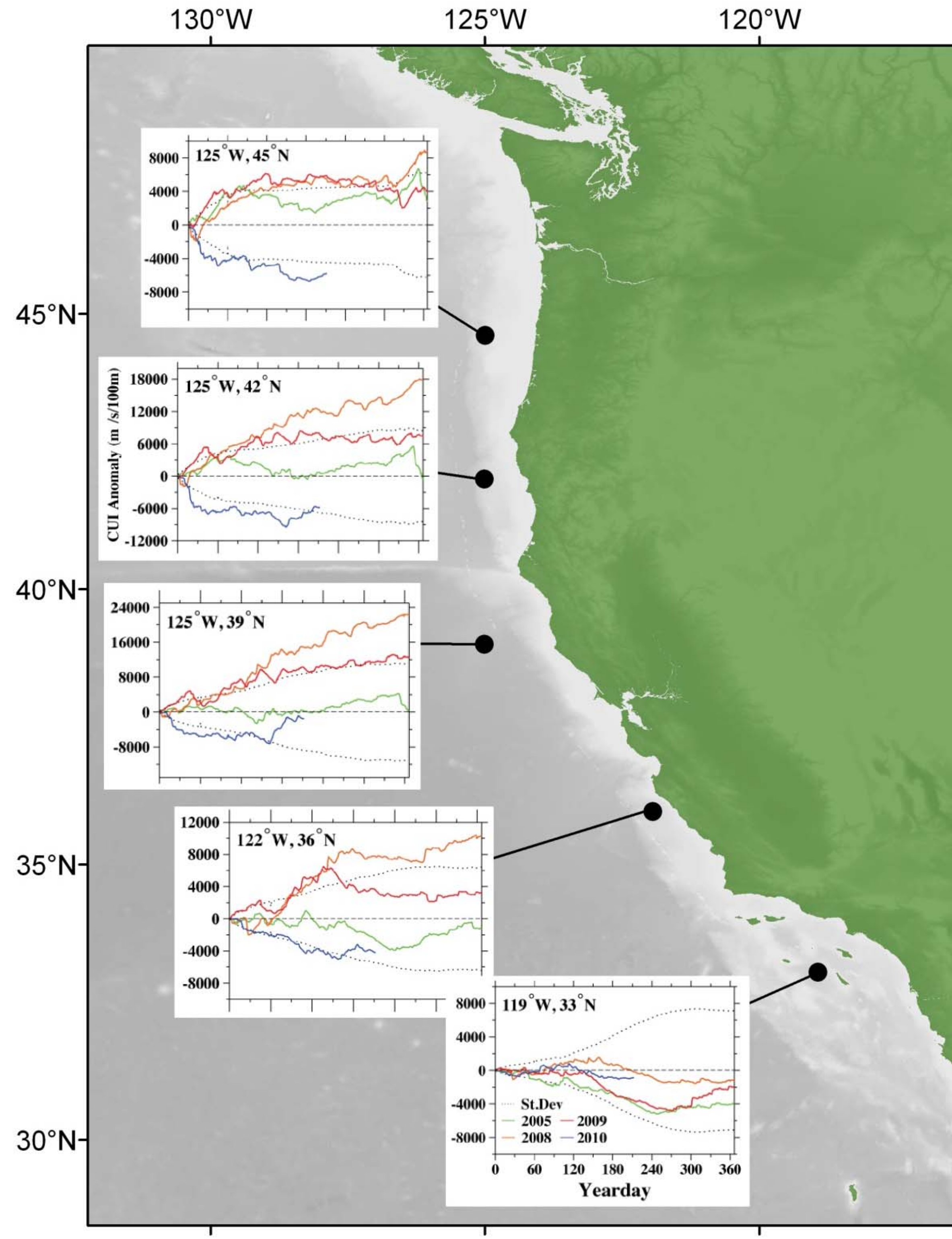



Figure 33. Map of the California Current cumulative upwelling index anomaly locations and trends. Filled circles represent the position of measurements, while each inset plot shows the difference from mean upwelling since 1967. Years 2005 (anomalous late), 2008 (normal), 2009, and 2010 are shown for reference.

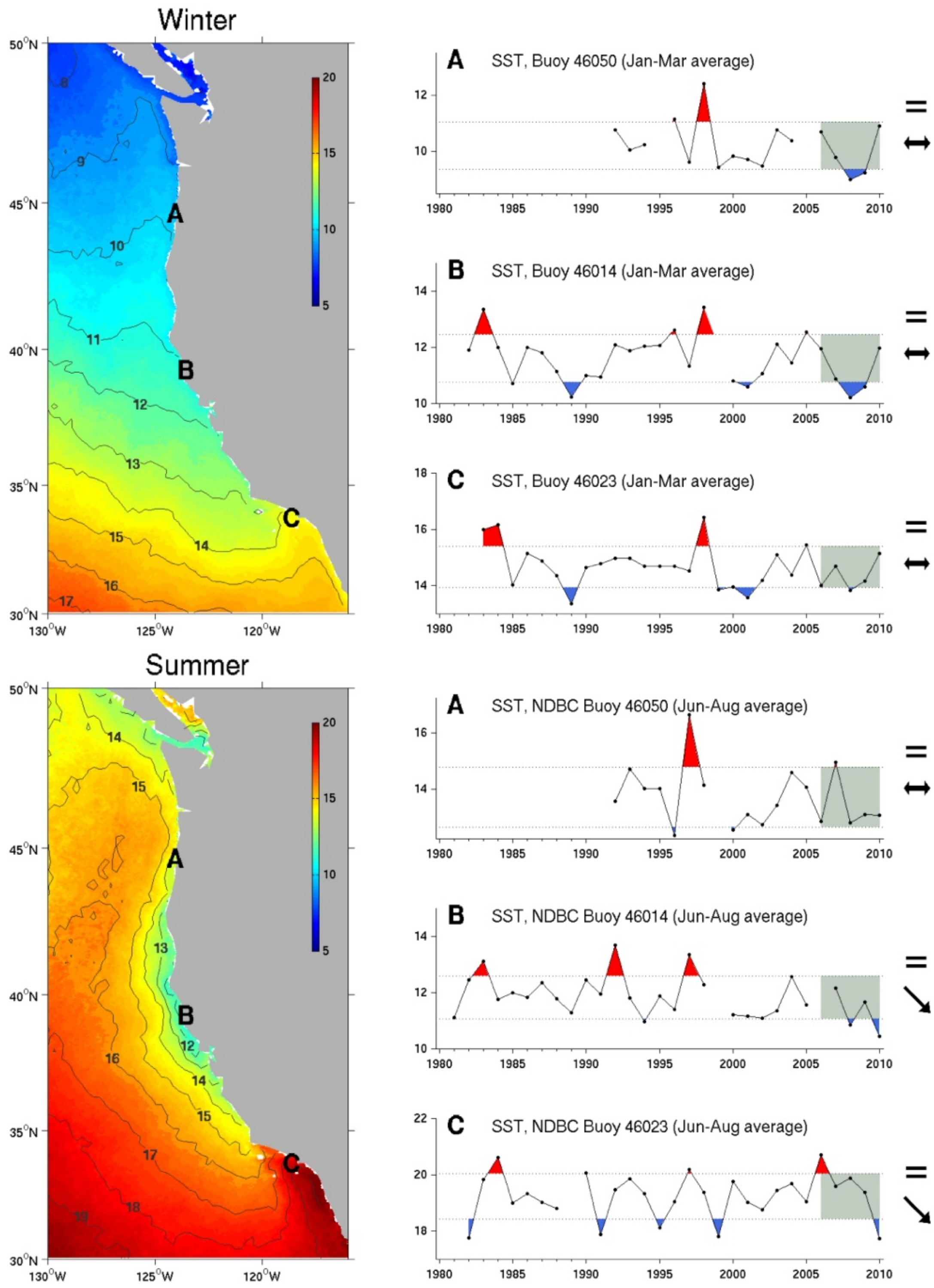



Figure 34. Winter and summer spatial means of Pathfinder SST (1999–2008) and SST time series from NDBC buoys. The locations of the NDBC buoys where the SST time series are taken from are labeled with the letters A, B, and C. All values on the figure have units of degrees Celsius. On the right side of each line chart, the equal sign indicates that the 2006–2010 mean is within the long-term SD; the down and horizontal arrows indicate whether the 2006–2010 trend is below or within 1 SD.

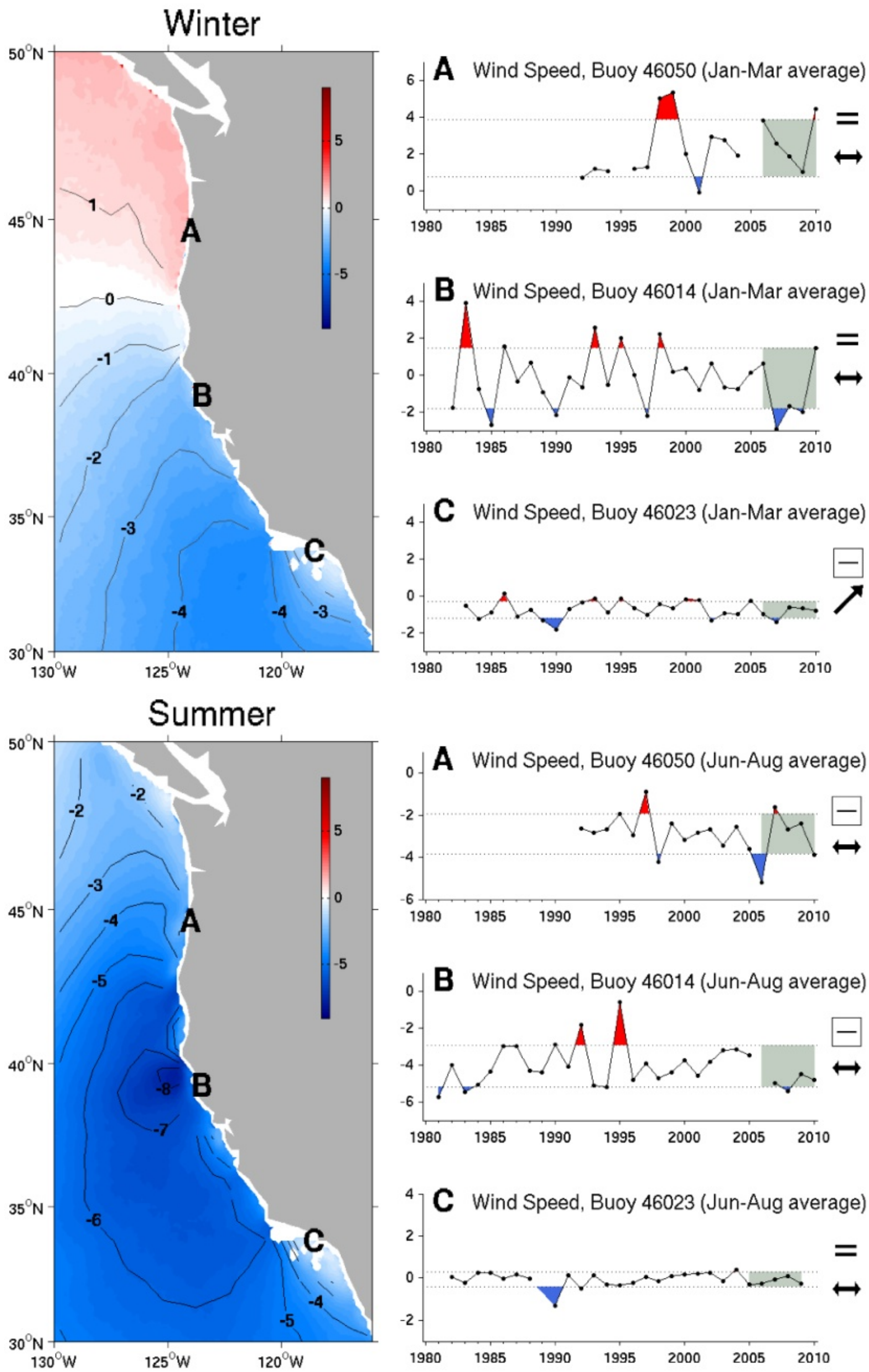



Figure 35. Winter and summer spatial means of QuikSCAT meridional winds (1999–2008) and meridional winds time series from NDBC buoys. Positive values indicate southerly winds and negative values indicate northerly, upwelling favorable winds. The locations of the NDBC buoys where the SST time series are taken from are labeled with the letters A, B, and C. All values on the figures have units of meters per second. On the right side of each line chart, the minus and equal signs indicate whether the 2006–2010 mean is below or within the long-term SD; the up and horizontal arrows indicate whether the 2006–2010 trend is above or within 1 SD.

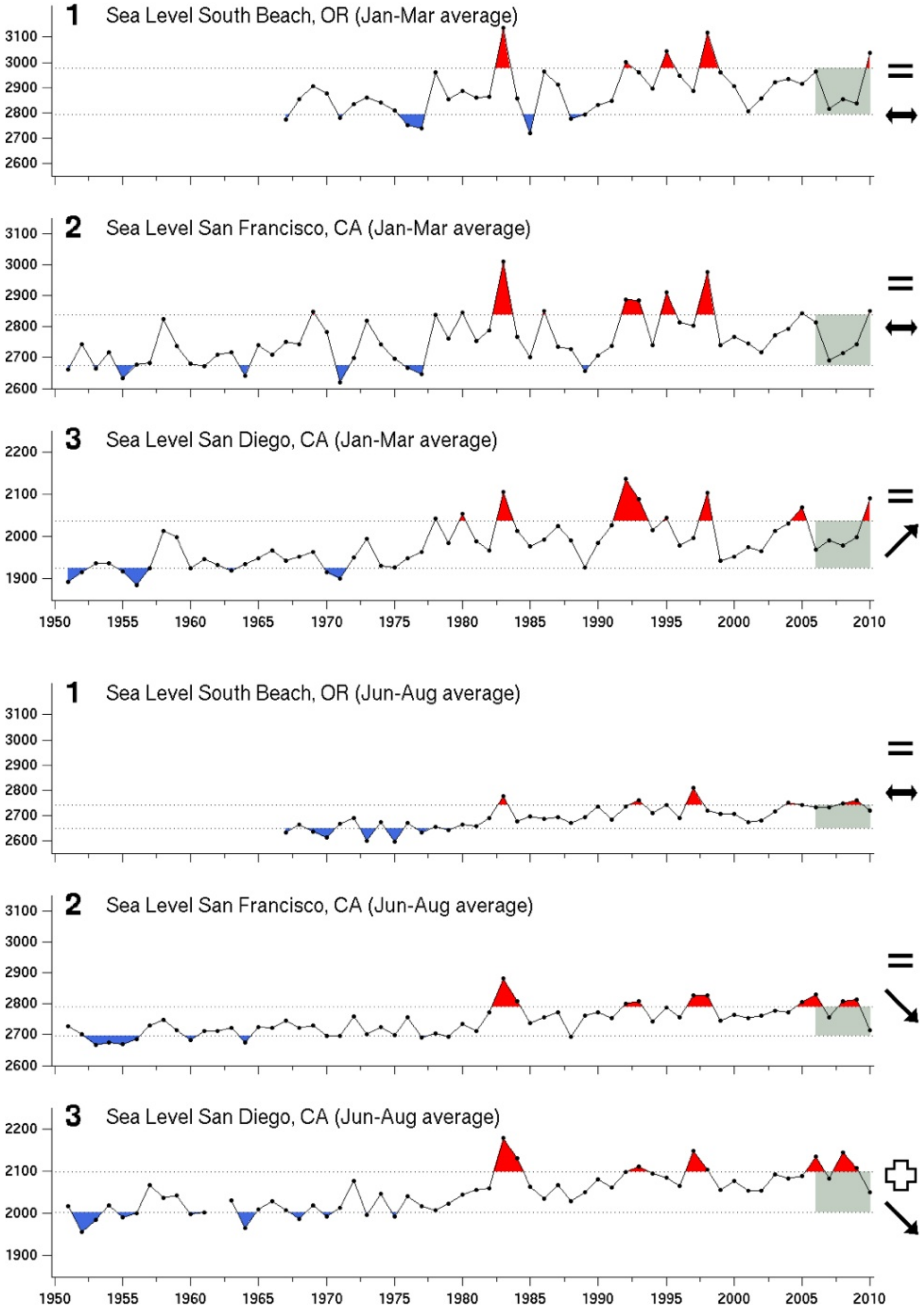



Figure 36. Winter (January-March) and summer (June-August) of sea level heights at three locations in the CCLME. All values on the y-axes have units of millimeters. On the right side of each line chart, the plus and equal signs indicate whether the 2006–2010 mean is above or within the long-term SD; the up, down, and horizontal arrows indicate whether the 2006–2010 trend is above, below, or within 1 SD.

event in August 2006, surveys found an absence of rockfish on rocky reefs and a large mortality event of macroscopic benthic invertebrates (Chan et al. 2008). Seasonality in oxygen concentrations shows summer hypoxia and well oxygenated winter waters along the Newport Hydrographic Line since September 2005. Strong summer upwelling in 2006 resulted in near anoxic water upwelled onto the shelf (Figure 37). In 2007 low oxygen concentrations were a result of relatively strong upwelling off Oregon. Despite higher than average upwelling in 2008, boundary waters remained well oxygenated save two occasions.

In the southern CCLME, deepening of the thermocline and decreased oxygen in deep source waters have resulted in increased subsurface oxygen depletion (Bograd et al. 2008, Figure 34). Large-scale wind forcing models predict hypoxia will continue to expand under Intergovernmental Panel on Climate Change warming scenarios (Rykaczewski and Checkley 2008).

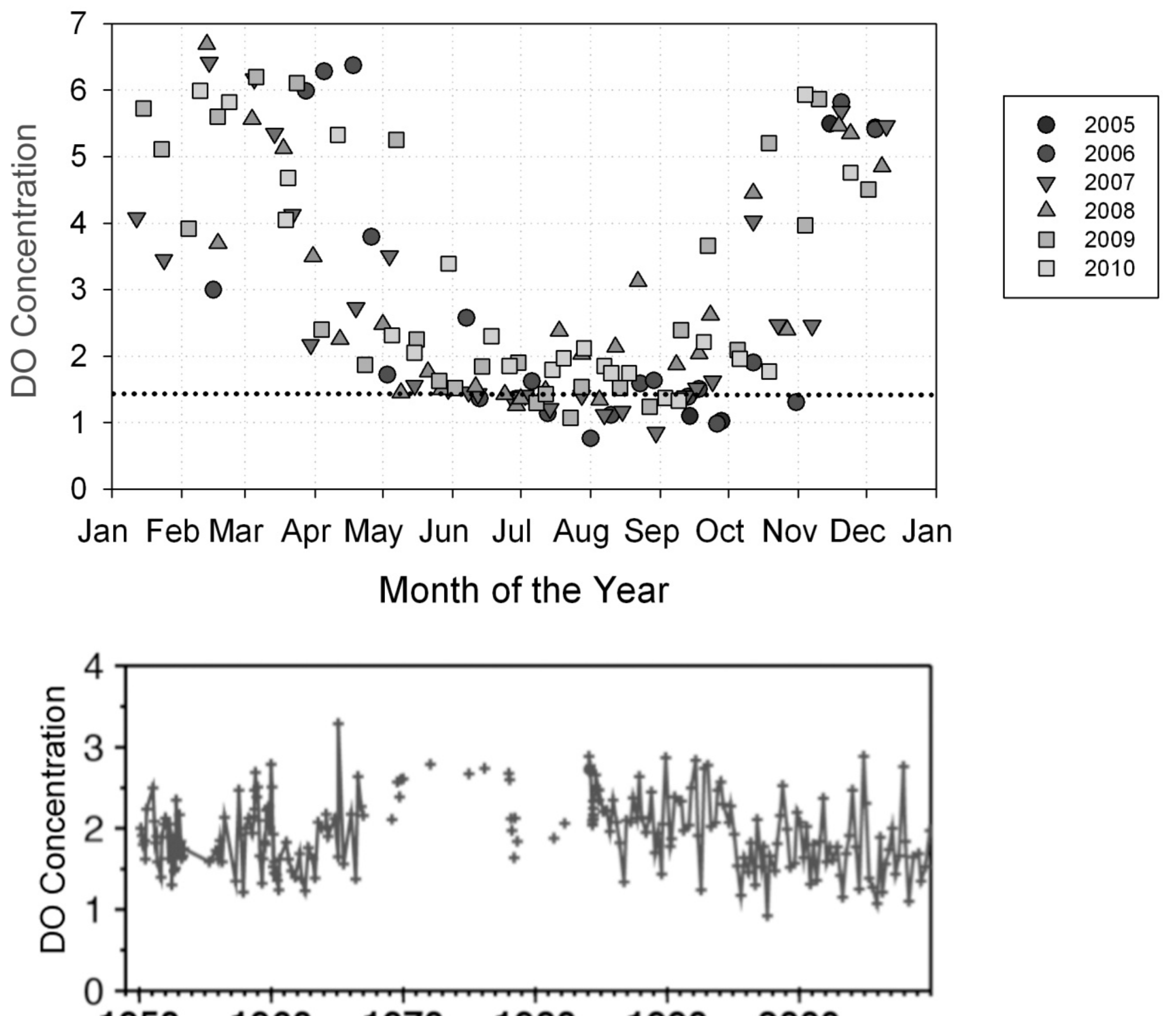



Figure 37. Dissolved oxygen concentrations (ml • $L^{-1}$) off the coast of Newport, Oregon, at 50 m depth at Newport Hydrographic Line Station NH 05 (upper chart). Dissolved oxygen at 200 m depth from the CalCOFI grid station 93.30 that is located off the coast of San Diego, California (lower chart).

## Implications of Climate Drivers for Coastal and Marine Spatial Planning

There are regional differences within the CCLME in climate forcing and ecosystem response (Figure 32 through Figure 36). Therefore, an assessment of the southern California Current region may vary from that for the northern California Current (Figure 1). When considering an overall IEA for the CCLME, it may prove most useful to evaluate each ecoregion/subecosystem separately initially. But in no single region are all the physical and especially biological attributes available for comprehensive analyses. Therefore, to understand ecosystem form, function, and control, we must combine information between regions with the goal for a uniform CCLME IEA. The IEA is spatially and temporally targeted for specific management foci; thus IEA evaluations will be scenario driven as a function of the management strategies being evaluated.

The northern CCLME is dominated by strong seasonal variability in winds, temperature, upwelling, and plankton production. In addition to weak, delayed, or otherwise ineffectual upwelling, warm water conditions in this region could result from either onshore transport of offshore subtropical water or northward transport of subtropical coastal waters. Low copepod species richness and high abundance of northern boreal copepods (Figure 25) is apparently associated with cold, subarctic water masses transported to the northern CCLME from the Gulf of Alaska. Therefore, copepod community composition may be used as an indicator of this physical oceanographic process.

Preliminary evidence suggests covariation between ecoregions. As an example, when fatty, subarctic northern boreal copepods are present in the northern CCLME during cool water conditions, the productivity of the planktivorous Cassin's auklet in the central subregion increases. Conversely, when the less fatty subtropical copepods dominate the system in warm water years (i.e., a higher southern copepod index), Cassin's auklet breeding success is reduced (Bograd et al. 2010). Because patterns in northern copepods affect central bird species, it is important to perform analyses across boundaries and ecoregions.

As noted previously, there are regional differences in oceanography and biology. Moreover, within each region, there are differences in habitats that may be related to bathymetry and geology. Understanding the relationships between topography, oceanography, species distributions, and interactions will promote better management of CCLME resources spatially as well as temporally. The relationships between bottom topography and ecosystem productivity are not well known, but so-called benthic-pelagic coupling is likely to be an important driver for top predators. Identification and assessment of predictable locations of high species diversity and increased trophic interactions can serve as an important science basis for coastal and marine spatial planning and a common currency to assess trade-offs across sectoral uses of CCLME regions.

## Effects of Anthropogenic Climate Change

Ocean temperatures have increased and are likely to continue to increase for the foreseeable future. Land is expected to heat faster than the ocean and these contrasts in temperatures may result in higher wind speeds (Bakun 1990, Snyder et al. 2003). Warmer waters are also increasing stratification (Roemmich and McGowan 1995, McGowan et al. 2003).

The effects of stronger winds and increased stratification on upwelling, temperature, and primary productivity in the CCLME are not well known (but see Schwing and Mendelssohn 1997, Mendelssohn and Schwing 2002), yet clearly will have ecosystem consequences beyond warming surface temperatures.

The timing of the seasonal cycle of productivity is changing (GRL 2006). Just as terrestrial biological systems are experiencing earlier phenology (IPCC 2007), we may observe an earlier (or later) start to the upwelling season in the CCLME, and these patterns may vary by ecoregion. If upwelling occurs earlier, this could result in an earlier seasonal cycle, from earlier phytoplankton blooms to earlier peaks in zooplankton abundance. In contrast, as noted previously, if the efficacy of upwelling is weakened or delayed by increased water stratification, the seasonal cycle of different organisms may be offset, leading to mismatches among trophic levels in both abundance and availability of prey.

With these contrasting scenarios in mind, the potential for increased interannual variability in the CCLME is probable. A more volatile climate with more extreme events will impact biological systems of the CCLME. Notably, by 2030 the minimum value of the PDO is expected to remain above the mean value for the twentieth century. In addition, evidence of variability and declines in biological systems in the CCLME since about 1990 has already been shown. Such changes and others (e.g., range shifts in species' distributions) are likely to continue.

## Linkages between Climate Drivers and some EBM Components

We examined the hypothesis of covarying trends in physical and biological attributes of the CCLME. In summary, most of the time series exhibited significant trends or change in variability over time, and covariance with other measurements, thereby supporting our hypothesis. This indicates there has been substantial ecological change in the CCLME, spanning multiple trophic levels. Moreover, many of the biological changes are related to physical conditions of the ecosystem in a manner consistent to expectations under global warming. For the biological components investigated, with few exceptions, this generally meant a decline in abundance or productivity and in some cases an increase in variance. Increased variance results in higher standard error on management targets, potentially requiring more precautionary management of stocks and resources.

Of particular importance is the recent substantial decline of coho salmon survival off Oregon and the dramatic plunge of Chinook salmon escapement in California in 2007 and 2008 after a peak in 2002. Related to this observation is the reproductive failure of Farallon Island Cassin's auklets in 2005 and 2006 after gradually improving reproductive success throughout the 1990s and early 2000s to a peak in 2002. Previously, changes in seabirds and salmon in central California have been related to one another (Roth et al. 2007), although the salmonid declines lag changes in other fish and birds by at least one year. Sydeman et al. (2006) and Jahncke et al. (2008) suggested that the decline in auklet breeding success in 2005 was tied to a reduction of prey abundance (euphausiid crustaceans) due to atmospheric blocking and weak upwelling, but the results in these papers were not conclusive due to limited information on the prey. Chinook salmon are known to feed directly on euphausiids (Brodeur 1990), particularly during their initial time at sea, as well as forage fish such as Pacific herring (Brodeur and Pearcy 1992), which are known to prey on euphausiids (Foy and Norcross 1999). The abundance and availability of euphausiids to these predators is undoubtedly related to oceanographic processes, such as upwelling and possibly currents, but to date the environmental forcing of these important zooplankton remains largely unknown.

We found no association between the abundance of *Thysanoessa spinifera* larvae from British Columbia and auklets or salmon in California, but that is not surprising given the distance between regions. These top predator species appear sensitive to variation in the abundance of prey, which are highly dependent on climatic and oceanic conditions, but linkages have been difficult to establish and may have more to do with spatial availability of prey rather than prey abundance. However, declines in the relative abundance of forage fish (juvenile rockfish, herring, and juvenile hake) were recorded and related to changes in salmon and seabird populations and productivity. Thus it is clear that predator-prey relationships are key to understanding recent failures in these species and that marine climate variability is playing a role in driving predator-prey interactions.

## EBM Driver and Pressure: Fisheries

Work documenting the status and trends of fisheries affects on EBM components will commence in FY2011.

## EBM Driver and Pressure: Habitat degradation

Work documenting the status and trends of habitat degradation and its effects on EBM components will commence in FY2011.

# Ecosystem Risk Assessment: A Case Study of the Puget Sound Marine Food Web

## Introduction

A key component of implementing an IEA is risk analysis. A risk analysis evaluates the chance within a time frame of an event with adverse consequences (Burgman 2005). Risk assessment is thus a probabilistic analysis that requires the delineation of favorable and unfavorable consequences, a task squarely in the realm of policy making. Once this delineation is made, however, science can offer guidance about the risk posed by alternative management decisions. In the context of the California Current IEA, a risk analysis should evaluate the risk to indicators posed by human activities and natural processes (Levin et al. 2009). Adverse consequences or undesirable states for the indicators can be defined by reference to the ecosystem goals established by policy makers.

For the purpose of assessment, risk is often broken down into likelihood and consequence components. In the general risk literature, likelihood is the probability of an event's occurrence and consequence is the conditional probability of an adverse result should the event occur (Burgman 2005). In ecotoxicological studies, risk is described based on the response of an organism (or population, community, etc.) to different levels of exposure to a stressor (Suter 2007). For instance, much is known about biochemical responses of Chinook salmon to exposure to toxic contaminants (e.g., Stein et al. 1995). Thus the exposure-response framework is convenient for evaluating risk due to chronic and persistent conditions faced by the subject of the risk analysis, rather than situations in which the primary focus is on risk due to infrequent, chance, or catastrophic singular events. Exposure can be viewed as the probability component of risk, while response can be viewed as the conditional probability component.

In an effort to embrace the move toward ecosystem-based fisheries management, fisheries scientists have recently adopted another risk analysis framework, called productivity-susceptibility analysis or PSA (Stobutzki et al. 2001, Hobday et al. 2004, Hobday et al. 2007, Patrick et al. 2010). The goal of a PSA is to determine the vulnerability of different fish stocks to current fisheries management practices. For example, Patrick et al. (2010) conducted a PSA for 162 U.S. fisheries stocks to evaluate their vulnerability to overfishing. The implicit assumption in their PSA was that decline or extinction of a stock is an adverse effect. Susceptibility of a stock to an adverse event is a type of probability, while productivity describes a conditional probability of an adverse effect on the stock should the event occur.

In this section, we borrow elements from exposure-response and PSA risk analyses to assess the risk to ecosystem components (e.g., species, habitats, etc.) posed by stressors associated with different human activities. A stressor is an element of a system that precipitates an unwanted outcome (Burgman 2005) and can be natural or human induced. We focus on common human activities that in particular circumstances could lead to adverse consequences for different ecosystem components. For instance, human activities like aquaculture and shipping, which offer a variety of benefits to people, can be associated with stressors for some ecosystem components. Examples of stressors potentially associated with aquaculture and shipping include nutrient inputs and noise pollution.

For our ecosystem risk assessment, we adopt elements of the exposure-response framework widely used in ecotoxicology and expand it to include stressors other than toxic contaminants. We borrow heavily from the PSA framework but broaden the approach so that it is applicable for human activities beyond fishing (Stobutzki et al. 2001, Hobday et al. 2004, Hobday et al. 2007, Rosenberg et al. 2007, Patrick et al. 2010). The result is a first-order risk analysis that integrates understanding of the extent or likely extent of exposure of different ecosystem components to the same stressor, and of an individual ecosystem component to different stressors, with an estimate of likely responses. We illustrate the approach using a case study of marine food web indicator species in Puget Sound, Washington, one of the three major estuaries nested within the CCLME.

# Methods

## Food Web Indicators in Puget Sound

We conducted the risk analysis on species under consideration by the Puget Sound Partnership (PSP), a regional management agency in Washington state, as food web indicators as of June 2010 (online at http://www.psp.wa.gov/documents.php). These species include but are not limited to Southern Resident killer whales, harbor seals (*Phoca vitulina*), Chinook salmon, canary rockfish, yelloweye rockfish, Pacific herring, and Dungeness crab (*Cancer magister*). We included partial information for two biogenic habitat forming groups, kelps and eelgrass (*Zostera marina*), in the risk analysis as well. The reason for their inclusion is that they can be considered key ecological associates for several of the PSP indicator species. We define a key ecological associate as a species with which the indicator species interacts strongly (e.g., Pacific herring and eelgrass were key ecological associates, Table 13). We acknowledge that this list of indicator species does not adequately represent benthic and detrital energy pathways. Nonetheless, it is the primary focus for the PSP and so warrants a risk analysis. The assumption

Table 13. Key ecological associates for Puget Sound food web indicator species.

| Indicator species | Key ecological associate | Reference |
|---|---|---|
| Southern Resident killer whale | Chinook salmon | NMFS 2008 |
| Harbor seal | Herring | Jeffries et al. 2003 |
| Chinook salmon, juvenile | Eelgrass | Fresh 2006 |
| Chinook salmon, adult | Southern Resident killer whale | NMFS 2008 |
| Canary rockfish, juvenile | Kelp | Drake et al. 2010 |
| Yelloweye rockfish | — | — |
| Pacific herring, embryo/larval | Eelgrass | Stick and Lindquist 2009 |
| Dungeness crab, juvenile | Eelgrass | Dethier 2006 |

of such an analysis is that risk to species thought to be indicators of food web structure and function equates to risk to food web structure and function itself.

## Quantifying Risk

### Overview

We quantified risk to ecosystem components caused by stressors associated with human activities using a modified version of PSA (Milton 2001, Stobutzki et al. 2001, Hobday et al. 2004, Hobday et al. 2007, Rosenberg et al. 2007, Patrick et al. 2010). This approach is a type of risk ranking method (Burgman 2005) that relies on qualitative estimates of likelihood and consequence to estimate risk, but can use quantitative information when it is available. Though the approach we used is general and could be adapted for ecosystem components such as habitats, community indices (e.g., diversity), or other ecosystem endpoints (sensu Harwell et al. 1999), for clarity hereafter we discuss the analysis in terms of risk to individual species. We refer to ecosystem-based risk to species throughout the paper, but the framework is intended to evaluate the risk of decline of a species population on the spatial scale at which management is implemented, rather than the risk of extinction of a species from throughout its range.

We defined risk in a two-dimensional space created by susceptibility and consequence axes. In our application, susceptibility $S$ is the probability that the stressors associated with an activity affect the species at a particular level of intensity. Consequence $C$ to a species is the conditional probability that the stressors associated with an activity have a particular level of impact on the species, given that the species is susceptible (Stobutzki et al. 2001). Values of susceptibility and consequence were determined by providing a score ranging from 1 to 3 for a standardized set of criteria related to each axis (n = 8 criteria/axis), and then averaging the scores to create susceptibility and consequence indices. The overall risk $R_i$ to species $i$ can be calculated as the Euclidean distance of the species from the origin in the susceptibility-consequence space, or

$$R_i = \sqrt{(S-1)^2 + (C-1)^2} \qquad (1)$$

Species with high susceptibility and consequence scores are considered to be at higher risk to a particular stressor.

The criteria we used were modified from a catalog of approximately 80 possibilities considered by Hobday et al. (2004, their Appendix H) and Patrick et al. (2010). The goal was to arrive at a list of criteria that at once provided for complementarity and parsimony, did not lead to high sensitivity of either axis to a single criterion, described risk inherent to individual species due to ecological and social factors, and revealed how the risk to each species varied among stressors. In order to increase the transparency of our analysis, we included a citation of the scientific peer-reviewed literature or government agency reports for each score. The bins for susceptibility and consequence scores were borrowed directly from Patrick et al. (2010) or modified so as to reduce subjectivity and facilitate rapid analysis. The criteria are described in detail below.

## Susceptibility criteria

The susceptibility criteria we selected include spatial, temporal, and management factors that describe the degree of exposure or likelihood of exposure of each species to stressors (Table 14). For this reason, we plot a species' susceptibility index on the abscissa in the figures. For each species, the scores for the criteria indicated with an asterisk (*) differed among stressors.

**Spatial factors**—*Spatial intensity (direct effect).** This criterion was used to describe the relationship between the distribution of the species (including information about relative abundance) and the relative intensity of the stressor throughout that distribution. We estimated spatial intensity using a three-step process, such that greater intensity implied greater susceptibility. First, we scored the relative abundance of the species in seven action areas designated by the Washington state legislature (PSP 2008). These action areas include Hood Canal, north central Puget Sound, San Juan/Whatcom, south central Puget Sound, south Puget Sound, Strait of Juan de Fuca, and Whidbey Island (Figure 38). Relative abundance was scored based on presence/absence data or absolute abundance such that a value of 1 indicated that a species was absent or very rare in the action area, a value of 2 indicated that the species occurred in some locations within the action area, and a value of 3 indicated that the species occurred commonly throughout the action area. Where there were discrepancies between historical and modern records regarding the relative abundance of mobile species in a particular action area, we used the larger score (Table 15).

Second, we scored the relative intensity of the stressor in each action area (e.g., fisheries landings, density of overwater structures, etc.). The scoring bins for the stressors were defined by taking the $\log_{10}$ of the stressor intensity and normalizing to a maximum integer value of 3 (estimates <1 were rounded to 1). Sources of data for stressors associated with each activity are described below.

Third, we calculated the score for the spatial intensity criterion by averaging each species' relative abundance score and stressor relative intensity score in each action area for which the species relative abundance score was greater than 1. In action areas where the species relative abundance score was equal to 1, spatial intensity was set equal to 1 as well. Sound-wide spatial intensity was calculated by averaging the action area–specific intensity cores.

In the future we recommend using a GIS-based approach to quantitatively calculate the overlap between species abundances and stressor intensities (Hobday et al. 2007). In addition, it would be best if the intensity of the stressor could be associated with a threshold value (e.g., $F_{MSY}$, total maximum daily load, etc.), so the bins for this criterion could be linked to an absolute assessment of susceptibility. However, in the absence of quantitative information about species and stressor intensity distributions, a qualitative scoring procedure that reflects the bins listed in Table 1 could be used.

*Spatial intensity (food web effect).** We used the same approach as described above for the direct effect spatial intensity criterion, but in this case calculated the overlap between the spatial distribution of relative stressor intensity and at most one key ecological associate, that is, a habitat-forming species or one known to be a critical prey resource for the indicator species

Table 14. Susceptibility criteria for risk analysis.

| Factor | Description | Susceptibility: Low (1) | Susceptibility: Moderate (2) | Susceptibility: High (3) |
|---|---|---|---|---|
| *Spatial factors* | | | | |
| Spatial intensity (direct effect)* | The overlap between the relative abundance of the ecosystem component and the relative intensity of the stressor throughout that distribution | Ecosystem component and stressor absent or rare | Ecosystem component occurs but is not ubiquitous and is subject to moderate intensity of stressor | Ecosystem component ubiquitous and subject to high stressor intensity |
| Spatial intensity (food web effect)* | The overlap between the relative abundance of key ecological associates (prey, predators, competitors, biogenic habitats) and the relative intensity of the stressor throughout that distribution | Key ecological associate and stressor absent or rare | Key ecological associate occurs but is not ubiquitous and is subject to moderate intensity of stressor | Key ecological associate ubiquitous and subject to high stressor intensity |
| *Temporal factors* | | | | |
| Temporal intensity (direct effect)* | The overlap between the monthly relative abundance of the ecosystem component and the monthly relative intensity of the stressor | Ecosystem component and stressor do not co-occur or stressor does not affect ecosystem component | Ecosystem component and stressor co-occur for some months of the year | Ecosystem component and stressor co-occur year-round |
| Temporal intensity (food web effect)* | The overlap between the monthly relative abundance of the ecosystem component and the monthly relative intensity of the stressor | Ecosystem component and stressor do not co-occur or stressor does not affect ecosystem component | Ecosystem component and stressor co-occur for some months of the year | Ecosystem component and stressor co-occur year-round |
| *Management factors* | | | | |
| Value of exploited species | The ex-vessel value of fished stocks; highly valued stocks are assumed to be more susceptible to stressors because fishing effort is likely to be greater | <$500/yr or <$1/lb | $500–$10,000/yr or $1.00–$2.25/lb | >$10,000/yr or >$2.25/lb |

Table 14 continued.  Susceptibility criteria for risk analysis.

| **Factor** | **Description** | **Susceptibility** Low (1) | **Susceptibility** Moderate (2) | **Susceptibility** High (3) |
|---|---|---|---|---|
| *Management factors (continued)* | | | | |
| Societal value | The degree to which societal preferences for the component (as expressed in replacement value, willingness to pay, contingent valuation, etc., analyses) reduce its susceptibility | >$1,000 | $100–$1,000 | <$10 |
| Effectiveness of current management strategy* | The track record of current management approaches used to mitigate the direct effects of the stressor | Very effective or not a stressor on the indicator species | Effective, currently considered a stressor on the indicator species, but one that is in control | Not effective, currently considered a stressor on the indicators species that is poorly managed |
| Current status | The status of the component will affect its susceptibility to increased effects of the stressor, best if current status can be evaluated relative to a baseline level | Low concern | Threatened or of concern | Endangered |

*Indicates that criterion varies across stressors for each species.

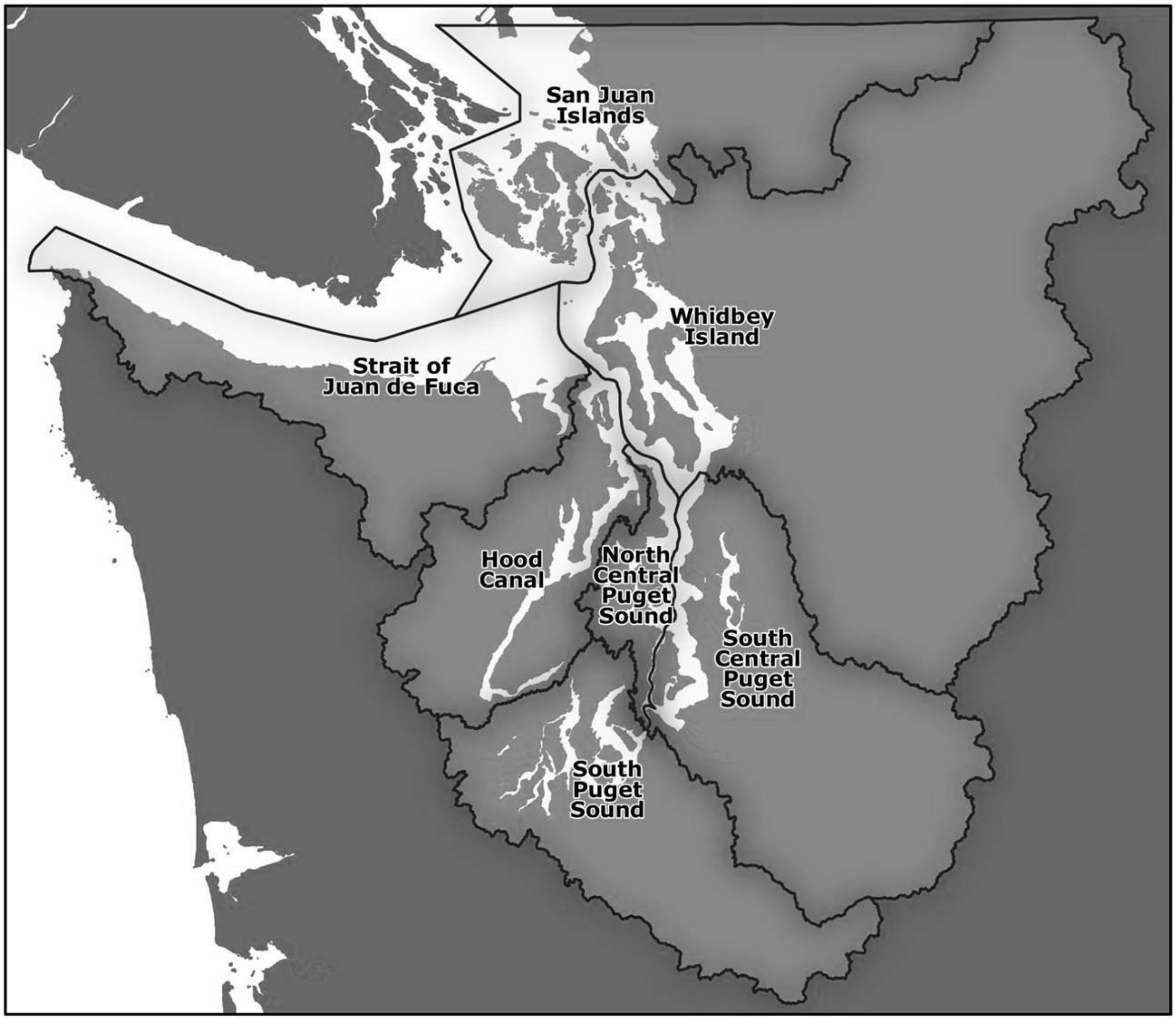



Figure 38. Map of the seven Puget Sound action areas. (Map by Jeremy Davies, NWFSC.)

(e.g., Pacific herring and eelgrass were key ecological associates, Table 13). The rationale for this criterion is that spatial overlap between a stressor and a key ecological associate will indirectly modify the susceptibility of the indicator species.

**Temporal factors**—*Temporal intensity (direct effect).** We used this criterion to describe the overlap between temporal variation in the relative abundance of the ecosystem component and in the relative intensity of the stressor (Table 14). We estimated temporal intensity using a three-step process, where greater intensity implies greater susceptibility. First, we scored the relative abundance of each species in each month of the year such that a value of 1 indicated a species was absent or very rare during a particular month, a value of 2 indicated the species was present in moderate quantities during a particular month, and a value of 3 indicated the species was abundant during a particular month. For each species, this procedure was completed for the major life stages that occur in Puget Sound. Scores for the different life stages of each species were averaged to generate monthly relative abundance scores (Table 16).

Table 15. Spatial distribution scores of Puget Sound food web indicator species.*

| Criterion | Southern Resident killer whale | Harbor seal | Chinook salmon | Canary rockfish | Yelloweye rockfish | Pacific herring | Dungeness crab | Eelgrass | Kelp |
|---|---|---|---|---|---|---|---|---|---|
| Hood Canal | 1.0 | 2.0 | 2.0 | 1.0 | 1.0 | 2.0 | 1.5 | 3.0 | 1.5 |
| North central Puget Sound | 2.0 | 1.5 | 3.0 | 2.0 | 2.0 | 3.0 | 1.0 | 3.0 | 2.0 |
| San Juan/Whatcom | 3.0 | 3.0 | 1.5 | 2.0 | 1.5 | 3.0 | 3.0 | 3.0 | 3.0 |
| South central Puget Sound | 2.0 | 1.5 | 3.0 | 2.0 | 2.0 | 1.5 | 2.0 | 3.0 | 2.0 |
| South Puget Sound | 1.5 | 3.0 | 1.5 | 2.0 | 1.5 | 3.0 | 1.5 | 2.0 | 2.0 |
| Strait of Juan de Fuca | 2.0 | 2.0 | 1.5 | 1.5 | 1.5 | 2.0 | 2.0 | 2.0 | 3.0 |
| Whidbey | 2.0 | 2.0 | 3.0 | 2.0 | 2.0 | 3.0 | 3.0 | 2.5 | 2.0 |
| Data quality | 1.0 | 1.0 | 1.0 | 2.0 | 2.0 | 2.0 | 2.0 | 1.0 | 1.0 |

*Records of species distributions were obtained from Krahn et al. 2002, Hauser 2006, Kriete 2007, http://www.orcanetwork.org/sightings/map.html #recent for Southern Resident killer whales; Jeffries et al. 2003 and Harvey et al. 2010 for harbor seals; Good et al. 2005 for Chinook salmon; Washington 1977 and Palsson et al. 2009 for canary and yelloweye rockfish; WDNR 1972 for Pacific herring; Dethier 2006 for Dungeness crab; and Mumford 2007 for kelp and eelgrass.

Table 16. Temporal distribution scores of Puget Sound food web indicator species* (table continued horizontally on next page).

| **Month** | **Southern Resident killer whale, calf** | **Southern Resident killer whale, adult** | **Harbor seal, pup** | **Harbor seal, adult** | **Chinook salmon, juvenile** | **Chinook salmon, adult** | **Canary rockfish, larvae** | **Canary rockfish, juvenile** | **Canary rockfish, adult** |
|---|---|---|---|---|---|---|---|---|---|
| January | 2 | 2 | 1 | 3 | 1 | 1 | 3 | 3 | 3 |
| February | 2 | 2 | 1 | 3 | 1 | 1 | 2 | 3 | 3 |
| March | 2 | 2 | 1 | 3 | 1 | 2 | 2 | 3 | 3 |
| April | 1 | 2 | 1 | 3 | 1 | 2 | 1 | 3 | 3 |
| May | 1 | 3 | 1 | 3 | 2 | 2 | 1 | 3 | 3 |
| June | 1 | 3 | 3 | 3 | 3 | 2 | 1 | 3 | 3 |
| July | 1 | 3 | 3 | 3 | 3 | 2 | 1 | 3 | 3 |
| August | 1 | 3 | 3 | 3 | 3 | 3 | 1 | 3 | 3 |
| September | 1 | 3 | 3 | 3 | 3 | 3 | 2 | 3 | 3 |
| October | 2 | 3 | 1 | 3 | 2 | 3 | 2 | 3 | 3 |
| November | 2 | 3 | 1 | 3 | 1 | 2 | 2 | 3 | 3 |
| December | 2 | 2 | 1 | 3 | 1 | 2 | 3 | 3 | 3 |
| Data quality | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 1 |

Table 16 continued horizontally. Temporal distribution scores of Puget Sound food web indicator species.*

| Month | Yelloweye rockfish, larvae | Yelloweye rockfish, juvenile | Yelloweye rockfish, adult | Pacific herring, egg/larval | Pacific herring, juvenile | Pacific herring, adult | Dungeness crab, egg | Dungeness crab, larvae | Dungeness crab, juv./adult |
|---|---|---|---|---|---|---|---|---|---|
| January | 1 | 3 | 3 | 2 | 3 | 3 | 1 | 3 | 3 |
| February | 2 | 3 | 3 | 3 | 3 | 3 | 1 | 3 | 3 |
| March | 2 | 3 | 3 | 3 | 2 | 3 | 1 | 3 | 3 |
| April | 3 | 3 | 3 | 2 | 2 | 3 | 1 | 3 | 3 |
| May | 3 | 3 | 3 | 2 | 2 | 3 | 1 | 3 | 3 |
| June | 2 | 3 | 3 | 2 | 2 | 2 | 1 | 3 | 3 |
| July | 2 | 3 | 3 | 1 | 2 | 2 | 1 | 3 | 3 |
| August | 1 | 3 | 3 | 1 | 3 | 2 | 1 | 3 | 3 |
| September | 1 | 3 | 3 | 1 | 3 | 3 | 1 | 1 | 3 |
| October | 1 | 3 | 3 | 1 | 3 | 3 | 3 | 1 | 3 |
| November | 1 | 3 | 3 | 1 | 3 | 3 | 3 | 1 | 3 |
| December | 1 | 3 | 3 | 1 | 3 | 3 | 3 | 1 | 3 |
| | | | | | | | | | |
| Data quality | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |

*Scores for the temporal variation in the relative abundance of indicator species are based on Krahn et al. 2002 and NMFS 2008 for Southern Resident killer whales; Scheffer and Slipp 1944 for harbor seals; Fresh 2006 and Shared Strategy for Puget Sound 2007 for Chinook salmon; Drake et al. 2010 for canary and yelloweye rockfish; Stout et al. 2001, Gustafson 2006, and Stick and Lindquist 2009 for Pacific herring; and Pauley et al. 1986 and Dethier 2006 for Dungeness crab. Eelgrass and kelp abundance were assumed constant year-round.

Second, we scored the relative intensity of the stressor in each month of the year. As with the scoring bins for temporal abundance of the indicator species, the scoring bins for each stressor were defined in relative terms (absent/rare, moderate, abundant). Sources of data for stressors associated with each activity are described below.

Third, we calculated the score for the actual temporal intensity criterion by averaging each species relative abundance score and stressor relative intensity score in each month of the year for which the species relative abundance score was greater than 1. In months where the species relative abundance score was equal to 1, temporal intensity was set equal to 1 as well. Sound-wide temporal intensity was calculated by averaging the month-specific intensity scores.

In the absence of quantitative information about temporal covariation in species and stressor intensity, a qualitative scoring procedure that reflects the bins listed in Table 14 could be used.

*Temporal intensity (food web effect).** We used the same approach described above for the direct effect temporal intensity criterion, but in this case calculated the overlap between temporal variation in relative stressor intensity and at most one key ecological associate. The rationale for this criterion is that temporal overlap between a stressor and a key ecological associate will indirectly modify the susceptibility of the indicator species.

**Management factors**—*Value of exploited species*. We determined the ex-vessel value of each of the indicator species for which a commercial fishery exists in Puget Sound. We assumed that highly valued stocks are more susceptible to stressors because fishing effort is likely to be greater, opening the possibility for cumulative impacts. Following Patrick et al. (2010), we used the higher of the annual landings value and price per pound to score this criterion.

*Societal value*. This criterion describes societal preferences for the species as expressed by willingness-to-pay (WTP), contingent valuation, or other similar analyses that quantify the values people attach to goods and amenities that cannot be bought and sold in the marketplace. We applied the criterion primarily to unexploited species and assumed that increased societal value would reduce the susceptibility of the species. In the future, this criterion would be a good place to include information about the value of species targeted by recreational fisheries (Anderson and Lee in prep.). In this application, we based the scoring bins on the $\log_{10}$-distribution of replacement values in Brown (1992) and on WTP values in Martin-Lopez et al. (2008).

*Effectiveness of current management strategy.** The susceptibility of a species to a stressor is determined in part by the effectiveness of current management approaches used to mitigate the direct effects of the stressor. We reviewed current reports from state and federal agencies and the academic literature to qualitatively score this criterion for each species. A species received a score of 1 if current management is considered to be very effective or the stressor did not directly affect the indicator species, a score of 2 if current management is effective because the stressor is under control, and a score of 3 if current management is not effective, such that the stressor effects on the indicator species are considered to be poorly managed.

*Current status of ecosystem component*. The susceptibility of a species to continued or increased perturbation by a stressor or stressors depends on its current status. The greater the decline in a species abundance from some reference level, the more susceptible it is likely to be to further impacts. We scored this criterion qualitatively such that a score of 1 indicated endangered status according to state, federal, or IUCN evaluations; a score of 2 indicated threatened status; and, a score of 3 indicated little concern for the species status. While in the future it may be desirable to incorporate historical successes and failures of alternative management approaches in a more explicit way, this criterion is the best opportunity to do so within our current framework.

### Consequence criteria

The consequence criteria we selected include resistance and recovery factors that describe the potential response of each species to stressors (Table 17). For each species, the scores for the criteria indicated with an asterisk (*) differ among stressors.

**Resistance factors**—*Mortality.** This criterion is intended to coarsely describe the effect of a stressor on the vital rates of a species, should it be exposed to the stressor. A species received a score of 1 if the stressor had a negligible impact on the species, a score of 2 if the stressor produced sublethal effects on the species, and a score of 3 if the stressor caused death.

*Behavioral/physiological response.** For mobile indicator species, this criterion captures information about the extent to which behavioral or physiological responses can influence the stressor's impact. Examples of individual responses that reduce the impact of fishing and pollution may include gear-avoidance behavior or sequestration and excretion of toxic contaminants, respectively. A species received a score of 1 if the behavioral/physiological response of the species reduced the impact of the stressor, a score of 2 if the behavioral/physiological response of the species did not alter the impact of the stressor, and a score of 3 if the behavioral/physiological response of the species increased the impact of the stressor.

*Frequency of natural disturbance.** Following Hobday et al. (2007), we applied this criterion to describe the extent to which a species is subject to natural disturbances of a similar type to the stressor. The rationale is that frequently disturbed species are adapted to resist or recover from such disturbances. We used the same scoring bins as Hobday et al. (2007), so that a species received a score of 1 if it experienced a natural disturbance of a similar type to the stressor daily to weekly, a score of 2 if it experienced a natural disturbance of a similar type to the stressor several times per year, and a score of 3 if it experienced a natural disturbance of a similar type to the stressor annually or less often.

**Recovery factors**—*Fecundity*. This criterion describes the number of offspring produced by a female each year and is measured at age of first maturity. Species with lower fecundity are likely to recover more slowly from a stressor's impacts than those with higher fecundity. We used the same scoring bins as Patrick et al. (2010) such that a species received a score of 1 if it produced greater than $10^2$ offspring per year, a score of 2 if it produced $10^2$–$10^3$ offspring per year, and a score of 3 if it produced equal to or greater than $10^4$ offspring per year.

Table 17. Consequence criteria for risk analysis.

| | | Consequence | | |
|---|---|---|---|---|
| **Factor** | **Description** | **Low (1)** | **Moderate (2)** | **High (3)** |
| Low resistance factors | | | | |
| Mortality* | Effect of stressor on vital rates of ecosystem component | Negligible | Sublethal | Lethal |
| Behavioral or physiological response* | Effect of stressor on behavior or physiology of mobile species | Behavioral or physiological response reduces impact | Behavioral or physiological response does not change impact | Behavioral or physiological response increases impact |
| Frequency of natural disturbance* | Ecosystem components subject to frequent natural disturbances of a similar type to the stressor should be more resistant to the stressor | Daily to weekly | Several times per year | Annually or less often |
| Slow recovery factors | | | | |
| Fecundity | The number of offspring produced by a female each year, measured at the age of first maturity | $\geq 10^4$ | $10^2$–$10^3$ | $<10^2$ |
| Age at maturity | Greater age at maturity corresponds to longer generation times and lower productivity | <2 years | 2–4 years | >4 years |
| Life stage* | If stressor affects individuals before they have the opportunity to reproduce, recovery is likely to be inhibited | Not affected or only mature life stages affected | Only immature life stages affected | All life stages affected |
| Reproductive strategy | Internal fertilization and parental care should enhance early life history survival | Internal fertilization and parental care | Fertilization or parental care but not both | External fertilization and no parental care |
| Population connectivity | Realized exchange with other populations, based on spatial patchiness of distribution; degree of isolation, and potential dispersal capability, based on monitoring surveys and population genetic or direct tracking estimates | Regular movement and exchange between Puget Sound and other regional populations (not a distinct population segment or evolution-arily significant unit) | Occasional movement and exchange between Puget Sound and other regional populations | Negligible movement and exchange between Puget Sound and other regional populations (distinct population segment or evolutionarily significant unit) |

*Indicates criterion varies across stressors for each species.

Age at maturity. The age at maturity of a species provides information about the productivity of a species that is complementary to the fecundity criterion. Because age at maturity is related to the mean generation time of a species, together these two life history traits are predictive of a species' intrinsic rate of population growth (May 1976). We assumed that greater age at maturity corresponds to longer generation times and a slower recovery rate from perturbation by a stressor; thus species that mature at younger ages received a lower consequence score. We used the scoring bins designated by Patrick et al. (2010) such that a score of 1 indicated a species with an age at maturity of less than 2 years, a score of 2 indicated a species with an age at maturity of 2–4 years, and a score of 3 indicated a species with an age at maturity of more than 4 years.

*Life stage.** This criterion describes the life stage or stages affected by a stressor. We assumed that a species is likely to have a greater capacity to recover from a stressor's impact if it is able to reproduce prior to the stressor having an effect (Stobutzki et al. 2001), but that stressors that affect both the immature and mature life stages are likely to reduce recovery most. A species received a score of 1 if the species were only affected by the stressor after maturity or if it were not affected by the stressor at all, a score of 2 if only immature stages were affected by the stressor, and a score of 3 if all life stages were affected by the stressor.

*Reproductive strategy*. The extent to which a species protects and nourishes its offspring influences the level of mortality that may be expected for the offspring in the first stages of life (Patrick et al. 2010). We assumed that internal fertilization and parental care are likely to speed the recovery rate of a species from perturbation by a stressor. A species received a score of 1 if the reproductive strategy included both parental care and internal fertilization, a score of 2 if the reproductive strategy included either parental care or internal fertilization but not both, and a score of 3 if its reproductive strategy did not include parental care and gametes were fertilized externally.

*Population connectivity*. This criterion refers to the realized exchange of individuals with other populations and is based on the spatial patchiness of the species' distribution, the degree of isolation of the species in the management region, and the potential dispersal capability of the species. Sources of information for this criterion include monitoring surveys and population genetic or direct tracking estimates. We assumed that greater connectivity would increase recovery rates (Hobday et al. 2007). A species received a score of 1 if there were evidence for regular movement and exchange of individuals between Puget Sound and other regional populations, a score of 2 if there were evidence for occasional movement and exchange of individuals between Puget Sound and other regional populations, and a score of 3 if movement and exchange of individuals between Puget Sound and other regional populations were negligible (making the Puget Sound population a distinct population segment or evolutionarily significant unit).

### Data quality and weighting criteria

In addition to determining a score for each susceptibility and consequence criterion, we also assigned a data quality rating (Table 18). The ratings generally follow those outlined by Patrick et al. (2010), such that a rating of 1 indicates the best quality data and a 4 indicates the worst quality data deemed acceptable for inclusion in the analysis. In the future, these ratings

Table 18. Data quality ratings for risk analysis.

| Data quality | Description | Example |
|---|---|---|
| 1 | Best data. Substantial information exists to support the score and is based on data collected for the ecosystem component in the study region. | Data-rich assessment of species status with reference to historical abundance and current population trajectory. |
| 2 | Adequate data. Information is based on limited spatial or temporal coverage, moderately strong or indirect statistical relationships, or for some other reason is deemed not sufficiently reliable to be designated as best data. | Use of fisheries landings data, which are confounded with fishing efforts, as proxies for species relative abundance; use of relatively old information, etc. |
| 3 | Limited data. Estimates with high variation and limited confidence, or based on studies of similar ecosystem components or of the focal ecosystem component in other regions. | Scoring based on a study of or management effectiveness for a species in the same genus or family. |
| 4 | Very limited data. Information based on expert opinion or on general literature reviews from a wide range of ecosystem components. | No literature exists to justify scoring for a focal species in relation to a particular stressor, but reasonable inference can be made by the person conducting the risk analysis. |

will be used to assign greater weight to criteria for which confidence in the scoring process was higher. Specifically, we will calculate an overall susceptibility score $S$ and consequence score $C$ as a weighted average of the susceptibility values $s_i$ and consequence values $c_i$ for each criterion $i$ as

$$S = \frac{\sum_{i=1}^{N} \frac{s_i}{d_i}}{\sum_{i=1}^{N} \frac{1}{d_i}} \qquad (2)$$

and

$$C = \frac{\sum_{i=1}^{N} \frac{c_i}{d_i}}{\sum_{i=1}^{N} \frac{1}{d_i}} \qquad (3)$$

where $d_i$ represents the data quality rating for criterion $i$ and $N$ is the number of criteria evaluated for each species.

## Primary Human Activities and Stressors in Puget Sound

To demonstrate this ecosystem-based approach to risk assessment, we focused on stressors created by three human activities: coastal development, industry, and fishing, previously identified as threats in Puget Sound (Newton et al. 2000, Neuman et al. 2009, Pearson et al. in press). The stressors associated with these activities that we explicitly consider include shoreline armoring and overwater structures, point source pollution by toxic contaminants, and overharvesting, respectively. Though each activity can produce a variety of stressors, we constrained our risk analysis to a limited set of activity-stressor combinations. In the future, we plan to expand this analysis to include other activities such as land-based transportation; commercial, residential, and agricultural development; commercial shipping and marine transportation; aquaculture; and anthropogenic climate change. Though some activities create the same type of stressors, we will evaluate each activity individually because the distributions and intensities of different activities produce different susceptibility scores.

In the following three subsections, we provide details about the methods we used to evaluate susceptibility and consequence criteria for which scores differed between the three activities. Scores for criteria that did not vary among stressors can be found in Table 19. In addition to analyzing risk due to coastal development, industry, and fishing, we include a plot of baseline risk that is the average of susceptibility and consequence scores for criteria that did not vary among stressors. This plot provides a sense of how management factors and life history traits influence each species' risk.

**Activity 1: Coastal development**

Stressors: Shoreline armoring and overwater structures.

Coastal development is common throughout Puget Sound, but especially in the central and south sound (Ruckelshaus and McClure 2007). Nearshore habitats have been modified for a variety of reasons, not the least of which is to provide protection from erosion, tidal inundation and storms, and to increase waterfront access for real estate development and marine transportation. Coastal development activities include the construction of bulkheads, riprap, dikes, docks, piers, boats, buoys, houseboats, launches, hoists, bridges, marinas, shipyards, and terminals. While these activities provide many benefits, they also act as stressors by altering habitat availability (e.g., eelgrass habitat for juvenile invertebrates and fishes), habitat quality (e.g., due to shading), flow dynamics, and connectivity (among nearshore habitat types).

**Spatial intensity of coastal development**—We approximated the spatial distribution of coastal development in each PSP action area by averaging scores for two data types, the percentage of modified shoreline and the areal density of overwater structures. We used Washington Department of Natural Resources Shore Zone Inventory data (1994–2000, http://fortress.wa.gov/dnr/app1/dataweb/dmmatrix.html) and the Overwater Structures database (2006, http://fortress.wa.gov/dnr/app1/dataweb/dmmatrix.html), as compiled by Ruckleshaus et al. (2009), to quantify shoreline modification in each PSP action area.

The percentage of modified shoreline data layer includes bulkheads, riprap, diking, and filling, and is often associated with protection or expansion of uplands. The areal density of overwater structures data layer includes simple (docks, piers, boats, buoys, boating homes, boat ramps, launches, hoists, bridges) and complex structures (marinas, shipyards, terminals, and their associated infrastructure). Scoring bins were defined as described above under spatial factors. The scores for percentage of modified shoreline and the areal density of overwater structures

Table 19. Baseline risk rankings for Puget Sound food web indicator species. Susceptibility and consequence scores[a] and data quality scores for criteria that did not vary among stressors.

| Criterion | Southern Resident killer whale | Harbor seal | Chinook salmon | Canary rockfish | Yelloweye rockfish | Pacific herring | Dungeness crab |
|---|---|---|---|---|---|---|---|
| Susceptibility and consequence scores[b] | | | | | | | |
| Susceptibility criteria | | | | | | | |
| Value of exploited species | — | — | 3 | 1 | 1 | 3 | 3 |
| Societal value | 1 | 2 | 1 | — | — | — | — |
| Current status | 3 | 1 | 2 | 2 | 2 | 2 | 1 |
| Consequence criteria | | | | | | | |
| Fecundity | 1 | 1 | 2 | 3 | 3 | 2 | 3 |
| Age at maturity | 1 | 2 | 2 | 1 | 1 | 2 | 2 |
| Reproductive strategy | 3 | 3 | 1 | 2 | 2 | 1 | 2 |
| Population connectivity | 1 | 1 | 1 | 2 | 2 | 2 | 3 |
| Data quality scores[c] | | | | | | | |
| Susceptibility criteria | | | | | | | |
| Value of exploited species | — | — | 1 | 1 | 1 | 1 | 1 |
| Societal value | 2 | 2 | 2 | — | — | — | — |
| Current status | 1 | 1 | 1 | 1 | 1 | 1 | 2 |
| Consequence criteria | | | | | | | |
| Fecundity | 1 | 1 | 1 | 1 | 1 | 2 | 1 |
| Age at maturity | 1 | 1 | 1 | 1 | 1 | 2 | 1 |
| Reproductive strategy | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Population connectivity | 1 | 1 | 1 | 2 | 2 | 1 | 2 |

[a]References for susceptibility and consequence criteria that did not vary among stressors are Brown 1992, CFR 70 FR 69903 2005, Martin-Lopez et al. 2008, and NMFS 2008 for Southern Resident killer whales; Scheffer and Slipp 1944, Brown 1992, Jeffries et al. 2003, Carretta et al. 2004, Martin-Lopez et al. 2008, and www.adfg.state.ak.us for harbor seals; PacFIN no date, CFR 63 FR 11482 1998, Myers et al. 1998, Good et al. 2005, PSAT 2007, Martin-Lopez et al. 2008, and www.fishbase.org for Chinook salmon; PacFIN no date, Love et al. 2002, CFR 75 FR 22276 2010, and Drake et al. 2010 for canary rockfish; PacFIN no date, CFR 75 FR 22276, Love et al. 2002, PSAT 2007, and Drake et al. 2010 for yelloweye rockfish; PacFIN no date, Stout et al. 2001, Gustafson et al. 2006, WDFW 2008, Stick and Lindquist 2009, PSP 2010, and http://www.fishbase.org/ for Pacific herring; and PacFIN no date, Pauley et al. 1986, Dinnel et al. 1993, Fisher and Velasquez 2008, and WDFW 2008 for Dungeness crab.
[b]See Table 14 and Table 17 for criteria definition and scoring bins.
[c]See Table 18 for criteria definition and scoring bins.

were averaged to produce a value for the relative amount of coastal development in each action area. This value was then averaged with the score for each species' relative abundance in each action area to produce a score for the spatial intensity criteria (direct and food web effects) (Table 20).

**Temporal intensity of coastal development**—We assumed that the amount of shoreline modification and density of overwater structures in each action area remains approximately constant throughout the year. Thus we did not incorporate potential impacts of new construction in the current analysis. The result is that the temporal intensity of coastal development varied entirely as a function of each species' seasonal abundance (Table 20).

**Other criteria—**For each species, we reviewed current reports from state and federal agencies and the academic literature to qualitatively score the other criteria that vary among stressors (effectiveness of management strategies targeting coastal development for indicator species, mortality of coastal development, behavioral/physiological response to coastal development, life stages affected by coastal development). This review drew heavily from work completed by the Puget Sound Nearshore Partnership and from NOAA biological reviews (http://www.nwr.noaa.gov/Publications/Biological-Status-Reviews/). We based our assessment of the effectiveness of management strategies targeting coastal development on the success of previous and current management decisions in mitigating stressors for each indicator species. For the mortality and behavioral/physiological response criteria, we determined a score for each species using coarse categories that describe the typical impacts of stressors associated with coastal development (e.g., loss of eelgrass habitat will leave juvenile Chinook salmon and Dungeness crabs more vulnerable to predation). Finally, for the life stages affected by coastal development criteria, we based our evaluations on our understanding of which life stage or stages are most likely to be affected by stressors associated with coastal development (Table 21).

**Activity 2: Industry**

Stressor: Point source pollution (toxic contaminants).

Puget Sound is home to a variety of industries, from aluminum smelters to petroleum refineries, pulp and paper mills, and a variety of manufacturing companies. In addition to the many socioeconomic benefits the industries provide in the region, they also represent a primary source of toxic contaminants or point source pollution that threatens the food web and human health (Ruckelshaus and McClure 2007). Chemicals of particular concern include metals such as cadmium, copper, and mercury, and persistent organic pollutants (POPs) such as polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), polybrominated diphenyl ethers (PBDEs), and dioxins and furans (EVS Environmental Consultants 2003b). All of these chemicals can be toxic to marine species in Puget Sound, with effects ranging from reproductive dysfunction to delayed development and maturation, cancer, or even death (EVS Environmental Consultants 2003b). For the purpose of this risk analysis, we focus on point source pollution (toxic contaminants) as the stressor associated with industrial activities (for a list of contaminants considered here, see Table 22).

Table 20. Risk ranking susceptibility and consequence scores[a] and data quality scores for criteria related to coastal development.

| Criterion | Southern Resident killer whale | Harbor seal | Chinook salmon | Canary rockfish | Yelloweye rockfish | Pacific herring | Dungeness crab |
|---|---|---|---|---|---|---|---|
| Susceptibility and consequence scores[b] | | | | | | | |
| Susceptibility criteria | | | | | | | |
| Spatial intensity (direct effect) | 1.9 | 2.1 | 2.1 | 1.9 | 1.8 | 2.3 | 1.9 |
| Spatial intensity (food web effect) | 2.1 | 2.3 | 2.3 | 2.1 | — | 2.3 | 2.3 |
| Temporal intensity (direct effect) | 2.3 | 2.3 | 2.3 | 2.7 | 2.6 | 2.5 | 2.5 |
| Temporal intensity (food web effect) | 2.3 | 2.5 | 3.0 | 3.0 | — | 3.0 | 3.0 |
| Effectiveness of current management strategy | 1.0 | 1.0 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 |
| Consequence criteria | | | | | | | |
| Mortality | 1.0 | 1.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 |
| Behavioral/physiological response | 1.0 | 1.0 | 3.0 | 3.0 | 2.0 | 3.0 | 3.0 |
| Frequency of natural disturbance | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 |
| Life stage | 1.0 | 1.0 | 2.0 | 2.0 | 2.0 | 3.0 | 2.0 |
| Data quality scores[c] | | | | | | | |
| Susceptibility criteria | | | | | | | |
| Spatial intensity (direct effect) | 1.0 | 1.0 | 1.0 | 1.5 | 1.5 | 1.5 | 1.5 |
| Spatial intensity (food web effect) | 1.0 | 1.5 | 1.0 | 1.0 | — | 1.0 | 1.0 |
| Temporal intensity (direct effect) | 1.0 | 1.0 | 1.3 | 1.0 | 1.0 | 1.0 | 1.0 |
| Temporal intensity (food web effect) | 1.3 | 1.0 | 1.0 | 1.0 | — | 1.0 | 1.0 |
| Effectiveness of current management strategy | 4.0 | 4.0 | 1.0 | 2.0 | 2.0 | 2.0 | 2.0 |
| Consequence criteria | | | | | | | |
| Mortality | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Behavioral/physiological response | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Frequency of natural disturbance | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Life stage | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |

[a]References for susceptibility and consequence criteria evaluations are Dethier 2006, Fresh 2006, NMFS 2006, Mumford 2007, Pentilla 2007, Ruckelshaus and McClure 2007, NMFS 2008, Drake et al. 2010, Essington et al. 2010, and Pearson et al. in press.
[b]See Table 14 and Table 17 for criteria and scoring bins.
[c]See Table 18 for data quality definitions.

Table 21. Spatial distribution[a, b] of coastal development intensity scores.

| Action area | Shoreline modification | Overwater structures | Combined score |
| --- | --- | --- | --- |
| Hood Canal | 2.0 | 1.0 | 1.5 |
| North central Puget Sound | 3.0 | 2.0 | 2.5 |
| San Juan/Whatcom | 2.0 | 1.0 | 1.5 |
| South central Puget Sound | 3.0 | 3.0 | 3.0 |
| South Puget Sound | 3.0 | 1.0 | 2.0 |
| Strait of Juan de Fuca | 2.0 | 1.0 | 1.5 |
| Whidbey | 3.0 | 1.0 | 2.0 |
| | | | |
| Data quality | 1.0 | 1.0 | 1.0 |

[a]References for spatial distribution of coastal development are Washington Department of Natural Resources (DNR) Shore Zone Inventory data (1994–2000, http://fortress.wa.gov/dnr/app1/dataweb/dmmatrix.html) and Overwater Structures database (2006, http://fortress.wa.gov/dnr/app1/dataweb/dmmatrix.html), as compiled by Ruckelshaus et al. (2009) in their Figure 2.4 through Figure 2.7.
[b]Note that temporal distribution of coastal development scores were assumed to be constant throughout the year.

**Spatial intensity of industrial pollution**—We approximated the spatial intensity of toxic contaminants released from industrial point sources in each PSP action area using data reported to the U.S. EPA Toxic Release Inventory (TRI) Program (www.epa.gov/tri) in 2008 (the most recent year for which complete data were available). The current TRI list contains information on releases of more than 600 chemicals from industries including manufacturing, metal and coal mining, electric utilities, and commercial hazardous waste treatment, among others. We included chemical releases to the ground, water, and air, in addition to data regarding off-site transfers and treated and recycled chemicals. Scoring bins were defined as described above under spatial factors. The value for the spatial intensity of industrial pollution was averaged with the score for each species' relative abundance in each action area to produce a score for the spatial intensity criterion (direct and food web effects) (Table 23).

**Temporal intensity of industrial pollution**—We were unable to find data describing temporal variability in chemical releases by industries in Puget Sound. Instead, we assumed that loadings were consistent year-round. The result is that the score for the temporal intensity of industrial pollution (direct and food web effects) varied entirely as a function of each species' seasonal abundance (Table 22).

**Effectiveness of management of industrial pollution**—Scores related to the effectiveness of management were based on a review of current regulations for industrial point source toxic contaminants (EVS Environmental Consultants 2003b) and a recent assessment of threats due to point source pollution conducted by Neuman et al. (2009) (Table 22). The EVS Environmental Consultants report describes current regulations regarding the discharge of pollutants to surface waters of the United States, implying that current management of toxic contaminants is effective, that is, the pollutants are considered a threat but one that is under control. Note that this review did not address the specific effects of toxic contaminants on each indicator species.

Table 22. Risk ranking susceptibility and consequence scores[a, b] and data quality scores for criteria related to industry.

| Criteria | Southern Resident killer whale | Harbor seal | Chinook salmon | Canary rockfish | Yelloweye rockfish | Pacific herring | Dungeness crab |
|---|---|---|---|---|---|---|---|
| Susceptibility and consequence scores[c] | | | | | | | |
| Susceptibility criteria | | | | | | | |
| Spatial intensity (direct effect) | 2.3 | 2.5 | 2.5 | 2.2 | 2.3 | 2.7 | 2.3 |
| Spatial intensity (food web effect) | 2.5 | 2.7 | 2.8 | 2.5 | — | 2.8 | 2.8 |
| Temporal intensity (direct effect) | 2.3 | 2.3 | 2.3 | 2.7 | 2.6 | 2.5 | 2.5 |
| Temporal intensity (food web effect) | 2.3 | 2.5 | 3.0 | 3.0 | — | 3.0 | 3.0 |
| Effectiveness of current management strategy | 1.5 | 1.5 | 1.9 | 2.0 | 2.0 | 2.0 | 2.0 |
| Consequence criteria | | | | | | | |
| Mortality | 2.3 | 2.4 | 1.9 | 2.0 | 2.0 | 1.9 | 1.9 |
| Behavioral/physiological response | 2.2 | 2.1 | 1.9 | 2.3 | 2.3 | 2.0 | 2.0 |
| Frequency of natural disturbance | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 |
| Life stage | 1.0 | 1.1 | 2.0 | 1.7 | 1.7 | 1.0 | 1.0 |
| Data quality scores[d] | | | | | | | |
| Susceptibility criteria | | | | | | | |
| Spatial intensity (direct effect) | 1.5 | 1.5 | 1.5 | 2.0 | 2.0 | 2.0 | 2.0 |
| Spatial intensity (food web effect) | 1.5 | 2.0 | 1.5 | 1.5 | — | 1.5 | 1.5 |
| Temporal intensity (direct effect) | 2.5 | 2.5 | 2.8 | 2.5 | 2.5 | 2.5 | 2.5 |
| Temporal intensity (food web effect) | 2.8 | 2.5 | 2.5 | 2.5 | — | 2.5 | 2.5 |
| Effectiveness of current management strategy | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 |
| Consequence criteria | | | | | | | |
| Mortality | 3.2 | 3.1 | 1.7 | 2.7 | 2.7 | 2.5 | 2.3 |
| Behavioral/physiological response | 3.2 | 3.1 | 1.7 | 2.7 | 2.7 | 3.0 | 2.3 |
| Frequency of natural disturbance | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Life stage | 1.7 | 2.5 | 1.0 | 1.0 | 1.0 | 1.0 | 2.3 |

[a]References for susceptibility and consequence criteria evaluations are NMFS 2008 for Southern Resident killer whales; Geraci and St. Aubin 1990, de Swart et al. 1993, Lund 1994, Hong et al. 1996, Ross et al. 1996, Shaw et al. 1999, Hall et al. 2003, Ross et al. 2004, and Cullon et al. 2005 for harbor seals; Hawkes et al. 1980, Roch and McCarter 1984, Arkoosh et al. 1994, Arkoosh et al. 1998, and Spromberg and Johnson 2008 for Chinook salmon; Drake et al. 2010 and Palsson et al. 2009 for canary and yelloweye rockfish; Carls et al. 1999, Stout et al. 2001, Gustafson et al. 2006, West et al. 2008, and Stick and Lindquist 2009 for Pacific herring; and Shaw et al. 2009 for Dungeness crab.

[b]The toxic contaminants considered for evaluating the spatial intensity criteria included all of those reported to the U.S. EPA Toxic Release Inventory (TRI) Program (for a full description, see http://www.epa.gov/tri/). We queried data for 2008 in all counties that border Puget Sound (using the TRI Explorer mapping

tool), determined the total toxic loadings reported to the EPA in each county, and then calculated the total toxic loadings for each PSP action area. The 17 chemicals of concern described in Table 22 are a subset of those reported to the EPA TRI program.
We evaluated 3 consequence criteria (mortality, behavioral/physiological response, and life stages affected) related to the 17 metals and chemicals (arsenic, cadmium, copper, lead, zinc, mercury, total PCBs, total PBDEs, carcinogenic PAHs, other high molecular weight PAHs, low molecular weight PAHs, bis(2-ethyl-hexyl)-phthalate, total dioxin TEQs, total DDT, triclopyr, nonylphenol, and oil or petroleum products), and considered of concern by the Washington Department of Ecology (Hart Crowser 2007, EnviroVision 2008). Also included is a list of species-specific references regarding the toxicity of these chemicals. These citations refer only to sources of information regarding toxic effects on each species; see Table 16 for references related to species distributions. Other relevant references include: EVS Environmental Consultants 2003a, 2003b, Hart Crowser 2007, EnviroVision 2008.
[c]See Table 14 and Table 17 for criteria definitions and scoring bins.
[d]See Table 18 for data quality definitions.

Table 23. Risk rankings and data quality for spatial distribution of industry intensity scores.[a, b]

| **Action area** | **Score** |
|---|---|
| Hood Canal | 3 |
| North central Puget Sound | 3 |
| San Juan/Whatcom | 3 |
| South central Puget Sound | 3 |
| South Puget Sound | 3 |
| Strait of Juan de Fuca | 2 |
| Whidbey | 3 |
| | |
| Data quality | 2 |

[a]The toxic contaminants considered for evaluating the spatial intensity criteria included all of those reported to the U.S. EPA Toxic Release Inventory (TRI) Program (for a full description, see http://www.epa.gov/tri/). We queried data for 2008 in all counties that border Puget Sound (using the TRI Explorer mapping tool), determined the total toxic loadings reported to the EPA in each county, then calculated the total toxic loadings for each PSP action area. The 17 chemicals of concern described in Table 22 are a subset of those reported to the EPA TRI program.
[b]Note that temporal distribution of industry intensity scores were assumed to be constant throughout the year, with a data quality score of 4.

The Neuman et al. (2009) report summarizes a threat rating activity conducted by a PSP working group to identify and evaluate direct threats to ecosystem components in Puget Sound. We drew on the severity rating in Neuman et al. (2009) in particular, which used the Open Standards for the Practice of Conservation approach (CMP 2007), to describe the level of damage expected for each ecosystem component from each threat, given the continuation of current circumstances and trends. Relevant ecosystem components for the present analysis included the marine mammals (Southern Resident killer whales, harbor seals), marine fish (canary rockfish, yelloweye rockfish, Pacific herring), marine invertebrates (Dungeness crab), and salmon (Chinook salmon) species groups. We converted the threat ratings for each species group treated in Neuman et al. (2009) as follows: no threat equals 1, low equals 1.5, medium equals 2, high equals 2.5, and very high equals 3. Finally, we generated an average score for this criterion using both the EVS Environmental Consultants (2003a) and Neuman et al. (2009) values for each species.

**Other criteria**—Scores for three of the remaining consequence criteria (mortality due to industrial pollutants, behavioral/physiological response to industrial pollutants, life stages affected by industrial pollutants) were based on published literature, most of which includes reviews of contaminant toxicity for higher-level taxonomic groups (e.g., fish) rather than for individual species (see Table 22). For each of these three criteria, we first assigned a score from 1 to 3 for the effect of each chemical on each indicator species, using the scoring categories delineated for these criteria in Table 17, and a data quality score (using Table 18). We calculated a summary score for each of the three criteria by averaging scores for each chemical. This procedure makes the first order assumption that chemicals have equivalent effects, but in the future it will be possible to weight chemicals according to the hazard they posed for different ecosystem components.

Because concentrations of toxic contaminants found in the tissues of organisms residing in Puget Sound are typically orders of magnitude higher than background environmental concentrations (EVS Environmental Consultants 2003a), indicator species were assigned a score of 3 for the frequency of natural disturbance criterion.

### Activity 3: Fishing

Stressor: Overharvest.

**Spatial intensity of fishing**—We estimated the amount of commercial fishing pressure in each action area. Currently there exist commercial, directed fisheries for only three of the indicator species (Chinook salmon, Dungeness crab, and Pacific herring), though there is a modest fishery for rockfishes in the Strait of Juan de Fuca action area and kelp throughout the sound (Mumford 2007, WDFW 2010). We used total commercial landings data (tribal and nontribal) from PacFIN (http://pacfin.psmfc.org/) summarized by action area to estimate fishing pressure for these species. We considered the two marine mammal species and eelgrass unexploited, though we recognize that the legacy of historical fishing or habitat destruction may influence their present status and risk. Scoring bins were defined as described above under spatial factors. Fishing intensity values were averaged with the relative abundance value for each species in each action area to produce a score for the spatial intensity criteria (direct and food web effects) (Table 24).

**Temporal intensity of fishing**—We determined the presence or absence of recreational and commercial fishing pressure on the indicator species in each month of the year based on WDFW regulations and stock status reviews (Bargmann 1998, Shared Strategy for the Puget Sound 2007, Stick and Lindquist 2009, WDFW 2010a, 2010b). We assumed that the two marine mammal species and eelgrass were unexploited. Each month in which current regulations prohibit fishing was assigned a score of 1, and remaining months were assigned a score of 2 or 3 depending on the relative intensity of fishing during that time of year. Fishing intensity values were averaged with the relative abundance value for each species in each month to produce a score for the temporal intensity criteria (direct and food web effects) (Table 25).

**Effectiveness of fisheries management**—Following Patrick et al. (2010), we assigned a score of 1 to exploited indicator species for which there exist catch limits, proactive accountability measures, and regular stock assessments, along with close monitoring of nontarget species; a score of 2 to exploited indicator species for which there exist catch limits, but no proactive accountability measures, regular stock assessments, or monitoring of nontarget species; and a score of 3 to exploited indicator species for which there exist no catch limits, proactive accountability measures, regular stock assessments, or monitoring of nontarget species. Nontargeted species subject to bycatch or incidental mortality in directed fisheries received a score of 1 if gear restrictions, observer coverage, and accountability measures (e.g., fines) exist; a score of 2 if one or more but not all three of the above exist; and a score of 3 if there exist no gear restrictions, observer coverage, or accountability measures (Table 26).

**Other criteria**—For the mortality criterion, we assumed that directed fisheries were capture fisheries, and therefore lethal (i.e., these species received a score of 3). Species that become entangled in fishing gear, are caught as bycatch, or fare poorly in catch-and-release fisheries, and may not survive such events received a score of 2. Species that become entangled in fishing gear, are caught as bycatch, or are subject to a catch-and-release fishery, and are capable of surviving such events received a score of 1 (Table 26).

The two remaining criteria that varied among stressors for each species, behavioral/physiological response to fishing and life stage exposed to fishing, were scored as described above under resistance factors and recovery factors (Table 26).

# Results

The baseline risk figure provides a visual representation of the inherent vulnerability of each species to natural and human-induced stressors (Figure 39). This first-cut risk assessment is based on a limited set of susceptibility criteria (commercial or societal value and current status) and consequence criteria (fecundity, age at maturity, reproductive strategy, and population connectivity) that did not vary among stressors. Some species with higher baseline risk, such as Pacific herring, Chinook salmon, and Southern Resident killer whales, begin at a disadvantage in terms of their vulnerability to stressors produced by human activities (Figure 39). Other species, such as rockfishes and harbor seals, have comparatively low baseline risk due to a combination of relatively recent management actions (Jeffries et al. 2003, Drake et al. 2010) and fortuitous life history traits. All of the Puget Sound food web indicator species are susceptible to stressors associated with coastal development (Figure 40). Each species exhibited a rightward shift in the

Table 24. Risk rankings and data quality for spatial distribution* of fishing intensity scores.

| Action area | Chinook salmon | Canary rockfish | Yelloweye rockfish | Pacific herring | Dungeness crab | Kelp |
|---|---|---|---|---|---|---|
| Hood Canal | 3.0 | 1.0 | 1.0 | 3.0 | 2.0 | 1.5 |
| North central Puget Sound | 2.0 | 1.0 | 1.0 | 3.0 | 2.0 | 2.0 |
| San Juan/Whatcom | 3.0 | 1.0 | 1.0 | 1.0 | 3.0 | 3.0 |
| South central Puget Sound | 3.0 | 1.0 | 1.0 | 3.0 | 2.0 | 2.0 |
| South Puget Sound | 3.0 | 1.0 | 1.0 | 3.0 | 2.0 | 2.0 |
| Strait of Juan de Fuca | 3.0 | 1.5 | 1.5 | 1.0 | 3.0 | 3.0 |
| Whidbey | 3.0 | 1.0 | 1.0 | 3.0 | 3.0 | 2.0 |
| Data quality | 2.0 | 1.0 | 1.0 | 2.0 | 2.0 | 4.0 |

*See Table 15 for references related to species distributions.

Table 25. Risk rankings and data quality for temporal distribution of fishing intensity scores.*

| Month | Chinook salmon, commercial | Chinook salmon, recreational | Canary rockfish | Yelloweye rockfish | Pacific herring | Dungeness crab, commercial | Dungeness crab, recreational | Kelp |
|---|---|---|---|---|---|---|---|---|
| January | 1.0 | 2.0 | 1.0 | 1.0 | 3.0 | 3.0 | 1.0 | 1.5 |
| February | 1.0 | 2.0 | 1.0 | 1.0 | 3.0 | 3.0 | 1.0 | 1.5 |
| March | 1.0 | 2.0 | 1.0 | 1.0 | 3.0 | 3.0 | 1.0 | 1.5 |
| April | 1.0 | 2.0 | 1.0 | 1.0 | 3.0 | 3.0 | 1.0 | 3.0 |
| May | 1.0 | 1.0 | 1.0 | 1.0 | 3.0 | 1.0 | 1.0 | 3.0 |
| June | 1.0 | 2.0 | 1.0 | 1.0 | 3.0 | 1.0 | 3.0 | 1.5 |
| July | 3.0 | 3.0 | 1.0 | 1.0 | 3.0 | 1.0 | 3.0 | 1.5 |
| August | 3.0 | 3.0 | 1.0 | 1.0 | 3.0 | 1.0 | 3.0 | 1.5 |
| September | 1.0 | 2.0 | 1.0 | 1.0 | 3.0 | 1.0 | 3.0 | 1.5 |
| October | 1.0 | 2.0 | 1.0 | 1.0 | 3.0 | 3.0 | 2.0 | 1.5 |
| November | 1.0 | 2.0 | 1.0 | 1.0 | 3.0 | 3.0 | 2.0 | 1.5 |
| December | 1.0 | 2.0 | 1.0 | 1.0 | 3.0 | 3.0 | 2.0 | 1.5 |
| Data quality | 1.0 | 4.0 | 1.0 | 1.0 | 2.0 | 2.0 | 2.0 | 4.0 |

*See footnote a of Table 26.

Table 26. Risk ranking susceptibility and consequence scores[a] and data quality scores for criteria related to fishing.

| Criterion | Southern Resident killer whale | Harbor seal | Chinook salmon | Canary rockfish | Yelloweye rockfish | Pacific herring | Dungeness crab |
|---|---|---|---|---|---|---|---|
| Susceptibility and consequence scores[b] | | | | | | | |
| Susceptibility criteria | | | | | | | |
| Spatial intensity (direct effect) | 1.0 | 1.0 | 2.5 | 1.1 | 1.1 | 2.5 | 2.1 |
| Spatial intensity (food web effect) | 2.5 | 2.5 | 1.0 | 2.2 | — | 1.0 | 1.0 |
| Temporal intensity (direct effect) | 1.0 | 1.0 | 1.9 | 1.0 | 1.0 | 2.7 | 2.6 |
| Temporal intensity (food web effect) | 1.9 | 2.7 | 1.0 | 2.4 | — | 1.0 | 1.0 |
| Effectiveness of current management strategy | 1.0 | 1.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 |
| Consequence criteria | | | | | | | |
| Mortality | 2.5 | 2.5 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 |
| Behavioral/physiological response | 1.0 | 1.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 |
| Frequency of natural disturbance | 3.0 | 2.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Life stage | 3.0 | 3.0 | 2.0 | 1.0 | 1.0 | 3.0 | 1.0 |
| Data quality scores[c] | | | | | | | |
| Susceptibility criteria | | | | | | | |
| Spatial intensity (direct effect) | 1.0 | 1.0 | 1.5 | 2.0 | 2.0 | 2.0 | 2.0 |
| Spatial intensity (food web effect) | 1.5 | 2.0 | 1.0 | 4.0 | — | 1.0 | 1.0 |
| Temporal intensity (direct effect) | 1.0 | 1.0 | 2.8 | 1.0 | 1.0 | 1.5 | 1.5 |
| Temporal intensity (food web effect) | 2.8 | 1.5 | 1.0 | 2.5 | — | 1.0 | 1.0 |
| Effectiveness of current management strategy | 1.0 | 1.0 | 1.0 | 2.0 | 2.0 | 2.0 | 2.0 |
| Consequence criteria | | | | | | | |
| Mortality | 2.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Behavioral/physiological response | 1.0 | 1.0 | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 |
| Frequency of natural disturbance | 2.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Life stage | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |

[a]References for susceptibility and consequence criteria evaluations are Carretta et al. 2004 for Southern Resident killer whales; Carretta et al. 2004 for harbor seals; PacFIN no date, Good et al. 2005, Fresh 2006, Committee 2007, and WDFW 2010b, for Chinook salmon; PacFIN no date, Palsson et al. 2009, Drake et al. 2010, and WDFW 2010a, for canary rockfish; PacFIN no date, Palsson et al. 2009, Drake et al. 2010, and WDFW 2010a for yelloweye rockfish; PacFIN no date, Pentilla 2007, and Stick and Lindquist 2009 for Pacific herring; and PacFIN no date, Fisher and Velasquez 2008, and WDFW 2010a, for Dungeness crab.
[b]See Table 14 and Table 17 for criteria definitions and scoring bins.
[c]See Table 18 for data quality definitions.

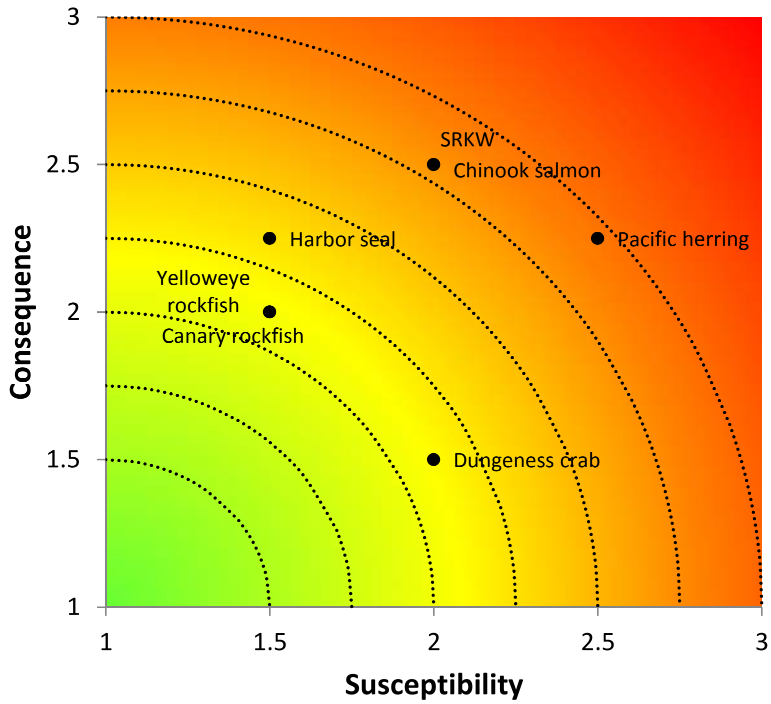



Figure 39. Baseline risk for seven Puget Sound food web indicator species.

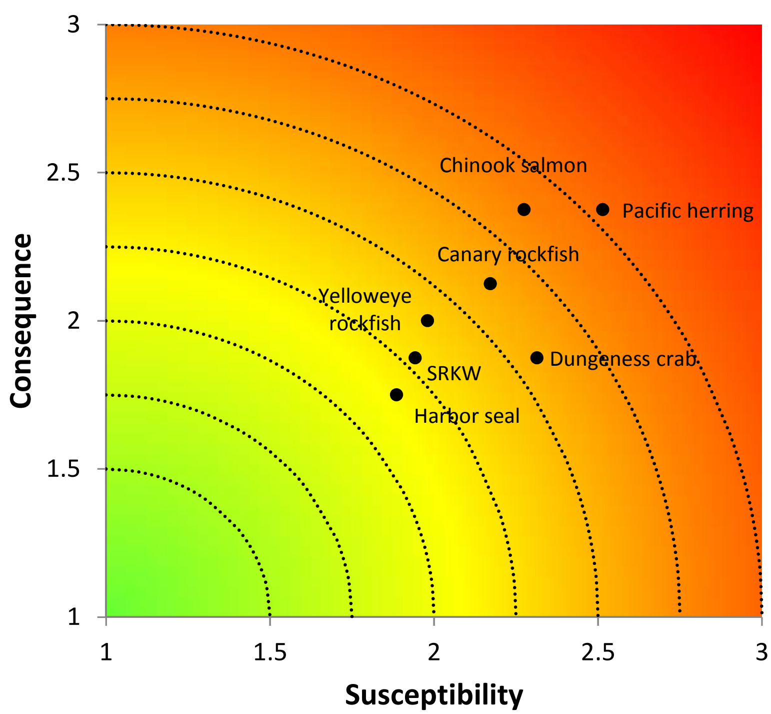



Figure 40. Risk due to coastal development (Activity 1).

coastal development risk plot (Figure 40) as compared to the baseline risk plot (Figure 39). In contrast, the consequence axis, or capacity to resist and recover from coastal development stressors, differed among species. For example, Southern Resident killer whales showed a downward shift on the y-axis as compared with the baseline risk plot, whereas Dungeness crabs showed an upward shift. These differences are due to variation among the species in their use of nearshore habitats.

Like shoreline armoring and overwater structures resulting from coastal development, toxic contaminant point source pollution associated with industrial activity generally increased the susceptibility of Puget Sound indicator species relative to their baseline risk (compare Figure 39 and Figure 41). However, unlike risk due to coastal development, industry also increased the consequence scores for many species as well. The result is that industry risk scores for all species were equal to or greater than 2.5 (Figure 41), suggesting that point source pollution from toxic contaminants is a ubiquitous threat to the Puget Sound food web.

Under current management policies, overharvest associated with fishing poses less of a risk than coastal development or industry to most of the indicator species (Figure 42). Most species showed reduced susceptibility (i.e., a leftward shift in the fishing risk plot) compared to the baseline risk plot, with little change in the consequence scores (compare Figure 39 and Figure 42). However, some species, such as Chinook salmon and Pacific herring, remained at relatively high risk due to fishing even under current fisheries management regulations.

# Discussion

We have outlined a generic and flexible approach to ecosystem-based risk analysis, and used Puget Sound marine food web indicator species to demonstrate the versatility of the approach. Though we focused on the entire Puget Sound, a convenient feature of this framework is that it is scalable. That is, the risk analysis could be repeated with a focus on a larger (e.g., entire California Current, decadal processes) or smaller (e.g., individual action areas within Puget Sound, seasons) spatial and temporal scales. Similarly, criteria could be redesigned to include those that incorporate information about historical management practices or the likely zone of influence of different stressors. In addition, the approach can be adapted for ecosystem components beyond indicator species, including habitats, community indices, and other endpoints (e.g., water quantity or quality).

Though this risk analysis is preliminary, it suggests that in Puget Sound species are differentially sensitive to alternative human activities. Indeed, it appears that under current management regulations, risk to indicator species due to coastal development and industry is generally greater than risk due to fishing.

Future steps for this ecosystem-based risk analysis will include:

- An analysis of the redundancy of the criteria (sensu Stobutzki et al. 2001).
- An attempt to associate risk scores with known thresholds for extinction, irreversible harm, etc.
- An examination of the utility of representing relative versus absolute risk.

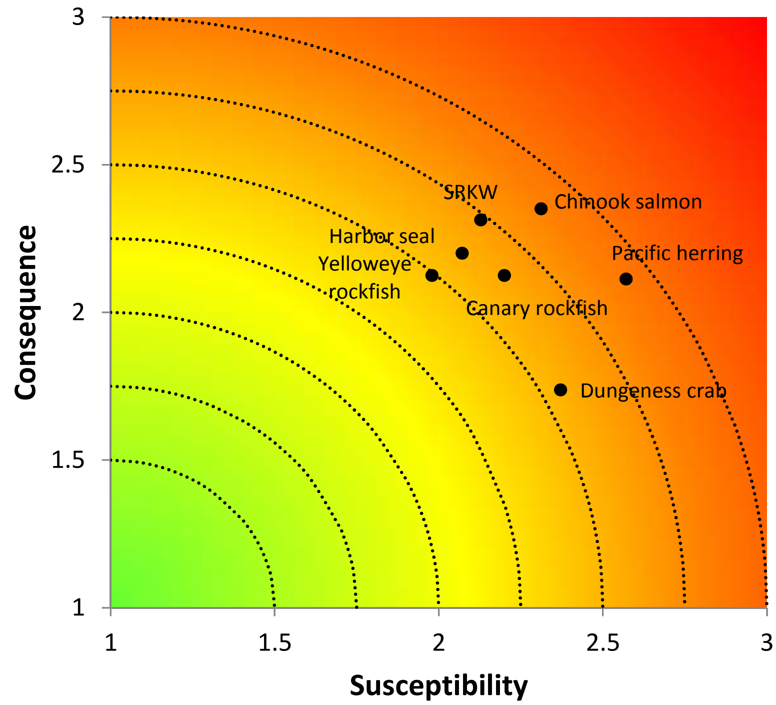



Figure 41. Risk due to industry (Activity 2).

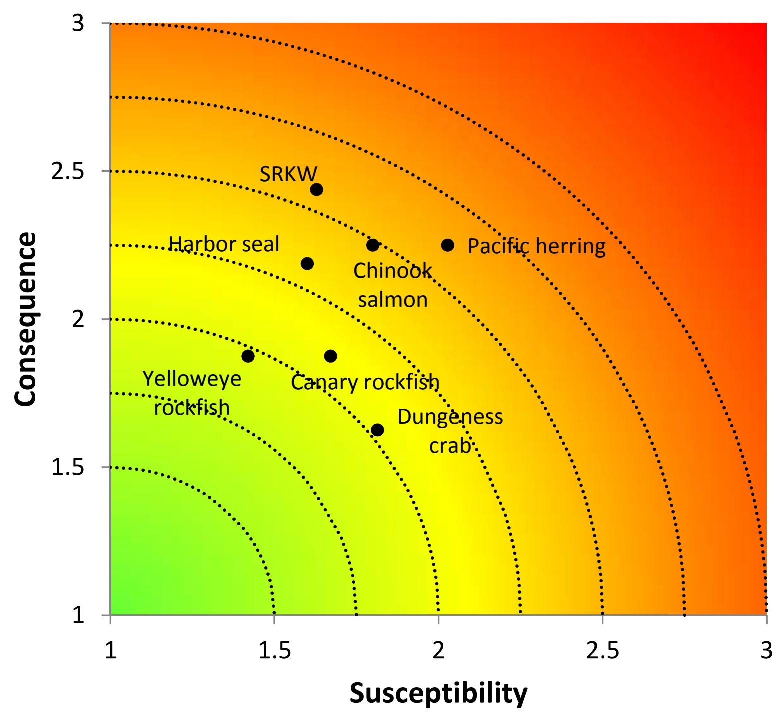



Figure 42. Risk due to fishing (Activity 3).

- An increased number and variety of human activities, with a particular focus on activities that introduce toxic contaminants to the environment.
- Scoring of the criteria by other experts, so as to qualify words like negligible, occasional, etc., and verify their objectivity.
- A representation of the data quality for each of the criteria using alternative weighting schemes or color-coding data points in the plots (sensu Patrick et al. 2010).

# The Evaluation of Management Strategies

## Introduction

In this section of the California Current IEA, we examine the potential of different management strategies to influence the status of natural and human system indicators. In other words, in this step of the IEA, management options are developed and assessed for their likely outcomes.

Like other sections of the IEA, this section focuses on the four EBM components jointly developed by the regional managers, policy makers, and scientists that formed the first year IEA team (i.e., groundfish, salmon, green sturgeon, and ecosystem health). As the IEA team considered how to approach the daunting, complex process of management strategy evaluation (MSE), it become clear that a formal scoping process with diverse stakeholder input is necessary prior to MSE. However, the team also concluded that some MSEs would help engage the management and stakeholder communities because they: 1) can help managers and the public understand how to frame appropriate scenarios for MSE, 2) illustrate the diversity of models and statistical tools available to forecast ecosystem status under different management or climate scenarios, and 3) expose gaps in the scientific toolbox that can be filled prior to conducting formal MSEs.

Thus in this section we present proof of concept MSEs. These are not meant to provide specific management advice, but instead are preliminary analyses meant to inform the development of specific MSEs. We anticipate a formal scoping process conducted in fiscal year 2011 will produces widely vetted management scenarios that will be evaluated in the fiscal year 2012 version of the California Current IEA.

This section has three MSE subsections, each focused on a specific evaluation. Again, these evaluations are meant to be illustrative of varying capacity to deal with diverse management scenarios. They are presented separately here, but as the specifics of the formal MSE process continue, we anticipate many of these scenarios could be combined in various ways to provide integrated management advice that deals with multiple ecosystem goals and includes multiple ocean-use sectors. The ultimate objective of the California Current IEA effort is to conduct MSEs that bridge diverse management objectives, sectors, and ecosystem pressures.

# MSE 1: Influence of Some Fisheries Management Options on Trade-offs between Groundfish and Ecosystem Health Objectives

## Introduction

Scientists from the NWFSC worked collaboratively with resource managers at NOAA's regional offices and NMSs to explore the potential influence of broad fisheries management options on groundfish and ecosystem health. In addition to examining the status quo management, we explored the consequences of several gear switching and spatial management scenarios using an Atlantis ecosystem model.

Most of the scenarios that involved minor management changes yielded results similar to status quo. This was especially apparent in cases in which spatial management was imposed in specific areas, such as the Monterey Bay NMS (MBNMS). However, when impacts did occur, they often involve local interactions that were difficult to predict a priori based solely on fishing patterns.

No single scenario maximized all performance metrics. Any policy choice would involve trade-offs between stakeholder groups and policy goals.

The scenarios revealed strong trophic effects in the food web. For instance, 50% reductions in fishing led to declines in forage fish (sardines and anchovies) because as their predators increased in abundance, forage fish experienced greater predation. The decline in forage fish subsequently caused declines in marine mammals and birds.

These simulations were intended to demonstrate the utility of using the Atlantis ecosystem model to evaluate management strategies within the context of an IEA. Our intention was not to evaluate specific policy options, but rather to illustrate a modeling that allows simultaneous consideration of multiple management alternatives that are relevant to numerous state, federal, and private interests. In some cases, we purposefully constructed scenarios that represent dramatic changes from status quo, not with the expectation that these represented realistic policy options, but with the intent to more clearly illustrate model outcomes.

### Context

While there is much promise for EBM in the California Current on the U.S. West Coast, at present there is a lack of integration among federal and state efforts, as well as a lack of understanding about how actions taken by different federal and state authorities influence the ability to achieve conservation goals. For instance, California's Marine Life Protection Act (MLPA) was enacted as a measure to preserve and restore biodiversity, yet there is little recognition that this goal may be affected by federal management of highly mobile predators. Similarly, federal quotas on catch and landings do not explicitly incorporate the effects of increasing numbers of MPAs in state waters. We need to ask the holistic question, "If we are going to achieve our conservation goals, what management actions do we need to take?" We believe that an integrated, quantitative approach is needed to allow us to set objectives, decide on management actions, and measure subsequent progress relative to those objectives.

NOAA's IEA for the California Current responds to this need. It is a synthesis and quantitative analysis that organizes science to inform EBM (Levin et al. 2008, 2009). It is explicitly defined as a framework for supporting management decision making, and it is designed to evaluate the status of the system and the effect of policy decisions in terms of management objectives. The components of the IEA include 1) public scoping to define goals and pressures, 2) development of ecosystem indicators, 3) risk analysis, 4) assessment of ecosystem status relative to goals, and 5) MSE. Part of the scoping portion of this IEA has involved meetings with NOAA managers and scientists to identify a set of alternative future fishery policy decisions, as well as alternative sets of climate and economic drivers. In total, through this process 10 scientists and managers have identified 71 scenarios or distinct components of scenarios.

The impacts and performance of management scenarios can be tested using forward projecting simulation models, such as the ecosystem model Atlantis (Fulton 2004, Fulton et al. 2005). Atlantis is a spatially explicit model that includes the food web, oceanography, and fisheries. Here we apply an Atlantis ecosystem model of the California Current (Horne et al. 2010) to predict the impacts and performance of management scenarios. A precedent for the use of Atlantis to screen fishery management policies was the work of Fulton et al. (2007) in Australia that informed the restructuring of the southern and eastern scalefish and shark fishery, which accounts for about one-half the value of Australia's seafood production. For the southern and eastern Australia fisheries, Fulton et al. (2007) used Atlantis to consider alternative portfolios of management options such as quotas, spatial management, gear restrictions, and buybacks. The work illustrated trade-offs between species, fleets, and management policies. It identified unexpected (but reasonable) responses of the biological and human/economic system, revealed potential flaws in management policies, and identified the relative economic and ecological performance of management portfolios.

Our modeling effort in the California Current can serve as a strategic decision support tool, helping resource managers identify policies that reach management goals. The work here can support management at several scales, including coast wide, regional (i.e., central California), in-state waters and state MPAs, and within the NMS.

**History of the modeling approach**

Atlantis, a simulation modeling approach developed by Commonwealth Scientific and Industrial Research Organization scientists in Australia, achieves the crucial goal of integrating physical, chemical, ecological, and fisheries dynamics in a three-dimensional, spatially explicit domain (Fulton 2001, 2004, Fulton et al. 2005). In Atlantis, ecosystem dynamics are represented by submodels that simulate hydrographic processes (light-driven and temperature-driven fluxes of water and nutrients), biogeochemical factors driving primary production, and food web relations among functional groups. The model represents key exploited species at the level of detail necessary to evaluate direct effects of fishing; it also represents other anthropogenic and climate impacts on the ecosystem as a whole. The generic Atlantis code is well developed at this time and Fulton (2001, 2004) and Fulton et al. (2005, 2007) have parameterized it for several systems in Australia. Recently they used the southeast Australia model to rank alternative policy scenarios, quantitatively evaluating alternative management packages of quotas, protected areas, closed seasons, and other policy options (Fulton et al. 2007).

We constructed the central California Atlantis model specifically to address scientific and management needs and data of the NMSs, the California Department of Fish and Game, and the California Ocean Science Trust Monitoring Enterprise. The central California model is largely based on a California Current Atlantis ecosystem model (Brand et al. 2007, Kaplan and Levin 2009) that addresses the impacts of climate, oceanography, nutrient dynamics, and spatially explicit fishing effort on a dynamic food web.

## Materials and Methods

The California Current Atlantis Model (CCAM) is detailed in Horne et al. (2010). The model extends along the U.S. West Coast and is bounded by the U.S-Canada border in the north, Point Conception in the south, the U.S. shoreline to the east, and the 2,400 isobath to the west (Figure 43). The model area is divided into 12 regions from north to south, based on biogeography and management boundaries, and each of these regions is subdivided into depth zones from east to west defined by bathymetric contours. The spatial resolution varies throughout the model extent, with the regions of northern California, Oregon, and Washington containing three depth zones, and those in central California each containing six or seven depth zones. These 64 dynamic boxes are flanked by 18 nondynamic boundary boxes on the north, south, and west edges. All model boxes are further divided into water column depth layers, ranging from one layer for nearshore boxes to seven for offshore boxes. Each box also contains one sediment layer. CCAM is driven by chemical, physical, and biological processes in each spatial box and depth layer. Physical forcing is governed by a regional ocean modeling system that dictates water fluxes, salinity, and temperature in each model box and depth layer (Hermann et al. 2009). Water flux drives the advection of plankton and nutrients.

The biological component of CCAM contains 62 functional groups: 5 bacteria/detritus, 8 plankton/algae, 14 invertebrate, 26 fish, 3 seabird, and 6 mammal (Table 27 and Table 28). Primary producers and invertebrates are modeled as biomass pools, while vertebrate groups are divided into 10 age-classes. Initial abundances for each biomass pool and vertebrate age-class are defined for each spatial box and depth layer based on estimates from stock assessments and other literature sources. Biological processes are governed by formulations that describe ingestion, growth, reproduction, movement, migration, etc. Each vertebrate group requires more than 15 parameters to drive these processes. Some of these parameters are defined per age-class, while others differentiate more generally between adult and juvenile groups. Invertebrates and primary producers require fewer parameters, as they are modeled as biomass pools rather than age structured (≈5–10 parameters/group).

## Incorporating Scenarios into Atlantis

We worked with managers and scientists from the IEA team to develop a set of alternative scenarios for fisheries management. Overall, the scenarios capture a range of options for spatial management and shifts in prevalence of particular fishing gears (Table 29). Using the Atlantis ecosystem model, we simulated the impact of each of these scenarios for 20 years. All scenarios presented here begin with the same base parameterization of the ecology and oceanography; the only variation is in the dynamics of fishing. Fishing is simulated on a per fleet basis, where a fleet is generally a gear (e.g., groundfish trawl, recreational hook and line). For each fleet (gear), we specify:

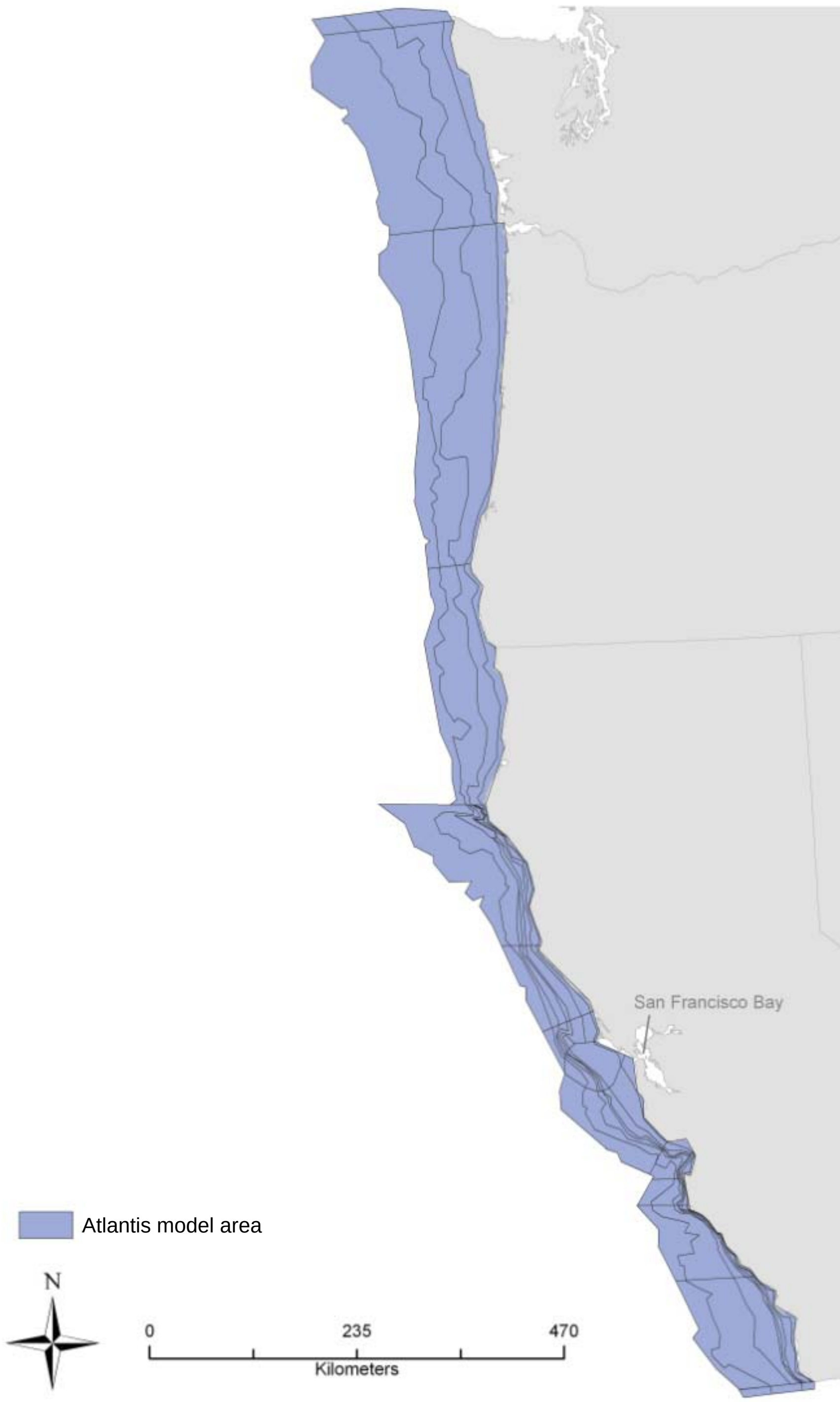



Figure 43. Atlantis model domain for the U.S. West Coast.

Table 27. Invertebrate biomass and life history parameters for the central California Atlantis model.[a] Clearance determines the rate at which predator growth and consumption increase with increased prey abundance (see Horne et al. 2010 for details).

| Functional group | Initial biomass concentration (max) | Max growth rate (/day) | Clearance ($m^3$ × day/mg N |
|---|---|---|---|
| Carnivorous infauna (polychaetes, nematodes)[b] | 786.910 | 0.07000 | 0.093120 |
| Deposit feeders[b] | 103.660 | 0.60000 | 0.074400 |
| Deep benthic filter feeders (anemones, deep corals)[b] | 108.710 | 0.00120 | 0.001485 |
| Other benthic feeders (geoducks, barnacles)[b] | 929.180 | 1.10000 | 0.238140 |
| Barnacles, soft corals, sponges[b] | 112.610 | 0.24000 | 0.022200 |
| Snails, abalone, nudibranchs[b] | 840.140 | 0.03000 | 0.036000 |
| Sea stars, whelks, brittlestars and basketstars[b] | 59.990 | 0.03260 | 0.030000 |
| Large crabs and lobsters[b] | 0.100 | 0.17500 | 0.017130 |
| Octopi, devilfish[b] | 34.040 | 0.10000 | 0.201000 |
| Meiobenthos (flagellates, cilliates, nematodes)[b] | 95.811 | 0.00688 | 0.002370 |
| Jumbo squid[c] | 0.100 | 0.02000 | 0.006000 |
| Market squid[c] | 0.048 | 0.15000 | 0.000300 |
| Juvenile crangon, mysid shrimp[c] | 0.036 | 0.38800 | 0.130320 |
| Adult crangon, mysid shrimp[c] | 0.012 | 0.50680 | 0.054096 |
| Gelatinous zooplankton[c] | 0.044 | 0.03000 | 0.045000 |
| Large carnivorous zooplankton[c] | 8.563 | 0.45000 | 0.230100 |
| Copepods (mesozooplankton)[c] | 0.309 | 1.80000 | 0.180000 |
| Microzooplankton (cilliates, dinoflagellates, nanoflagellates, etc.)[c] | 3.020 | 0.50000 | 0.624900 |

[a]Biomass/distribution references: California Dept. Fish and Game, http://www.dfg.ca.gov/marine/table_inv_ip.asp and J. Caselle, PISCO, Univ. California Santa Barbara, Marine Science Institute. Pers. commun., October 2007.
[b]Biomass measured in units of mg nitrogen/$m^2$.
[c]Biomass measured in units of mg nitrogen/$m^3$.

- The proportion of each model spatial cell that is open or closed to that fleet
- The fishing mortality (percent/year) applied to each spatial cell that is open to fishing

The scenarios begin in 2010 and apply a particular combination of spatial management and fleet-specific fishing mortalities for 20 years.

### Scenario 1: Status quo

This scenario aims to evaluate the predicted performance of existing levels of harvest, state MPAs, rockfish conservation areas (RCAs), and essential fish habitat (EFH) closures. The scenario projects the Atlantis ecosystem model for 20 years, imposing fishing mortality from all existing fleets onto all relevant species or functional groups. Spatial fishing closures in the model are based on EFH, RCA, and central California state MPAs in place in 2007 (Figure 44 and Figure 45). EFH, RCA, and central California state MPA closures are assumed to persist to the end of the simulation. We include only these three types of spatial management, detailed in Table 29. Smaller areas such as the Yelloweye RCA, Recreational RCA, marine gardens,

Table 28. Vertebrate biomass and life history parameters for the central California Atlantis model.

| Group | Initial biomass (mt) | Mortality | k[a] | *Linf*[a] | Max age (years) | a[b] | B[b] | Age at maturity (years) | Age at recruitment (days) | Biomass/distribution references |
|---|---|---|---|---|---|---|---|---|---|---|
| Dover sole | 423,049 | 0.0900 | 0.08 | 50 | 53 | 0.0041 | 3.2495 | 5.0 | 360 | Sampson 2005 |
| Canary rockfish | 21,088 | 0.0600 | 0.16 | 56 | 75 | 0.0155 | 3.0300 | 8.0 | 90 | Stewart 2007 |
| Shortbelly rockfish | 64,000 | 0.3500 | 0.20 | 28 | 17 | 0.0095 | 3.0650 | 2.0 | 30 | Field et al. 2007 |
| Yelloweye rockfish, cowcod | 595 | 0.0473 | 0.05 | 69 | 110 | 0.0193 | 2.9852 | 16.1 | 53 | Wallace 2007 |
| Benthopelagics, mesopelagics | 244,363 | 0.4582 | 0.35 | 25 | 8 | 0.0030 | 2.9980 | 2.2 | 30 | Brand et al. 2007 |
| Deep demersal (mostly grenadiers) | 179,207 | 0.0819 | 0.10 | 97 | 65 | 0.0640 | 3.0692 | 25.1 | 90 | Brand et al. 2007 |
| Deep small rockfish | 489,619 | 0.0628 | 0.11 | 31 | 77 | 0.0075 | 3.2383 | 12.7 | 45 | Fay 2005 |
| Deep large rockfish | 172,271 | 0.0675 | 0.09 | 61 | 90 | 0.0092 | 3.2310 | 12.8 | 45 | Hamel 2005b, Helser 2005, Rogers 2005 |
| Small flatfish | 314,932 | 0.3507 | 0.23 | 47 | 19 | 0.0066 | 3.1410 | 3.8 | 195 | Builder-Ramsey et al. 2002, Keller et al. 2005, Keller et al. 2006a, Keller et al. 2006b, Keller et al. 2007, Stewart 2005 |
| Sculpins, misc. nearshore | 60,181 | 0.6221 | 0.06 | 56 | 18 | 0.0105 | 3.0267 | 3.2 | 35 | Brand et al. 2007, Field 2004, Caselle[c] |
| Surfperch, misc. | 685,808 | 0.3200 | 0.24 | 35 | 13 | 0.0030 | 3.0739 | 2.2 | 30 | Caselle[c] |
| Midwater rockfish (except canary) | 252,991 | 0.1384 | 0.19 | 50 | 59 | 0.0195 | 2.9276 | 18.6 | 141 | Field 2007, Hamel 2005a, He et al. 2007, MacCall 2007, Wallace and Lai 2005 |
| Small shallow rockfish | 48,221 | 0.1659 | 0.13 | 28 | 45 | 0.0108 | 3.1108 | 4.6 | 73 | Brand et al. 2007 |
| Shallow large rockfish | 62,044 | 0.2018 | 0.14 | 47 | 41 | 0.0245 | 2.7311 | 6.3 | 58 | Builder-Ramsey et al. 2002, Keller et al. 2005, Keller et al. 2006a, Keller et al. 2006b, Keller et al. 2007 |
| Hake | 3,698,000 | 0.2300 | 0.33 | 91 | 23 | 0.0204 | 2.7376 | 3.5 | 70 | Helser and Martell 2007 |
| Sablefish | 156,676 | 0.0700 | 0.23 | 78 | 85 | 0.0024 | 3.3469 | 5.0 | 360 | Schirripa 2007 |
| Large piscivorous flatfish | 113,779 | 0.2068 | 0.14 | 92 | 29 | 0.0044 | 3.2478 | 7.0 | 180 | Brand et al. 2007, Clark and Hare 2007, Kaplan and Helser 2007, Lai et al. 2005 |
| Lingcod, cabezon | 34,744 | 0.2505 | 0.14 | 108 | 20 | 0.0031 | 3.3021 | 3.9 | 90 | Cope and Punt 2005, Jagielo and Wallace 2005 |
| Albacore tuna | 1,310 | 0.3000 | 0.10 | 140 | 10 | 0.0453 | 2.7900 | 5.0 | 30 | Brand et al. 2007 |
| Large planktivores | 1,259,290 | 0.5000 | 0.29 | 41 | 14 | 0.0035 | 3.3657 | 1.5 | 60 | Dorval et al. 2007, MacCall and Stauffer 1983, Stauffer and Charter 1982 |
| Small planktivores | 3,736,609 | 0.7546 | 0.52 | 20 | 9 | 0.0086 | 2.9982 | 1.7 | 60 | Brand et al. 2007 |

Table 28 continued.  Vertebrate biomass and life history parameters for the central California Atlantis model.

| Group | Initial biomass (mt) | Mortality | k | L*inf* | Max age (years) | a | B | Age at maturity (years) | Age at recruitment (days) | Biomass/distribution references |
|---|---|---|---|---|---|---|---|---|---|---|
| Salmon | 37,534 | 0.2700 | 0.15 | 153 | 7 | 0.0133 | 3.0000 | 4.0 | 350 | Brand et al. 2007 |
| Large demersal sharks | 936 | 0.2000 | 0.25 | 202 | 49 | 0.0135 | 3.0000 | 10.0 | 360 | Brand et al. 2007 |
| Small demersal sharks | 117,835 | 0.1512 | 0.13 | 98 | 49 | 0.0045 | 3.0276 | 31.2 | 360 | Builder-Ramsey et al. 2002, Keller et al. 2005, Keller et al. 2006a, Keller et al. 2006b, Keller et al 2007 |
| Misc. pelagic sharks | 3,742 | 0.1850 | 0.13 | 200 | 15 | 0.0068 | 2.9400 | 9.0 | 360 | Brand et al. 2007 |
| Skates and rays | 96,239 | 0.2000 | 0.05 | 194 | 20 | 0.0044 | 3.0547 | 7.5 | 60 | Gertseva and Schirripa 2007, Keller et al. 2005, Keller et al. 2006a, Keller et al. 2006b, Keller et al 2007 |
| Pinnipeds | 34,587 | NA[d] | 0.95 | 350 | 17 | 0.0015 | 3.3745 | 4.5 | 330 | Carretta et al. 2007 |
| Transient orcas | 194 | NA[d] | 0.40 | 915 | 50 | 0.1430 | 2.4070 | 13.0 | 480 | Brand et al. 2007 |
| Baleen whales | 49,789 | NA[d] | 0.22 | 2,007 | 86 | 0.5980 | 2.3380 | 7.7 | 375 | Barlow and Forney 2007, Carretta et al. 2006 |
| Toothed whales | 3,493 | NA[d] | 0.11 | 1,343 | 67 | 0.4775 | 2.3561 | 9.8 | 448 | Barlow and Forney 2007, Carretta et al. 2006 |
| Small whales, dolphins | 5,199 | NA[d] | 0.59 | 225 | 20 | 0.1430 | 2.4070 | 5.8 | 329 | Barlow and Forney 2007 |
| Sea otter | 101 | NA[d] | 0.71 | 133 | 15 | 1.0000 | 2.1000 | 4.0 | 150 | Lance et al. 2004 |
| Migratory birds | 1,534 | NA[d] | NA[d] | 45 | 34 | 12.4650 | 1.1228 | 6.2 | 53 | Parrish and Loggerwell 2001 |
| Planktivorous seabirds | 41 | NA[d] | NA[d] | 23 | 6 | 7.5982 | 1.0000 | 3.0 | 39 | Manuwal and Thoresen 1993, Page et al. 1999 |
| Piscivorous seabirds | 1,072 | NA[d] | NA[d] | 67 | 22 | 11.8728 | 1.0380 | 4.5 | 32 | Huff et al. 2006, Parrish and Loggerwell 2001, Thayer[e] |

[a] k and L*inf* are von Bertalanffy growth parameters.
[b] a and B are length-weight conversions.
[c] J. Caselle, PISCO, Univ. California Santa Barbara, Marine Science Institute.  Pers. commun., October 2007.
[d] NA = Not applicable.
[e] J. Thayer, Point Reyes Bird Observatory, Petaluma, CA.  Pers. commun., October 2007.

Table 29. Spatial management included in status quo scenario.[a] EFH is essential fish habitat,[b] RCA is rockfish conservation area,[c] SMR is California state marine reserve, SMCA is California state marine conservation area, and SMRMA is California state marine recreational management area.

| Area name | Type | Regulation | Region | Source |
|---|---|---|---|---|
| Nontrawl RCA | RCA | No fixed gear fisheries, 0–100 fm | N of lat 46°16′ | NMFS 2010a |
| Nontrawl RCA | RCA | No fixed gear fisheries, 30–100 fm | Lat 46°16′ to 45°3.83′ | NMFS 2010a |
| Nontrawl RCA | RCA | No fixed gear fisheries, 30–125 fm | Lat 45°3.83′ to 43° | NMFS 2010a |
| Nontrawl RCA | RCA | No fixed gear fisheries, 20–100 fm | Lat 43° to 40°10′ | NMFS 2010a |
| Nontrawl RCA | RCA | No fixed gear fisheries, 30–150 fm | Lat 40°10′ to 34°27′ | NMFS 2010a |
| Trawl RCA | RCA | No trawl fisheries, 0–200 fm | N of Lat 48°10′ | NMFS 2010a |
| Trawl RCA | RCA | No trawl fisheries, 75–200 fm | Lat 48°10′ to 40°10′ | NMFS 2010a |
| Trawl RCA | RCA | No trawl fisheries, 100–150 fm | S of Lat 40°10′ | NMFS 2010a |
| Nongroundfish trawl RCA | RCA | No California halibut trawl fishing, 100–200 fm | Lat 40°10′ to 38° | NMFS 2010a |
| Nongroundfish trawl RCA | RCA | No California halibut trawl fishing, 100–150 fm | Lat 38° to 34°27′ | NMFS 2010a |
| Olympic 2 | EFH | No bottom trawl gear | Washington | NMFS 2010a |
| Biogenic 1 | EFH | No bottom trawl gear | Washington | NMFS 2010a |
| Biogenic 2 | EFH | No bottom trawl gear | Washington | NMFS 2010a |
| Grays Canyon | EFH | No bottom trawl gear | Washington | NMFS 2010a |
| Biogenic 3 | EFH | No bottom trawl gear | Washington | NMFS 2010a |
| Astoria Canyon | EFH | No bottom trawl gear | Oregon | NMFS 2010a |
| Siletz deepwater | EFH | No bottom trawl gear | Oregon | NMFS 2010a |
| Daisy Bank/Nelson Island | EFH | No bottom trawl gear | Oregon | NMFS 2010a |
| Newport Rockpile, Stonewall Bank | EFH | No bottom trawl gear | Oregon | NMFS 2010a |
| Heceta Bank | EFH | No bottom trawl gear | Oregon | NMFS 2010a |
| Deepwater off Coos Bay | EFH | No bottom trawl gear | Oregon | NMFS 2010a |
| Bandon High Spot | EFH | No bottom trawl gear | Oregon | NMFS 2010a |
| Rogue Canyon | EFH | No bottom trawl gear | Oregon | NMFS 2010a |
| Eel River Canyon | EFH | No bottom trawl gear other than demersal seine | California | NMFS 2010a |
| Blunts Reef | EFH | No bottom trawl gear other than demersal seine | California | NMFS 2010a |
| Mendocino Ridge | EFH | No bottom trawl gear other than demersal seine | California | NMFS 2010a |
| Delgada Canyon | EFH | No bottom trawl gear other than demersal seine | California | NMFS 2010a |
| Tolo Bank | EFH | No bottom trawl gear other than demersal seine | California | NMFS 2010a |
| Point Arena north | EFH | No bottom trawl gear other than demersal seine | California | NMFS 2010a |

Table 29 continued. Spatial management included in status quo scenario.[a] EFH is essential fish habitat,[b] RCA is rockfish conservation area,[c] SMR is California state marine reserve, SMCA is California state marine conservation area, and SMRMA is California state marine recreational management area.

| Area name | Type | Regulation | Region | Source |
|---|---|---|---|---|
| Point Arena south biogenic area | EFH | No bottom trawl gear other than demersal seine | California | NMFS 2010a |
| Cordell Bank biogenic area | EFH | No bottom trawl gear other than demersal seine | California | NMFS 2010a |
| Cordell Bank (50 fm (91 m) isobath) | EFH | No bottom contact gear | California | NMFS 2010a |
| Farallon Islands, Fanny Shoal | EFH | No bottom trawl gear other than demersal seine | California | NMFS 2010a |
| Half Moon Bay | EFH | No bottom trawl gear other than demersal seine | California | NMFS 2010a |
| Monterey Bay/Canyon | EFH | No bottom trawl gear other than demersal seine | California | NMFS 2010a |
| Point Sur Deep | EFH | No bottom trawl gear other than demersal seine | California | NMFS 2010a |
| Big Sur Coast/Port San Luis | EFH | No bottom trawl gear other than demersal seine | California | NMFS 2010a |
| East San Lucia Bank | EFH | No bottom trawl gear other than demersal seine | California | NMFS 2010a |
| Point Conception | EFH | No bottom trawl gear other than demersal seine | California | NMFS 2010a |
| Nehalem Bank/Shale Pile | EFH | No bottom trawl gear | Oregon | NMFS 2010a |
| Lovers Point SMR | SMR | No take | California | CDFG 2010 |
| Piedras Blancas SMR | SMR | No take | California | CDFG 2010 |
| Carmel Pinnacles SMR | SMR | No take | California | CDFG 2010 |
| Morro Bay SMRMA | SMRMA | No take | California | CDFG 2010 |
| Edward F. Ricketts SMCA | SMCA | No take in the model (simplified from real world) | California | CDFG 2010 |
| Carmel Bay SMCA | SMCA | No take in the model (simplified from real world) | California | CDFG 2010 |
| Point Lobos SMR | SMR | No take in the model (simplified from real world) | California | CDFG 2010 |
| Año Nuevo SMCA | SMCA | No take in the model (simplified from real world) | California | CDFG 2010 |
| Pacific Grove Marine Gardens SMCA | SMCA | No take in the model (simplified from real world) | California | CDFG 2010 |
| Asilomar SMR | SMR | No take | California | CDFG 2010 |
| Soquel Canyon SMCA | SMCA | No take in the model (simplified from real world) | California | CDFG 2010 |
| Portuguese Ledge SMCA | SMCA | No take in the model (simplified from real world) | California | CDFG 2010 |

Table 29 continued. Spatial management included in status quo scenario.[a] EFH is essential fish habitat,[b] RCA is rockfish conservation area,[c] SMR is California state marine reserve, SMCA is California state marine conservation area, and SMRMA is California state marine recreational management area.

| Area name | Type | Regulation | Region | Source |
|---|---|---|---|---|
| White Rock (Cambria) SMCA | SMCA | No take in the model (simplified from real world) | California | CDFG 2010 |
| Cambria SMCA | SMCA | No take in the model (simplified from real world) | California | CDFG 2010 |
| Point Sur SMR | SMR | No take | California | CDFG 2010 |
| Point Buchon SMR | SMR | No take | California | CDFG 2010 |
| Greyhound Rock SMCA | SMCA | No take in the model (simplified from real world) | California | CDFG 2010 |
| Point Lobos SMCA | SMCA | No take in the model (simplified from real world) | California | CDFG 2010 |
| Point Sur SMCA | SMCA | No take in the model (simplified from real world) | California | CDFG 2010 |
| Big Creek SMR | SMR | No take | California | CDFG 2010 |
| Big Creek SMCA | SMCA | No take in the model (simplified from real world) | California | CDFG 2010 |
| Piedras Blancas SMCA | SMCA | No take in the model (simplified from real world) | California | CDFG 2010 |
| Point Buchon SMCA | SMCA | No take in the model (simplified from real world) | California | CDFG 2010 |
| Vandenberg SMR | SMR | No take | California | CDFG 2010 |
| Natural Bridges SMR | SMR | No take | California | CDFG 2010 |

[a] We include the MPAs that were put in place in September 2007 for central California (CDFG 2010). In reality each area prohibits certain gears, but not necessarily all gears. However, given the small size of these areas relative to our model domain, we simplified this to prohibit all fishing in these areas. Other similar MPAs established after 2007 and state managed spatial areas in Oregon and Washington are not included.
[b] Each area prohibits certain gears, but not necessarily all gears.
[c] We included trawl and nontrawl RCAs only, as described for 2007–2008 in NMFS (2010a) and Table A-1. Recreational RCAs and the Yelloweye RCA were not included. The boundaries of the trawl and nontrawl RCAs differ from each other and vary by latitude. In reality, the trawl RCA varies seasonally and in response to management needs; in the model we included this RCA as fixed at the depths and latitudes indicated in the table.

research reserves, and the like are generally not included (see PFMC 2008b for a full list of spatial management units).

Fishing mortality is apportioned between each of 20 gear types (Table 30). For the groundfish gears (numbers 1–7), fishing mortality is derived from estimates of total mortality, including discards, from Bellman et al. (2008). For the nongroundfish gears (numbers 8–20), fishing mortality is based on landings reported in the PacFIN database (http://pacfin.psmfc.org /pacfin_pub/data.php). For these simple simulations, we assume that fishing mortality (% mortality per year) remains constant over the course of the simulation. We do not vary fishing mortality or attempt to model time-varying quotas.

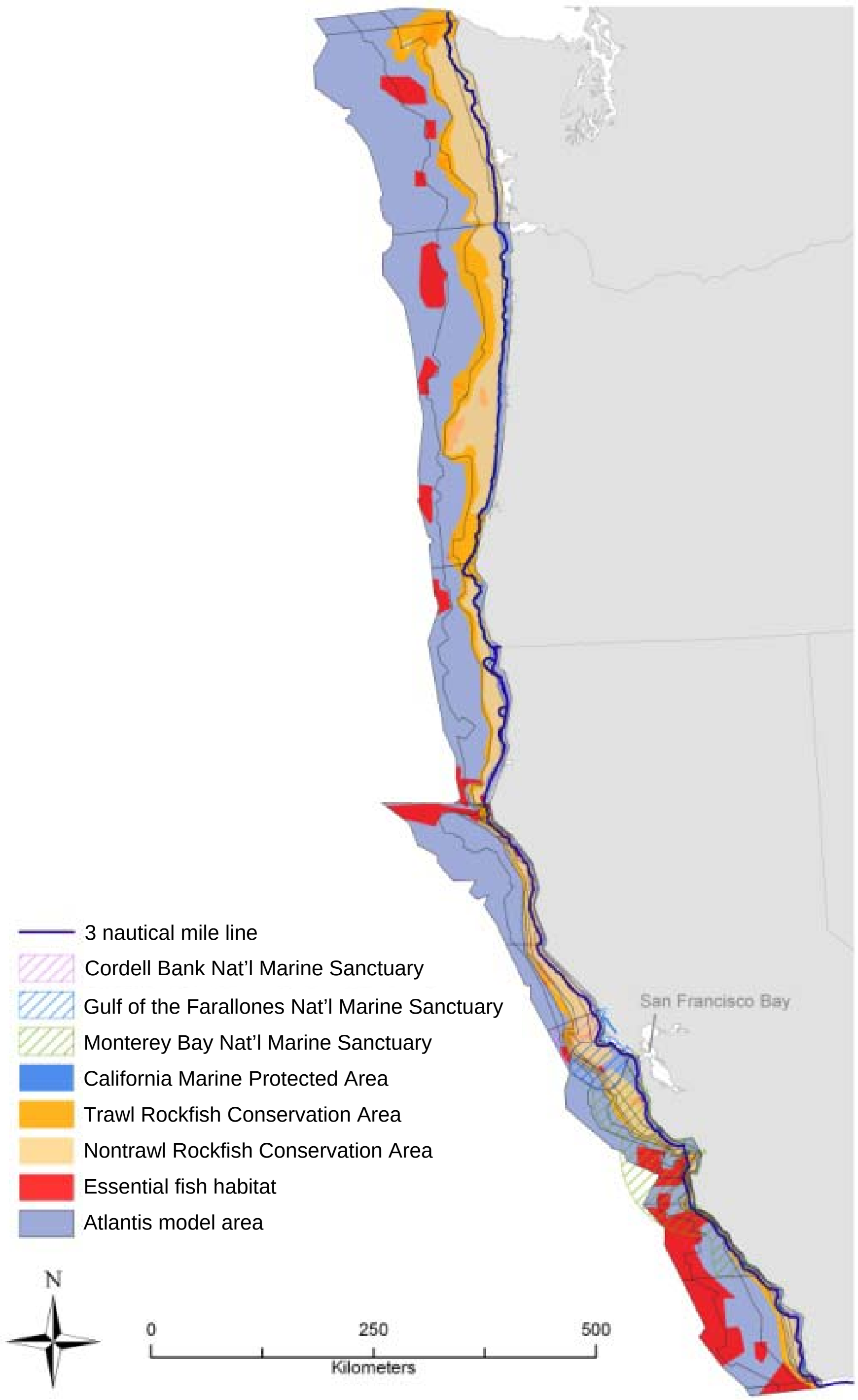



Figure 44. Status quo spatial management for the U.S. West Coast.

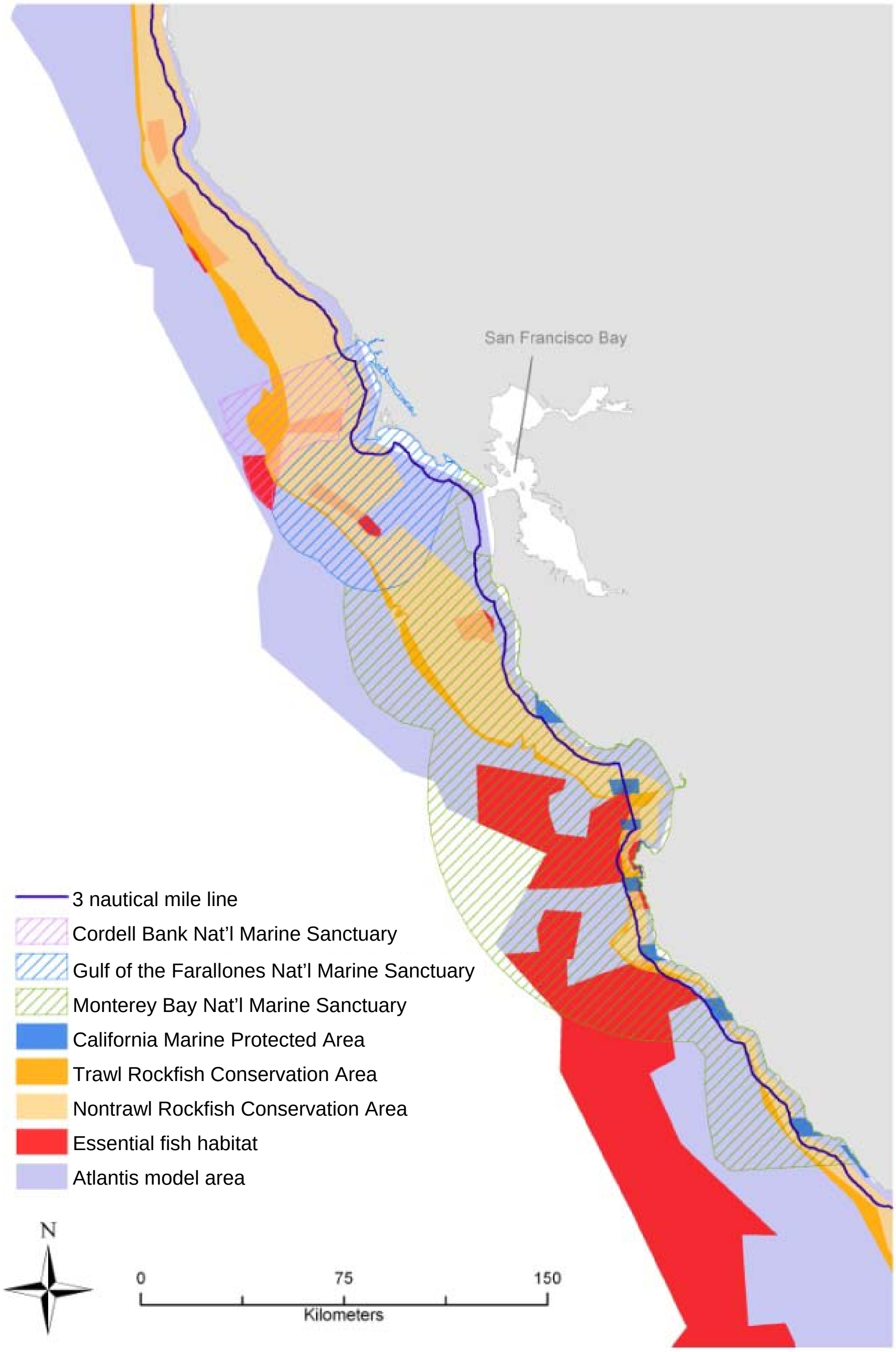



Figure 45. Status quo spatial management for central California.

Table 30. Fleets (gears), spatial management closures, and gear description (whether bottom contact and impact factor on hard, soft, and biogenic habitat, taken from NMFS 2005). Gear impact factors of 1.0 indicate the most damage and 0.0 the least.

| | | | | | | **Status quo spatial management (X = closed)** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | **Bottom** | **Gear impact factor** | | | **State** | | **EFH Cordell** | **Trawl** | **Nontrawl** |
| | **Fleet** | **contact?** | **Hard** | **Soft** | **Biogenic** | **MPA** | **EFH** | **Bank** | **RCA** | **RCA** |
| 1 | Limited entry bottom trawl | Yes | 0.81 | 0.31 | 0.74 | X | X | X | X | |
| 2 | California halibut (trawl) | Yes | 0.81 | 0.31 | 0.74 | X | X | X | X | |
| 3 | Pink shrimp (trawl) | Yes | 0.81 | 0.31 | 0.74 | X | X | X | X | |
| 4 | Nonnearshore fixed gear (pot and demersal longline) | Yes | 0.18 | 0.12 | 0.23 | X | | X | | X |
| 5 | Nearshore fixed gear (hook and line, jigging) | | 0.18 | 0.06 | 0.22 | X | | | | X |
| 6 | At sea hake midwater trawl | | | | | X | | | X | |
| 7 | Shoreside hake midwater trawl | | | | | X | | | X | |
| 8 | Purse seine (coastal pelagics) | | | | | X | | | | X |
| 9 | Crab pot | Yes | 0.18 | 0.12 | 0.23 | X | | X | | X |
| 10 | Highly migratory species (tuna, shark, swordfish, longline, gillnet, troll) | | | | | X | | | | X |
| 11 | Lobster pot | Yes | 0.18 | 0.12 | 0.23 | X | | X | | X |
| 12 | Mollusks (diving) | | | | | X | | | | X |
| 13 | Urchin (diving) | | | | | X | | | | X |
| 14 | Pacific halibut (longline) | Yes | 0.18 | 0.06 | 0.22 | X | | X | | X |
| 15 | Sea cucumber (diving) | | | | | X | | | | X |
| 16 | Hagfish (pot) | Yes | 0.18 | 0.12 | 0.23 | X | | X | | X |
| 17 | Salmon | | | | | X | | | | X |
| 18 | Shellfish | | | | | X | | | | X |
| 19 | Spot prawn trap | Yes | 0.18 | 0.12 | 0.23 | X | | X | | X |
| 20 | Recreational hook and line | | | | | X | * | * | * | * |

* Recreational fishing open in coastal model cells (except for California MPA), closed in all other model cells.

In the status quo run, a single fishing mortality rate per fleet and species is calculated and applied equally to each cell that is open to fishing. For instance, a limited entry trawl exploitation rate of 4.6%/$yr^{-1}$ was applied to the large flatfish group in all cells that were fully open to fishing by this gear. Cells partly closed to fishing have proportional decreases in fishing mortality. The combination of these exploitation rates and spatial closures was set such that total catch per fleet and functional group matched the 2007 catch estimates from Bellman et al. (2008) and PacFIN. In simple terms, one can think of our approach as applying a uniform exploitation rate (%/$yr^{-1}$) across the entire model domain, but then using a cookie cutter approach to remove fishing by certain fleets from certain cells. Despite this extremely simple approach to simulating fishing mortality per fleet, when combined with observed biomass distributions (e.g., from trawl surveys such as Keller et al. 2006), the method is intended to yield a roughly realistic spatial distribution of catch.

**Scenario 2: Gear shift**

These scenarios capture the desire to reduce bycatch by encouraging fishers to switch from trawl gear to fixed gear (pot or longline) that has lower bycatch rates. New individual quota regulations recently enacted by the PFMC allow for such gear switching (http://www .pcouncil.org/groundfish/fishery-management-plan/fmp-amendment-20/). Bellman et al. (2008) estimated total mortality for limited entry trawl and fixed gear; this can be used to parameterize a switch between these two gears. All details of the scenarios will be the same as Scenario 1 (status quo), except for the following.

Shift to pot + longline in Monterey Bay NMS. Within MBNMS (boxes 41–68), this involves reducing limited entry trawl fishing mortality rates by 25, 50, and 100% from status quo. Fixed gear (longline and pot fishing) mortality is increased 25, 50, or 100% from status quo, to represent a transfer of vessels from the trawl fleet. This results in a decrease in fishing mortality on most nontarget species, due to the higher selectivity of longline or pot gear. By simply scaling the mortality caused by fixed gear, we are assuming that the ratio of pot vessels to longline vessels remains constant within the fixed gear category. MBNMS covers 12% of the model domain.

Shift to pot + longline, coast-wide. These scenarios are identical to Scenario 2a, but involve a 25% coast-wide (rather than within-sanctuary) decrease in limited entry trawl fishing mortality rates, and a 25% increase in fixed gear fishing mortality. This corresponds to 40 permitted vessels switching gears (NMNS 2010b).

**Scenario 3: Close rockfish conservation area to bottom-contact gear**

Status quo spatial management involves an offshore RCA that prohibits trawl gear and a separate inshore RCA that prohibits nontrawl commercial gear. The offshore trawl RCA allows bottom-contact gear (longline and pot) that may harm biogenic habitat. Scenario 3 converts all RCAs to prohibit all bottom-contact gear (trawl, longline, and pot).

As in other scenarios, RCAs will be permanent and will not vary seasonally. In the model, the RCA covers depths ranging from 0 to 200 fathoms (0–366 m), but varying by gear and latitude (Table 29). The result is that model cells spanning 0–550 m are completely or partially closed to fishing by trawl and fixed gear (pots and demersal longline).

In this scenario and others that involve spatial management, we assume there is no effort displacement, that is, there is no spatial redistribution of fishers due to the closure. The fishing mortality rate calculated in the status quo scenario is applied to all model cells open to fishing; the set of cells that are open and closed changes in response to spatial management.

Prohibit all bottom-contact gear in existing trawl RCA and nontrawl RCA in Monterey Bay NMS. This area covers 12% of the model domain.

Prohibit all bottom-contact gear in existing trawl RCA and nontrawl RCA, coast wide.

Prohibit all bottom-contact gear in existing trawl RCA and nontrawl RCA in all three Central California NMS. This area covers 16% of the model domain.

**Scenario 4: Consolidate spatial management**

The status quo EFH closures ban trawling across large areas. However, these EFH closures allow other bottom-contact gear (longline and pot) that may harm biogenic habitat, though perhaps to a lesser extent than trawl gear. Thus the existing regulations may perpetuate moderate habitat impacts, but over a large geographic area.

Scenarios 4a-b provide an alternative to this, by concentrating the spatial extent of fishing. Thus the goal in Scenarios 4a-b is to ban all bottom-contact gear in 50% of the EFH, but open the other 50% of EFH to trawling. In these scenarios, areas deeper than 550 m are open to fishing with trawl and fixed gear; inshore areas are closed.

Consolidate spatial management, Monterey Bay.

Consolidate spatial management, coast wide.

**Scenario 5: Ban all fishing in RCA and EFH**

These are bounding scenarios, meant to provide a frame of reference for less restrictive scenarios.

Prohibit fishing in RCA and EFH in MBNMS. All fleets, including nongroundfish gears, are prohibited from fishing in MBNMS RCA and EFH. This includes RCA and EFH in boxes 41–68. Fishing mortality rates are set to zero for RCA and EFH within the sanctuary.

Prohibit fishing in RCA and EFH in coast-wide NMS. This is the same as Scenario 5a above, but all fishing mortality for all gears is set to zero in the RCA and EFH in all West Coast sanctuaries.

Prohibit fishing. This is a 20-year run with no fishing mortality, meant to predict biomass levels for unfished population.

Maintain status quo fishing mortality rates, but with no spatial management. This is a 20-year run. Status quo fishing mortality rates are applied to all cells, including cells that were previously closed as RCA or EFH. Thus total catch and total mortality increase coast wide.

**Scenario 6: Multipliers of status quo fishing mortality**

These four scenarios multiplied status quo fishing mortality for all fleets and species by 50%, 150%, 200%, and 500%. As with all the scenarios, the projection is for 20 years.

Multiply status quo F by 50%.

Multiply status quo F by 150%.

Multiply status quo F by 200%.

Multiply status quo F by 500%.

**Calculation of habitat integrity metric**

Though Atlantis does calculate abundance of benthic invertebrates and biogenic habitat such as corals and sponges, we lack quantitative data to adequately parameterize the dynamic impacts of particular gears on particular types of benthos and benthic habitat in the California Current. However, as part of an EFH Environmental Impact Statement, NMFS (2005) has published qualitative estimates of the relative impacts of particular gear types on substrate. We have used these impact estimates, combined with the maps of spatial management and the scalars of effort that define our scenarios, to create a qualitative index of habitat integrity for each scenario. The result is a metric that is scaled relative to status quo habitat integrity, with zero representing full exposure of all habitat to gear that can fully damage it (at least in the short term). The habitat integrity metric responds positively when areas are closed to spatial management or when fishing effort is switched toward gears that are less destructive to the benthos. The metric is static; we are calculating only exposure of habitat to fishing gears in the scenarios, rather than the biological response over time.

NMFS (2005) lists the relative impacts of gears on habitat type. For instance, bottom trawls may cause more than 4 times more damage than pot gear, and they may cause more than 2.5 times more damage to hard substrate than soft sand or mud. Scaling the relative impacts to a maximum of 1 (which would represent extreme impacts of dredge gear in estuaries with soft substrate) yields the values in Table 30. This scaling also converts the original qualitative estimates to quantitative values consistent with estimates from Collie et al. (2000), who reported mean initial declines in abundance due to trawling of 51%. Collie et al. (2000) reported that trawling and dredging caused declines of 59% in biogenic habitat, 57% in mud, 58% in gravel, and 21% in sand.

The habitat integrity metric was calculated based on impact per gear and substrate, substrate per polygon, fishing effort per gear and polygon relative to status quo (2008), and the proportion of each polygon open to fishing. We assumed that each gear acted independently on a polygon; therefore, the proportion of the habitat that remains intact is the product of the proportion of habitat that remains intact from each gear:

$$P_p = \prod_{g=1}^{numgears} (1 - E_{g,p} * A_{g,p} * \sum_{s=1}^{numsubstrates} (I_{g,s} * H_{g,p})) \qquad (4)$$

where $P_p$ is the proportion of habitat in polygon *p* that remains intact, $E_{g,p}$ is the effort by that gear in that polygon, $A_{g,p}$ is the proportion of polygon *p* open to fishing by gear *g* relative to initial levels, $I_{g,s}$ is the impact factor per gear and substrate from Table 30, and $H_{s,p}$ is the proportion of the habitat in polygon *p* that is substrate *s*. The habitat integrity metric is then:

$$HabitatIntegrityMetric_i = \frac{\sum_{p=1}^{numpolygons} P_{p,i} * a_p}{\sum_{p=1}^{numpolygons} P_{p,StatusQuo} * a_p} \qquad (5)$$

where $HabitatIntegrityMetric_i$ is the total undisturbed habitat in scenario *i* relative to StatusQuo and $a_p$ is the area of the polygon *p* ($km^2$).

## Results

### Coast-wide biomass and catch

**Scenarios 5a–6d (sensitivity analysis scenarios)**—Table 31 and Table 32 summarize the coast-wide catch and biomass for year 20 of each scenario relative to status quo (Scenario 1). Scenarios 5a-6d primarily represent strong perturbations intended as sensitivity analyses, and therefore showed the strongest biomass responses. We discuss them first to set the context for other scenarios.

Scenarios 5a–5c and 6a, which removed all fishing from all or some polygons, showed moderate to strong increases in the biomass of many fished species, such as large piscivorous flatfish (arrowtooth), Pacific hake, sablefish, small demersal sharks, yelloweye rockfish, and cowcod (Table 31). For instance, arrowtooth flounder increased 2.6 times above initial levels, and 2.4 times relative to status quo year 20 (Figure 46). Scenarios 5a and 5b, which involved the NMS or MBNMS only, had more moderate responses, though a few groups showed relatively strong increases (e.g., nearshore miscellaneous fish). Notably, these two scenarios also predicted strong decreases in yelloweye and cowcod. Albacore tuna (*Thunnus alalunga*) and salmon declined in these two scenarios, but results for these groups should be interpreted cautiously because the stocks are only in the model domain for a fraction of the year. Marine mammals and birds were generally affected by less than 5% in Scenarios 5a and b, except for diving seabirds that declined 12% due to shark predation. However, Scenario 6a (50% status quo fishing) deviated from this, since increased fish predation on small planktivores (sardines and anchovies) drove their abundance down, leading to lower abundances of marine mammal and bird groups.

Smaller-bodied fish groups generally declined or showed only minor increases in these scenarios; these groups included small flatfish, midwater rockfish, deep small rockfish, and small shallow rockfish. Abundance of larger-bodied predators generally increased the most as fishing was released; these groups included large Pacific hake, sablefish, Dover sole, and in some cases miscellaneous pelagic sharks, piscivorous flatfish (arrowtooth), lingcod, and cabezon. Year 20 catches for Scenarios 5a and 5b (NMS spatial closures) of most groups were lower than status quo year 20 catch (Table 32), with the exception of groups that were locally overfished within the sanctuaries in the status quo model. These included canary rockfish, lingcod and cabezon, small shallow rockfish, large planktivores, yelloweye and cowcod, and skates and rays. Year 20 catches for Scenario 6a (50% status quo fishing) were lower than status quo except for skates and

Table 31. Biomass per functional group at year 20, relative to year 20 biomass under status quo (scenario 1).

| | 1. Status quo | 2a. Gearshift, MBNMS 25% | 2a. Gearshift, MBNMS, 50% | 2a. Gearshift, MBNMS, 100% | 2b. Gearshift, 25% | 3a. RCA no bottom contact, MBNMS | 3b. RCA no bottom contact | 3c. RCA no bottom contact, Central CA | 4a. Consolidate impacts, MBNMS | 4b. Consolidate impacts | 5a. No fishing MBNMS | 5b. No fishing, NMS | 5c. No fishing | 5d. Fishing, no spatial management | 6a. F x 0.5 | 6b. F x 1.5 | 6c. F x 2 | 6d. F x 5 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Large planktivores | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.99 | 1.00 | 1.00 | 1.00 | 1.00 | 1.01 | 0.93 | 1.49 | 2.38 | 2.44 | 2.42 | 2.65 |
| Canary rockfish | 1.00 | 0.98 | 0.99 | 0.99 | 1.01 | 1.00 | 1.05 | 1.00 | 1.00 | 1.00 | 1.01 | 1.02 | 1.03 | 0.89 | 0.65 | 0.59 | 0.58 | 0.45 |
| Small planktivores | 1.00 | 1.01 | 1.01 | 1.01 | 1.00 | 1.00 | 0.99 | 1.00 | 1.00 | 1.00 | 1.00 | 0.99 | 1.03 | 0.90 | 0.90 | 0.87 | 0.84 | 0.66 |
| Large pisciv. flatfish | 1.00 | 1.01 | 1.01 | 1.02 | 1.23 | 1.02 | 1.74 | 1.02 | 1.00 | 0.98 | 1.02 | 1.15 | 2.39 | 0.81 | 0.63 | 0.24 | 0.16 | 0.04 |
| Shortbelly rockfish | 1.00 | 1.02 | 1.02 | 1.02 | 1.00 | 1.01 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.01 | 1.09 | 0.55 | 0.27 | 0.35 | 0.39 | 0.47 |
| Lingcod, cabezon | 1.00 | 0.67 | 0.67 | 0.67 | 1.07 | 0.82 | 1.29 | 1.01 | 1.00 | 1.00 | 0.95 | 0.81 | 1.39 | 0.03 | 0.75 | 0.70 | 0.60 | 0.21 |
| Salmon | 1.00 | 1.14 | 1.14 | 1.14 | 1.00 | 0.92 | 1.01 | 0.93 | 1.00 | 1.00 | 1.05 | 0.80 | 43.52 | 0.04 | 16.38 | 0.27 | 0.03 | 0.00 |
| Albacore | 1.00 | 0.32 | 0.32 | 0.32 | 1.00 | 0.25 | 1.00 | 0.29 | 1.00 | 1.00 | 0.49 | 0.38 | 21.07 | 0.00 | 2.56 | 0.34 | 0.21 | 0.06 |
| Migratory birds | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.73 | 0.72 | 0.73 | 0.72 |
| Pacific hake | 1.00 | 1.03 | 1.03 | 1.03 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.04 | 1.09 | 1.70 | 1.04 | 1.32 | 0.80 | 0.64 | 0.25 |
| Sablefish | 1.00 | 1.03 | 1.03 | 1.04 | 1.01 | 1.01 | 1.09 | 1.01 | 0.99 | 0.99 | 1.02 | 1.03 | 1.59 | 0.96 | 1.45 | 0.98 | 0.84 | 0.36 |
| Deep vertical migrators | 1.00 | 1.01 | 1.01 | 1.01 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.01 | 1.00 | 0.99 | 1.02 | 1.06 | 1.33 | 1.31 | 1.29 | 1.17 |
| Deep demersal fish | 1.00 | 1.01 | 1.01 | 1.01 | 1.01 | 1.00 | 1.00 | 1.00 | 1.00 | 0.99 | 1.01 | 1.01 | 1.30 | 0.99 | 0.97 | 0.76 | 0.68 | 0.34 |
| Shallow pisciv. fish (sculpin) | 1.00 | 0.71 | 0.71 | 0.71 | 0.98 | 0.98 | 0.95 | 0.98 | 1.00 | 1.00 | 1.00 | 1.01 | 0.85 | 1.32 | 0.30 | 0.30 | 0.30 | 0.24 |
| Midwater rockfish | 1.00 | 0.98 | 0.98 | 0.98 | 1.00 | 1.00 | 1.01 | 1.00 | 1.00 | 1.00 | 1.01 | 1.02 | 1.02 | 0.77 | 0.64 | 0.56 | 0.54 | 0.42 |
| Nearshore fish (surfperch) | 1.00 | 0.98 | 0.98 | 0.97 | 1.00 | 1.01 | 1.08 | 1.01 | 1.00 | 0.99 | 1.00 | 1.23 | 0.50 | 4.94 | 0.43 | 0.70 | 0.74 | 0.66 |
| Dover sole | 1.00 | 1.09 | 1.10 | 1.11 | 1.10 | 1.02 | 1.06 | 1.01 | 0.99 | 0.98 | 1.01 | 1.04 | 1.31 | 1.00 | 1.73 | 1.19 | 1.00 | 0.34 |
| Small shallow rockfish | 1.00 | 1.00 | 1.00 | 1.00 | 0.99 | 0.87 | 0.96 | 0.92 | 1.00 | 1.00 | 0.95 | 0.93 | 0.72 | 0.48 | 0.33 | 0.29 | 0.32 | 0.46 |
| Deep small rockfish | 1.00 | 1.01 | 1.01 | 1.02 | 1.01 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.01 | 0.95 | 1.31 | 0.81 | 0.80 | 0.80 | 0.76 |
| Deep large rockfish | 1.00 | 1.02 | 1.02 | 1.02 | 1.02 | 1.00 | 1.01 | 1.00 | 1.00 | 0.99 | 1.00 | 1.01 | 1.09 | 1.21 | 0.72 | 0.62 | 0.56 | 0.55 |
| Small flatfish | 1.00 | 1.02 | 1.02 | 1.03 | 1.03 | 1.01 | 1.09 | 1.02 | 1.00 | 1.00 | 1.01 | 1.05 | 1.05 | 1.24 | 0.47 | 0.53 | 0.53 | 0.47 |
| Small demersal sharks | 1.00 | 1.16 | 1.16 | 1.18 | 1.12 | 1.04 | 1.67 | 1.03 | 1.00 | 1.03 | 1.06 | 1.16 | 1.99 | 0.49 | 0.72 | 0.33 | 0.22 | 0.02 |

Table 31 continued. Biomass per functional group at year 20, relative to year 20 biomass under status quo (scenario 1).

| | 1. Status quo | 2a. Gearshift, MBNMS 25% | 2a. Gearshift, MBNMS, 50% | 2a. Gearshift, MBNMS, 100% | 2b. Gearshift, 25% | 3a. RCA no bottom contact, MBNMS | 3b. RCA no bottom contact | 3c. RCA no bottom contact, Central CA | 4a. Consolidate impacts, MBNMS | 4b. Consolidate impacts | 5a. No fishing MBNMS | 5b. No fishing, NMS | 5c. No fishing | 5d. Fishing, no spatial management | 6a. F x 0.5 | 6b. F x 1.5 | 6c. F x 2 | 6d. F x 5 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Large demersal sharks | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.01 | 1.00 | 1.00 | 1.00 | 1.00 | 1.02 | 0.94 | 1.20 | 0.01 | 0.04 | 0.06 | 0.27 |
| Yelloweye and cowcod | 1.00 | 1.16 | 1.16 | 1.16 | 1.12 | 0.34 | 1.56 | 0.34 | 1.00 | 1.00 | 0.35 | 0.06 | 1.90 | 0.01 | 0.87 | 0.40 | 0.29 | 0.10 |
| Misc. pelagic sharks | 1.00 | 1.05 | 1.05 | 1.05 | 1.00 | 0.98 | 1.00 | 0.98 | 1.00 | 1.00 | 1.03 | 1.02 | 3.54 | 0.74 | 0.52 | 0.13 | 0.07 | 0.00 |
| Shallow large rockfish | 1.00 | 0.31 | 0.31 | 0.31 | 1.00 | 0.77 | 1.02 | 0.93 | 1.03 | 1.00 | 0.96 | 0.91 | 1.28 | 0.30 | 0.77 | 0.29 | 0.19 | 0.04 |
| Skates and rays | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.99 | 1.00 | 0.99 | 1.00 | 1.00 | 1.00 | 1.02 | 0.83 | 1.36 | 1.41 | 1.48 | 1.49 | 1.49 |
| Surface seabirds | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.97 | 1.00 | 1.04 | 1.04 | 1.04 | 1.04 |
| Diving seabirds | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.02 | 0.88 | 1.68 | 0.46 | 0.46 | 0.46 | 0.45 |
| Pinnipeds | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.01 | 0.96 | 0.94 | 0.91 | 0.86 | 0.79 |
| Transient orcas | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.01 | 0.99 | 0.79 | 0.79 | 0.79 | 0.79 |
| Baleen whales | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.99 | 0.93 | 0.87 | 0.87 | 0.87 | 0.86 |
| Small toothed whales | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.01 | 0.98 | 1.05 | 1.31 | 1.32 | 1.31 | 1.24 |
| Toothed whales | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.02 | 0.99 | 0.41 | 0.41 | 0.41 | 0.39 |
| Sea otter | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| Cephalopods | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.99 | 1.00 | 1.00 | 1.01 | 1.00 | 1.01 | 1.04 | 0.00 | 0.94 | 1.00 | 1.00 | 2.38 |
| Shallow benth. filt. feeders | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.01 | 0.88 | 1.31 | 1.08 | 1.11 | 1.11 | 1.19 |
| Other benth. filt. feeders | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.99 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.04 | 0.95 | 1.08 | 1.04 | 1.02 | 0.89 |
| Deep benth. filt. feeders | 1.00 | 1.01 | 1.01 | 1.01 | 1.00 | 1.00 | 1.03 | 1.00 | 1.00 | 1.00 | 1.00 | 1.11 | 0.54 | 3.52 | 0.78 | 1.08 | 1.13 | 1.48 |
| Benthic herb. grazers | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.04 | 1.05 | 3.25 | 0.95 | 1.81 | 0.55 | 0.31 | 0.01 |
| Deep macrozoobenthos | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.99 | 1.09 | 1.05 | 1.03 | 1.03 | 0.98 |
| Megazoobenthos | 1.00 | 1.19 | 1.19 | 1.19 | 1.00 | 1.00 | 1.46 | 1.00 | 1.07 | 1.33 | 1.07 | 0.87 | 31.48 | 0.10 | 5.73 | 0.17 | 0.03 | 0.00 |
| Shallow macrozoobenthos | 1.00 | 1.01 | 1.01 | 1.01 | 1.00 | 1.00 | 1.02 | 1.00 | 1.00 | 1.00 | 1.00 | 1.07 | 0.64 | 1.96 | 0.89 | 1.12 | 1.09 | 0.89 |
| Shrimp | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.01 | 0.91 | 7.37 | 0.95 | 1.01 | 1.04 | 2.83 |

Table 31 continued.  Biomass per functional group at year 20, relative to year 20 biomass under status quo (scenario 1).

| | 1. Status quo | 2a. Gearshift, MBNMS 25% | 2a. Gearshift, MBNMS, 50% | 2a. Gearshift, MBNMS, 100% | 2b. Gearshift, 25% | 3a. RCA no bottom contact, MBNMS | 3b. RCA no bottom contact | 3c. RCA no bottom contact, Central CA | 4a. Consolidate impacts, MBNMS | 4b. Consolidate impacts | 5a. No fishing MBNMS | 5b. No fishing, NMS | 5c. No fishing | 5d. Fishing, no spatial management | 6a. F x 0.5 | 6b. F x 1.5 | 6c. F x 2 | 6d. F x 5 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Large zooplankton | 1.00 | 1.02 | 1.00 | 1.02 | 1.00 | 1.01 | 0.98 | 1.01 | 1.01 | 1.06 | 0.99 | 1.00 | 0.91 | 1.17 | 1.07 | 1.08 | 1.08 | 0.88 |
| Deposit feeders | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.99 | 1.00 | 1.00 | 1.01 | 1.00 | 1.04 | 0.74 | 1.89 | 0.88 | 1.14 | 1.23 | 2.37 |
| Macroalgae | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.93 | 1.13 | 0.97 | 1.05 | 1.09 | 1.35 |
| Seagrass | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| Carnivorous infauna | 1.00 | 1.01 | 1.01 | 1.01 | 1.00 | 1.00 | 1.02 | 1.00 | 1.00 | 1.00 | 1.00 | 1.05 | 0.80 | 2.37 | 0.96 | 1.07 | 1.06 | 0.96 |
| Gelatinous zooplankton | 1.00 | 0.96 | 0.96 | 0.95 | 0.99 | 1.00 | 0.96 | 0.99 | 1.00 | 1.00 | 0.97 | 1.04 | 0.98 | 1.01 | 1.17 | 1.14 | 1.06 | 1.27 |
| Large phytoplankton | 1.00 | 1.56 | 1.02 | 2.57 | 1.00 | 1.37 | 2.41 | 2.68 | 1.03 | 2.40 | 1.25 | 2.31 | 2.04 | 2.35 | 1.39 | 1.39 | 1.38 | 1.32 |
| Small phytoplankton | 1.00 | 0.96 | 1.01 | 0.96 | 1.00 | 0.97 | 1.00 | 0.97 | 0.99 | 0.91 | 1.00 | 0.98 | 0.37 | 1.36 | 1.16 | 1.19 | 1.39 | 1.47 |
| Mesozooplankton | 1.00 | 0.95 | 0.95 | 0.97 | 0.99 | 0.99 | 0.78 | 0.96 | 1.00 | 0.98 | 0.92 | 0.87 | 0.56 | 0.66 | 1.35 | 1.32 | 1.42 | 1.35 |
| Microzooplankton | 1.00 | 1.11 | 0.89 | 0.72 | 1.05 | 1.12 | 0.61 | 0.78 | 0.86 | 0.64 | 0.64 | 0.67 | 0.73 | 0.58 | 0.61 | 0.60 | 0.89 | 1.06 |
| Pelagic bacteria | 1.00 | 0.86 | 0.99 | 1.08 | 1.01 | 0.88 | 1.21 | 1.00 | 1.08 | 1.28 | 1.15 | 1.13 | 1.08 | 1.70 | 1.14 | 1.21 | 1.03 | 1.52 |
| Benthic bacteria | 1.00 | 1.00 | 1.00 | 1.01 | 1.00 | 1.00 | 1.01 | 1.00 | 1.00 | 0.99 | 1.00 | 0.99 | 0.90 | 2.14 | 1.12 | 1.08 | 1.00 | 1.85 |

Table 32. Catch per functional group at year 20, relative to year 20 catch under status quo (scenario 1).

| | 1. Status quo | 2a. Gearshift, MBNMS 25% | 2a. Gearshift, MBNMS, 50% | 2a. Gearshift, MBNMS, 100% | 2b. Gearshift, 25% | 3a. RCA no bottom contact, MBNMS | 3b. RCA no bottom contact | 3c. RCA no bottom contact, Central CA | 4a. Consolidate impacts, MBNMS | 4b. Consolidate impacts | 5a. No fishing MBNMS | 5b. No fishing, NMS | 5c. No fishing | 5d. Fishing, no spatial management | 6a. F x 0.5 | 6b. F x 1.5 | 6c. F x 2 | 6d. F x 5 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Large planktivores | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.09 | 1.00 | 1.07 | 1.00 | 1.00 | 1.02 | 1.11 | 0.00 | 3.47 | 1.07 | 3.43 | 4.62 | 8.63 |
| Canary rockfish | 1.00 | 3.12 | 3.12 | 3.14 | 0.91 | 2.04 | 0.67 | 1.38 | 1.00 | 1.00 | 1.16 | 1.99 | 0.00 | 10.46 | 0.39 | 1.09 | 1.42 | 2.70 |
| Small planktivores | 1.00 | 0.95 | 0.95 | 0.95 | 1.00 | 1.00 | 0.99 | 1.00 | 1.00 | 1.00 | 0.97 | 1.02 | 0.00 | 1.65 | 0.43 | 1.28 | 1.66 | 3.31 |
| Large pisciv. flatfish | 1.00 | 1.01 | 1.00 | 1.00 | 0.96 | 1.00 | 0.79 | 1.00 | 1.00 | 1.00 | 1.00 | 1.01 | 0.00 | 1.34 | 0.33 | 0.38 | 0.33 | 0.18 |
| Shortbelly rockfish | 1.00 | 0.08 | 0.08 | 0.08 | 0.76 | 0.56 | 0.48 | 0.54 | 1.00 | 1.00 | 0.55 | 0.54 | 0.00 | 0.74 | 0.17 | 0.57 | 0.82 | 2.20 |
| Lingcod and cabezon | 1.00 | 1.87 | 1.87 | 1.87 | 0.87 | 1.53 | 0.42 | 0.97 | 1.00 | 1.00 | 1.18 | 1.66 | 0.00 | 0.54 | 0.39 | 1.04 | 1.20 | 0.98 |
| Salmon | 1.00 | 1.10 | 1.10 | 1.10 | 1.00 | 0.94 | 1.01 | 0.95 | 1.00 | 1.00 | 1.03 | 0.85 | 0.00 | 0.07 | 7.97 | 0.44 | 0.08 | 0.00 |
| Albacore | 1.00 | 0.41 | 0.41 | 0.41 | 1.00 | 0.33 | 1.00 | 0.38 | 1.00 | 1.00 | 0.57 | 0.47 | 0.00 | 0.00 | 2.14 | 0.62 | 0.41 | 0.14 |
| Migratory birds | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Pacific hake | 1.00 | 0.99 | 0.99 | 0.99 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.99 | 0.98 | 0.00 | 1.08 | 0.74 | 1.10 | 1.14 | 1.07 |
| Sablefish | 1.00 | 0.97 | 0.97 | 0.97 | 0.99 | 0.99 | 0.90 | 0.99 | 1.01 | 1.01 | 0.98 | 0.98 | 0.00 | 1.27 | 0.56 | 1.13 | 1.29 | 1.31 |
| Deep vertical migrators | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Deep demersal fish | 1.00 | 0.99 | 0.99 | 1.00 | 1.01 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.97 | 0.97 | 0.00 | 1.05 | 0.45 | 1.12 | 1.34 | 1.69 |
| Shallow pisciv. fish (sculpin) | 1.00 | 4.35 | 4.34 | 4.34 | 0.98 | 1.49 | 0.95 | 1.16 | 0.98 | 1.00 | 1.08 | 1.30 | 0.00 | 6.56 | 0.34 | 1.02 | 1.36 | 2.52 |
| Midwater rockfish | 1.00 | 1.66 | 1.65 | 1.64 | 0.94 | 1.25 | 0.81 | 1.02 | 1.00 | 1.00 | 1.02 | 1.14 | 0.00 | 3.07 | 0.28 | 0.71 | 0.89 | 1.67 |
| Nearshore fish (surfperch) | 1.00 | 8.44 | 8.44 | 8.44 | 1.00 | 1.01 | 1.07 | 0.99 | 0.94 | 0.99 | 1.00 | 1.00 | 0.00 | 4.33 | 0.23 | 1.06 | 1.47 | 3.03 |
| Dover sole | 1.00 | 0.94 | 0.93 | 0.90 | 0.82 | 1.00 | 0.81 | 0.98 | 1.01 | 1.03 | 0.99 | 0.97 | 0.00 | 1.37 | 0.72 | 1.49 | 1.67 | 1.45 |
| Small shallow rockfish | 1.00 | 1.73 | 1.73 | 1.73 | 0.99 | 2.46 | 0.95 | 1.71 | 1.00 | 1.00 | 1.53 | 2.23 | 0.00 | 7.52 | 0.07 | 0.42 | 0.35 | 1.13 |
| Deep small rockfish | 1.00 | 0.89 | 0.87 | 0.84 | 0.82 | 0.99 | 0.98 | 0.99 | 1.02 | 1.09 | 0.99 | 1.00 | 0.00 | 1.62 | 0.38 | 1.16 | 1.54 | 3.64 |
| Deep large rockfish | 1.00 | 0.93 | 0.92 | 0.90 | 0.85 | 1.00 | 0.97 | 0.99 | 1.02 | 1.10 | 0.99 | 0.99 | 0.00 | 1.55 | 0.26 | 0.63 | 0.75 | 1.68 |
| Small flatfish | 1.00 | 0.99 | 0.97 | 0.93 | 0.77 | 1.00 | 0.28 | 0.80 | 1.00 | 1.01 | 0.94 | 0.74 | 0.00 | 2.04 | 0.24 | 0.81 | 1.06 | 2.30 |
| Small demersal sharks | 1.00 | 1.01 | 1.02 | 1.03 | 1.13 | 1.10 | 1.18 | 1.07 | 0.99 | 0.96 | 1.06 | 1.59 | 0.00 | 1.94 | 0.30 | 0.42 | 0.37 | 0.07 |

Table 32 continued.  Catch per functional group at year 20, relative to year 20 catch under status quo (scenario 1).

| | 1. Status quo | 2a. Gearshift, MBNMS 25% | 2a. Gearshift, MBNMS, 50% | 2a. Gearshift, MBNMS, 100% | 2b. Gearshift, 25% | 3a. RCA no bottom contact, MBNMS | 3b. RCA no bottom contact | 3c. RCA no bottom contact, Central CA | 4a. Consolidate impacts, MBNMS | 4b. Consolidate impacts | 5a. No fishing MBNMS | 5b. No fishing, NMS | 5c. No fishing | 5d. Fishing, no spatial management | 6a. F x 0.5 | 6b. F x 1.5 | 6c. F x 2 | 6d. F x 5 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Large demersal sharks | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Yelloweye and cowcod | 1.00 | 0.97 | 0.97 | 0.97 | 0.85 | 1.67 | 0.25 | 1.67 | 1.00 | 1.00 | 1.68 | 1.30 | 0.00 | 0.86 | 0.47 | 0.66 | 0.61 | 0.56 |
| Misc. pelagic sharks | 1.00 | 1.01 | 1.01 | 1.01 | 1.00 | 0.99 | 1.00 | 0.99 | 1.00 | 1.00 | 1.01 | 1.01 | 0.00 | 0.94 | 0.28 | 0.21 | 0.15 | 0.01 |
| Shallow large rockfish | 1.00 | 1.05 | 1.05 | 1.05 | 1.00 | 1.16 | 1.02 | 1.07 | 0.97 | 1.00 | 1.04 | 1.15 | 0.00 | 1.46 | 0.83 | 0.98 | 0.85 | 0.42 |
| Skates and rays | 1.00 | 1.77 | 1.77 | 1.77 | 1.00 | 2.44 | 1.00 | 2.20 | 1.00 | 1.00 | 1.62 | 1.92 | 0.00 | 15.62 | 2.69 | 7.40 | 9.90 | 27.10 |
| Surface seabirds | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Diving seabirds | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Pinnipeds | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Transient orcas | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Baleen whales | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Small toothed whales | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Toothed whales | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Sea otter | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Cephalopods | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.01 | 1.00 | 1.00 | 1.00 | 1.01 | 1.06 | 0.00 | 0.40 | 0.93 | 1.07 | 1.15 | 0.98 |
| Shallow benth. filt. feeders | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Other benth. filt. feeders | 1.00 | 0.99 | 0.99 | 0.99 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.97 | 1.04 | 0.00 | 1.88 | 0.53 | 1.45 | 1.86 | 3.54 |
| Deep benth. filt. feeders | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Benthic herb. grazers | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.00 | 1.00 | 0.89 | 0.84 | 0.63 | 0.05 |
| Deep macrozoobenthos | 1.00 | 0.98 | 0.98 | 0.98 | 1.00 | 1.00 | 0.93 | 1.00 | 0.99 | 0.96 | 0.99 | 1.10 | 0.00 | 1.58 | 0.52 | 1.52 | 2.01 | 4.71 |
| Megazoobenthos | 1.00 | 1.13 | 1.13 | 1.13 | 1.00 | 1.00 | 1.30 | 1.00 | 1.05 | 1.22 | 1.05 | 0.91 | 0.00 | 0.19 | 2.73 | 0.26 | 0.06 | 0.00 |
| Shallow macrozoobenthos | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Shrimp | 1.00 | 0.98 | 0.98 | 0.98 | 1.00 | 1.00 | 0.95 | 0.99 | 1.00 | 0.99 | 0.99 | 1.01 | 0.00 | 1.93 | 0.85 | 1.15 | 1.33 | 2.85 |

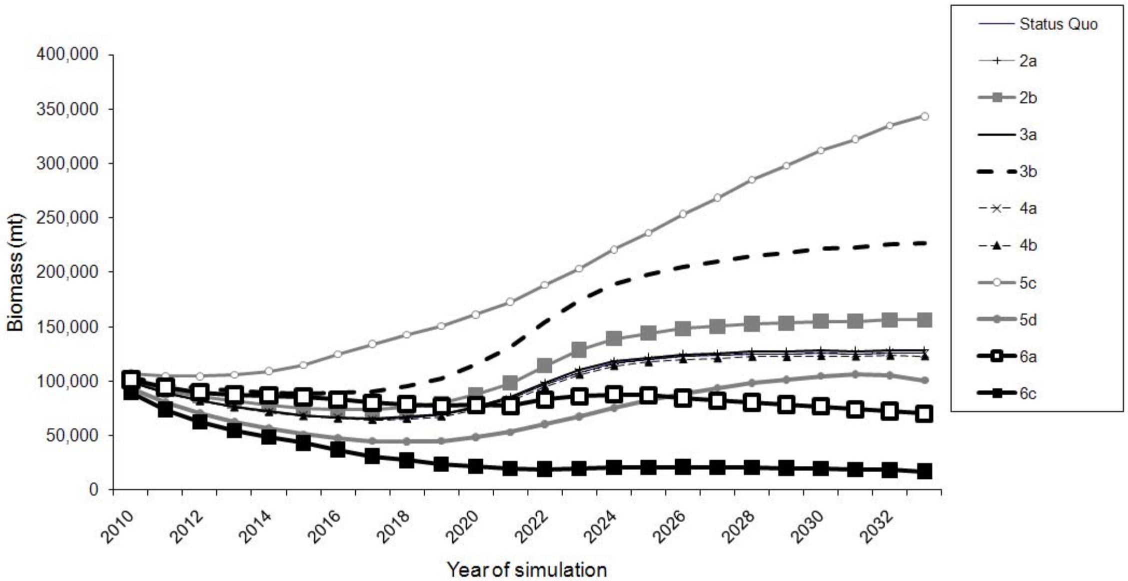



Figure 46. Abundance trends for arrowtooth flounder, summed over the whole model domain. Biomass time series from 11 of the scenarios are shown here as an example of the dynamics for each functional group.

rays, large planktivores, albacore tuna, and salmon; the two former groups are overfished in the status quo model, while the latter two groups' dynamics are largely external to the model due to their migrations.

Scenario 5d (fishing, no spatial management) and 6b–6d (1.5, 2, and 5 × status quo fishing) increased fishing rates in all or some cells. Scenario 5d, which involved moderate increases in total fishing mortality, showed declines in most harvested species but increases in a few small-bodied, productive stocks such as nearshore fish (surfperch), small flatfish, and more lightly fished deep rockfish groups (Table 31). Scenarios 6b–6d involved strong coast-wide increases in fishing and resulted in very low abundance of most harvested groups, with a few exceptions such as large planktivores, Dover sole, and skates and rays. These scenarios showed 5–50% declines in most marine mammal and bird groups. Catches of fished groups did not necessarily decline by year 20 (Table 32), even though fishing was driving declines in biomass; essentially over the relatively short time span of these scenarios, increased fishing mortality rates compensated for the declining stock abundance. For instance, in Scenario 6d (5 × status quo fishing), of the 20 harvested fish groups, year 20 catch declined for 7 and increased for 13, relative to status quo year 20 catch.

**Gear shift (Scenarios 2a–2b)**—Evaluated on a coast-wide basis, the gear shift within MBNMS (Scenario 2a) had minor impacts (Table 31). Even with 100% gear shift from trawl to longline/pot gear, most functional groups remained within 5% of status quo abundance. This might be expected, since MBNMS covers only a small portion (12%) of our model domain. Only three vertebrate groups (excluding albacore tuna and salmon) declined by more than 5%: the lingcod and cabezon group, shallow piscivorous fish, and shallow large rockfish. These three groups experienced higher coast-wide catches in this scenario (Table 32), both initially (year 1) and in year 20. Two groups that had lower coast-wide catch rates (year 1 catch), small demersal sharks and yelloweye and cowcod rockfish, increased in abundance by 15–20%. Five other groups experienced increased catch rates and five experienced decreased catch rates, but did not show biomass responses of more than 10%. Salmon and albacore tuna abundance changed substantially, but are primarily governed by factors outside the model domain. Overall, the coast-wide response was modest and driven by a mix of local trophic interactions and fishing rates, rather than directly following from the fishing experiments simulated.

The coast-wide 25% gear shift from trawl to pot/longline (Scenario 2b) reduced fishing mortality rates on many species primarily caught by trawls (as parameterized from the total mortality estimates in Bellman et al. 2008). Catches in years 1 and 20 were lower than status quo catch for Dover sole, lingcod and cabezon, large piscivorous flatfish (arrowtooth flounder), yelloweye and cowcod, chilipepper rockfish, deep small and deep large rockfish, and small flatfish (Table 32). The first four of these groups showed 10–23% increases in abundance in response to this drop in catch (Table 31). No functional group declined in abundance by more than 2% relative to status quo at year 20. Catches of small demersal sharks were 1% higher than status quo at year 1, but 12% higher at year 20, reflecting their trend of increasing abundance in this scenario. In summary, the results from the coast-wide 25% gear shift for the most part follow directly from the shift in fishing rates dictated by the scenario. This is in contrast with the gear shift within MBNMS, which had more moderate effects that were less dictated by fishing pressure, though some groups such as small demersal sharks and yelloweye and cowcod responded qualitatively similarly to the coast-wide gear shift.

**Scenarios 3a–3c (RCA prohibiting bottom contact)**—Scenarios 3a and 3c, which represented additional spatial restrictions in MBNMS and central California, led to minor biomass responses on a coast-wide basis (Table 31). No vertebrate group increased by more than 4%. In both scenarios, yelloweye and cowcod declined 65%, shallow rockfish groups declined 7–35%, and albacore tuna declined 75–80%. Lingcod declined 18% in Scenario 3a. These declines in abundance were driven by increases in initial catch (year 1) for these groups, as well as canary rockfish, shallow piscivorous fish, small demersal sharks, and skates. Year 20 catches of these groups were also higher than status quo year 20, with the exception of albacore tuna (Table 32). For both scenarios, only the shortbelly rockfish catch was lower than status quo, both in year 1 and year 20.

The response of Scenario 3b, which closed the RCA in the entire model domain to bottom-contact gear, was quite different from the results from the more local management changes applied in Scenarios 3a and 3b. Scenario 3b predicted coast-wide increases in abundance of 30–75% for large piscivorous flatfish (arrowtooth flounder), lingcod and cabezon, small demersal sharks, and yelloweye and cowcod (Table 31). This is a result of reductions in catch (year 1) for these groups relative to status quo; year 20 catch remained below year 20 status quo catch for all of these groups except small demersal sharks (Table 32). No vertebrates declined by more than 5%. Overall, this scenario differed from the more local perturbations (3a, c) and was driven by the specified reductions in catch of target species of as much as 85% (year 1 relative to status quo).

**Scenarios 4a–4b (consolidate spatial impacts)**—These scenarios consolidated bottom impacts within MBNMS (4a) and coast wide (4b). There were slight net changes in areas open to the major gears: Scenario 4a and 4b increased total coast-wide area open to trawling by 2 and 7%, respectively, while decreasing total area open to longline/pot by 0 and 2%. No biomass response of greater than 3% was predicted for any vertebrate groups (Table 31). Biomass response was primarily limited to megazoobenthos (large crabs), with increases of as much as 33%, and some plankton groups, with increases of as much as 2.4 times. The manipulation to catch rates was minimal, with year 1 and year 20 catch generally within 5% of status quo; maximum deviation from status quo catch was an increase of 9–11% for deep rockfish (Table 32).

**Performance metrics**

We scored the scenarios based on the quantitative metrics that capture the ecosystem attributes of interest to the fishery managers involved in the IEA process (Table 33). These metrics include the habitat integrity metric, bycatch of rockfish (in year 1), and projections for year 20 landed value and abundances of protected species and rockfish biomass and spawning stock. We normalized these scores relative to Scenario 1 (i.e., the metrics are always equal to 1.0 for status quo). Since fishery and sanctuary managers involved in the IEA process indicated that scenarios 1–4b were of the most interest, below we focus on those, with scenarios 5a–6d primarily serving as sensitivity analyses.

The performance metrics ranged from insensitive (mammal and bird biomass) to much more sensitive metrics related to rockfish and landed value. Generally, perturbations at large scales (coast wide) or of higher magnitude (e.g., 100% gear switching in MBNMS) were required to force strong responses. In the scenarios involving small scale perturbations (i.e., MBNMS or central California), strong responses of more than 10% tended to involve unexpected local trophic interactions, rather than direct response to fishing pressure. Specifically, Scenarios 2a, 3a, and 3c led to declines in the three performance metrics related to rockfish, even though direct fishing pressure on most rockfish groups was reduced. This unexpected result stems from the lower biomass and higher initial bycatch of shallow large rockfish and yelloweye and cowcod, as described above for these three scenarios.

Within the scenarios of most interest to managers (1–4b), the scenario involving closure of the RCA to bottom contact led to the largest increase in rockfish biomass, at 8% above status quo (Table 34). The 25% gear shift coast wide also led to slight increases in rockfish biomass. Across all scenarios, the rockfish biomass metric was primarily influenced by strong recovery trends. In the scenarios of most interest to managers (1–4b), biomass of all rockfish groups increased above initial levels, except for shallow large rockfish and yelloweye and cowcod. By year 20 of the status quo simulation, five of the rockfish groups had increased to quasi-equilibrium levels and midwater rockfish were still increasing in abundance.

These increasing biomass trends are indicative of low fishing mortalities parameterized in the model for status quo and mandated in fishery rebuilding plans. The variation in our biomass metric was limited, but followed two trends: 1) slight increases in rockfish biomass (<14%) in scenarios where coast-wide fishing mortality reductions were enacted or 2) slight decreases (≤13%) in rockfish biomass in cases where local management changes at the scale of MBNMS or central California actually led to higher overall catches of rockfish. Decreases in our rockfish biomass metric were caused specifically by decreases in yelloweye and cowcod, large shallow

Table 33. Performance metrics for scenarios. Metrics were normalized relative to status quo to generate the values presented in the text, figures, and Table 34.

| **Management goal** | **Performance metric** | **Formula for scenario *i*** |
|---|---|---|
| Habitat integrity | Based on area closed to each gear and impact factor of each gear on each habitat type | See Equation 4 and Equation 5 in text |
| Rockfish age structure | Spawning biomass/total biomass of all rockfish groups, year 20 | $\sum_{group=1}^{8}(SpawnBiomass_{group,yr20,i} / SpawnBiomass_{group,yr20,SQ})$ |
| Rockfish abundance | Biomass of all rockfish groups, year 20 | $\sum_{group=1}^{8}(Biomass_{group,yr20,i} / Biomass_{group,yr20,SQ})$ |
| Marine mammal and bird abundance | Biomass of marine mammals and birds, year 20 | $\sum_{group=1}^{9}(Biomass_{group,yr20,i} / Biomass_{group,yr20,SQ})$ |
| Avoid bycatch of nontarget species | Total catch of yelloweye and cowcod, canary, midwater, and deep large rockfish in year 1 | $\sum_{group=1}^{4}(Catch_{group,yr1,i})$ |
| Economic yield | Landed value, year 20 | $\sum_{gear=1}^{20}\sum_{group=1}^{30}(Catch_{group,gear,yr20} * \Pr ice_{group,gear})$ |

Table 34. Values for performance metrics for each scenario. See Table 30 for definition of metrics. The metric "avoid rockfish bycatch" in Scenario 5c is undefined because there is no catch or bycatch of any species in this scenario.

| Scenario | Proportion rockfish mature | Rockfish biomass | Mammal and bird biomass | Habitat integrity | Landed value | Avoid rockfish bycatch |
|---|---|---|---|---|---|---|
| 1. Status quo | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 2a. Gearshift, MBNMS, 25% | 0.97 | 0.93 | 1.00 | 1.01 | 0.88 | 0.74 |
| 2a. Gearshift, MBNMS, 50% | 0.97 | 0.94 | 1.00 | 1.01 | 0.88 | 0.75 |
| 2a. Gearshift, MBNMS, 100% | 0.97 | 0.94 | 1.00 | 1.03 | 0.89 | 0.76 |
| 2b. Gearshift, 25% | 1.01 | 1.02 | 1.00 | 1.07 | 0.95 | 1.14 |
| 3a. RCA no bottom contact, MBNMS | 0.95 | 0.87 | 1.00 | 1.05 | 0.96 | 0.81 |
| 3b. RCA no bottom contact | 1.02 | 1.08 | 1.00 | 1.79 | 0.80 | 1.16 |
| 3c. RCA no bottom contact, Central CA | 0.96 | 0.90 | 1.00 | 1.10 | 0.98 | 0.90 |
| 4a. Consolidate impacts, MBNMS | 1.00 | 1.00 | 1.00 | 0.99 | 1.00 | 0.99 |
| 4b. Consolidate impacts | 1.00 | 1.00 | 1.00 | 0.97 | 1.01 | 0.95 |
| 5a. No fishing MBNMS | 0.96 | 0.91 | 1.00 | 1.12 | 0.98 | 0.92 |
| 5b. No fishing, NMS | 0.92 | 0.87 | 1.00 | 1.28 | 0.94 | 0.71 |
| 5c. No fishing | 1.05 | 1.14 | 0.98 | 5.45 | 0.00 | NA |
| 5d. Fishing, no spatial management | 0.80 | 0.69 | 1.07 | 0.39 | 1.12 | 0.27 |
| 6a. F × 0.5 | 1.03 | 0.63 | 0.84 | 2.36 | 0.51 | 1.88 |
| 6b. F × 1.5 | 0.97 | 0.49 | 0.84 | 0.41 | 0.96 | 0.63 |
| 6c. F × 2 | 0.94 | 0.46 | 0.83 | 0.16 | 1.08 | 0.47 |
| 6d. F × 5 | 0.74 | 0.41 | 0.81 | -0.02 | 1.22 | 0.19 |

rockfish, and small shallow rockfish; one or more of these groups experienced higher bycatch rates at year 1 in each of the MBNMS or central California scenarios.

The coast-wide RCA bottom-contact closure (Scenario 3b) performed best in terms of avoiding rockfish bycatch, followed by the 25% coast-wide gear shift (Table 34).

These might be expected a priori, based on the magnitude of these management changes and the species caught by trawl versus longline/pot gear. Amounts of rockfish bycatch in sensitivity analysis scenarios 6a–6d were roughly proportional to the scalar of fishing effort. Unexpectedly, gear shifts and RCA closures within MBNMS or central California led to higher coast-wide rockfish bycatch than status quo. This was due primarily to an increase in catch of the midwater rockfish, a group that includes Pacific ocean perch (*Sebastes alutus*), widow, and darkblotched rockfish.

Age structure of rockfish improved slightly relative to status quo in Scenario 3b (RCA no bottom contact) and Scenario 2a (gearshift, 25%), but with only 2 and 1% gains, respectively (Table 34). Over the 20-year simulations here, even the scenario with no fishing (5c) showed only a 5% gain in this metric. Over the course of 50-year simulations (not detailed here), the increase was only 6%. On the other hand, increases in fishing mortality quickly truncated the age structure, leading to as much as 25% reductions in the proportion of biomass mature by year 20. The relative insensitivity of age structure, particularly to decreased fishing, is a result of the general trend in recovery for the rockfish stocks described above. Most scenarios (particularly 1–4b) included fishing mortality rates that were conservative enough to lead to increasing biomass, in many cases to levels that began to reach stable age structure by year 20.

The management options that we tested primarily involved groundfish fleets, and had little indirect effect on mammals and birds. Therefore, trends in abundance of mammal and birds were consistent across Scenarios 1–4b. All mammal and bird groups increased in abundance over the course of these 20-year simulations. Marine mammals increased between 10% (transient orcas) and 190% (toothed whales), with the exception of pinnipeds, which increased 540%. Migratory birds (e.g., shearwaters), piscivorous seabirds (e.g., guillemots and cormorants) and planktivorous birds (e.g., auklets) increased 260%, 210%, and 50%, respectively. Our biomass metric for these groups varied less than 1% between scenarios 1 and 4b (Table 34). The sensitivity analysis scenarios (5a–6d) drove a slightly more dynamic response, with a slight positive interaction between moderate fishing and mammal and bird abundance, due to reduction in predators such as sharks. More severe fishing (≥ 1.5 × status quo) led to declines in forage resources and ultimately mammals and birds.

Aggregating across fleets, landed value in year 20 varied at most 20% between the scenarios of most interest to managers (Table 34, Scenarios 1–4b). The switch away from trawl gear led to lower catches of small flatfish, lingcod and cabezon, and (in Scenario 2a) sablefish. As a result, landed value declined 5–12%. In Scenarios 3a–4b, declines in landed value were driven by the change in area available to bottom contact gears such as trawl and fixed gear. In the sensitivity analysis scenarios (5a–6d), landed value was directly related to fishing effort, either as area was opened to fleets or as effort was scaled as high as five times. Even though the total revenue was high in these scenarios with high fishing, much of this revenue came from productive stocks such as mackerel, sardines, and small flatfish. Catches of less productive stocks, such as small demersal sharks, large piscivorous flatfish (arrowtooth flounder), and shallow large rockfish, declined to low levels.

The habitat index was simply based on the footprint of the fishing gear, rather than on model outputs. Our habitat integrity metric ranged from zero for Scenario 6d (5 × status quo fishing), to 5.45 for Scenario 5c (no fishing) (Table 34). Scenarios 1–4b, which were of most management relevance, generally scored within 10% of status quo (value of 1.0), with the largest exception involving prohibition of all bottom-contact gear in RCA (value of 1.79, Scenario 3b). Scenarios in this set (1–4b) that involved only MBNMS had equal to or less than 5% deviation from status quo, while scenarios changing spatial management in all of central California had as much as a 10% deviation from status quo. To put this in perspective, MBNMS covered 12% and central California 16% of the model domain. On a coast-wide basis, gear shift scenarios had only a slight positive impact (<7%), since pot and longline gear has a moderate impact on the benthos (though less than trawl) and since the footprint of other bottom-contact fleets remained unchanged. The sensitivity analysis scenarios (5a–6d) generally involved wholesale increases or decreases in fishing from all fleets, rather than trade-offs between areas and fleets, thus resulting in more dramatic changes in this metric of habitat.

We calculated landed value per fleet (gear) in year 20 of the simulations. Figure 47 illustrates the results for four of these fleets and scenarios with the largest response to the management actions. Limited entry trawl fleet revenue declined up to 18% due to the direct effect of the gear switching and up to 45% due to the increased spatial closures involved in the RCA scenarios. The gear switch led to a 28% increase in fixed gear revenue, slightly more than the direct 25% increase in effort. The halibut longline fleet was not directly manipulated (in terms of area closed or effort) in Scenario 3b (RCA no bottom contact), but reductions in other demersal gear led to 73% increases in revenue for this fleet. Consolidating bottom-contact impacts in MBNMS (Scenario 4a, not shown) did not affect any of these six fleets by more than 1%, while consolidating bottom-contact impacts coast wide (Scenario 4b, not shown) led to a 7% decline in halibut longline fleet revenue as this fleet was pushed farther offshore.

### Options for regional and coast-wide management

As part of the IEA scoping process, we developed our scenarios to address themes that originated with scientists and managers from the NMS program and NOAA's Regional Offices. Of the 18 scenarios tested here, 3 distinct scenarios involving management at the scale of the NMSs are presented in Figure 48. Consolidating bottom impacts to deeper regions of MBNMS (Scenario 4a) performed approximately as well as status quo, while the local gear shift (Scenario 2a) and the local prohibition on bottom contact in the RCA (Scenario 3a) had lower scores related to rockfish biomass and avoiding rockfish bycatch (Figure 49).

On the other hand, management actions related to the coast-wide scale were able to outperform status quo, but with clear trade-offs between performance metrics, rather than a single "silver bullet" management strategy. Closing the RCA to bottom-contact gear minimized habitat impact and reduced rockfish bycatch, but sacrificed landed value. Consolidating spatial impacts performed within 1% of status quo for all six performance metrics, but performed more poorly than either the gear shift or the RCA closure in terms of habitat integrity and simple avoidance of rockfish bycatch. The gear shift scenario performed only 7% better than status quo

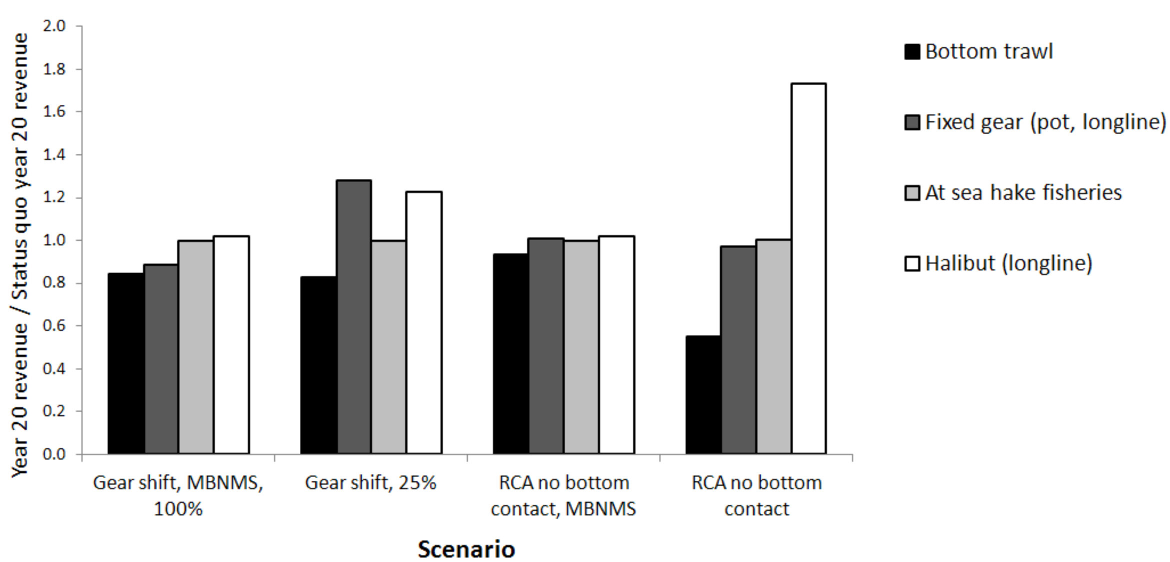



Figure 47. Revenue of four fleets under alternate scenarios.

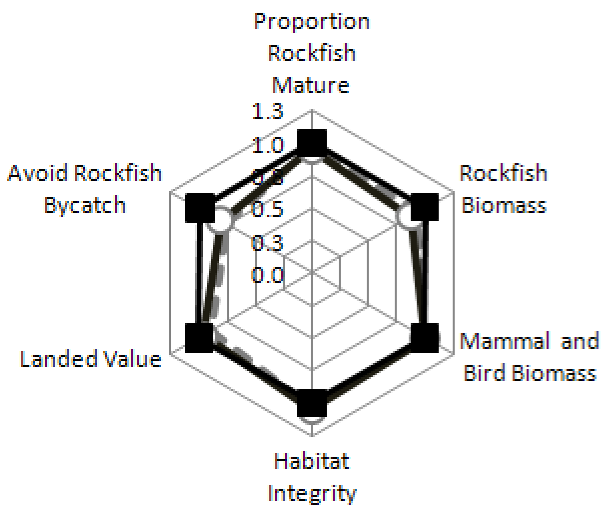



Figure 48. Performance of Scenario 2a (gear shift, MBNMS 100%), indicated by dashed gray line and circles; Scenario 3a (RCA no bottom contact, MBNMS), indicated by solid black line; and Scenario 4a (consolidate impacts, MBNMS), indicated by solid black line with squares. Scores of each axis have been normalized by performance in status quo.

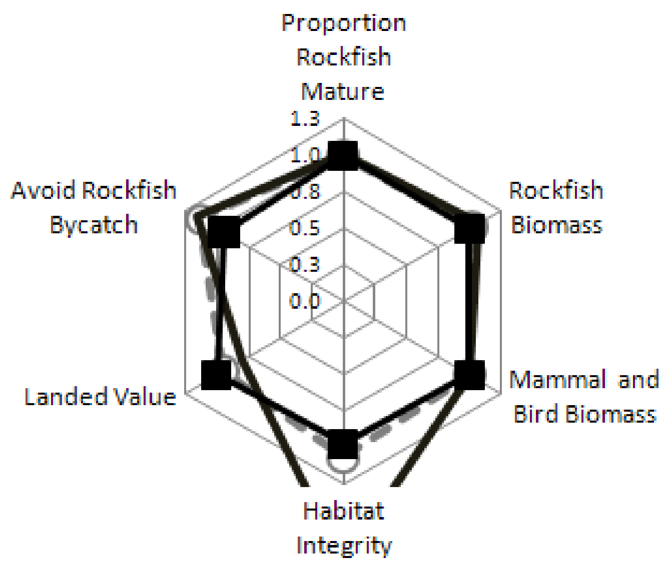



Figure 49. Performance of Scenario 2b (gear shift, 25%), indicated by dashed gray line and circles; Scenario 3b (RCA no bottom contact), indicated by solid black line; and Scenario 4b (consolidate impacts), indicated by solid black line with squares. Scores of each axis have been normalized by performance in status quo. The habitat integrity metric has a value of 1.79 (see Table 31), but here we have truncated the axis.

in terms of our habitat impact metric, but did not greatly sacrifice yield (–5%), and performed almost as well as the RCA closure in terms of avoiding rockfish bycatch. Thus though the gear shift scenario holds some promise as a compromise strategy, it is not a clear optimal strategy.

### Scoring scenarios on the basis of ecological indicators

As part of this California Current IEA, in the Selecting and Evaluating Indicators for the California Current section, the IEA team identified a set of 12 ecological indicators related to attributes of groundfish and ecosystem health. These indicators were identified on the basis of data availability, practicality, and theoretical soundness. We can score our scenarios above using this set of ecological indicators, asking the question, "If resource managers view the impacts of policies through the lens of observable indicators, how will they rank the scenarios?" We focus on the values of indicators calculated from 1) data from all model regions and 2) data within MBNMS. We chose MBNMS since this is a reasonably large representative region for scenarios involving coast-wide management changes, and since several of the other scenarios specifically manipulated fishing policies within the sanctuary.

From the Atlantis output, we calculated 8 of those 12 indicators. Omitted are nutrient levels, taxonomic distinctness, spatial distribution, and size structure. We operationalized the remaining conceptual indicators, expanding them to represent the 18 metrics described below. For instance, zooplankton biomass anomaly is specified here as four indicators: deviation from mean abundance of gelatinous zooplankton, krill, copepods, and microzooplankton.

Table 35 presents the value of indicators in year 20 of our simulation, calculated from all regions' data (top) and only from data within MBNMS (bottom). The table lists only the nine indicators that here we will call intuitive indicators: those that responded (for the most part) as we might expect a priori based on the direct effect of fishing pressure. Table 36 is similar, but here we have grouped the nine indicators that responded in less predictable or expected ways. Since some indicators are expected to be positively related to attributes (e.g., groundfish biomass and groundfish) and others negatively related (number of assessed species below B40 and groundfish), we have used a color scheme where red indicates declines in ecosystem health or groundfish status, yellow represents static values, and green represents improvements.

The indicators in Table 35 generally show poor indicator scores (red) in the scenarios for which fishing is increased above status quo, whether calculated from coast-wide or MBNMS data. These indicators include those related to age structure, biomass, population growth rate, and number of nonassessed species below management thresholds. The primary exception to this is the MBNMS gear shift scenarios, which show declines in age structure indicators locally and coast wide. Age structure of midwater rockfish also appears to improve in the scenarios with the heaviest fishing, though this is only a transient effect due to the short (20 year) simulations here, over which time biomass of this group was declining. Surprisingly, scenarios with fishing reduced from status quo generally did not substantially improve the indicator scores. This is due to several effects including 1) over the short 20-year simulations, age structure did not reach equilibrium levels, and therefore reduced fishing could decrease the proportion of mature individuals rather than increase it; and 2) aggregate metrics such as groundfish biomass and mean groundfish population growth rate can mask direct effects of fishing (negative) and indirect trophics effects (often positive).

Table 35. Intuitive indicators: Values of ecosystem indicators at year 20 for each scenario, calculated from coast-wide data or within MBNMS. All indicators are scaled relative to status quo (scenario 1). Since some indicators are positively related to groundfish and ecosystem health and others negatively related, the red/yellow/green color scheme signifies indicator values that we expect to relate to decreased/static/increased ecosystem health or groundfish status.

| | | Age structure, proportion mature | | | | | Number nonassessed | | Groundfish | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Scale** | **Scenario** | **Groundfish** | **Lingcod** | **Shallow large rockfish** | **Midwater rockfish** | **Shortbelly rockfish** | **Spp. < B40** | **Spp. < B25** | **Pop. growth rate** | **Biomass** |
| **Coast wide** | 1. Status quo | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| | 2a. Gear shift, MBNMS 25% | 0.92 | 1.00 | 0.89 | 0.76 | 1.05 | 0.96 | 0.96 | 0.93 | 1.00 |
| | 2a. Gear shift, MBNMS, 50% | 0.92 | 1.00 | 0.89 | 0.76 | 1.05 | 0.96 | 0.96 | 0.93 | 1.00 |
| | 2a. Gear shift, MBNMS, 100% | 0.92 | 1.00 | 0.89 | 0.76 | 1.05 | 0.96 | 0.96 | 0.93 | 1.00 |
| | 2b. Gear shift, 25% | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| | 3a. RCA no bottom contact, MBNMS | 0.99 | 0.99 | 0.95 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| | 3b. RCA no bottom contact | 1.01 | 1.01 | 1.00 | 1.01 | 0.99 | 1.00 | 1.01 | 1.00 | 1.01 |
| | 3c. RCA no bottom contact, Central CA | 1.00 | 1.00 | 0.99 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| | 4a. Consoli-date impacts, MBNMS | 1.00 | 1.00 | 1.01 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| | 4b. Consoli-date impacts | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.01 | 1.00 | 1.00 |
| | 5a. No fishing, MBNMS | 1.00 | 1.00 | 0.99 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| | 5b. No fishing, NMS | 0.99 | 0.99 | 0.98 | 0.99 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |

Table 35 continued. Intuitive indicators: Values of ecosystem indicators at year 20 for each scenario, calculated from coast-wide data or within MBNMS. All indicators are scaled relative to status quo (scenario 1). Since some indicators are positively related to groundfish and ecosystem health and others negatively related, the red/yellow/green color scheme signifies indicator values that we expect to relate to decreased/static/increased ecosystem health or groundfish status.

| | | Age structure, proportion mature | | | | | Number nonassessed | | Groundfish | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Scale** | **Scenario** | **Groundfish** | **Lingcod** | **Shallow large rockfish** | **Midwater rockfish** | **Shortbelly rockfish** | **Spp. < B40** | **Spp. < B25** | **Pop. growth rate** | **Biomass** |
| **Coast wide (cont.)** | 5c. No fishing | 0.97 | 1.01 | 1.10 | 0.77 | 1.05 | 0.83 | 0.83 | 0.82 | 0.96 |
| | 5d. Fishing, no spatial management | 0.93 | 0.89 | 0.62 | 1.02 | 1.03 | 1.00 | 0.91 | 1.08 | 1.09 |
| | 6a. F × 0.5 | 0.93 | 0.93 | 0.98 | 1.21 | 0.52 | 1.11 | 0.95 | 0.94 | 0.98 |
| | 6b. F ×1.5 | 0.93 | 0.91 | 0.76 | 1.26 | 0.76 | 1.04 | 1.04 | 0.93 | 0.95 |
| | 6c. F × 2 | 0.94 | 0.91 | 0.66 | 1.31 | 0.87 | 1.01 | 1.02 | 0.94 | 0.95 |
| | 6d. F × 5 | 0.96 | 0.87 | 0.30 | 1.30 | 1.03 | 1.07 | 1.01 | 1.00 | 0.98 |
| **MBNMS** | 1. Status quo | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| | 2a. Gear shift, MBNMS 25% | 0.90 | 1.00 | 0.89 | 0.76 | 1.05 | 0.93 | 0.98 | 0.93 | 1.01 |
| | 2a. Gear shift, MBNMS, 50% | 0.90 | 1.00 | 0.89 | 0.76 | 1.05 | 0.93 | 0.99 | 0.93 | 1.01 |
| | 2a. Gear shift, MBNMS, 100% | 0.90 | 1.00 | 0.89 | 0.76 | 1.05 | 0.94 | 0.98 | 0.93 | 1.01 |
| | 2b. Gear shift, 25% | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.02 | 1.02 | 1.00 | 1.00 |
| | 3a. RCA no bottom contact, MBNMS | 0.99 | 0.99 | 0.95 | 1.00 | 1.00 | 1.02 | 1.02 | 1.00 | 1.00 |
| | 3b. RCA no bottom contact | 1.01 | 1.01 | 1.00 | 1.01 | 0.99 | 1.02 | 1.03 | 1.00 | 1.00 |
| | 3c. RCA no bottom contact, Central CA | 1.00 | 1.00 | 0.99 | 1.00 | 1.00 | 1.02 | 1.02 | 1.00 | 1.00 |

Table 35 continued. Intuitive indicators: Values of ecosystem indicators at year 20 for each scenario, calculated from coast-wide data or within MBNMS. All indicators are scaled relative to status quo (scenario 1). Since some indicators are positively related to groundfish and ecosystem health and others negatively related, the red/yellow/green color scheme signifies indicator values that we expect to relate to decreased/static/increased ecosystem health or groundfish status.

| | | **Age structure, proportion mature** | | | | | **Number nonassessed** | | **Groundfish** | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Scale** | **Scenario** | **Groundfish** | **Lingcod** | **Shallow large rockfish** | **Midwater rockfish** | **Shortbelly rockfish** | **Spp. < B40** | **Spp. < B25** | **Pop. growth rate** | **Biomass** |
| **MBNMS (cont.)** | 4a. Consolidate impacts, MBNMS | 1.00 | 1.00 | 1.01 | 1.00 | 1.00 | 0.99 | 0.99 | 1.00 | 1.00 |
| | 4b. Consolidate impacts | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.01 | 1.00 | 1.00 |
| | 5a. No fishing, MBNMS | 1.00 | 1.00 | 0.99 | 1.00 | 1.00 | 1.03 | 1.03 | 1.00 | 1.00 |
| | 5b. No fishing, NMS | 0.99 | 0.99 | 0.98 | 0.99 | 1.00 | 1.02 | 1.02 | 1.00 | 1.00 |
| | 5c. No fishing | 0.96 | 1.01 | 1.10 | 0.77 | 1.05 | 0.80 | 0.84 | 0.82 | 0.97 |
| | 5d. Fishing, no spatial management | 0.93 | 0.89 | 0.62 | 1.02 | 1.03 | 1.03 | 0.93 | 1.07 | 1.07 |
| | 6a. F × 0.5 | 2.04 | 1.04 | 0.97 | 0.48 | 0.53 | 1.06 | 0.84 | 0.85 | 0.94 |
| | 6b. F × 1.5 | 0.00 | 1.08 | 0.75 | 1.43 | 0.77 | 1.10 | 1.01 | 0.84 | 0.84 |
| | 6c. F × 2 | 0.00 | 1.02 | 0.65 | 1.41 | 0.88 | 1.06 | 0.98 | 0.86 | 0.87 |
| | 6d. F × 5 | 0.00 | 0.99 | 0.30 | 1.31 | 1.04 | 1.03 | 0.97 | 0.90 | 0.84 |

Table 36. Less intuitive indicators: Values of ecosystem indicators at year 20 for each scenario, calculated from coast-wide data or within MBNMS. All indicators are scaled relative to status quo (scenario 1). Since some indicators are positively related to groundfish and ecosystem health and others negatively related, the red/yellow/green color scheme signifies indicator values that we expect to relate to decreased/static/increased ecosystem health or groundfish status.

| | | Number assessed | | Zooplankton anomaly | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Scale:** | **Scenario** | **Spp. < B40** | **Spp. < B25** | **Krill** | **Gelatinous** | **Copepods** | **Micro-zooplankton** | **NPP** | **Top predator biomass** | **Seabird reproduction, juveniles** |
| **Coast wide** | 1. Status quo | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| | 2a. Gear shift, MBNMS 25% | 1.15 | 0.91 | 0.97 | 0.92 | 1.02 | 0.83 | 0.94 | 0.86 | 0.57 |
| | 2a. Gear shift, MBNMS, 50% | 1.15 | 0.91 | 0.96 | 0.92 | 1.01 | 0.84 | 0.94 | 0.86 | 0.57 |
| | 2a. Gear shift, MBNMS, 100% | 1.15 | 0.91 | 0.97 | 0.94 | 1.03 | 0.85 | 0.95 | 0.86 | 0.57 |
| | 2b. Gear shift, 25% | 1.01 | 1.00 | 0.99 | 0.99 | 0.99 | 0.87 | 0.96 | 1.00 | 1.00 |
| | 3a. RCA no bottom contact, MBNMS | 1.10 | 1.04 | 1.00 | 0.99 | 0.97 | 0.86 | 0.97 | 1.00 | 1.00 |
| | 3b. RCA no bottom contact | 1.04 | 1.00 | 0.98 | 0.99 | 0.98 | 0.90 | 0.98 | 1.00 | 1.00 |
| | 3c. RCA no bottom contact, Central CA | 1.10 | 1.04 | 1.04 | 0.99 | 1.00 | 1.10 | 0.95 | 1.00 | 1.00 |
| | 4a. Consolidate impacts, MBNMS | 1.00 | 1.00 | 0.98 | 1.01 | 1.01 | 1.17 | 1.03 | 1.00 | 1.00 |
| | 4b. Consolidate impacts | 1.00 | 1.00 | 1.02 | 0.99 | 1.01 | 0.89 | 1.01 | 1.00 | 1.00 |
| | 5a. No fishing, MBNMS | 1.10 | 1.05 | 0.95 | 1.03 | 1.15 | 1.68 | 1.07 | 1.00 | 1.00 |
| | 5b. No fishing, NMS | 1.11 | 1.04 | 0.96 | 1.14 | 1.28 | 1.23 | 1.13 | 1.00 | 1.00 |
| | 5c. No fishing | 1.30 | 1.49 | 1.05 | 1.00 | 1.27 | 0.80 | 0.80 | 0.85 | 0.57 |
| | 5d. Fishing, no spatial management | 1.08 | 0.96 | 1.00 | 0.93 | 1.34 | 0.90 | 1.05 | 1.03 | 1.00 |
| | 6a. F × 0.5 | 1.41 | 1.47 | 0.98 | 0.92 | 1.27 | 1.09 | 1.16 | 1.05 | 1.04 |
| | 6b. F × 1.5 | 1.43 | 1.00 | 1.03 | 1.09 | 1.23 | 1.36 | 1.08 | 1.05 | 1.09 |
| | 6c. F × 2 | 1.25 | 1.14 | 1.06 | 0.95 | 1.18 | 0.90 | 1.00 | 1.01 | 1.10 |
| | 6d. F × 5 | 1.16 | 1.07 | 0.98 | 1.03 | 1.15 | 0.95 | 1.06 | 1.06 | 1.08 |
| **MBNMS** | 1. Status Quo | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| | 2a. Gear shift, MBNMS 25% | 1.15 | 0.93 | 0.97 | 0.83 | 1.27 | 1.45 | 1.03 | 0.86 | 0.77 |

Table 36 continued. Less intuitive indicators: Values of ecosystem indicators at year 20 for each scenario, calculated from coast-wide data or within MBNMS. All indicators are scaled relative to status quo (scenario 1). Since some indicators are positively related to groundfish and ecosystem health and others negatively related, the red/yellow/green color scheme signifies indicator values that we expect to relate to decreased/static/increased ecosystem health or groundfish status.

| | | Number assessed | | Zooplankton anomaly | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Scale:** | **Scenario** | **Spp. < B40** | **Spp. < B25** | **Krill** | **Gelatinous** | **Copepods** | **Micro-zooplankton** | **NPP** | **Top predator biomass** | **Seabird reproduction, juveniles** |
| **MBNMS (cont.)** | 2a. Gear shift, MBNMS, 50% | 1.15 | 0.93 | 0.96 | 0.83 | 1.24 | 1.06 | 1.01 | 0.86 | 0.77 |
| | 2a. Gear shift, MBNMS, 100% | 1.15 | 0.93 | 0.97 | 0.83 | 1.27 | 1.29 | 1.07 | 0.86 | 0.77 |
| | 2b. Gear shift, 25% | 1.01 | 1.00 | 0.99 | 1.00 | 1.02 | 1.06 | 0.90 | 1.00 | 1.00 |
| | 3a. RCA no bottom contact, MBNMS | 1.10 | 1.03 | 1.00 | 0.92 | 0.87 | 1.12 | 0.92 | 1.00 | 1.00 |
| | 3b. RCA no bottom contact | 1.04 | 1.00 | 0.98 | 0.75 | 0.74 | 1.20 | 0.90 | 1.00 | 1.00 |
| | 3c. RCA no bottom contact, Central CA | 1.10 | 1.03 | 1.04 | 0.99 | 0.98 | 1.08 | 0.87 | 1.00 | 1.00 |
| | 4a. Consolidate impacts, MBNMS | 1.00 | 1.00 | 0.98 | 1.00 | 1.00 | 1.60 | 1.00 | 1.00 | 1.00 |
| | 4b. Consolidate impacts | 1.00 | 1.00 | 1.02 | 0.96 | 0.93 | 0.96 | 1.02 | 1.00 | 1.00 |
| | 5a. No fishing, MBNMS | 1.10 | 1.03 | 0.95 | 0.96 | 1.01 | 1.16 | 0.99 | 1.00 | 1.00 |
| | 5b. No fishing, NMS | 1.11 | 1.02 | 0.96 | 0.87 | 1.06 | 1.13 | 0.92 | 1.00 | 1.00 |
| | 5c. No fishing | 1.32 | 1.31 | 1.05 | 0.96 | 0.94 | 1.34 | 0.85 | 0.85 | 0.77 |
| | 5d. Fishing, no spatial management | 1.08 | 0.96 | 1.00 | 0.88 | 1.64 | 1.08 | 0.79 | 1.02 | 1.00 |
| | 6a. F × 0.5 | 1.28 | 1.37 | 0.98 | 0.76 | 0.82 | 1.06 | 1.48 | 1.14 | 0.62 |
| | 6b. F × 1.5 | 1.47 | 1.48 | 1.03 | 0.99 | 0.92 | 1.20 | 1.34 | 0.94 | 0.54 |
| | 6c. F × 2 | 1.54 | 1.10 | 1.06 | 0.70 | 1.14 | 1.12 | 1.34 | 0.95 | 0.46 |
| | 6d. F × 5 | 1.30 | 1.03 | 0.98 | 0.86 | 1.26 | 0.97 | 1.20 | 1.10 | 1.15 |

The indicators in Table 36 were less directly driven by fishing mortality, are less intuitive, or are not related to easily explained patterns; these indicators are less useful as indicators for capturing the main impacts of the scenarios. The number of assessed species below management thresholds generally increased above status quo projections, irrespective of the management scenario. Zooplankton response was either minimal or varied depending on the scale of data (MBNMS vs. coastal, e.g., microzooplankton). Top predator abundance and seabird reproduction declined in the gear shift scenarios due to trophic interactions rather than direct fishing pressure, but declined as much in the scenario with no fishing. These aggregate indicators partly masked the species-level declines described above.

Managers viewing the impacts of policies through the lens of observable indicators might visualize scenario results in multicriteria plots similar to those used for the performance metrics (Figure 48 and Figure 49). Figure 50 through Figure 53 present results in a similar format, summing the indicators from key scenarios in Table 35 and Table 36 into the components of interest in the IEA: ecosystem health, ecosystem function, groundfish abundance, and groundfish condition. To begin to identify economic and ecological trade-offs, we have also plotted landed value of the fisheries catch.

Judged in terms of coast-wide indicators, the coast-wide management actions generally performed similarly to status quo (Figure 50). Exceptions to this included the scenario prohibiting bottom contact in the RCA, which reduced landed value. The slight reductions in ecosystem function stemming from the prohibition on bottom contact in the RCA and the gear shift scenario reflect slight declines in primary production. However, this may be a sign of the high temporal and spatial variability of phytoplankton, rather than a broad signal of ecosystem

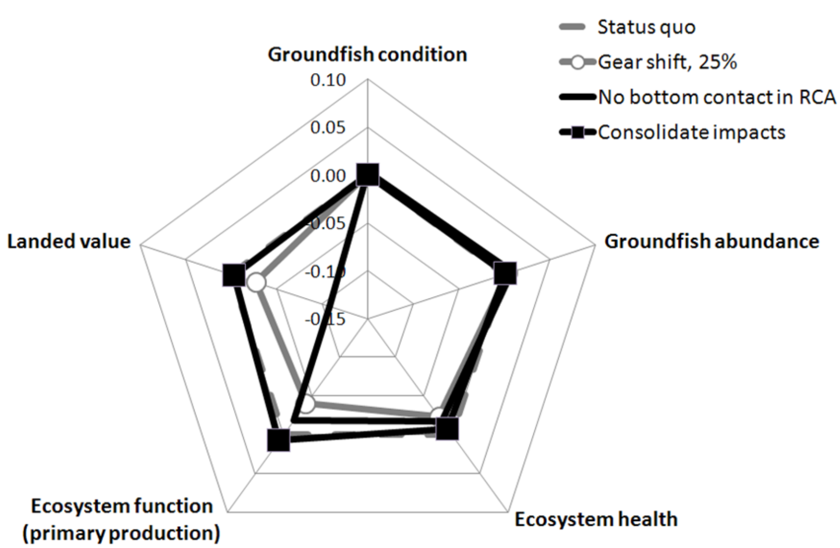



Figure 50. Performance of alternative management scenarios in terms of ecosystem components relevant to the IEA. Values are calculated using the indicators in Table 35 and Table 36. Note that values here represent proportional difference from a status quo projection. The scenarios include a gear shift from trawl to longline and pot, eliminating bottom-contact gear in the RCA and consolidating the footprint of bottom-contact impacts. Here the management action occurs coast wide and the indicators are calculated on a coast-wide basis.

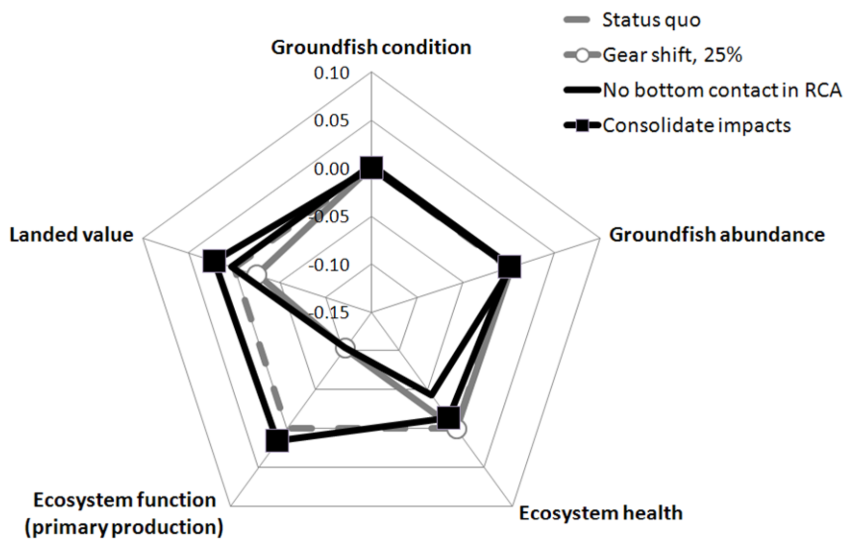



Figure 51. Performance of alternative management scenarios in terms of ecosystem components relevant to the IEA. Values are calculated using the indicators in Table 35 and Table 36. Note that values here represent proportional difference from a status quo projection. The scenarios include a gear shift from trawl to longline and pot, eliminating bottom-contact gear in the RCA, and consolidating the footprint of bottom-contact impacts. Here the management action occurs coast wide and the indicators are calculated within MBNMS.

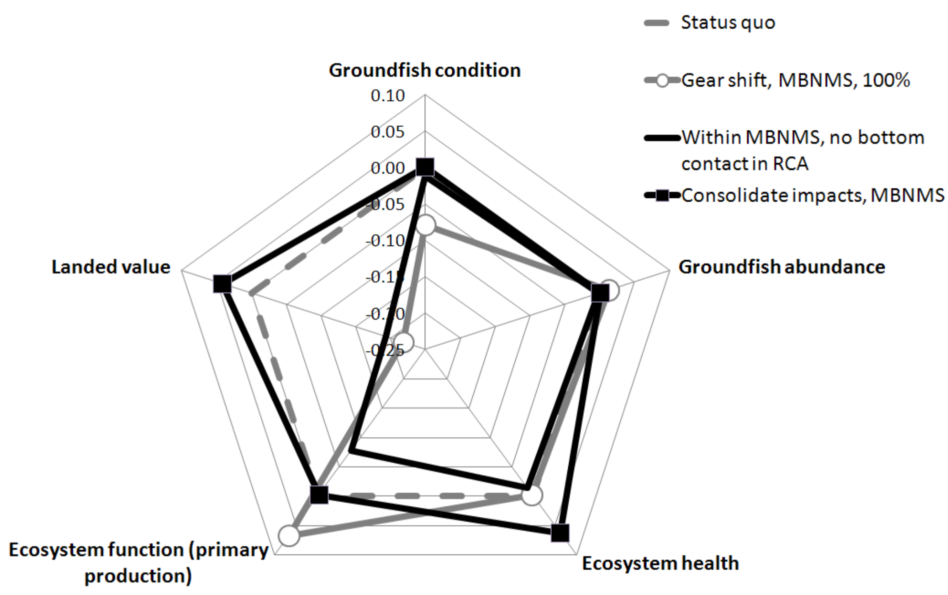



Figure 52. Performance of alternative management scenarios in terms of ecosystem components relevant to the IEA. Values are calculated using the indicators in Table 35 and Table 36. Note that values here represent proportional difference from a status quo projection. The scenarios include a gear shift from trawl to longline and pot, eliminating bottom-contact gear in the RCA, and consolidating the footprint of bottom-contact impacts. Here the management action occurs within MBNMS and the indicators are calculated within MBNMS.

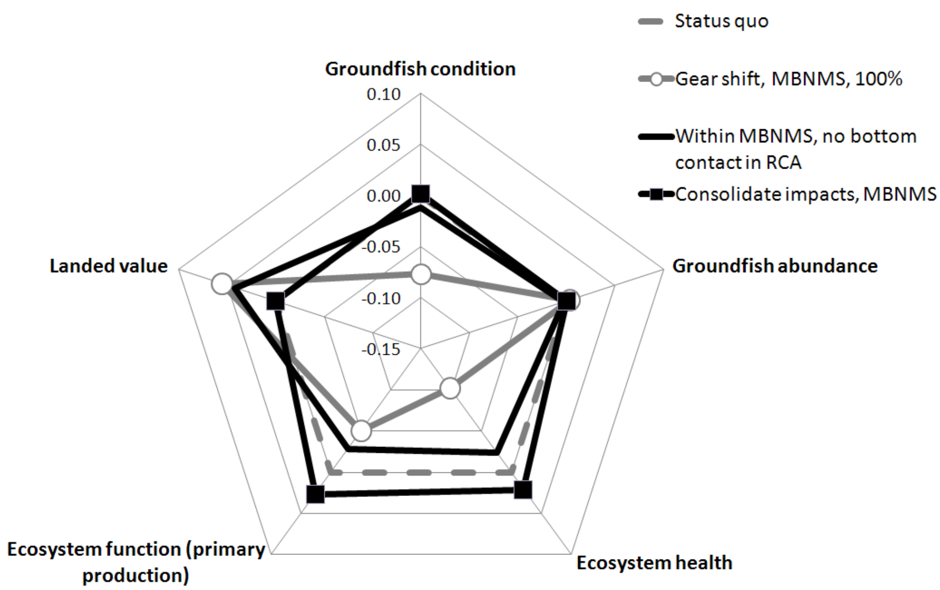



Figure 53. Performance of alternative management scenarios in terms of ecosystem components relevant to the IEA. Values are calculated using the indicators in Table 35 and Table 36. Note that values here represent proportional difference from a status quo projection. The scenarios include a gear shift from trawl to longline and pot, eliminating bottom-contact gear in the RCA, and consolidating the footprint of bottom-contact impacts. Here the management action occurs within MBNMS and the indicators are calculated coast wide.

function. Groundfish abundance and condition and ecosystem health are generally invariant between the scenarios.

Considering the same set of policy scenarios, but based on indicators calculated from within MBNMS, leads to similarly invariant indicators of groundfish abundance and condition (Figure 51). As at the coast-wide scale, approximate 10% declines in primary production occur within the sanctuary for the gear switch and RCA closure. Landed value varies less than 4% between scenarios; as discussed above, the RCA closure does not cause substantial declines in landed value within MBNMS. Four percent declines in ecosystem health under the RCA closure are caused mostly by local declines in two indicators, gelatinous zooplankton and copepods.

Considering the scenarios that simulated management actions within MBNMS, local indicators predict no large differences in groundfish abundance between scenarios. In the MBNMS gear shift scenario, groundfish condition (age structure indicators) declines due to an increase in the proportion of immature fish during these short, 20-year simulations. Primary production, our proxy for ecosystem function, varies approximately 10% between these scenarios. As mentioned before, landed value within the sanctuary declines due to local conservation actions such as the gear shift and RCA closure.

When these same scenarios with local management actions are viewed at a coast-wide scale, we predicted no more than 5% variation between scenarios, with the exception of the gear shift within MBNMS. The gear shift led to an 8% reduction in groundfish condition (due to a decrease in the proportion of mature midwater and shallow large rockfish), 10% reductions in ecosystem health (due to slight declines in seabirds, top predators, and small zooplankton), and lower primary production.

## Discussion

### Lessons learned from model results

Most of the scenarios that involved minor management changes yielded results similar to status quo. This is due to the fact that on the scale of the coast-wide performance metrics presented here, changes within specific areas such as MBNMS did not have large impacts. On the other hand, when such impacts did occur, for instance to yelloweye and cowcod rockfish, they tended to involve local interactions that were difficult to predict a priori based solely on fishing patterns.

No single scenario maximized all performance metrics. Any policy choice would involve trade-offs between stakeholder groups and policy goals. Of the scenarios most relevant to management, the coast-wide 25% gear shift appeared to be one possible compromise between the coast-wide closure of RCA to bottom contact (which sacrificed revenue) and scenarios such as the one consolidating bottom impacts to more than 550 m (which did not perform substantially differently from status quo). However, stakeholders who place more weight on biogenic habitat (e.g., corals and sponges) might prefer the full closure of the RCA to bottom contact.

The scenarios involved winners and losers among fleets and species. For instance, there were direct impacts of the scenarios on fleets (e.g., on trawl and longline + pot fleets), as well as indirect effects such as halibut longline fisheries that gained revenue when trawl effort declined. For individual species in the scenarios of most relevance to managers, the key impact was in the gear shift scenarios, which cut fishing mortality on flatfish and some rockfish and led to biomass increases for many of these groups. In the sensitivity analysis scenarios, broad life history differences drove the responses, with unproductive groups declining at moderate fishing pressures and being replaced by more productive groups or species.

From the standpoint of current fisheries management, it is encouraging that in the scenarios with fishing rates near status quo, fish biomasses generally increased and plateaued over the course of the 20-year simulations and age structure stabilized. The strong recovery trends for fish, marine mammals, and birds suggest that we must carefully interpret our performance metrics. Some performance metrics may be more sensitive to stock depletion than recovery (e.g., proportion of rockfish mature and rockfish biomass), or may be more sensitive to fish than unharvested protected groups.

The scenarios revealed strong trophic effects in the food web. For instance, 50% reductions in fishing led to declines in small planktivores (sardines and anchovies) due to fish predation; this subsequently caused declines in marine mammal and bird abundance. Scenarios with strong increases in fishing on all groups indirectly led to increases in abundance of some small bodied prey groups, such as nearshore fish (surfperch) and small flatfish. Declines of diving seabirds, due to predation, were an unexpected consequence of spatial fishery closures within the sanctuaries. These results demonstrate the strength of using the full ecosystem model, which captures these food web effects, rather than traditional single species models.

Ecological indicators can be useful proxies to gauge the effects of management policies. We have shown that a set of eight indicators can detect coast-wide and local (MBNMS) impacts of these management scenarios. Specifically, gear shift policies caused up to 24% changes in indicators calculated from either coast-wide data or data within the MBNMS. Other management relevant scenarios (1–4b) tended to cause less dramatic shifts in local ecology and the indicator values (<5% change in indicators). We did identify a second set of indicators that responded contrary to our prior expectation, denoting the need for a full suite of indicators. Careful consideration is also warranted regarding how underlying population dynamics contribute to the calculation of these metrics (e.g., for indices based on proportion of biomass mature).

**Lessons learned from development of these scenarios**

We learned several lessons simply from assembling the data involved in these scenarios, creating the relevant maps, and converting the scenario descriptions into quantitative inputs for the ecosystem model. One was the relative catch composition of trawl gear, which targets a wide range of flatfish and rockfish, versus longline + pot gear, which primarily target sablefish. A switch from trawl to longline + pots therefore involves a substantial transfer of fishing mortality from the former species to the latter. Such a gear shift would also involve substantial capital investment and changes in fishing personnel and skill sets.

Each of the scenarios shown here includes spatial closures for each of the 20 fleets (gears). Creating the scenarios involved substantial amounts of GIS work to identify the specific open/closed fishing areas per gear, to delineate these on maps, and to calculate their areal extent. In the Atlantis model, these define where fishing mortality per fleet is applied and the extent of habitat damage. However, we can provide the basic geographic information independent of Atlantis model results. The geographic analysis alone reveals characteristics of the scenarios. For instance, for central California specifically, Scenarios 3a, 3b, and 3c (prohibit bottom gear in RCA) add additional spatial closures for trawl gear but not longline + pot gear, due to the status quo overlap of the existing trawl and nontrawl RCA.

Finally, independent of specific model results, it is clear that we have only a qualitative understanding of the impact of certain gears on benthic habitat. Here we have weighted the footprint of each gear based on gear impact factors from an EFH environmental impact statement, consistent with Collie et al. (2000). Essentially this is a placeholder framework for an approach informed by quantitative local data on gear impacts.

## Summary

These simulations are intended primarily as a proof of concept, to demonstrate the utility within the IEA of using the Atlantis ecosystem model to screen particular policies. We view our work to date as a strategic framework for considering management needs of the NMSs, California Department of Fish and Game and Ocean Science Trust, and the PFMC. The approach allows integration of sanctuary, coast-wide federal and state actions, and allows consideration of management alternatives relative to clearly defined policy goals.

# MSE 2: Potential Impacts of Climate Change on California Current Marine Fisheries and Food Webs

*[Editors' note: The evaluation presented below is derived from Ainsworth et al. in press.]*

## Introduction

Since the industrial revolution, air and ocean temperatures have increased globally and ocean pH and DO levels have decreased (Byrne et al. 2010, Sabine et al. 2004). There is strong evidence that anthropogenic emissions of greenhouse gases have contributed to these changes and the rate of emissions is projected to increase (IPCC 2007). We took a cursory look at some of the potential implications of climate change on marine food web structure in the northern California Current and other North Pacific shelf ecosystems. We analyzed the marine food web responses to changing climate with respect to five major aspects of climate change: changes in annual mean level of primary production, temperature-induced latitudinal range shifts of fish and invertebrates, changes in the size structure of zooplankton communities, ocean acidification, and ocean deoxygenation.

## Methods

Ecopath with Ecosim (EwE) food web models were employed for the northern California Current (Field 2004) and four other Pacific eastern boundary current ecosystems. Together, the models provided complete geographic coverage of the North Pacific shelf from Cape Mendocino, California, to Yakutat Bay, Alaska. EwE is a trophodynamic ecosystem model that summarizes living and nonliving components of the ecosystem into functional groups: groups of species aggregated according to life history and niche characteristics (Christensen and Pauly 1992). The model acts as a thermodynamic accounting system, tracking the flow of energy between groups according to a diet matrix, while accounting for energy lost in respiration, emigration, and decomposition.

Because of the idiosyncratic nature of climate change impacts and because EwE (version 5.1) offers a limited set of options for introducing climate change impacts to food webs, we used simple productivity forcing functions to represent positive or negative impacts on biological productivity of the five climate effects. To account for the substantial range of uncertainty involved in applying these functions to functional group production rates, we used three scenarios per climate effect representing nominal, moderate, and substantial effect strengths. The moderate scenarios represented the best guess, while the nominal and substantial scenarios increased or decreased the production change by 50%.

Simulations attempted to reproduce ecosystem changes associated with the IPCC AR4 protocols (Special Report on Emission Scenarios, A1B scenario) over the time period 2010 to 2060. To model changes in primary production, we employed outputs from the NOAA Geophysical Fluid Dynamics Laboratory (GFDL) Earth System Model (ESM 2.1), scaling the production function on phytoplankton in EwE to achieve the predicted level of primary productivity using an approach similar to Brown et al (2010). To model the effects of temperature-induced range shifts of species, we utilized outputs of a dynamic bioclimatic envelope model (Cheung et al. 2009), which was itself driven by temperatures forecasted by the GFDL ES M2.1 model. In short, range shifts were simulated in EwE by increasing the production of warm water fish species (mimicking encroachment) and decreasing production of cold water species (mimicking withdrawal).

To represent changes in the size structure of zooplankton communities with increasing ocean temperatures, we increased the abundance of small-bodied plankters relative to large-bodied plankters (e.g., Morán 2009), consulting an empirical relationship proposed by Bouman et al. (2003). The impacts of ocean acidification were approximated by adjusting species productivity based on outcomes of published laboratory studies. Taxa predicted to be affected included crustaceans (especially shrimp), echinoderms, mollusks, and euphausiids. Finally, consumer productivity was assumed to change linearly with the DO concentration, while projected DO was based on forecasts by Whitney et al. (2007). We considered the impacts of these effects individually and in concert, assuming additivity of production factors on individual species. Note that this simplifying assumption does not preempt the possibility of nonadditive effects on aggregate properties of the food webs (e.g., fisheries landings, biodiversity).

## Results and Discussion

Model simulations predicted that the performance of fisheries and the relative abundance of species in the northern California Current are expected to change, but not in a uniform way. Despite the implementation of mainly negative forcing functions (that reduce productivity), many fisheries and species benefited because of indirect feeding relationships. Individually, primary production, zooplankton community size structure, DO, and ocean acidification effects reduced or increased total fisheries landings by only a small amount (±10%) in the year 2060 relative to the control scenario without climate effects. However, the cumulative impacts of these effects reduced landings by 40% (Figure 54). The impacts were even more severe when range shifts were included in the cumulative impacts scenario: there was a reduction in total landings of more than 70% under the moderate scenario (with pelagic fisheries being virtually eliminated), and a reduction of 85% under the substantial scenario. Other ecosystems studied confirmed that range shifts emerge as the dominant climate effect. This is interesting in light of the fact that this effect has the firmest foundation in terms of the supporting science, although Ainsworth et al. (in press) point out several important caveats.

Cumulative impacts including range shifts caused a reduction in ecosystem biomass in the northern California Current of 20%, while climate effects studied in isolation had little negative impact. This suggests that synergies can occur through food web dynamics. This can be confirmed by examining changes in ecosystem biodiversity (Figure 55). Although no one climate effect had a serious impact on biodiversity, the cumulative impacts scenario showed potential for a severe decline. This result was consistent across all five ecosystems tested. Considering the behavior of individual functional groups, it was suggested that populations already stressed by fishing might experience the most severe reductions under climate change.

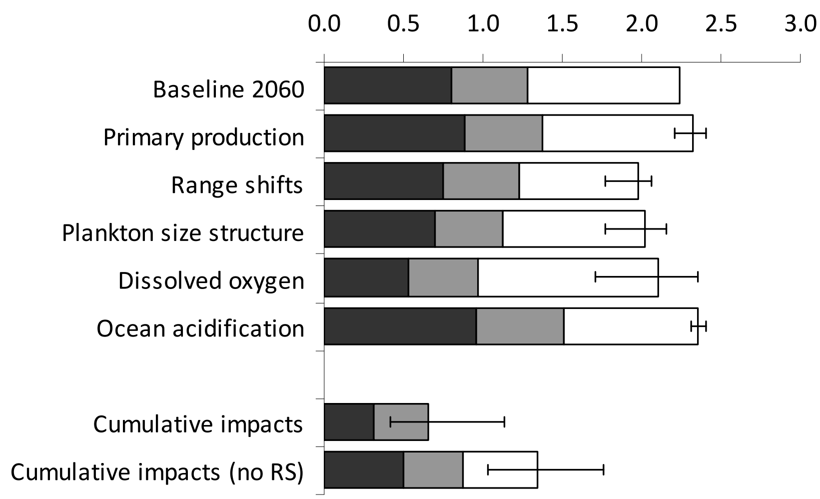



Figure 54. Projected fishery landings (t • $km^{-2}$) in the northern California Current (2060). Baseline shows projected landings without climate change. Error bars show the range of outputs predicted using three effect sizes (nominal, moderate, and substantial); bar shows median. Dark gray is demersal fish, light gray is pelagic fish, and white is invertebrates.

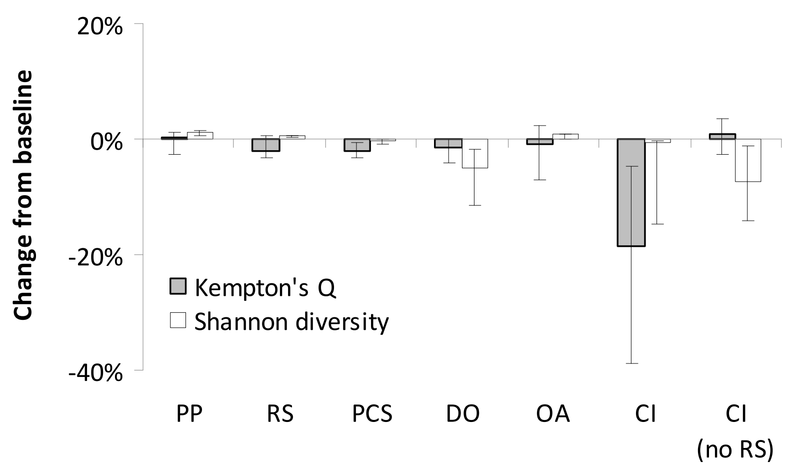



Figure 55. Biodiversity impacts in the northern California Current (2060): primary production (PP), range shifts (RS), plankton community size structure (PCS), dissolved oxygen (DO), ocean acidification (OA), and cumulative impacts (CI). Biodiversity indices are: Shannon Diversity (Shannon and Weaver 1949) and Kempton's Q (Ainsworth and Pitcher 2006).

# MSE 3: Fishing Catch Shares in the Face of Global Change, a Framework for Integrating Cumulative Impacts and Single Species Management

*[Editors' note: The evaluation presented below is derived from Kaplan et al. 2010.]*

Any fishery management scheme, such as individual fishing quotas (IFQs) or MPAs, should be designed to be robust to potential shifts in the biophysical system. One such shift is ocean acidification caused by increasing atmospheric $CO_2$ levels. Ocean acidification may lead to mortality of shell-forming corals, benthos, and plankton groups due to reduced calcification rates in an acidic ocean. Here we couple possible catch scenarios under an IFQ scheme with ocean acidification impacts on shelled benthos and plankton, using an Atlantis ecosystem model for the U.S. West Coast. The ecosystem model includes the full food web, oceanography, and fisheries.

IFQ harvest scenarios alone in most cases did not have strong impacts on the food web beyond the direct effects on harvested species. However, when we added impacts of ocean acidification, the abundance of commercially important groundfish such as English sole (*Pleuronectes vetulus*), arrowtooth flounder, and yellowtail rockfish (*Sebastes flavidus*) declined up to 20–80% due to the loss of shelled prey items from their diet. English sole exhibited a tenfold decline in potential catch and economic yield when confronted with strong acidification impacts on shelled benthos (Figure 56). Our estimated reference points clearly illustrate the dramatic impact of this acidification regime on English sole (Table 37).

As current catches are only a third of the quota, there appears to be much scope for a future expansion of catch. However this may not actually be possible, as unfished spawning stock biomass fell by 90% when confronted with strong acidification impacts on benthos. Maximum sustainable yield therefore fell 90% as well. It seems prudent to complement IFQs with careful consideration of potential global change effects such as acidification. Our analysis provides an example of how new ecosystem modeling tools that evaluate cumulative impacts can be integrated with established management reference points and decision mechanisms.

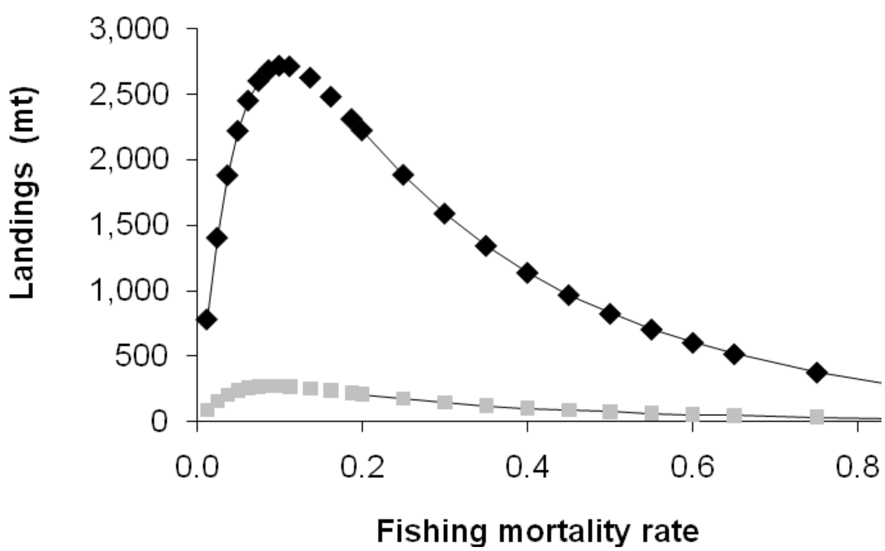



Figure 56. Yield of English sole under various fishing mortality rates with current ecological processes (top curve) versus strong ocean acidification impacts on benthos (bottom curve). Yield is based on catches in year 50 of a 50-year simulation; this is an approximation of an equilibrium sustainable yield.

Table 37. Decision table for English sole evaluating the impact of status quo harvest on three alternate IFQ scenarios, faced with either no ocean acidification or strong acidification impacts on benthos. Harvest policies were simulated for 20 years. Results are reported as spawning biomass (SB) at the end of the simulation, relative to 2009 biomass or relative to the appropriate estimate of unfished spawning biomass ($SB_0$).

| | **State of nature** | | | | | |
|---|---|---|---|---|---|---|
| | **No acidification ($SB_{0NoAcid}$ = 123,000)** | | | **Strong acidification on benthos ($SB_{0Acid}$ = 15,000)** | | |
| **Harvest policy (catch )** | **$SB_{2028}$** | **$SB_{2028}$/ $SB_{2009}$** | **$SB_{2028}$/ $SB_{0NoAcid}$** | **$SB_{2028}$** | **$SB_{2028}$/ $SB_{2009}$** | **$SB_{2028}$/ $SB_{0Acid}$** |
| Status quo (557 mt) | 137,000 | 2.69 | 1.12 | 24,500 | 0.48 | 1.63 |
| Scenario 1 (1,131 mt) | 125,000 | 2.45 | 1.02 | 13,000 | 0.26 | 0.87 |
| Scenario 2 (1,772 mt) | 115,000 | 2.26 | 0.94 | 3,500 | 0.07 | 0.23 |
| Scenario 3 (1,772 mt) | 115,500 | 2.27 | 0.94 | 3,500 | 0.07 | 0.23 |

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# Appendix A: Performance Testing of Ecosystem Indicators at Multiple Spatial Scales for the California Current IEA using the Atlantis Ecosystem Model

## Introduction

Whether conducted with a fishing hook from a pier or a submarine at 1,500 m, monitoring is a key component of management plans for marine systems, informing decision makers about the status and trends of ecosystem components. In the context of active adaptive management (Walters 1987), monitoring allows us to evaluate the impacts of policy decisions; for instance, rather than simply implementing a harvest level in perpetuity, a series of alternative fishing levels can be tested and evaluated at different times or sites. Even passive adaptive management, which represents simple policy adjustments based on new information but without explicit policy experimentation, requires adequate monitoring and evaluation. In oceanographically dynamic systems such as the California Current, monitoring of the types summarized in McClatchie et al. (2009) serves to describe not just anthropogenic effects but also natural fluctuations in ecosystem state, such as effects of El Niño or the Pacific Decadal Oscillation.

Monitoring and subsequent analysis and interpretation to create time series of ecosystem indicators is a key component of NOAA's integrated ecosystem assessment (IEA) for the California Current (Levin et al. 2008, 2009). IEA is a synthesis and quantitative analysis that organizes science to inform ecosystem-based management (Levin et al. 2009). Explicitly defined as a framework for supporting management decision making, it is designed to evaluate the status of the system and the effect of policy decisions in terms of management objectives. These objectives are usually defined in terms of attributes, such as biodiversity, that represent goals of stakeholders or decision makers, but are not always easily measured in the field. Evaluating ecosystem status and the effects of policy necessitates distilling monitoring time series into a set of measurable indicators that either directly capture or can serve as proxies for these attributes of interest. Other authors have suggested scores of potential indicators, both for general use and for specific geographies (e.g., Rochet and Trenkel 2003, Trenkel and Rochet 2003, Link 2005, Rice and Rochet 2005, Rodionov and Overland 2005). The challenge is to identify a small, comprehensible set of indicators appropriate for the California Current.

In this appendix, we present results from simulation testing of ecosystem indicators for the California Current using the Atlantis ecosystem simulation model (Horne et al. 2010) and simple statistical techniques. These techniques, which estimate the strength of correlations between attributes of interest and potential indicators, are similar to those used by Fulton et al. (2005) to screen candidate indicators for two systems in Australia. Ultimately, the utility of an indicator is also related to additional factors, such as monitoring costs, measurement error, process "noise," public interest, and relevance to policy reference points (Rice and Rochet 2005, deReynier et al. 2010, Selecting and Evaluating Indicators for the California Current section of this technical memorandum). However, the necessary first step in indicator screening is to evaluate the statistical relationship with attributes, as presented here.

We test the relationship between attributes and indicators at a coast-wide scale, similar to an analysis using the Ecosim modeling platform (Samhouri et al. 2009). Here however, the ability of the California Current Atlantis model to track numbers-at-age and weight-at-age allows consideration of attributes and indicators related to size composition and age structure (e.g., size-at-age, recruitment, and population age composition). The Atlantis model also enables us to consider ecosystem drivers including not just a range of fishing intensities and configurations, but also nutrient inputs. A priori we might expect the utility of certain indicators to depend on the type of drivers and the overall system response to those drivers.

The explicit, map-based nature of the Atlantis model allows us to test questions related to the spatial scaling of indicators and attributes. For instance:

- Are different attribute-indicator pairs at local scales than coast-wide scales needed?
- What do local indicators say about coast-wide attributes (upscaling)?
- What do coast-wide indicators say about local attributes (downscaling)?

These questions are driven by the distinctions between small-scale monitoring programs (in state waters or in national marine sanctuaries [NMSs]) versus coast-wide surveys such as the NWFSC shelf/slope survey (Keller et al. 2007). Is there a "one size fits all" set of attributes and indicators or should they vary with scale? How much information content about local processes is contained in a coast-wide survey and vice versa? Addressing these questions is crucial in the context of the IEA, in which scientists and managers must choose when high-quality local monitoring (e.g., Newport Line data, Peterson and Keister 2003) should be extrapolated to make inferences about the overall status of the California Current. Similarly, regional agencies such as California's Ocean Science Trust must make decisions about whether coast-wide stock assessments and monitoring should factor into decisions about local status of groups within marine protected areas (MPAs).

Below we describe the implementation of the Atlantis ecosystem modeling framework in the California Current and present a set of 23 model simulations forced by 5 different types of scenarios. We screen a list of ecosystem indicators and attributes, and calculate the strength of correlations between them to identify 29 promising attribute-indicator pairs related to ecosystem health and 60 related to groundfish. We evaluate the full set of simulations, then focus on specific types of scenarios (such as fishing vs. nutrient additions), identifying how scenario type influences the appropriate set of attribute-indicator pairs. Finally, we test the correlations when the indicators or the attributes have been calculated from local rather than coast-wide data. We find that spatial scale has a strong influence on indicator utility (correlation), and that only a small fraction of the indicators relevant at coast-wide scales are appropriate at local scales or for inferring attribute status across scales.

# Methods: Atlantis

Atlantis is a recently developed simulation modeling approach that successfully integrates physical, chemical, ecological, and anthropogenic processes in a three-dimensional, spatially explicit domain (Fulton et al. 2003, 2004a, 2004b, 2004c). In Atlantis, ecosystem dynamics are represented by spatially explicit submodels that simulate hydrographic processes (light-driven and temperature-driven fluxes of water and nutrients), biogeochemical factors driving primary production, and food web relations among flora and fauna. The model represents key exploited species at the level of detail necessary to evaluate direct effects of fishing and also represents other anthropogenic and climate impacts on the ecosystem as a whole.

Key ecological options and assumptions in the present application and in most other Atlantis models built to date (summarized in Fulton et al. in press) include density-dependent movement, with predators moving toward areas with higher food availability; forced migrations into and out of the model domain (e.g., for highly migratory species such as whales); reproduction based on standard Beverton Holt stock recruitment relationships (for fish) and fixed offspring/adult (for mammals and birds); predation governed by a modified Holling Type II functional response with gape limitation, allowing predator diets to vary in relation to prey availability and length relative to the predator's length; and dynamic weight-at-age, meaning that realized consumption rates throughout the modeled time period translate into variable weight per individual within a cohort. Primary production is influenced by temperature, light, and nutrient availability, with nutrients and plankton advected by current fields. Though many options for these ecological processes are available within the Atlantis code base, analyses by Fulton (2001, 2004) and Fulton et al. (2003, 2004a, 2004b, 2004c) have supported the appropriateness of these particular representations, in particular for the functional response, physiological detail, and typical levels of aggregation for functional groups and spatial cells.

# Methods: Model of the California Current

The California Current Atlantis model is fully detailed in Horne et al. (2010). The geographic extent of the model extends along the U.S. West Coast from the Canadian border to Point Conception (lat 34°27′N), and out to 1,200 m depth. An earlier version of the model (Brand et al. 2007) has been applied to test ecosystem indicators (Kaplan and Levin 2009), harvest strategies, and the effects of ocean acidification (Kaplan et al. 2010). The simulations presented here include updated estimates of abundance from stock assessments and surveys, as well as added spatial resolution in central California; full details of the modifications are contained in Horne et al. (2010).

The model includes 60 functional groups, ranging from phytoplankton to marine mammals, birds, and harvested fish groups. It has particular emphasis on groundfish species, modeling some species such as Pacific hake (*Merluccius productus*) and canary rockfish (*Sebastes pinniger*) as single species rather than aggregated functional groups. The primary producer and invertebrate groups are modeled as simple biomass pools per model cell, while the vertebrate groups are modeled in terms of numbers-at-age and weight-at-age per cell. The model's initial conditions represent approximately 2005–2008, and we project this forward for

50 years under a set of scenarios described below. Water temperature and the flux of nutrients and plankton are forced with a repeating 47-year loop of output (1958–2004, with 2005 then restarting the loop) from a regional ocean modeling system. Fulton et al. (in press) contains a comparison of the California Current model to other Atlantis models, as well a summary of lessons learned from this and other applications of Atlantis.

## Methods: Attributes and Indicators

In the context of the California Current IEA, here we focus on attributes and indicators of goals related to groundfish and ecosystem health (Table A-1 and Table A-2). The Selecting and Evaluating Indicators for the California Current section of this document summarizes key attributes and indicators related to these goals. We have retained its conceptual framework, its four key attributes, and all of the indicators that can be tested within Atlantis.

We have also supplemented the attribute and indicator list with information drawn from scientific literature and management documents (Table A-1 and Table A-2). Samhouri et al. (2009) and Fulton et al. (2005) provide summaries of attributes and indicators suggested by other authors in the peer-reviewed literature, and we have drawn on those here. The National Marine Sanctuaries Program recently published condition reports for U.S. West Coast sanctuaries. These list the key attributes and indicators of interest to NMS staff and stakeholders within each sanctuary, which we have included. Through a series of stakeholder workshops and expert review panels, the California Ocean Science Monitoring Enterprise has identified attributes and indicators of interest for the California state MPAs. Where these attributes and indicators can be included given the resolution of Atlantis, we list them, primarily derived from a monitoring plan for the north central California coast. Finally, the Pacific Fishery Management Council uses 40% of unfished abundance as a target biomass for most stocks and 25% as an overfishing threshold. We treat the number of species that fall below these fishery-management reference points as indicators (for assessed species) and as attributes (for unassessed species). We treat assessed species as “observed” (through the lens of current monitoring and stock assessment), thus suitable as indices. We treat unassessed species as “unobserved,” thus their stock levels are attributes for which we seek suitable indicators.

We use Atlantis to generate annual time series of each indicator and attribute listed in the tables, and test the simple Pearson correlation between unlagged time series of the indicators and attributes. We consider only years 6–50 of the simulation, omitting years 1–5 (2010–2014) to eliminate some transient behavior, particularly in the age structure. For the indices and attributes that are based on abundance, our annual values represent abundance on January 1. The exception to this is for species that seasonally migrate outside the model domain on January 1. In these cases, our annual estimates are based on abundance at the start of the last quarter when they were within the model domain. Future work can easily incorporate the lagged cross correlation (i.e., for leading and lagging indicators). Unlike Fulton et al. (2005) and Samhouri et al. (2009), we consider the correlation across all years of the 50-year simulations described below. These other authors considered only the indicator-attribute correlation of the end points of simulations; our goal is to consider annual monitoring and indicator strategies for the California Current, rather than indicators of a final state after some long-term management program.

Table A-1. Attributes for ecosystem health and groundfish goals.

| Goal | Attribute type | Key attribute | Source |
|---|---|---|---|
| Ecosystem health | Energetics | NPP to biomass | Samhouri et al. 2009, 2010 |
| | Ecosystem structure | Mean trophic level of biomass | Samhouri et al. 2009, 2010 |
| | Ecosystem structure | Shannon Index | Samhouri et al. 2009, 2010; CBNMS 2009, MBNMS 2007, Draft North Central Coast MPA Monitoring Plan |
| | Energetics | Net primary productivity | Samhouri et al. 2009 |
| | Ecosystem structure | Total biomass | Samhouri et al. 2009 |
| Groundfish | Population size | Number unassessed groups below 40% | Pacific Fishery Management Council target |
| | Population size | Number unassessed groups below 24% | Pacific Fishery Management Council threshold |
| | Population size | Target groups' biomass (summed) | Samhouri et al. 2009, 2010 |
| | Population size | Total catch | CBNMS 2009, OCNMS 2008, MBNMS 2007 |
| | Population size | Rockfish | CBNMS 2009, OCNMS 2008 |
| | Population condition | Mean proportion mature, groundfish | Pomeroy et al. 2004, from MLPA Master Plan |

Table A-2. Indicators for ecosystem health and groundfish goals.

| Goal | Indicator likely to reflect: | Indicator | Source |
|---|---|---|---|
| Ecosystem health | Ecosystem structure | Mean trophic level of catch | Fulton 2005, Kaplan and Levin 2009 |
| | Ecosystem structure | Phytoplankton | Samhouri et al. 2009, MBNMS 2007 |
| | Ecosystem structure | Total catch | Samhouri et al. 2009 |
| | Ecosystem structure | Unfished groups (surfperch, sculpins, etc.) | Samhouri et al. 2009, Draft North Central Coast MPA Monitoring Plan |
| | Ecosystem structure | Detritivores | Samhouri et al. 2009 |
| | Ecosystem structure | Flatfish | Samhouri et al. 2009 |
| | Ecosystem structure | Benthic invertebrates | Samhouri et al. 2009 |
| | Ecosystem structure | Herbivores | Samhouri et al. 2009 |
| | Ecosystem structure | Rockfish, flatfish | Samhouri et al. 2009 |
| | Ecosystem structure | Invertivores | Samhouri et al. 2009 |
| | Ecosystem structure | Habitat structure | Pomeroy et al. 2004, from MLPA Master Plan |
| | Ecosystem structure | Kelp | Draft North Central Coast MPA Monitoring Plan |
| | Ecosystem structure | Seastar, abalone, urchins | Draft North Central Coast MPA Monitoring Plan |
| | Ecosystem structure | Dungeness crab, seastars | Draft North Central Coast MPA Monitoring Plan |
| | Ecosystem structure | Dungeness, other crabs | Draft North Central Coast MPA Monitoring Plan |

Table A-2 continued. Indicators for ecosystem health and groundfish goals.

| Goal | Indicator likely to reflect: | Indicator | Source |
|---|---|---|---|
| Ecosystem health (cont.) | Ecosystem structure | Gelatinous zooplankton | Samhouri et al. 2009 |
| | Ecosystem structure | Forage fish, jellyfish | Samhouri et al. 2009 |
| | Ecosystem structure | Zooplanktivorous fish | Samhouri et al. 2009 |
| | Ecosystem structure | Zooplankton | Samhouri et al. 2009 |
| | Ecosystem structure | Zooplankton, phytoplankton | Samhouri et al. 2009 |
| | Ecosystem structure | Benthic fish, pelagic fish | Fulton 2005, Kaplan and Levin 2009 |
| | Ecosystem structure | Piscivorous fish, planktivorous fish | Fulton 2005, Kaplan and Levin 2009 |
| | Ecosystem structure | Piscivorous fish, scavengers | Fulton 2005, Kaplan and Levin 2009 |
| | Ecosystem structure | Piscivorous fish | Samhouri et al. 2009 |
| | Ecosystem structure | Invertivores, herbivores | Samhouri et al. 2009 |
| | Ecosystem structure | Marine mammals, birds | Samhouri et al. 2009 |
| | Ecosystem structure | Seabirds | Samhouri et al. 2009, MBNMS 2007, Draft North Central Coast MPA Monitoring Plan |
| | Ecosystem structure | Marine mammals | MBNMS 2007 |
| | Ecosystem structure | Finfish biomass, crustacean biomass | Selecting and Evaluating Indicators for the CCLME section |
| | Ecosystem structure | Cetacean biomass | Selecting and Evaluating Indicators for the CCLME section |
| | Ecosystem structure | Sablefish biomass | Selecting and Evaluating Indicators for the CCLME section |
| | Ecosystem structure | Lingcod size structure | Draft North Central Coast MPA Monitoring Plan |
| | Population condition | Mean weight at maturity, assessed spp. | Selecting and Evaluating Indicators for the CCLME section |
| | Ecosystem structure | Reeftop invertebrates | CBNMS 2009 |
| | Ecosystem structure | Biologically structured habitats | CBNMS 2009, OCNMS 2008, Draft North Central Coast MPA Monitoring Plan |
| | Ecosystem structure | Benthic invertebrates | Draft North Central Coast MPA Monitoring Plan |
| | Ecosystem structure | Piscivores | Draft North Central Coast MPA Monitoring Plan |
| | Ecosystem structure | Forage fish | MBNMS 2007 |
| | Ecosystem structure | Planktivores | Draft North Central Coast MPA Monitoring Plan |
| | Ecosystem structure | Krill | CBNMS 2009, MBNMS 2007 |
| | Ecosystem structure | Unfished groups (surfperch, sculpins, etc.) | Draft North Central Coast MPA Monitoring Plan |
| | Ecosystem structure | Salmon | OCNMS 2008, MBNMS 2007 |

Table A-2 continued. Indicators for ecosystem health and groundfish goals.

| Goal | Indicator likely to reflect: | Indicator | Source |
|---|---|---|---|
| Ecosystem health (cont.) | Ecosystem structure | Diving, migratory birds | CBNMS 2009, OCNMS 2008 |
| | Ecosystem structure | Baleen whales | CBNMS 2009, MBNMS 2007 |
| | Ecosystem structure | Pinnipeds | CBNMS 2009, OCNMS 2008 |
| | Ecosystem structure | Sea otters | OCNMS 2008, MBNMS 2007 |
| Groundfish | Population size | Number of assessed groups below 40% | Pacific Fishery Management Council target |
| | Population size | Number of assessed groups below 25% | Pacific Fishery Management Council threshold |
| | Population size | Bottomfish | Samhouri et al. 2009 |
| | Population size | Roundfish | Samhouri et al. 2009 |
| | Population size | Rockfish | Samhouri et al. 2009 |
| | Population size | Lingcod | Draft North Central Coast MPA Monitoring Plan |
| | Population size | Rockfish (shallow large, midwater, and shortbelly) | Draft North Central Coast MPA Monitoring Plan |
| | Population size | Halibut, small flatfish (nearshore) | Draft North Central Coast MPA Monitoring Plan |
| | Population size | Shallow large rockfish (blue) | Draft North Central Coast MPA Monitoring Plan |
| | Population size | Shallow small rockfish (black and yellow, gopher, kelp, brown) | Draft North Central Coast MPA Monitoring Plan |
| | Population size | Rockfish (shallow small, shallow large, canary, and midwater rockfish) | Draft North Central Coast MPA Monitoring Plan |
| | Population size | Lingcod and rockfish (yelloweye, midwater, large shallow) | Draft North Central Coast MPA Monitoring Plan |
| | Population condition | Shallow large rockfish size structure | Draft North Central Coast MPA Monitoring Plan |
| | Population condition | Midwater rockfish size structure | Draft North Central Coast MPA Monitoring Plan |
| | Population condition | Shortbelly rockfish size structure | Draft North Central Coast MPA Monitoring Plan |
| | Population condition | Recruitment success, groundfish | Pomeroy et al. 2004, from MLPA Master Plan |
| | Population condition | Recruitment success, assessed spp. | Pomeroy et al. 2004, from MLPA Master Plan |
| | Population condition | Mean weight at maturity, groundfish | Fulton et al. 2005 |

With the increasing number of MPAs and other forms of spatial management in the California Current, we might ask whether coast-wide monitoring is likely to detect impacts of spatial management of various scales. As described in the Methods: Scenarios subsection below, three types of scenarios involved manipulations of particular geographic zones in the model. For these sets of scenarios, we tested not only the correlation of coast-wide attributes and indicators, but also the correlation of attributes and indicators calculated only from data within the manipulated zones. Our a priori hypothesis was that attributes and indicators would only be tightly correlated when calculated from local-scale data, if the perturbation were itself local.

Following Fulton et al. (2005), we require that an indicator and attribute have strong significant correlations ($P < 0.05$, $|r| > 0.5$) in at least 85% of cases to report them as a recommended pairing from this analysis. Eighty-five percent of cases equates to 20 of 23 scenarios described below.

We considered and rejected one method for detrending the time series before performing the cross correlations. Specifically, we tested the implications of detrending all scenarios by subtracting the biomass (or catch) time series under the status quo scenario from the biomass (or catch) time series under each scenario. Since many of the scenarios inherit biomass trends and trajectories from status quo, the result of this detrending is to greatly reduce the number of significant correlations between attributes and indicators. We have rejected this method on the grounds that the indicator analysis needs to retain rather than remove similarity of biomass trajectories, since this is the basis for using some species as proxies or indicators for broader sets of groups and attributes.

## Methods: Scenarios

For this analysis of lower trophic level species, we tested the following scenarios:

- Status quo fishing
- Multipliers of total fishing mortality
- Multipliers of specific gears' fishing mortality
- Pulse fishing for all gears
- Spatial hotspots of additional fishing mortality (near ports)
- MPAs
- Nutrient additions

These scenarios capture two of the main drivers of ecosystem state considered in the IEA, specifically fishing and habitat disturbance. A third driver, climate change, can be incorporated in future modeling.

The scenarios are designed to force diverging ecosystem dynamics, such that we can evaluate the performance of ecosystem indicators across a range of possible drivers and pressures. Below we describe the specifications for the scenarios and give a brief characterization of model behavior under each scenario. Table A-3 details the ecosystem response to each alternate scenario, listing the final abundance of each functional group relative to final abundance in the status quo scenario. The model behavior influences the general time series trends of attributes and indicators, thus structuring their correlations. Though our analysis considers correlations through the entire course of the 50 years, Table A-4 presents a simplified view that details the 50-year change in biomass of each functional group relative to its initial biomass. This simplified representation of the time series dynamics of each simulation provides

Table A-3. Relative changes in biomass compared to the status quo scenario. Bold values indicate cases where biomass declined by more than 0.9 × the status quo scenario after 50 years. Italics indicate cases where biomass increased by more than 1.1 × the status quo scenario after 50 years.

| **Scenario** | **Large planktivores** | **Canary rockfish** | **Small planktivores** | **Large pisciv. flatfish** | **Shortbelly rockfish** | **Lingcod, cabezon** | **Salmon** | **Albacore tuna** | **Migratory birds** | **Pacific hake** | **Sablefish** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Fishing mortality 0.5 × status quo | 0.97 | *1.28* | 1.01 | *1.43* | **0.75** | 1.05 | *167.63* | *3.89* | 1.02 | *1.35* | *1.21* |
| Fishing mortality 1.5 × status quo | 1.02 | *1.23* | 0.97 | **0.48** | *1.40* | 0.96 | **0.01** | **0.58** | 1.00 | **0.77** | **0.80** |
| Fishing mortality 2.0 × status quo | 0.95 | *1.32* | 0.94 | **0.39** | *1.73* | **0.85** | **0.00** | **0.33** | 1.02 | **0.63** | **0.66** |
| Fishing mortality 5.0 × status quo | **0.86** | *1.34* | **0.71** | **0.12** | *4.42* | **0.36** | **0.00** | **0.12** | *1.11* | **0.27** | **0.25** |
| | | | | | | | | | | | |
| Trawl fisheries 2 × status quo | 1.02 | 1.04 | 1.02 | **0.37** | *1.82* | 0.91 | *1.15* | *1.17* | 1.05 | **0.61** | **0.71** |
| Pelagic fisheries 4 × status quo | 0.95 | 1.04 | **0.79** | *2.40* | **0.76** | **0.79** | **0.86** | 1.02 | *1.24* | **0.33** | **0.86** |
| Demersal fisheries 4 × status quo | 0.98 | 0.91 | 1.01 | **0.15** | *2.82* | **0.54** | *1.16* | 0.96 | 1.03 | 0.98 | **0.33** |
| Forage fish fisheries 10 × status quo | **0.46** | *2.24* | **0.39** | **0.08** | **0.55** | **0.59** | **0.16** | *2.53* | 1.00 | **0.69** | **0.80** |
| | | | | | | | | | | | |
| Pulse fishing 1.5 × status quo, yr 10–12 | 1.03 | **0.89** | 1.00 | *1.29* | 0.92 | 0.94 | **0.75** | 0.99 | 1.04 | 1.01 | 0.97 |
| Pulse fishing 4 × status quo, yr 10–12 | 1.06 | 1.09 | 1.00 | *1.82* | **0.76** | **0.86** | **0.26** | 0.99 | 1.05 | 1.02 | 0.92 |
| Pulse fishing 1.5 × status quo, yr 10–20 | 1.04 | 0.99 | 1.01 | 0.97 | 0.94 | 1.00 | **0.39** | 0.93 | 0.99 | 1.01 | 0.96 |
| Pulse fishing 4 × status quo, yr 10–20 | 1.06 | 1.10 | 1.02 | *1.53* | **0.63** | **0.86** | **0.00** | **0.90** | *1.13* | 1.03 | **0.87** |
| | | | | | | | | | | | |
| Spatial fishing 1.5 × fishing mortality near ports | 0.99 | 1.04 | 0.99 | **0.85** | 1.04 | 0.99 | **0.08** | **0.72** | 0.96 | 0.92 | 0.96 |
| Spatial fishing 2 × fishing mortality near ports | 0.99 | *1.11* | 0.98 | **0.68** | *1.16* | 0.98 | **0.01** | **0.57** | 0.94 | **0.85** | 0.91 |
| | | | | | | | | | | | |
| MPA 50% reduction in nearshore fishing | 1.00 | *1.23* | 1.02 | 1.01 | 0.96 | 0.94 | *109.09* | *2.83* | 1.04 | 1.07 | 1.00 |
| MPA 100% closure in CA NMS | 0.98 | 1.09 | 1.00 | *1.30* | **0.78** | 1.10 | *1.37* | 1.10 | 1.04 | *1.31* | *1.24* |
| MPA 100% closure in WA and selected NMS | 0.98 | 1.08 | 1.00 | *1.49* | **0.73** | 1.10 | *1.67* | *2.11* | 1.06 | *1.27* | 0.97 |
| | | | | | | | | | | | |
| Nutrient addition low | 0.99 | 0.93 | 1.01 | *1.32* | 0.95 | 0.94 | 0.91 | 1.00 | 1.05 | 1.01 | 0.95 |
| Nutrient addition medium | 0.99 | 0.93 | 1.01 | 1.07 | 1.01 | 0.99 | 0.97 | 1.00 | 1.01 | 1.01 | 0.97 |
| Nutrient addition high | 0.99 | 0.95 | 1.00 | 1.04 | 0.99 | 0.99 | 1.00 | 0.99 | 1.01 | 1.01 | 0.99 |
| Nutrient addition 5 × high | **0.86** | *1.34* | **0.71** | **0.12** | *4.42* | **0.36** | **0.00** | **0.12** | *1.11* | **0.27** | **0.25** |
| Nutrient addition 10 × high | **0.86** | *1.38* | **0.71** | **0.13** | *4.37* | **0.37** | **0.00** | **0.12** | *1.11* | **0.27** | **0.25** |

Table A-3 continued horizontally. Relative changes in biomass compared to the status quo scenario. Bold values indicate cases where biomass declined by more than 0.9 × the status quo scenario after 50 years. Italics indicate cases where biomass increased by more than 1.1 × the status quo scenario after 50 years.

| **Scenario** (column list repeated from previous page) | **Deep vertical migrators** | **Deep demersal fish** | **Shallow pisciv. fish (sculpin)** | **Midwater rockfish** | **Nearshore fish (surfperch)** | **Dover sole** | **Small shallow rockfish** | **Deep small rockfish** | **Deep large rockfish** | **Small flatfish** | **Small demersal sharks** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Fishing mortality 0.5 × status quo | 0.97 | *1.24* | 0.98 | 1.07 | *1.12* | *1.38* | **0.64** | 1.03 | **0.77** | 0.95 | *2.46* |
| Fishing mortality 1.5 × status quo | 1.02 | **0.81** | 1.03 | 0.94 | 0.94 | **0.80** | **0.86** | *1.25* | *1.83* | 1.09 | **0.37** |
| Fishing mortality 2.0 × status quo | 1.04 | **0.64** | 1.05 | **0.89** | 0.92 | **0.60** | **0.82** | *1.22* | *1.72* | *1.11* | **0.13** |
| Fishing mortality 5.0 × status quo | 1.08 | **0.14** | 0.96 | **0.69** | 0.99 | **0.16** | 0.98 | 1.04 | *1.34* | 1.03 | **0.00** |
| | | | | | | | | | | | |
| Trawl fisheries 2 × status quo | 1.03 | 0.91 | *1.11* | 0.91 | 1.00 | **0.60** | 1.07 | *1.16* | *1.64* | 1.09 | **0.16** |
| Pelagic fisheries 4 × status quo | 1.07 | 1.00 | *1.34* | **0.87** | **0.89** | 1.06 | **0.80** | 1.07 | *1.48* | 0.98 | **0.14** |
| Demersal fisheries 4 × status quo | 1.02 | **0.25** | *1.23* | 0.97 | 1.02 | **0.23** | **0.66** | **0.90** | **0.69** | 1.04 | **0.01** |
| Forage fish fisheries 10 × status quo | 0.95 | 1.01 | **0.21** | **0.78** | **0.01** | 0.91 | **0.22** | *1.14* | *1.58* | **0.70** | **0.17** |
| | | | | | | | | | | | |
| Pulse fishing 1.5 × status quo, yr 10–12 | 1.00 | 0.98 | 0.98 | 1.02 | 0.95 | 1.01 | 0.99 | 0.98 | 1.01 | 0.98 | 0.93 |
| Pulse fishing 4 × status quo, yr 10–12 | 1.00 | 0.94 | 0.96 | 1.01 | **0.87** | 1.01 | **0.75** | 0.99 | 0.93 | 0.99 | **0.72** |
| Pulse fishing 1.5 × status quo, yr 10–20 | 1.01 | 0.96 | 1.00 | 0.98 | 0.94 | 0.97 | **0.82** | 1.01 | 0.96 | 1.00 | **0.84** |
| Pulse fishing 4 × status quo, yr 10–20 | 0.99 | **0.80** | 1.01 | 0.96 | **0.80** | **0.88** | **0.84** | *1.22* | *1.66* | 1.00 | **0.33** |
| | | | | | | | | | | | |
| Spatial fishing 1.5 × fishing mortality near ports | 1.01 | 0.92 | 1.00 | 0.98 | 0.99 | 0.96 | **0.81** | 1.01 | 0.96 | 1.00 | **0.82** |
| Spatial fishing 2 × fishing mortality near ports | 1.02 | **0.85** | 0.99 | 0.96 | 0.97 | 0.92 | **0.77** | 1.06 | 0.97 | 1.00 | **0.66** |
| | | | | | | | | | | | |
| MPA 50% reduction in nearshore fishing | 1.00 | 1.00 | 1.08 | 1.00 | 1.01 | 1.00 | 0.97 | 0.99 | 0.97 | 1.00 | 1.00 |
| MPA 100% closure in CA NMS | 0.97 | *1.22* | 0.97 | 1.05 | 1.09 | *1.86* | 0.94 | 1.03 | 0.95 | 0.96 | *3.51* |
| MPA 100% closure in WA and selected NMS | 0.97 | *1.14* | 0.98 | 1.05 | 1.07 | *1.47* | 0.94 | 0.98 | 0.96 | 0.95 | *1.18* |
| | | | | | | | | | | | |
| Nutrient addition low | 1.01 | 1.00 | 1.00 | 1.03 | 0.99 | 1.02 | 1.00 | 0.98 | 1.02 | 0.98 | 0.96 |
| Nutrient addition medium | 1.01 | 1.00 | 1.01 | 1.00 | 1.00 | 1.00 | 0.99 | 0.99 | 1.00 | 0.99 | 1.00 |
| Nutrient addition high | 1.00 | 1.00 | 1.02 | 1.01 | 1.00 | 1.00 | 0.92 | 1.00 | 1.00 | 0.99 | 1.00 |
| Nutrient addition 5× high | 1.08 | **0.14** | 0.96 | **0.69** | 0.99 | **0.16** | 0.98 | 1.04 | *1.34* | 1.03 | **0.00** |
| Nutrient addition 10 × high | 1.09 | **0.14** | 0.98 | **0.68** | 0.99 | **0.16** | 0.95 | 1.04 | *1.34* | 1.03 | **0.00** |

Table A-3 continued horizontally. Relative changes in biomass compared to the status quo scenario. Bold values indicate cases where biomass declined by more than 0.9 × the status quo scenario after 50 years. Italics indicate cases where biomass increased by more than 1.1 × the status quo scenario after 50 years.

| **Scenario** (column list repeated from previous page) | **Large demersal sharks** | **Yelloweye and cowcod** | **Misc. pelagic sharks** | **Shallow large rockfish** | **Skates and rays** | **Surface seabirds** | **Diving seabirds** | **Pinnipeds** | **Transient orcas** | **Baleen whales** | **Small toothed whales** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Fishing mortality 0.5 × status quo | **0.28** | *1.81* | *5.33* | *1.96* | 0.99 | 1.00 | *1.51* | 1.03 | 1.00 | 1.00 | 0.97 |
| Fishing mortality 1.5 × status quo | *7.34* | **0.58** | **0.16** | **0.57** | 0.96 | 1.00 | **0.77** | 0.93 | 1.00 | 1.00 | **0.67** |
| Fishing mortality 2.0 × status quo | *35.09* | **0.41** | **0.03** | **0.36** | 0.94 | 1.01 | **0.74** | 0.91 | 1.00 | 1.00 | 1.05 |
| Fishing mortality 5.0 × status quo | *1,886.52* | **0.14** | **0.00** | **0.08** | **0.88** | 1.04 | **0.77** | **0.81** | 1.00 | 1.03 | **0.74** |
| | | | | | | | | | | | |
| Trawl fisheries 2 × status quo | *13.97* | **0.55** | **0.84** | 1.01 | 0.99 | 1.00 | 0.95 | 0.93 | 1.00 | 1.00 | **0.73** |
| Pelagic fisheries 4 × status quo | *243.28* | **0.91** | **0.00** | 1.01 | 0.99 | 1.03 | *2.00* | **0.87** | 1.00 | 1.02 | **0.81** |
| Demersal fisheries 4 × status quo | *2.06* | **0.29** | *1.16* | 1.01 | 0.97 | 1.00 | *1.20* | 0.90 | 1.00 | 1.00 | 0.91 |
| Forage fish fisheries 10 × status quo | **0.43** | **0.87** | **0.17** | **0.24** | **0.28** | 0.96 | **0.68** | **0.79** | 1.00 | 0.93 | **0.52** |
| | | | | | | | | | | | |
| Pulse fishing 1.5 × status quo, yr 10–12 | 1.10 | 0.96 | 1.07 | 1.00 | 0.98 | 1.00 | 0.97 | 0.97 | 1.00 | 1.00 | 1.05 |
| Pulse fishing 4 × status quo, yr 10–12 | *2.22* | 0.95 | **0.86** | 1.00 | 0.93 | 1.00 | 0.94 | **0.88** | 1.00 | 1.00 | 1.00 |
| Pulse fishing 1.5 × status quo, yr 10–20 | *2.42* | **0.95** | **0.72** | 0.98 | 1.00 | 1.00 | 0.98 | 0.99 | 1.00 | 1.00 | 1.04 |
| Pulse fishing 4 × status quo, yr 10–20 | *20.90* | **0.82** | **0.16** | 0.90 | 0.93 | 1.02 | **0.88** | **0.89** | 1.00 | 1.01 | **0.82** |
| | | | | | | | | | | | |
| Spatial fishing 1.5 × fishing mortality near ports | *2.62* | 0.91 | **0.42** | **0.80** | 1.00 | 1.00 | 0.91 | 0.99 | 1.00 | 1.00 | 0.99 |
| Spatial fishing 2 × fishing mortality near ports | *5.43* | **0.84** | **0.17** | **0.65** | 0.99 | 1.00 | **0.83** | 0.97 | 1.00 | 1.00 | 0.99 |
| | | | | | | | | | | | |
| MPA 50% reduction in nearshore fishing | **0.28** | 0.96 | 1.07 | *1.99* | 0.97 | 1.00 | *1.37* | 0.96 | 1.00 | 1.00 | 1.02 |
| MPA 100% closure in CA NMS | **0.30** | *2.43* | *2.49* | *1.40* | 0.98 | 1.00 | *1.23* | 1.05 | 1.00 | 1.00 | 1.02 |
| MPA 100% closure in WA and selected NMS | **0.29** | 1.07 | *1.62* | *1.53* | 0.99 | 1.00 | *1.29* | 0.99 | 1.00 | 1.00 | 1.04 |
| | | | | | | | | | | | |
| Nutrient addition low | 0.94 | 0.98 | *1.14* | 1.01 | 0.99 | 1.00 | 0.97 | 0.97 | 1.00 | 1.00 | 1.03 |
| Nutrient addition medium | 1.06 | 1.00 | 1.05 | 1.00 | 1.00 | 1.00 | 1.00 | 0.99 | 1.00 | 1.00 | 1.06 |
| Nutrient addition high | 1.01 | 0.99 | 1.04 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.03 |
| Nutrient addition 5 × high | *1,886.52* | **0.14** | **0.00** | **0.08** | **0.88** | 1.04 | **0.77** | **0.81** | 1.00 | 1.03 | **0.74** |
| Nutrient addition 10 × high | *1,881.22* | **0.14** | **0.00** | **0.08** | **0.88** | 1.04 | **0.77** | **0.82** | 1.00 | 1.03 | **0.73** |

Table A-3 continued horizontally. Relative changes in biomass compared to the status quo scenario. Bold values indicate cases where biomass declined by more than 0.9 × the status quo scenario after 50 years. Italics indicate cases where biomass increased by more than 1.1 × the status quo scenario after 50 years.

| **Scenario** (column list repeated from previous page) | **Toothed whales** | **Sea otters** | **Cepha-lopods** | **Shallow benthic filter feeders** | **Other benthic filter feeders** | **Deep benthic filter feeders** | **Benthic herb. grazers** | **Deep macrozoo-benthos** | **Megazoo-benthos** | **Shallow macrozoo-benthos** | **Shrimp** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Fishing mortality 0.5 × status quo | 1.00 | 1.00 | 1.00 | 0.98 | *1.25* | 1.06 | *4.30* | 1.00 | *53.82* | 1.03 | 1.01 |
| Fishing mortality 1.5 × status quo | 1.00 | 1.00 | 1.00 | 1.01 | **0.87** | 0.97 | **0.23** | 0.99 | **0.28** | 0.97 | 0.99 |
| Fishing mortality 2.0 × status quo | 0.99 | 1.00 | 0.97 | 1.01 | 0.84 | 0.97 | **0.05** | 0.97 | **0.21** | 0.99 | 0.99 |
| Fishing mortality 5.0 × status quo | 0.99 | 1.00 | 0.99 | 1.09 | **0.48** | 0.92 | **0.00** | 0.91 | **0.08** | 0.97 | 0.99 |
| | | | | | | | | | | | |
| Trawl fisheries 2 × status quo | 1.00 | 1.00 | 1.00 | 0.99 | 1.03 | 0.99 | 1.00 | 1.00 | 0.99 | 0.98 | 0.98 |
| Pelagic fisheries 4 × status quo | 0.94 | 1.00 | 1.01 | 1.06 | **0.70** | 0.92 | 1.01 | 1.00 | 0.94 | 0.96 | 0.99 |
| Demersal fisheries 4 × status quo | 1.01 | 1.00 | 1.01 | 1.01 | **0.85** | 1.00 | **0.00** | 0.92 | **0.10** | 0.99 | 1.00 |
| Forage fish fisheries 10 × status quo | **0.86** | 1.00 | **0.00** | **0.76** | *3.84* | **0.08** | 0.97 | **0.68** | **0.65** | **0.37** | **0.00** |
| | | | | | | | | | | | |
| Pulse fishing 1.5 × status quo, yr 10–12 | 1.00 | 1.00 | 1.00 | 1.01 | 0.95 | 0.98 | 0.94 | 1.00 | 0.90 | 0.98 | 1.00 |
| Pulse fishing 4 × status quo, yr 10–12 | 1.00 | 1.00 | 0.99 | 1.03 | **0.84** | 0.95 | **0.71** | 1.00 | **0.62** | 0.96 | 1.00 |
| Pulse fishing 1.5 × status quo, yr 10–20 | 1.00 | 1.00 | 1.00 | 1.01 | **0.90** | 0.96 | **0.75** | 1.01 | **0.66** | 0.96 | 1.00 |
| Pulse fishing 4 × status quo, yr 10–20 | 1.01 | 1.00 | 1.00 | 1.08 | **0.58** | **0.89** | **0.18** | 0.99 | **0.43** | 0.91 | 1.00 |
| | | | | | | | | | | | |
| Spatial fishing 1.5 × fishing mortality near ports | 1.00 | 1.00 | 1.01 | 1.00 | 0.93 | 0.98 | **0.63** | 1.00 | **0.39** | 0.98 | 1.00 |
| Spatial fishing 2 × fishing mortality near ports | 1.00 | 1.00 | 1.00 | 1.00 | **0.88** | 0.97 | **0.55** | 0.99 | **0.28** | 0.97 | 1.00 |
| | | | | | | | | | | | |
| MPA 50% reduction in nearshore fishing | 1.00 | 1.00 | 1.00 | 1.00 | 1.01 | 1.00 | 1.00 | 1.00 | *1.26* | 1.00 | 1.00 |
| MPA 100% closure in CA NMS | 1.00 | 1.00 | 1.00 | 0.99 | *1.18* | 1.05 | *3.17* | 0.99 | *2.25* | 1.03 | 1.01 |
| MPA 100% closure in WA and selected NMS | 1.00 | 1.00 | 0.99 | 0.99 | *1.17* | 1.05 | *4.71* | 0.99 | *3.05* | 1.03 | 1.01 |
| | | | | | | | | | | | |
| Nutrient addition low | 1.00 | 1.00 | 1.00 | 1.01 | 1.01 | 1.00 | 1.00 | 1.00 | 1.00 | 0.98 | 1.00 |
| Nutrient addition medium | 1.00 | 1.00 | 0.98 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| Nutrient addition high | 1.00 | 1.00 | 0.99 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.99 | 1.00 |
| Nutrient addition 5 × high | 0.99 | 1.00 | 0.99 | 1.09 | 0.48 | 0.92 | **0.00** | 0.91 | **0.08** | 0.97 | 0.99 |
| Nutrient addition 10 × high | 0.99 | 1.00 | 0.99 | 1.09 | 0.48 | 0.92 | **0.00** | 0.91 | **0.08** | 0.97 | 0.98 |

Table A-3 continued horizontally. Relative changes in biomass compared to the status quo scenario. Bold values indicate cases where biomass declined by more than 0.9 × the status quo scenario after 50 years. Italics indicate cases where biomass increased by more than 1.1 × the status quo scenario after 50 years.

| **Scenario** (column list repeated from previous page) | **Large zoo-plankton** | **Deposit feeders** | **Macro-algae** | **Sea-grass** | **Carni-vorous infauna** | **Gelat-inous zoo-plankton** | **Large phyto-plankton** | **Small phyto-plankton** | **Mesozoo-plankton** | **Microzoo-plankton** | **Pelagic bacteria** | **Benthic bacteria** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fishing mortality 0.5 × status quo | 0.96 | 0.97 | 0.96 | 1.00 | 0.99 | *1.18* | 0.94 | 1.01 | *1.15* | **0.86** | 1.04 | 0.99 |
| Fishing mortality 1.5 × status quo | 0.94 | 0.99 | 1.04 | 1.00 | 1.00 | 1.01 | **0.84** | *1.13* | 0.96 | 0.90 | 0.97 | 1.01 |
| Fishing mortality 2.0 × status quo | 0.94 | 1.00 | 1.08 | 1.00 | 1.00 | 1.09 | 1.02 | *1.14* | *1.25* | 0.91 | 0.91 | 1.03 |
| Fishing mortality 5.0 × status quo | 1.00 | **0.85** | *1.34* | 1.00 | 1.07 | 1.03 | 1.04 | 1.00 | 1.05 | 0.93 | 1.00 | 1.08 |
| Trawl fisheries 2 × status quo | 0.94 | 0.97 | 1.00 | 1.00 | 1.00 | 1.09 | **0.89** | 0.98 | *1.29* | **0.80** | 1.04 | 1.03 |
| Pelagic fisheries 4 × status quo | 0.98 | 0.91 | 1.00 | 1.00 | 1.04 | 1.03 | 0.92 | 1.05 | 1.09 | *1.19* | **0.73** | 1.02 |
| Demersal fisheries 4 × status quo | 0.99 | 0.98 | *1.25* | 1.00 | 1.00 | 1.02 | 0.99 | 0.97 | 1.04 | 0.97 | 1.02 | 1.02 |
| Forage fish fisheries 10 × status quo | **0.88** | **0.57** | 1.00 | 1.00 | **0.50** | 1.08 | 1.01 | 0.97 | *1.32* | 1.08 | **0.87** | **0.75** |
| Pulse fishing 1.5 × status quo, yr 10–12 | 0.97 | 1.01 | 1.00 | 1.00 | 1.00 | *1.24* | 1.00 | 0.97 | *1.34* | **0.87** | 0.98 | 1.00 |
| Pulse fishing 4 × status quo, yr 10–12 | 0.96 | 1.02 | 1.00 | 1.00 | 1.01 | *1.15* | 0.98 | *1.16* | *1.13* | 1.09 | 1.08 | 1.00 |
| Pulse fishing 1.5 × status quo, yr 10–20 | 0.99 | 0.99 | 1.00 | 1.00 | 1.01 | *1.14* | 0.92 | 0.94 | *1.13* | **0.78** | 1.06 | 1.03 |
| Pulse fishing 4 × status quo, yr 10–20 | 0.94 | 0.96 | 1.00 | 1.00 | 1.04 | 1.01 | 0.98 | *1.21* | *1.72* | **0.87** | 1.00 | 1.02 |
| Spatial fishing 1.5 × fishing mortality near ports | 0.95 | 0.98 | 1.04 | 1.00 | 1.01 | 1.10 | 0.94 | *1.13* | 1.09 | **0.80** | 1.01 | 1.03 |
| Spatial fishing 2 × fishing mortality near ports | 0.95 | 0.99 | 1.08 | 1.00 | 1.01 | *1.26* | 0.94 | *1.21* | *1.37* | 0.97 | 0.92 | 1.01 |
| MPA 50% reduction in nearshore fishing | 0.98 | 0.99 | 1.00 | 1.00 | 1.00 | 1.07 | 1.00 | 0.98 | *1.39* | 1.00 | 0.99 | 1.00 |
| MPA 100% closure in CA NMS | 0.96 | 0.98 | 1.00 | 1.00 | 0.99 | 1.04 | 1.01 | 1.00 | 1.03 | 0.92 | 0.94 | 0.99 |
| MPA 100% closure in WA and selected NMS | 0.93 | 1.00 | 1.00 | 1.00 | 0.99 | *1.11* | 1.10 | 1.07 | *1.35* | 0.95 | **0.86** | 0.99 |
| Nutrient addition low | 0.97 | 1.00 | 1.00 | 095 | 0.99 | *1.29* | 1.06 | 0.98 | *1.58* | **0.86** | 0.94 | 1.01 |
| Nutrient addition medium | 0.92 | 1.01 | 1.00 | 0.95 | 1.00 | 1.05 | **0.84** | 1.05 | *1.47* | **0.85** | 0.98 | 1.01 |
| Nutrient addition high | 0.98 | 0.99 | 1.00 | 0.95 | 1.00 | 1.05 | **0.36** | 1.06 | *1.43* | *1.66* | 1.06 | 1.01 |
| Nutrient addition 5 × high | 1.00 | **0.85** | *1.34* | 1.00 | 1.07 | 1.03 | 1.04 | 1.00 | 1.05 | 0.93 | 1.00 | 1.08 |
| Nutrient addition 10 × high | 0.95 | **0.85** | *1.34* | 0.95 | 1.07 | 1.05 | 1.05 | 1.06 | *1.22* | 0.92 | 0.90 | 1.08 |

Table A-4. Changes in biomass compared to initial conditions. Bold values indicate cases where biomass declined by more than 0.9 × over 50 years. Italics indicates cases where biomass increased by more than 1.1 × over 50 years.

| Scenario | Large planktivores | Canary rockfish | Small planktivores | Large pisciv. flatfish | Shortbelly rockfish | Lingcod, cabezon | Salmon | Albacore tuna | Migratory birds | Pacific hake | Sablefish |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Status quo | 7.73 | 0.47 | 0.11 | 0.41 | 0.20 | 3.18 | 0.00 | 0.04 | 4.01 | 0.91 | 1.60 |
| Fishing mortality 0.5 × status quo | *7.50* | **0.60** | **0.11** | **0.59** | **0.15** | *3.35* | **0.22** | **0.17** | *4.09* | *1.23* | *1.93* |
| Fishing mortality 1.5 × status quo | *7.87* | **0.57** | **0.11** | **0.20** | **0.28** | *3.05* | **0.00** | **0.03** | *4.00* | **0.71** | *1.29* |
| Fishing mortality 2.0 × status quo | *7.34* | **0.61** | **0.10** | **0.16** | **0.34** | *2.69* | **0.00** | **0.01** | *4.07* | **0.57** | 1.06 |
| Fishing mortality 5.0 × status quo | *6.66* | **0.63** | **0.08** | **0.05** | **0.87** | *1.16* | **0.00** | **0.01** | *4.46* | **0.25** | **0.40** |
| Trawl fisheries 2 × status quo | *7.90* | **0.49** | **0.11** | **0.15** | **0.36** | *2.88* | **0.00** | **0.05** | *4.22* | **0.56** | *1.14* |
| Pelagic fisheries 4 × status quo | *7.31* | **0.48** | **0.09** | 0.99 | **0.15** | *2.51* | **0.00** | **0.05** | *4.96* | **0.30** | *1.37* |
| Demersal fisheries 4 × status quo | *7.58* | **0.42** | **0.11** | **0.06** | **0.56** | *1.71* | **0.00** | **0.04** | *4.13* | **0.90** | **0.52** |
| Forage fish fisheries 10 × status quo | *3.59* | 1.04 | **0.04** | **0.03** | **0.11** | *1.88* | **0.00** | **0.11** | *4.01* | **0.63** | *1.28* |
| Pulse fishing 1.5 × status quo, yr 10–12 | *7.95* | **0.41** | **0.11** | **0.53** | **0.18** | *3.00* | **0.00** | **0.04** | *4.18* | 0.93 | *1.55* |
| Pulse fishing 4 × status quo, yr 10–12 | *8.23* | **0.51** | **0.11** | **0.75** | **0.15** | *2.75* | **0.00** | **0.04** | *4.20* | 0.93 | *1.47* |
| Pulse fishing 1.5 × status quo, yr 10–20 | *8.03* | **0.46** | **0.11** | **0.40** | **0.19** | *3.18* | **0.00** | **0.04** | *3.96* | 0.92 | *1.54* |
| Pulse fishing 4 × status quo, yr 10–20 | *8.19* | **0.51** | **0.11** | **0.63** | **0.12** | *2.75* | **0.00** | **0.04** | *4.51* | 0.94 | *1.39* |
| Spatial fishing 1.5 × fishing mortality near ports | *7.67* | **0.48** | **0.11** | **0.35** | **0.21** | *3.16* | **0.00** | **0.03** | *3.85* | **0.84** | *1.53* |
| Spatial fishing 2 × fishing mortality near ports | *7.65* | **0.52** | **0.11** | **0.28** | **0.23** | *3.13* | **0.00** | **0.02** | *3.75* | **0.78** | *1.45* |
| MPA 50% reduction in nearshore fishing | *7.75* | **0.57** | **0.11** | **0.42** | **0.19** | *3.01* | **0.14** | **0.12** | *4.18* | 0.98 | *1.60* |
| MPA 100% closure in CA NMS | *7.55* | **0.51** | **0.11** | **0.54** | **0.16** | *3.50* | **0.00** | **0.05** | *4.16* | *1.20* | *1.98* |
| MPA 100% closure in WA and selected NMS | *7.56* | **0.50** | **0.11** | **0.62** | **0.15** | *3.49* | **0.00** | **0.09** | *4.26* | *1.16* | *1.55* |
| Nutrient addition low | *7.66* | **0.43** | **0.11** | **0.54** | **0.19** | *3.00* | **0.00** | **0.04** | *4.21* | 0.93 | *1.52* |
| Nutrient addition medium | *7.68* | **0.43** | **0.11** | **0.44** | **0.20** | *3.15* | **0.00** | **0.04** | *4.05* | 0.92 | *1.55* |
| Nutrient addition high | *7.66* | **0.44** | **0.11** | **0.43** | **0.20** | *3.15* | **0.00** | **0.04** | *4.04* | 0.92 | *1.59* |
| Nutrient addition 5 × high | *6.66* | **0.63** | **0.08** | **0.05** | **0.87** | *1.16* | **0.00** | **0.01** | *4.46* | **0.25** | **0.40** |
| Nutrient addition 10 × high | *6.66* | **0.64** | **0.08** | **0.05** | **0.86** | *1.18* | **0.00** | **0.01** | *4.46* | **0.25** | **0.40** |

Table A-4 continued horizontally. Changes in biomass compared to initial conditions. Bold values indicate cases where biomass declined by more than 0.9 × over 50 years. Italics indicates cases where biomass increased by more than 1.1 × over 50 years.

| **Scenario** (column list repeated from previous page) | **Deep vertical migrators** | **Deep demersal fish** | **Shallow pisciv. fish (sculpin)** | **Midwater rockfish** | **Nearshore fish (surfperch)** | **Dover sole** | **Small shallow rockfish** | **Deep small rockfish** | **Deep large rockfish** | **Small flatfish** | **Small demersal sharks** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Status quo | 3.12 | 0.51 | 0.19 | 2.02 | 2.13 | 1.35 | 2.40 | 1.04 | 0.59 | 0.47 | 0.11 |
| Fishing mortality 0.5 × status quo | *3.01* | **0.64** | **0.18** | *2.16* | *2.39* | *1.86* | *1.54* | 1.07 | **0.45** | **0.45** | **0.28** |
| Fishing mortality 1.5 × status quo | *3.17* | **0.42** | **0.19** | *1.90* | *2.00* | 1.07 | *2.06* | *1.30* | 1.07 | **0.52** | **0.04** |
| Fishing mortality 2.0 × status quo | *3.25* | **0.33** | **0.20** | *1.80* | *1.96* | **0.81** | *1.97* | *1.27* | 1.00 | **0.52** | **0.02** |
| Fishing mortality 5.0 × status quo | *3.37* | **0.07** | **0.18** | *1.39* | *2.10* | **0.22** | *2.36* | 1.08 | **0.78** | **0.49** | **0.00** |
| Trawl fisheries 2 × status quo | *3.23* | **0.47** | **0.21** | *1.85* | *2.13* | **0.81** | *2.58* | *1.21* | 0.96 | **0.51** | **0.02** |
| Pelagic fisheries 4 × status quo | *3.35* | **0.52** | **0.25** | *1.76* | *1.90* | *1.43* | *1.93* | *1.11* | **0.87** | **0.46** | **0.02** |
| Demersal fisheries 4 × status quo | *3.17* | **0.13** | **0.23** | *1.96* | *2.17* | **0.32** | *1.57* | 0.93 | **0.41** | **0.49** | **0.00** |
| Forage fish fisheries 10 × status quo | *2.97* | **0.52** | **0.04** | *1.57* | **0.03** | *1.23* | **0.53** | *1.19* | 0.92 | **0.33** | **0.02** |
| Pulse fishing 1.5 × status quo, yr 10–12 | *3.13* | **0.50** | **0.18** | *2.06* | *2.03* | *1.37* | *2.37* | 1.01 | **0.59** | **0.46** | **0.10** |
| Pulse fishing 4 × status quo, yr 10–12 | *3.12* | **0.48** | **0.18** | *2.05* | *1.86* | *1.36* | *1.81* | 1.03 | **0.54** | **0.47** | **0.08** |
| Pulse fishing 1.5 × status quo, yr 10–20 | *3.16* | **0.49** | **0.19** | *1.99* | *2.01* | *1.31* | *1.97* | 1.05 | **0.56** | **0.47** | **0.09** |
| Pulse fishing 4 × status quo, yr 10–20 | *3.10* | **0.41** | **0.19** | *1.95* | *1.71* | *1.18* | *2.01* | *1.27* | 0.97 | **0.47** | **0.04** |
| Spatial fishing 1.5 × fishing mortality near ports | *31.4* | **0.47** | **0.19** | *1.97* | *2.11* | *1.29* | *1.93* | 1.05 | **0.56** | **0.47** | **0.09** |
| Spatial fishing 2 × fishing mortality near ports | *3.17* | **0.44** | **0.18** | *1.93* | *2.06* | *1.24* | *1.84* | *1.10* | **0.57** | **0.47** | **0.07** |
| MPA 50% reduction in nearshore fishing | *3.13* | **0.52** | **0.20** | *2.03* | *2.15* | *1.35* | *2.34* | 1.03 | **0.57** | **0.47** | **0.11** |
| MPA 100% closure in CA NMS | *3.04* | **0.63** | **0.18** | *2.12* | *2.32* | *2.50* | *2.25* | 1.07 | **0.56** | **0.45** | **0.39** |
| MPA 100% closure in WA and selected NMS | *3.03* | **0.59** | **0.18** | *2.12* | *2.29* | *1.98* | *2.26* | 1.02 | **0.56** | **0.45** | **0.13** |
| Nutrient addition low | *3.14* | **0.51** | **0.19** | *2.08* | *2.11* | *1.37* | *2.39* | 1.02 | **0.59** | **0.46** | **0.11** |
| Nutrient addition medium | *3.14* | **0.52** | **0.19** | *2.03* | *2.13* | *1.35* | *2.37* | 1.03 | **0.58** | **0.47** | **0.11** |
| Nutrient addition high | *3.13* | **0.51** | **0.19** | *2.03* | *2.14* | *1.35* | *2.22* | 1.04 | **0.58** | **0.47** | **0.11** |
| Nutrient addition 5 × high | *3.37* | **0.07** | **0.18** | *1.39* | *2.10* | **0.22** | *2.36* | 1.08 | **0.78** | **0.49** | **0.00** |
| Nutrient addition 10 × high | *3.39* | **0.07** | **0.18** | *1.37* | *2.10* | **0.22** | *2.28* | 1.08 | **0.78** | **0.48** | **0.00** |

Table A-4 continued horizontally. Changes in biomass compared to initial conditions. Bold values indicate cases where biomass declined by more than 0.9 × over 50 years. Italics indicates cases where biomass increased by more than 1.1 × over 50 years.

| **Scenario** (column list repeated from previous page) | **Large demersal sharks** | **Yelloweye and cowcod** | **Misc. pelagic sharks** | **Shallow large rockfish** | **Skates and rays** | **Surface seabirds** | **Diving seabirds** | **Pinnipeds** | **Transient orcas** | **Baleen whales** | **Small toothed whales** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Status quo | 0.00 | 0.90 | 0.02 | 0.34 | 4.81 | 1.54 | 1.28 | 6.77 | 0.89 | 2.30 | 2.67 |
| Fishing mortality 0.5 x status quo | **0.00** | 1.63 | **0.13** | **0.67** | *4.74* | *1.54* | *1.93* | *6.95* | **0.89** | *2.30* | *2.57* |
| Fishing mortality 1.5 x status quo | **0.00** | **0.52** | **0.00** | **0.19** | *4.64* | *1.55* | 0.98 | *6.26* | **0.89** | *2.30* | *1.79* |
| Fishing mortality 2.0 x status quo | **0.01** | **0.37** | **0.00** | **0.12** | *4.50* | *1.56* | 0.94 | *6.18* | **0.89** | *2.31* | *2.80* |
| Fishing mortality 5.0 x status quo | **0.55** | **0.13** | **0.00** | **0.03** | *4.23* | *1.60* | 0.98 | *5.50* | **0.89** | *2.37* | *1.97* |
| Trawl fisheries 2 × status quo | **0.00** | **0.50** | **0.02** | **0.34** | *4.76* | *1.55* | *1.21* | *6.33* | **0.89** | *2.30* | *1.95* |
| Pelagic fisheries 4 × status quo | **0.07** | **0.82** | **0.00** | **0.34** | *4.78* | *1.59* | *2.55* | *5.92* | **0.89** | *2.35* | *2.17* |
| Demersal fisheries 4 × status quo | **0.00** | **0.26** | **0.03** | **0.34** | *4.65* | *1.54* | *1.53* | *6.11* | **0.89** | *2.30* | *2.43* |
| Forage fish fisheries 10 × status quo | **0.00** | **0.78** | **0.00** | **0.08** | *1.33* | *1.49* | **0.87** | *5.36* | **0.89** | *2.14* | *1.39* |
| Pulse fishing 1.5 × status quo, yr 10–12 | **0.00** | **0.87** | **0.03** | **0.34** | *4.74* | *1.55* | *1.24* | *6.56* | **0.89** | *2.30* | *2.81* |
| Pulse fishing 4 × status quo, yr 10–12 | **0.00** | **0.86** | **0.02** | **0.34** | *4.48* | *1.55* | *1.20* | *5.94* | **0.89** | *2.31* | *2.67* |
| Pulse fishing 1.5 × status quo, yr 10–20 | **0.00** | **0.85** | **0.02** | **0.33** | *4.82* | *1.55* | *1.25* | *6.71* | **0.89** | *2.31* | *2.77* |
| Pulse fishing 4 × status quo, yr 10–20 | **0.01** | **0.73** | **0.00** | **0.31** | *4.48* | *1.58* | *1.12* | *6.05* | **0.89** | *2.33* | *2.20* |
| Spatial fishing 1.5 × fishing mortality near ports | **0.00** | **0.82** | **0.01** | **0.27** | *4.80* | *1.55* | *1.16* | *6.72* | **0.89** | *2.30* | *2.65* |
| Spatial fishing 2 × fishing mortality near ports | **0.00** | **0.75** | **0.00** | **0.22** | *4.78* | *1.55* | *1.06* | *6.56* | **0.89** | *2.31* | *2.64* |
| MPA 50% reduction in nearshore fishing | **0.00** | **0.87** | **0.03** | **0.68** | *4.66* | *1.55* | *1.75* | *6.51* | **0.89** | *2.30* | *2.72* |
| MPA 100% closure in CA NMS | **0.00** | *2.19* | **0.06** | **0.48** | *4.72* | *1.54* | *1.57* | *7.08* | **0.89** | *2.30* | *2.72* |
| MPA 100% closure in WA and selected NMS | **0.00** | 0.96 | **0.04** | **0.52** | *4.74* | *1.54* | *1.64* | *6.69* | **0.89** | *2.30* | *2.77* |
| Nutrient addition low | **0.00** | **0.88** | **0.03** | **0.34** | *4.74* | *1.55* | *1.23* | *6.55* | **0.89** | *2.30* | *2.74* |
| Nutrient addition medium | **0.00** | **0.90** | **0.02** | **0.34** | *4.79* | *1.55* | *1.28* | *6.73* | **0.89** | *2.30* | *2.82* |
| Nutrient addition high | **0.00** | **0.89** | **0.02** | **0.34** | *4.80* | *1.55* | *1.27* | *6.75* | **0.89** | *2.30* | *2.74* |
| Nutrient addition 5 × high | **0.55** | **0.13** | **0.00** | **0.03** | *4.23* | *1.60* | 0.98 | *5.50* | **0.89** | *2.37* | *1.97* |
| Nutrient addition 10 × high | **0.55** | **0.13** | **0.00** | **0.03** | *4.24* | *1.61* | 0.98 | *5.52* | **0.89** | *2.37* | *1.95* |

Table A-4 continued horizontally. Changes in biomass compared to initial conditions. Bold values indicate cases where biomass declined by more than 0.9 × over 50 years. Italics indicates cases where biomass increased by more than 1.1 × over 50 years.

| **Scenario** (column list repeated from previous page) | **Toothed whales** | **Sea otters** | **Cepha-lopods** | **Shallow benthic filter feeders** | **Other benthic filter feeders** | **Deep benthic filter feeders** | **Benthic herb. grazers** | **Deep macrozoo-benthos** | **Megazoo-benthos** | **Shallow macrozoo-benthos** | **Shrimp** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Status quo | 1.25 | 7.89 | 104.34 | 3.38 | 0.00 | 1.09 | 0.00 | 0.62 | 0.00 | 5.94 | 363.87 |
| Fishing mortality 0.5 × status quo | *1.25* | *7.89* | *103.89* | *3.32* | **0.00** | *1.16* | **0.00** | **0.62** | **0.05** | *6.14* | *365.81* |
| Fishing mortality 1.5 × status quo | *1.25* | *7.89* | *104.65* | *3.42* | **0.00** | 1.05 | **0.00** | **0.61** | **0.00** | *5.79* | *361.30* |
| Fishing mortality 2.0 × status quo | *1.24* | *7.89* | *100.84* | *3.43* | **0.00** | 1.06 | **0.00** | **0.60** | **0.00** | *5.90* | *358.98* |
| Fishing mortality 5.0 × status quo | *1.23* | *7.89* | *103.67* | *3.68* | **0.00** | 1.00 | **0.00** | **0.56** | **0.00** | *5.78* | *358.45* |
| Trawl fisheries 2 × status quo | *1.24* | *7.89* | *104.43* | *3.36* | **0.00** | 1.08 | **0.00** | **0.62** | **0.00** | *5.83* | *358.35* |
| Pelagic fisheries 4 × status quo | *1.17* | *7.89* | *104.89* | *3.57* | **0.00** | 1.00 | **0.00** | **0.62** | **0.00** | *5.72* | *359.84* |
| Demersal fisheries 4 × status quo | *1.26* | *7.89* | *105.52* | *3.41* | **0.00** | 1.09 | **0.00** | **0.57** | **0.00** | *5.89* | *362.20* |
| Forage fish fisheries 10 × status quo | *1.08* | *7.90* | **0.00** | *2.57* | **0.00** | **0.09** | **0.00** | **0.42** | **0.00** | *2.22* | **0.06** |
| Pulse fishing 1.5 × status quo, yr 10–12 | *1.25* | *7.89* | *104.04* | *3.42* | **0.00** | 1.07 | **0.00** | **0.62** | **0.00** | *5.83* | *363.43* |
| Pulse fishing 4 × status quo, yr 10–12 | *1.25* | *7.89* | *103.63* | *3.49* | **0.00** | 1.04 | **0.00** | **0.62** | **0.00** | *5.72* | *363.68* |
| Pulse fishing 1.5 × status quo, yr 10–20 | *1.25* | *7.89* | *104.05* | *3.42* | **0.00** | 1.05 | **0.00** | **0.62** | **0.00** | *5.68* | *363.04* |
| Pulse fishing 4 × status quo, yr 10–20 | *1.25* | *7.89* | *104.29* | *3.65* | **0.00** | 0.97 | **0.00** | **0.61** | **0.00** | *5.40* | *363.63* |
| Spatial fishing 1.5 × fishing mortality near ports | *1.25* | *7.89* | *105.09* | *3.39* | **0.00** | 1.06 | **0.00** | **0.61** | **0.00** | *5.82* | *363.78* |
| Spatial fishing 2 × fishing mortality near ports | *1.25* | *7.89* | *104.67* | *3.40* | **0.00** | 1.06 | **0.00** | **0.61** | **0.00** | *5.78* | *363.45* |
| MPA 50% reduction in nearshore fishing | *1.25* | *7.89* | *104.05* | *3.37* | **0.00** | 1.09 | **0.00** | **0.62** | **0.00** | *5.93* | *363.29* |
| MPA 100% closure in CA NMS | *1.25* | *7.89* | *104.00* | *3.34* | **0.00** | *1.15* | **0.00** | **0.61** | **0.00** | *6.10* | *365.83* |
| MPA 100% closure in WA and selected NMS | *1.25* | *7.89* | *103.46* | *3.33* | **0.00** | *1.14* | **0.00** | **0.61** | **0.00** | *6.11* | *365.93* |
| Nutrient addition low | *1.25* | *7.89* | *104.42* | *3.41* | **0.00** | 1.09 | **0.00** | **0.62** | **0.00** | *5.85* | *363.94* |
| Nutrient addition medium | *1.25* | *7.89* | *102.47* | *3.38* | **0.00** | 1.09 | **0.00** | **0.62** | **0.00** | *5.92* | *363.94* |
| Nutrient addition high | *1.25* | *7.89* | *103.66* | *3.38* | **0.00** | 1.09 | **0.00** | **0.61** | **0.00** | *5.90* | *364.21* |
| Nutrient addition 5 × high | *1.23* | *7.89* | *103.67* | *3.68* | **0.00** | 1.00 | **0.00** | **0.56** | **0.00** | *5.78* | *358.45* |
| Nutrient addition 10 × high | *1.23* | *7.89* | *103.30* | *3.68* | **0.00** | 1.00 | **0.00** | **0.56** | **0.00** | *5.78* | *358.19* |

Table A-4 continued horizontally. Changes in biomass compared to initial conditions. Bold values indicate cases where biomass declined by more than 0.9 × over 50 years. Italics indicates cases where biomass increased by more than 1.1 × over 50 years.

| **Scenario** (column list repeated from previous page) | **Large zoo-plankton** | **Deposit feeders** | **Macro-algae** | **Sea-grass** | **Carni-vorous infauna** | **Gelat-inous zoo-plankton** | **Large phyto-plankton** | **Small phyto-plankton** | **Mesozoo-plankton** | **Microzoo-plankton** | **Pelagic bacteria** | **Benthic bacteria** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Status quo | 2.98 | 3.01 | 0.00 | 0.99 | 1.06 | 1.21 | 0.18 | 101.55 | 0.74 | 3.07 | 5.90 | 3.04 |
| Fishing mortality 0.5 × status quo | *2.87* | *2.93* | **0.00** | 0.99 | 1.05 | *1.43* | **0.17** | *102.86* | **0.85** | *2.65* | *6.13* | *3.02* |
| Fishing mortality 1.5 × status quo | *2.79* | *2.98* | **0.00** | 0.99 | 1.06 | *1.22* | **0.15** | *114.72* | **0.70** | *2.78* | *5.70* | *3.07* |
| Fishing mortality 2.0 × status quo | *2.81* | *3.03* | **0.00** | 0.99 | 1.06 | *1.32* | **0.18** | *116.19* | 0.92 | *2.79* | *5.36* | *3.13* |
| Fishing mortality 5.0 × status quo | *2.99* | *2.55* | **0.00** | 0.99 | *1.13* | *1.26* | **0.18** | *101.15* | **0.77** | *2.85* | *5.90* | *3.27* |
| Trawl fisheries 2 × status quo | *2.81* | *2.92* | **0.00** | 0.99 | 1.05 | *1.33* | **0.16** | *99.28* | 0.95 | *2.47* | *6.12* | *3.13* |
| Pelagic fisheries 4 × status quo | *2.91* | *2.74* | **0.00** | 0.99 | 1.10 | *1.25* | **0.16** | *107.07* | **0.80** | *3.66* | *4.30* | *3.10* |
| Demersal fisheries 4 × status quo | *2.96* | *2.95* | **0.00** | 0.99 | 1.06 | *1.23* | **0.18** | *98.89* | **0.76** | *2.97* | *6.00* | *3.10* |
| Forage fish fisheries 10 × status quo | *2.61* | *1.72* | **0.00** | 0.99 | **0.53** | *1.31* | **0.18** | *98.90* | 0.97 | *3.33* | *5.13* | *2.27* |
| Pulse fishing 1.5 × status quo, yr 10–12 | *2.89* | *3.03* | **0.00** | 0.99 | 1.06 | *1.51* | **0.18** | *98.66* | 0.98 | *2.68* | *5.77* | *3.03* |
| Pulse fishing 4 × status quo, yr 10–12 | *2.85* | *3.07* | **0.00** | 0.99 | 1.07 | *1.40* | **0.17** | *117.99* | **0.83** | *3.35* | *6.40* | *3.03* |
| Pulse fishing 1.5 × status quo, yr 10–20 | *2.94* | *2.99* | **0.00** | 0.99 | 1.06 | *1.38* | **0.16** | *95.90* | **0.83** | *2.40* | *6.28* | *3.13* |
| Pulse fishing 4 × status quo, yr 10–20 | *2.81* | *2.90* | **0.00** | 0.99 | 1.10 | *1.23* | **0.17** | *123.27* | *1.27* | *2.68* | *5.91* | *3.11* |
| Spatial fishing 1.5 × fishing mortality near ports | *2.83* | *2.96* | **0.00** | 0.99 | 1.06 | *1.33* | **0.17** | *114.51* | **0.80** | *2.46* | *5.96* | *3.14* |
| Spatial fishing 2 × fishing mortality near ports | *2.81* | *2.98* | **0.00** | 0.99 | 1.06 | *1.53* | **0.17** | *122.76* | 1.01 | *2.97* | *5.41* | *3.06* |
| MPA 50% reduction in nearshore fishing | *2.92* | *2.99* | **0.00** | 0.99 | 1.06 | *1.30* | **0.18** | *99.87* | 1.02 | *3.08* | *5.82* | *3.03* |
| MPA 100% closure in CA NMS | *2.87* | *2.96* | **0.00** | 0.99 | 1.05 | *1.26* | **0.18** | *101.07* | **0.76** | *2.81* | *5.55* | *3.02* |
| MPA 100% closure in WA and selected NMS | *2.77* | *3.00* | **0.00** | 0.99 | 1.05 | *1.35* | **0.19** | *108.51* | 0.99 | *2.90* | *5.06* | *3.03* |
| Nutrient addition low | *2.88* | *3.01* | **0.00** | 0.94 | 1.05 | *1.56* | **0.19** | *98.10* | *1.16* | *2.64* | *5.54* | *3.07* |
| Nutrient addition medium | *2.75* | *3.03* | **0.00** | 0.94 | 1.06 | *1.28* | **0.15** | *106.89* | 1.08 | *2.61* | *5.78* | *3.08* |
| Nutrient addition high | *2.91* | *2.99* | **0.00** | 0.94 | 1.06 | *1.27* | **0.06** | *107.42* | 1.05 | *5.09* | *6.23* | *3.08* |
| Nutrient addition 5 × high | *2.99* | *2.55* | **0.00** | 0.99 | *1.13* | *1.26* | **0.18** | *101.15* | **0.77** | *2.85* | *5.90* | *3.27* |
| Nutrient addition 10 × high | *2.82* | *2.57* | **0.00** | 0.94 | *1.13* | *1.27* | **0.19** | *107.74* | **0.90** | *2.84* | *5.33* | *3.28* |

some intuition into the indicator-attribute correlations in the Results subsection below. Figure A-1 summarizes the end points of the scenarios (Table A-4) in two dimensions, which approximate the overall impacts of fishing (x-axis) and the shifts between a depleted versus enriched pelagic system (y-axis).

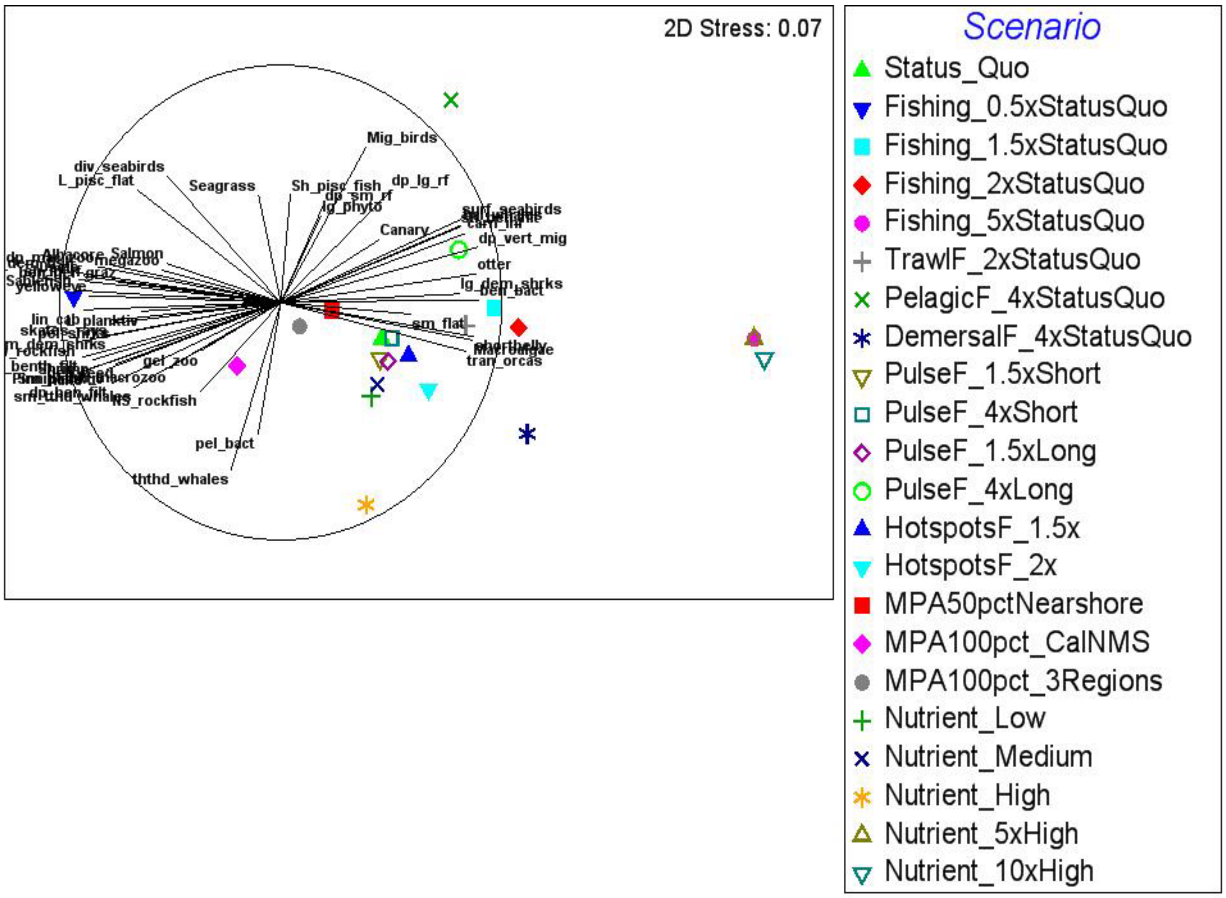


Figure A-1. Two-dimensional nonmetric multidimensional scaling plot of functional groups (text labels, linked to the origin with black radii) and scenarios (symbols). Correlations between each functional group's abundance and the x and y axes are represented by the x position and y position, respectively. In general, moving from left to right represents an increase in fishing and a depletion of target groundfish, while moving from top to bottom represents a shift from depletion of small pelagic fish to one with enriched pelagic productivity (via nutrients). The scenario that depletes pelagic fish (top right, green cross) differs substantially from most other scenarios; it is also negatively correlated with abundance of many target species. The two most extreme nutrient enrichment scenarios (far right) are similar to the most extreme fishing scenario, but moderate nutrient scenarios show less of a negative response for target groundfish (x-axis) and more of a shift toward enhanced pelagic productivity (y-axis). L or lg is large, dp is deep, and rf is rockfish.

## Status Quo Scenario

For the Atlantis simulations of the California Current, we began the model at current biomass levels (approximately 2007 abundances) and projected the model forward for 50 years with specified levels of fishing mortality. The status quo scenario imposed fishing mortality from 20 existing fleets and gears onto all relevant species or functional groups. Spatial fishing closures in the model were based on existing closures that limit bottom contact or bottom trawl gear (http://www.nwr.noaa.gov/Groundfish-Halibut/Groundfish-Fishery-Management /Groundfish-EFH/upload/Map-Gfish-EFH-Close.pdf). Spatial closures were assumed to persist to the end of the simulation.

For the groundfish gears, fishing mortality in the status quo scenario was derived from estimates of total mortality, including discards, from Bellman et al. (2008). For the nongroundfish gears, fishing mortality was based on landings reported in the Pacific Fisheries Information Network database (http://pacfin.psmfc.org/pacfin_pub/data.php). For these simple simulations, we assumed that fishing mortality (percent mortality per year) remained constant over the course of the simulation. We did not vary fishing mortality or attempt to model time-varying quotas.

All other scenarios were based on status quo, with the modifications listed below. See Table A-3 and Table A-4 for biomass results from all scenarios after 50-year simulations.

## Multipliers of Total Fishing Mortality: 50%, 150%, 200%, 500%

These four scenarios multiplied total fishing mortality from status quo by 50%, 150%, 200%, or 500%. The predominant effect of these scenarios was to cause decreases in vertebrate biomass as fishing increased (Table A-3, Table A-4, and Figure A-1). Six groups, however, showed increases in biomass with fishing pressure: canary rockfish, shortbelly rockfish (*Sebastes jordani*), benthopelagics, small shallow rockfish, large demersal sharks, and planktivorous seabirds. Biomass for sea otters (*Enhydra lutris*), toothed whales, baleen whales, pinnipeds, and migratory birds remained stable. Additionally, shallow piscivorous fish, deep large rockfish, deep small rockfish, and small cetaceans showed variable responses as fishing pressure increased.

## Multipliers of Specific Gears' Fishing Mortality

These four scenarios multiplied status quo fishing mortality from specific gears by a scaling factor:

- 2 × trawl fisheries (including bottomfish, shrimp, and hake)
- 4 × demersal fisheries (trawl, pot, and longline gears)
- 4 × pelagic fisheries (including midwater trawl, purse seine, pelagic longline, and troll)
- 10 × fishing on forage fish (small planktivores), myctophids, and krill

When fishing pressure was doubled in the trawl fishery, biomass declined most drastically for yelloweye rockfish (*Sebastes ruberrimus*), flatfish, and small demersal sharks (0.55, 0.37, and 0.16 times status quo, respectively) (Table A-3, Table A-4, and Figure A-1).

Substantial declines were also evident for hake, sablefish (*Anoplopoma fimbria*), sole, and pelagic sharks. Large demersal sharks, however, showed unique behavior, as their biomass increased to nearly 14 times status quo after 50 years. Shortbelly rockfish and deep large rockfish showed smaller increases in biomass (1.8 and 1.6 times status quo, respectively). Biomass of other groups remained similar to status quo values after 50 years.

When fishing pressure was quadrupled for all demersal fisheries, the most prominent impact was on flatfish, which declined to 14% of status quo biomass after 50 years. Nine other groups showed substantial declines in biomass under this scenario, five of which declined to below 50% of status quo: flatfish, sablefish, deep demersal fish, Dover sole (*Microstomus pacificus*), and yelloweye rockfish. As in the previous scenario, substantial increases in biomass were evident in large demersal sharks and shortbelly rockfish (2.8 and 2.0 times status quo, respectively). Biomass for other groups remained similar to status quo values after 50 years.

A quadruple increase in pelagic fishing pressure precipitated the decline of 13 vertebrate groups (Figure A-1). Most substantial declines were seen in pelagic sharks, small demersal sharks, and hake, with reductions to 0.0, 0.14, and 0.33 times status quo, respectively. Increases in biomass were seen in 6 groups, but the most dramatic change was in large demersal sharks, which increased 247 times status quo.

A tenfold increase in pressure on forage fish led to the decline of 23 vertebrate groups. The greatest declines in vertebrates were seen in flatfish and nearshore fish (0.08 and 0.01 times status quo, respectively). Salmon (*Oncorhynchus* spp.), pelagic sharks, and small demersal sharks all declined to less than 20% of status quo. In addition to vertebrate declines, cephalopods and shrimp also showed substantial decreases in biomass under this scenario, falling to very low abundances. Substantial increases were seen in canary rockfish, albacore tuna (*Thunnus alalunga*), deep small rockfish, and deep large rockfish.

## Pulse Fishing

To include the effect of pulses of fishing in the California Current, we simulated these four scenarios:

- 1.5 × status quo fishing for years 10–12 of the simulation
- 4 × status quo fishing for years 10–12 of the simulation
- 1.5 × status quo fishing for years 10–20 of the simulation
- 4 × status quo fishing for years 10–20 of the simulation

These involved scaling fishing mortalties from all gears for these time periods. For all other years of the 50-year simulation, fishing was at status quo levels.

Overall, the increase in fishing pressure to 1.5 times status quo had minimal impact on biomass after 50 years (Table A-3, Table A-4, and Figure A-1). Applying a pulse of pressure between years 10 and 12 of the simulation had little effect on biomass after 59 years. Canary rockfish and salmon show moderate declines, while flatfish increase. When the increased fishing was applied for a longer period of time, salmon biomass declined substantially to 0.38 times status quo. Small shallow rockfish, small demersal sharks, and pelagic sharks showed moderate declines. Large demersal sharks increased to 2.4 times status quo. Other groups showed minimal change from status quo.

Increasing fishing pressure to 4 times status quo between years 10 and 12 resulted in the decline of 8 vertebrate groups. Salmon was the most heavily affected and decreased to 28% of status quo. This pulse in fishing resulted in an increase in flatfish and large demersal shark biomass. Lengthening the duration of the pulse caused more groups to decline after 50 years. Under this scenario, 15 vertebrate groups showed a decrease in biomass. Pelagic sharks and salmon were most affected and fell to 0.16 and 0.003 times status quo levels, respectively. Five groups showed an increase in biomass, but most prominent was the change in large demersal sharks to 20 times status quo.

### Spatial Hotspots of Additional Fishing Mortality (near Ports)

These scenarios increased fishing mortality in specific model cells near major fishing ports. This sort of effort concentration could happen under individual transferable quotas, increased fuel prices, or other added costs in the future. We increased effort covering all depth ranges off Oregon (boxes 5–7), Monterey and Moss Landing (boxes 49–54), and Morro Bay (boxes 70–75). The scenarios were:

- 1.5 × all gears' fishing mortalities near these three ports
- 2 × all gears' fishing mortalities near these three ports

All other model cells continued with status quo fishing.

The major effect of increasing fishing in these scenarios was the decline in biomass for 12 vertebrate groups (Table A-3, Table A-4, and Figure A-1). The most heavily impacted groups under these scenarios were salmon and pelagic sharks. Three vertebrate groups increased in biomass under these scenarios: canary rockfish, shortbelly rockfish, and large demersal sharks.

### Marine Protected Areas

These scenarios simulated effects of additional spatial management in the California Current. The status quo scenario already includes spatial management zones such as the Rockfish Conservation Area, essential fish habitat, and California state MPAs. The MPA scenarios added further closures that affected all gears, as follows:

- 50% reduction in the area each fleet can access in the nearshore boxes (0–50 m)
- 100% closure in central California NMSs, for all gears
- 100% closure for all boxes off Washington, Monterey Bay (within the bay itself), and Gulf of the Farallones and Cordell Bank NMS (boxes 1–3, 49–54, 27–33, and 35–40, respectively).

When fishing was reduced in nearshore boxes, the main effect was an increase in several groups, including canary rockfish, albacore, shallow large rockfish, and piscivorous seabirds (Table A-3, Table A-4, and Figure A-1). Most notable, however, was the increase in salmon to

109 times status quo. Large demersal sharks declined to 0.28 times status quo, but no other vertebrate groups substantially declined under this scenario.

The effects of closing fishing within central California NMSs were similar to the effects of closing fishing off Washington and selected central California zones for most groups. One difference, however, was the increase in tuna in the latter scenario. Additionally, cowcod (*Sebastes levis*) + yelloweye, small demersal sharks, and pelagic sharks benefitted more from the central California closures than the more widely distributed closures.

### Nutrient Additions

These scenarios added large amounts of nitrate (N) to all model cells closest to shore to represent large increases in future anthropogenic inputs. The status quo model includes nutrients and inputs of N from depth due to upwelling; thus, these nutrient addition scenarios add N in excess of natural levels. We simulated the following levels of nutrient addition:

1. Low, representing N addition equivalent to the N usually found in a coastal zone with weak upwelling
2. Medium, representing N addition equivalent to the N usually found in a coastal zone with medium upwelling
3. High, representing N addition equivalent to the N usually found in a coastal zone with strong upwelling
4. 5 × high
5. 10 × high

Pulsing nutrients into the system at low, medium, and high levels generally had little effect on vertebrate biomass after 50 years (Table A-3, Table A-4, and Figure A-1). The largest effects of these scenarios were seen in the increase of zooplankton biomass as nutrients increased. Phytoplankton biomass decreased despite an increase in nutrients, as zooplankton responded to increased primary production and effectively grazed on phytoplankton biomass. Such trophic effects, however, were not as apparent among the vertebrate groups.

The greatest effects of the two largest nutrient loading scenarios (5 × and 10 × high) were seen in large demersal sharks (Table A-3, Table A-4, and Figure A-1). Under the status quo scenario, large demersal sharks go extinct early in the simulation, while under the 5 × and 10 × high scenarios the additional nutrient loading allows for this group to maintain a reasonable biomass after 50 years (1,800 × the low levels associated with quasi-extinction in the status quo model). Other vertebrate groups that showed an increase in biomass included canary rockfish, shortbelly rockfish, deep large rockfish, and migratory birds. While a few groups benefitted in these scenarios, 19 other vertebrate groups showed substantial declines in biomass, with small demersal sharks and pelagic sharks declining to near extinction.

## Methods: Spatial Scaling of Attributes and Indicators

For the scenarios that were the most spatially heterogeneous (MPAs, nutrients, and fishing hotspots), we retested the attribute-indicator correlations, but with the attributes, indicators, or both derived from local data as follows:

| Attributes | Indicators, coast-wide | Indicators, local |
|---|---|---|
| Coast wide | For example, coast-wide trawl survey to determine coast-wide population status | Upscaling, for example, extrapolating from local monitoring to infer coast-wide population status |
| Local | Downscaling, for example, inferring local attribute status from a coast-wide survey and population estimate | For example, monitoring an MPA to determine population status within the MPA |

We define local to mean within the model polygons subjected to additional perturbations in each scenario. For the nutrient scenarios, local involves the nearshore boxes; for the fishing hotspots, it is a range of all depth zones off Oregon, Monterey Bay, and Moro Bay; and for MPAs, it refers to the polygons closed within each specific scenario (1-nearshore, 2-central California NMS, or 3-Washington, Monterey Bay, and Gulf of the Farallones and Cordell Bank NMSs).

For each of the MPAs, nutrient, or fishing hotspot scenarios we calculated local attributes, local indicators, coast-wide attributes, and coast-wide indicators. We then performed a correlation analysis (identical to the one described above) on each possible attribute × indicator combination (coast-wide × coast-wide, local × local, coast-wide × local, and local × coast-wide) (table above). For each combination, we report the attributes and indicators that are consistently significantly correlated, grouped by scenario type (MPAs, nutrients, and fishing hotspots).

## Results

Considering all 23 scenarios, for each attribute related to ecosystem health we found at least one significantly correlated indicator, except for the attribute total catch (Table A-5). Benthic invertebrate abundance was positively ($r > 0.5$) and consistently (≥20 of 23 scenarios) related to mean trophic level of biomass and total living biomass, and therefore negatively related to the ratio of net primary production (NPP) to biomass. A very simple indicator, bottomfish biomass, was significantly and consistently related to two of the ecosystem health attributes, NPP and total living biomass. As in the Samhouri et al. (2010) research involving an Ecosim food web model for British Columbia, sablefish abundance was related to ecosystem health, though in our results this relationship was limited only to one attribute, NPP. Phytoplankton abundance was negatively related ($r < -0.5$) to biodiversity (as measured by the Shannon Diversity Index); heavily overfished scenarios tended to have higher abundances of large phytoplankton.

The indicators forage fish abundance, piscivore:scavenger, and pinniped abundance were negatively related to the number of unassessed groups below B25 and B40. (B40 is the level of spawning stock biomass at which stocks are considered at their optimal yield—40% of virgin spawning biomass. B25 is the level of spawning stock biomass at which stocks are overfished—

Table A-5. All scenarios. Indicators that were significantly ($P < 0.05$) and strongly ($|r| > 0.5$) correlated to each attribute in greater than or equal to 20 of 23 simulations. Indicators with very strong correlations ($|r| > 0.7$) are marked with an asterisk (*).

| Attribute | Correlation | Indicator |
|---|---|---|
| NPP | Positive | Phytoplankton,* bottomfish, sablefish, lingcod proportion (prop.) mature |
| | Negative | Zooplankton:phytoplankton |
| NPP:B | Negative | Benthic invertebrates |
| Mean trophic level of B | Positive | Benthic invertebrates |
| Shannon Diversity Index | Negative | Phytoplankton |
| Total living biomass | Positive | Phytoplankton, bottomfish, benthic invertebrates* |
| No. nonassessed below B40 | Positive | Scavengers, Dungeness crab + seastar, shallow larger fish, Dungeness + crab, marine mammal + birds, seabird, midwater rockfish prop. mature, diving + migratory birds, baleen whales |
| | Negative | Piscivore:scavenger, forage fish, pinnipeds |
| No. nonassessed below B25 | Positive | Shallow large rockfish, marine mammal + birds, seabird, midwater rockfish prop. mature, immature groundfish spp., immature assessed spp., diving + migratory birds, baleen whales, sea otters |
| | Negative | Flatfish, kelp, seastar abalone urchin, lingcod, halibut + small flatfish, forage fish:jellyfish, piscivore:scavenger, shortbelly rockfish prop. mature, forage fish, pinnipeds |
| Target group biomass | Positive | Flatfish, invertivores,* kelp, seastar abalone urchin, lingcod, halibut + small flatfish, forage fish:jellyfish, piscivore:planktivore, piscivore:scavenger, shallow large rockfish prop. mature, shortbelly rockfish prop. mature, forage fish, pinnipeds |
| | Negative | Rockfish:flatfish, shallow large rockfish, benthic:pelagic, marine mammal + birds, seabird, finfish:crustacean, midwater rockfish prop. mature, immature groundfish spp., immature assessed spp., diving + migratory birds, baleen whales, sea otters |
| Total catch | | [None] |
| Rockfish | Positive | Roundfish,* rockfish,* rockfish:flatfish,* shallow large + midwater + shortbelly rockfish,* shallow + midwater + canary rockfish,* lingcod + yelloweye + midwater + large shallow rockfish,* zooplanktivorous fish,* marine mammal, finfish:crustacean,* cetacean, immature groundfish spp.,* immature assessed spp., zooplanktivorous fish* |
| | Negative | Invertivores,* kelp, seastar abalone urchin, forage fish:jellyfish, zooplankton, piscivore:planktivore,* piscivore, sablefish, piscivores, krill |
| Groundfish prop. mature | Positive | Flatfish, invertivores, kelp, seastar abalone urchin, halibut + small flatfish, forage fish:jellyfish, piscivore:planktivore,* piscivore,* sablefish,* shallow large rockfish prop. mature, shortbelly rockfish prop. mature, piscivores, pinnipeds |
| | Negative | Roundfish, rockfish, rockfish:flatfish, habitat structure, shallow large + midwater + shortbelly rockfish, shallow + midwater + canary rockfish,* lingcod + yelloweye + midwater + large shallow rockfish, zooplanktivorous fish,* benthic:pelagic, marine mammal + birds, seabird, finfish:crustacean,* immature groundfish spp., immature assessed spp., habitat structure, zooplanktivorous fish,* diving + migratory birds, baleen whales, sea otters |

25% of virgin spawning biomass.) This derives from the projections that included simultaneous increasing trends in unassessed species, forage fish, piscivores, and pinnipeds. One implication of this result is that forage fish (such as sardines (*Sardinops sagax*) might serve as a bellwether to indicate the status of species not formally included in stock assessments. The unassessed groups tended to be out of phase with several marine mammal, bird, and rockfish groups, thus these latter groups were positively correlated with the number of unassessed groups below B25 and B40.

Compared to attributes of ecosystem health, attributes of groundfish were related to more indicators (Table A-5). These significant and consistent indicators primarily included those that were direct measurements of groundfish populations, but included metrics of additional groups as well. Two of the attributes, target groups' biomass and groundfish proportion mature, involve a very similar set of species, and generally were related to the same set of indicators. These included simple biomass ratios (piscivore:planktivore and foragefish:jellyfish), abundance of seastars, abalone and urchins, and abundance of kelp. Other significant indicators tended to be direct measurements of groundfish abundance (e.g., flatfish biomass) or indicators of age structure (percent of mature individuals in certain rockfish populations).

Negative correlations between these attributes of groundfish population size and the numbers of immature groundfish and immature assessed species are likely due to density-dependent effects in the model. Negative correlations between these attributes and some rockfish metrics reflect the large proportion of the groundfish and catches that are flatfish rather than rockfish. Negative correlations with some marine mammal and seabird indicators simply reflect the consistent increases in mammal and bird groups, which contrast with declines in target and groundfish species seen in many of the more heavily fished scenarios.

Across these 23 scenarios, total catch was not significantly and consistently related to any indicator. Since this attribute included all harvested species, declines in one species can be masked by increases in others. However, within individual types of scenarios, total catch was positively related to certain indicators. For instance, as described below in the two fishing hotspot scenarios, total catch was positively related to bottomfish abundance, but this was not the case in the other types of scenarios.

The attribute rockfish was primarily positively related to direct measurements of the rockfish groups' abundance, as well as to the finfish:crustacean ratio, abundance of marine mammals and cetaceans, and the abundance of immature groundfish and assessed species. Several of the indicators that were negatively related to rockfish abundance were positively related to the target groups' biomass and mean proportion of groundfish mature. This is due to the fact that in many of the scenarios, long-lived and slow-growing rockfish groups show trends that differ from more productive components of the groundfish assemblage.

In the discussion above, we defined strong correlations as $|r| > 0.5$ and used this as the cutoff for reporting indicator-attribute pairs. Limiting the analysis to very strong correlations of $|r| > 0.7$ greatly reduces the number of indicator-attribute pairs selected (Table A-5). For attributes of ecosystem health, only benthic invertebrates are chosen as very strong ($|r| > 0.7$) indicators (except for phytoplankton, which is of course related to NPP). For attributes of groundfish, target group biomass is only strongly correlated with invertivores. The attribute rockfish biomass is exclusively strongly related to direct metrics of rockfish abundance. Similarly, groundfish proportion mature is exclusively strongly related to metrics of rockfish abundance; two metrics of rockfish species age structure are included at the 0.5 level but excluded at the 0.7 level.

### Analysis of Scenario Types

For the 9 fishing scenarios, most attributes of ecosystem health were related to the same small group of indicators as when we evaluated the full set of 23 scenarios (above). This was true for the attributes NPP, NPP:B, mean trophic level of biomass, Shannon Diversity, and total living biomass. As in the full set of 23 scenarios, total catch was not well correlated with any indicator (Table A-6).

For the other attributes related to groundfish and the number of groups below B25 or B40, the indicators selected were primarily a subset of the 126 attribute-indicators selected in the full set of 23 scenarios (Table A-6). Relative to the analysis with the full set of 23 scenarios, here we added only 4 indicators (all related to number of assessed groups below B40) and lost 24. This follows naturally from the fact that for an indicator to have been labeled “consistently correlated” we required strong correlations in at least 8 of 9 fishing scenarios (88.9%); thus, 3 weak correlations would disqualify an indicator-attribute pair, while for the full set only 4 weak correlations (of 23) were required for disqualification. The four added indicators were all related to number of nonassessed species below B40, with two of the added indicators direct measures of flatfish abundance and another that represented summed abundance of immature assessed species. This same attribute lost five indicator-attribute pairs, most notably three positive indicators for B40 related to scavengers and crabs and one based on baleen whales.

The attribute groundfish proportion mature lost one positive indicator (pinnipeds) and 10 negative indicators, with the latter related to marine mammals and birds, abundance of particular rockfish groups, and the benthic:pelagic ratio. The attribute target group biomass also lost two biomass ratio indicators (piscivore:planktivore and benthic:pelagic), relative to the full set of scenarios. The attribute rockfish lost four negatively correlated indicators: invertivores, forage:jellyfish, krill, and zooplankton. Notably these again include a biomass ratio, and three are metrics of plankton rather than direct metrics of rockfish populations. Overall, the results from considering only the fishing scenarios suggest that the effects of fishing on ecosystem health can be detected with indicators similar to those originally presented in Table A-5. However, detecting the effects of fishing on groundfish requires a set of indicators that is fairly focused on groundfish metrics, with only a few other types of metrics such as biomass ratios and marine mammal or bird abundance.

From the pulse fishing scenarios, we identified a larger set of indicator-attribute pairs than for the full set of scenarios or the simple fishing scenarios (Table A-7). This may in part be due to the fact that there were only four pulse fishing scenarios, and attribute-indicator pairs were labeled consistent if they were selected in three or four of these scenarios. Three of the attributes of ecosystem health had a set of indicators identical to those from the fishing scenario, but NPP and number of nonassessed species below B40 and B25 had approximately twice more indicator-attribute pairs for pulse fishing than for the simple fishing scenarios. Groundfish attributes also gained many indicator-attribute pairs relative to simple fishing, including direct metrics of

Table A-6. Fishing (based on nine scenarios). Indicators that were significantly ($P < 0.05$) and strongly ($|r| > 0.5$) correlated to each attribute in greater than or equal to 20 of 23 simulations.

| **Attribute** | **Correlation** | **Indicator** |
|---|---|---|
| NPP | Positive | Phytoplankton, bottomfish, sablefish, lingcod prop. mature |
| | Negative | Zooplankton:phytoplankton |
| NPP:B | Negative | Benthic invertebrates |
| Mean trophic level of B | Positive | Benthic invertebrates |
| Shannon Diversity Index | Negative | Phytoplankton |
| Total living biomass | Positive | Phytoplankton, bottomfish, benthic invertebrates |
| No. nonassessed below B40 | Positive | Marine mammal + birds, seabird, midwater rockfish prop. mature, immature assessed spp., diving + migratory birds |
| | Negative | Flatfish, invertivores, seastar abalone urchin, halibut + small flatfish, piscivore:scavenger, forage fish, pinnipeds |
| No. nonassessed below B25 | Positive | Marine mammal + birds, seabird, midwater rockfish prop. mature, immature groundfish spp., immature assessed spp., diving + migratory birds, baleen whales |
| | Negative | Flatfish, seastar abalone urchin, lingcod, halibut + small flatfish, forage fish:jellyfish, piscivore:scavenger, shortbelly rockfish prop. mature, forage fish, pinnipeds |
| Target group biomass | Positive | Flatfish, invertivores, kelp, seastar abalone urchin, lingcod, halibut + small flatfish, forage fish:jellyfish, piscivore:scavenger, shallow large rockfish prop. mature, shortbelly rockfish prop. mature, forage fish, pinnipeds |
| | Negative | Rockfish:flatfish, shallow large rockfish, marine mammal + birds, seabird, finfish:crustacean, midwater rockfish prop mature, immature groundfish spp., immature assessed spp., diving + migratory birds, baleen whales, sea otters |
| Total catch | | [None] |
| Rockfish | Positive | Roundfish, rockfish, rockfish:flatfish, shallow large + midwater + shortbelly rockfish, shallow + midwater + canary rockfish, lingcod + yelloweye + midwater + large shallow rockfish, zooplanktivorous fish, marine mammal, finfish:crustacean, cetacean, immature groundfish spp., immature assessed spp., zooplanktivorous fish |
| | Negative | Kelp, seastar abalone urchin, piscivore:planktivore, piscivore, sablefish, piscivores |
| Groundfish prop. mature | Positive | Flatfish, invertivores, kelp, seastar abalone urchin, halibut + small flatfish, forage fish:jellyfish, piscivore:planktivore, piscivore, sablefish, shallow large rockfish prop. mature, shortbelly rockfish prop. mature, piscivores |
| | Negative | Roundfish, rockfish, rockfish:flatfish, shallow + midwater + canary rockfish, zooplanktivorous fish, finfish:crustacean, immature groundfish spp., immature assessed spp., zooplanktivorous fish |

groundfish populations and metrics of other groups such as forage fish, noncommercial species, and zooplankton. Most notably, unlike in the previous types of scenarios, the attribute total catch was related to many indicators in these scenarios, including metrics related to harvested and unharvested species.

Table A-7. Pulse fishing (based on four scenarios). Indicators that were significantly ($P < 0.05$) and strongly ($|r| > 0.5$) correlated to each attribute in greater than or equal to 20 of 23 simulations.

| Attribute | Correlation | Indicator |
|---|---|---|
| NPP | Positive | Phytoplankton, bottomfish, shallow small rockfish, zooplankton, sablefish, lingcod prop. mature, assessed spp. weight at maturity, reeftop invertebrates, krill |
| | Negative | Zooplankton:phytoplankton |
| NPP:B | Negative | Benthic invertebrates |
| Mean trophic level of B | Positive | Benthic invertebrates |
| Shannon Diversity Index | Negative | Phytoplankton |
| Total living biomass | Positive | Phytoplankton, bottomfish, benthic invertebrates, assessed spp. weight at maturity |
| No. nonassessed below B40 | Positive | Noncommercial species, scavengers, habitat structure, shallow large + midwater + shortbelly rockfish, Dungeness crab + seastar, shallow large rockfish, Dungeness + crab, benthic:pelagic, marine mammal + birds, seabird, finfish:crustacean, midwater rockfish prop. mature, immature groundfish spp., immature assessed spp., habitat structure, noncommercial species B, diving + migratory birds, baleen whales, sea otters |
| | Negative | Total catch, flatfish, invertivores, kelp, seastar abalone urchin, lingcod, halibut + small flatfish, forage fish:jellyfish, piscivore:scavenger, invertivore:herbivore, shallow large rockfish prop. mature, shortbelly rockfish prop. mature, forage fish, pinnipeds |
| No. nonassessed below B25 | Positive | Noncommercial species, scavengers, rockfish:flatfish, habitat structure, shallow large + midwater + shortbelly rockfish, Dungeness crab + seastar, shallow large rockfish, Dungeness + crab, lingcod + yelloweye + midwater + large shallow rockfish, benthic:pelagic, marine mammal + birds, seabird, finfish:crustacean, midwater rockfish prop. mature, immature groundfish spp., immature assessed spp., habitat structure, noncommercial species B, diving + migratory birds, baleen whales, sea otters |
| | Negative | Total catch, flatfish, invertivores, kelp, seastar abalone urchin, lingcod, halibut + small flatfish, forage fish:jellyfish, piscivore:scavenger, invertivore:herbivore, shallow large rockfish prop. mature, shortbelly rockfish prop. mature, forage fish, pinnipeds |
| Target group biomass | Positive | Total catch, flatfish, invertivores, kelp, seastar abalone urchin, lingcod, halibut + small flatfish, forage fish:jellyfish, zooplankton:phytoplankton, piscivore:planktivore, piscivore:scavenger, piscivore, invertivore:herbivore, shallow large rockfish prop. mature, shortbelly rockfish prop. mature, piscivores, forage fish, pinnipeds |
| | Negative | Noncommercial species, roundfish, rockfish, rockfish:flatfish, habitat structure, shallow large + midwater + shortbelly rockfish, shallow large rockfish, shallow + midwater + canary rockfish, lingcod + yelloweye + midwater + large shallow rockfish, gelatinous zooplankton, zooplanktivorous fish, benthic:pelagic, marine mammal + birds, seabird, finfish:crustacean, midwater rockfish prop. mature, immature groundfish spp., immature assessed spp., habitat structure, zooplanktivorous fish, noncommercial species B, diving + migratory birds, baleen whales, sea otters |

Table A-7 continued. Pulse fishing (based on four scenarios). Indicators that were significantly (P < 0.05) and strongly (|r| > 0.5) correlated to each attribute in greater than or equal to 20 of 23 simulations.

| Attribute | Correlation | Indicator |
|---|---|---|
| Total catch | Positive | Flatfish, invertivores, kelp, seastar abalone urchin, lingcod, halibut + small flatfish, forage fish:jellyfish, zooplankton:phytoplankton, piscivore:scavenger, invertivore:herbivore, shallow large rockfish prop. mature, shortbelly rockfish prop. mature, forage fish, pinnipeds |
| | Negative | No. assessed below B25, noncommercial species, scavengers, herbivores, Dungeness crab + seastar, shallow large rockfish, Dungeness + crab, benthic:pelagic, marine mammal + birds, seabird, finfish:crustacean, lingcod prop. mature, midwater rockfish prop. mature, immature groundfish spp., immature assessed spp., assessed spp. weight at maturity, noncommercial species B, diving + migratory birds, baleen whales, sea otters |
| Rockfish | Positive | Noncommercial species, roundfish, rockfish, rockfish:flatfish, shallow large + midwater + shortbelly rockfish, shallow + midwater + canary rockfish, lingcod + yelloweye + midwater + large shallow rockfish, zooplanktivorous fish, marine mammal + birds, seabird, marine mammal, finfish:crustacean, cetacean, immature groundfish spp., immature assessed spp., zooplanktivorous fish, noncommercial species B, diving + migratory birds, baleen whales, sea otters |
| | Negative | Bottomfish, flatfish, invertivores, kelp, seastar abalone urchin, halibut + small flatfish, forage fish:jellyfish, zooplankton, piscivore:planktivore, piscivore, invertivore:herbivore, sablefish, shallow large rockfish prop. mature, shortbelly rockfish prop. mature, groundfish mean weight at maturity, piscivores, krill, pinnipeds |
| Groundfish prop. mature | Positive | Flatfish, invertivores, kelp, seastar abalone urchin, halibut + small flatfish, forage fish:jellyfish, zooplankton, piscivore:planktivore, piscivore, invertivore:herbivore, sablefish, shallow large rockfish prop. mature, shortbelly rockfish prop. mature, piscivores, forage fish, pinnipeds |
| | Negative | Mean trophic level catch, noncommercial species, roundfish, rockfish, rockfish:flatfish, habitat structure, shallow large + midwater + shortbelly rockfish, shallow + midwater + canary rockfish, lingcod + yelloweye + midwater + large shallow rockfish, zooplanktivorous fish, benthic:pelagic, marine mammal + birds, seabird, marine mammal, finfish:crustacean, cetacean, midwater rockfish prop. mature, immature groundfish spp., immature assessed spp., habitat structure, zooplanktivorous fish, noncommercial species B, diving + migratory birds, baleen whales, sea otters |

Focusing on the 5 nutrient enrichment scenarios identified a set of attribute-indicator pairs that was quite similar to the results from analysis of the full 23 scenarios (Table A-8). Relative to the full 23 scenarios, nutrient enrichment added only 14 indicators-attribute pairs and removed 10 of the original 126 pairs. Relative to the full set of 23 scenarios, the additions included 4 positively correlated indicators of the number of nonassessed species below B25, with 3 of these indicators related to rockfish. Focusing on the nutrient enrichment scenarios also added five positively correlated indicators of rockfish biomass, four of which were indicators related to marine mammal and birds. Two negatively correlated indicators of rockfish biomass

Table A-8. Nutrients (based on five scenarios), coast-wide × coast-wide. Indicators that were significantly ($P < 0.05$) and strongly ($|r| > 0.5$) correlated to each attribute in greater than or equal to 20 of 23 simulations.

| Attribute | Correlation | Indicator |
|---|---|---|
| NPP | Positive | Phytoplankton, bottomfish, lingcod prop. mature |
| | Negative | Zooplankton:phytoplankton |
| NPP:B | Negative | Benthic invertebrates |
| Mean trophic level of B | Positive | Benthic invertebrates |
| Shannon Diversity Index | Negative | Phytoplankton |
| Total living biomass | Positive | Phytoplankton, bottomfish, benthic invertebrates |
| No. nonassessed below B40 | Positive | Scavengers, Dungeness crab + seastar, shallow large rockfish, Dungeness + crab, marine mammal + birds, seabird, midwater rockfish prop. mature, diving + migratory birds, baleen whales |
| | Negative | Piscivore:scavenger, pinnipeds |
| No. nonassessed below B25 | Positive | Rockfish:flatfish, shallow large + midwater + shortbelly rockfish, shallow large rockfish, lingcod + yelloweye + midwater + large shallow rockfish, benthic:pelagic, marine mammal + birds, seabird, midwater rockfish prop. mature, immature groundfish spp., immature assessed spp., diving + migratory birds, baleen whales, sea otters |
| | Negative | Flatfish, kelp, seastar abalone urchin, lingcod, halibut + small flatfish, forage fish:jellyfish, piscivore:scavenger, shallow large rockfish prop. mature, forage fish, pinnipeds |
| Target group biomass | Positive | Flatfish, invertivores, kelp, seastar abalone urchin, halibut + small flatfish, forage fish:jellyfish, piscivore:planktivore, piscivore:scavenger, piscivore, shallow large rockfish prop. mature, piscivores, forage fish, pinnipeds |
| | Negative | Rockfish:flatfish, shallow large rockfish, benthic:pelagic, marine mammal + birds, seabird, finfish:crustacean, immature groundfish spp., immature assessed spp., diving + migratory birds, baleen whales, sea otters |
| Total catch | | [None] |
| Rockfish | Positive | Roundfish, rockfish, rockfish:flatfish, shallow large + midwater + shortbelly rockfish, shallow + midwater + canary rockfish, lingcod + yelloweye + midwater + large shallow rockfish, zooplanktivorous fish, benthic:pelagic, marine mammal + birds, seabird, marine mammal, finfish:crustacean, cetacean, immature groundfish spp., immature assessed spp., zooplanktivorous fish, diving + migratory birds, sea otters |
| | Negative | Invertivores, kelp, seastar abalone urchin, forage fish:jellyfish, zooplankton, piscivore:planktivore, piscivore, sablefish, piscivores, forage fish, krill, pinnipeds |
| Groundfish prop. mature | Positive | Invertivores, kelp, seastar abalone urchin, forage fish:jellyfish, piscivore:planktivore, piscivore, sablefish, piscivores, forage fish, pinnipeds |
| | Negative | Roundfish, rockfish, rockfish:flatfish, habitat structure, shallow large + midwater + shortbelly rockfish, shallow + midwater + canary rockfish, lingcod + yelloweye + midwater + large shallow rockfish, zooplanktivorous fish, benthic:pelagic, marine mammal + birds, seabird, marine mammal, finfish:crustacean, cetacean, immature groundfish spp., immature assessed spp., habitat structure, zooplanktivorous fish, diving + migratory birds, baleen whales, sea otters |

were also added, forage fish and pinnipeds, as were two negatively correlated indicators of groundfish proportion mature, both related to marine mammals and seabirds.

Indicators that were significant in the full set of scenarios but not for nutrient enrichment included four positively correlated indicators of groundfish, two of which were metrics of flatfish abundance and two of which were metrics of rockfish age structure. Two negatively correlated indicators of rockfish age structure, and 1 related to forage fish abundance, were also lost in the nutrient scenarios relative to the full set of 23 scenarios. Overall, detecting impacts of the nutrient enrichment scenario appeared to require a set of attributes and indicators similar to those presented in Table A-5, but with additional focus on indicators related to marine mammals and birds, and reduced focus on indicators related to rockfish age structure.

Focusing on the 2 fishing hotspot scenarios identified 57 positively correlated attribute-indicator pairs and 43 negatively correlated pairs that had not been identified in the analysis of the full set of 23 scenarios (Table A-9). No attribute-indicator pairs were lost from the original set of pairs identified for the full set of scenarios. The large number of attribute-indicator pairs is likely a function of the limited number of scenarios involving fishing hotspots. Most of these additional indicators were associated with attributes of groundfish, rather than ecosystem health. For instance, no additional indicators were correlated with NPP:B, mean trophic level of biomass, or total living biomass, and only one additional indicator (benthic invertebrates) was correlated with the Shannon Diversity Index.

Analysis of the 3 MPA scenarios similarly identified 55 additional positively correlated attribute-indicator pairs and 36 negatively correlated attribute-indicator pairs, relative to the full set of 23 scenarios (Table A-10). As for fishing hotspots, most of these additional indicators were associated with attributes of groundfish, rather than ecosystem health. On the other hand, the additional indicators were a mix of metrics both directly calculated based on groundfish data (such as rockfish age structure) and metrics involving other functional groups, such as phytoplankton, forage fish, scavengers, Dungeness crabs (*Cancer magister*), mammals, seabirds, and noncommercial species. Also similar to the fishing hotspot scenarios, no additional indicators were correlated with ecosystem attributes NPP:B, mean trophic level of biomass, or total living biomass, and only one additional indicator (benthic invertebrates) was correlated with the Shannon Diversity Index. Only two positively and three negatively correlated indicators were lost relative to the full set of scenarios. The positively correlated indicators lost included bottomfish and shallow large rockfish proportion mature. Negatively correlated indicators lost included invertivores, zooplankton, and the number of immature individuals of assessed species.

In summary, we found that the fishing and nutrient scenarios had a large enough sample size (number of simulations) from which to draw some lessons, while the results for pulse fishing, fishing hotspots, and MPAs are limited by the small sample size (four or fewer simulations). These latter scenario types are perhaps most useful as context for understanding the summary of results from all simulations (above) and the results involving spatial scaling (below). For the fishing and nutrient scenarios, which had sample sizes of 5 or more, we identified a set of indicators applicable to ecosystem health that was consistent with the indicators selected in the analysis of all 23 simulations. For attributes of the groundfish community, the analysis suggested a need to tailor indicators to the type of perturbation. For instance, detecting impacts of the fishing scenarios required more indicators that were direct

Table A-9. Fishing hotspots (based on two scenarios). Indicators that were significantly ($P < 0.05$) and strongly ($|r| > 0.5$) correlated to each attribute in greater than or equal to 20 of 23 simulations.

| Attribute | Correlation | Indicator |
|---|---|---|
| NPP | Positive | Phytoplankton, total catch, bottomfish, shallow small rockfish, zooplankton, piscivore:planktivore, piscivore, sablefish, lingcod prop. mature, assessed spp. weight at maturity, piscivores, krill |
| | Negative | Rockfish, shallow + midwater + canary rockfish, zooplanktivorous fish, zooplankton:phytoplankton, zooplanktivorous fish |
| NPP:B | Negative | Benthic invertebrates |
| Mean trophic level of B | Positive | Benthic invertebrates |
| Shannon Diversity Index | Positive | Benthic invertebrates |
| | Negative | Phytoplankton |
| Total living biomass | Positive | Phytoplankton, bottomfish, benthic invertebrates |
| No. nonassessed below B40 | Positive | Mean trophic level catch, noncommercial species, scavengers, Dungeness crab + seastar, shallow large rockfish, Dungeness + crab, benthic:pelagic, marine mammal + birds, seabird, midwater rockfish prop. mature, immature assessed spp., noncommercial species B, diving + migratory birds, baleen whales, sea otters |
| | Negative | Flatfish, invertivores, seastar abalone urchin, halibut + small flatfish, forage fish:jellyfish, piscivore:scavenger, invertivore:herbivore, shortbelly rockfish prop. mature, forage fish, pinnipeds |
| No. nonassessed below B25 | Positive | Mean trophic level catch, noncommercial species, scavengers, habitat structure, Dungeness crab + seastar, shallow large rockfish, Dungeness + crab, benthic:pelagic, marine mammal + birds, seabird, midwater rockfish prop. mature, immature groundfish spp., immature assessed spp., habitat structure, noncommercial species B, diving + migratory birds, baleen whales, sea otters |
| | Negative | Flatfish, invertivores, kelp, seastar abalone urchin, lingcod, halibut + small flatfish, forage fish:jellyfish, piscivore:scavenger, invertivore:herbivore, shortbelly rockfish prop. mature, forage fish, pinnipeds |
| Target group biomass | Positive | Flatfish, invertivores, kelp, seastar abalone urchin, lingcod, halibut + small flatfish, forage fish:jellyfish, piscivore:planktivore, piscivore:scavenger, piscivore, invertivore:herbivore, shallow large rockfish prop. mature, shortbelly rockfish prop. mature, piscivores, forage fish, pinnipeds |
| | Negative | Noncommercial species, scavengers, roundfish, rockfish, rockfish:flatfish, habitat structure, shallow large + midwater + shortbelly rockfish, Dungeness crab + seastar, shallow large rockfish, shallow + midwater + canary rockfish, Dungeness + crab, lingcod + yelloweye + midwater + large shallow rockfish, zooplanktivorous fish, benthic:pelagic, marine mammal + birds, seabird, marine mammal, finfish:crustacean, cetacean, midwater rockfish prop. mature, immature groundfish spp., immature assessed spp., habitat structure, zooplanktivorous fish, noncommercial species B, diving + migratory birds, baleen whales, sea otters |

Table A-9 continued. Fishing hotspots (based on two scenarios). Indicators that were significantly ($P < 0.05$) and strongly ($|r| > 0.5$) correlated to each attribute in greater than or equal to 20 of 23 simulations.

| Attribute | Correlation | Indicator |
|---|---|---|
| Total catch | Positive | Phytoplankton, bottomfish, scavengers, herbivores, Dungeness crab + seastar, shallow large rockfish, shallow small rockfish, Dungeness + crab, lingcod prop. mature, midwater rockfish prop. mature, groundfish mean weight at maturity, assessed spp. weight at maturity, reeftop invertebrates, krill |
| | Negative | Piscivore:scavenger |
| Rockfish | Positive | Noncommercial species, roundfish, rockfish, rockfish:flatfish, shallow large + midwater + shortbelly rockfish, shallow + midwater + canary rockfish, lingcod + yelloweye + midwater + large shallow rockfish, zooplanktivorous fish, benthic:pelagic, marine mammal + birds, seabird, marine mammal, finfish:crustacean, cetacean, immature groundfish spp., immature assessed spp., zooplanktivorous fish, noncommercial species B, diving + migratory birds, baleen whales, sea otters |
| | Negative | Phytoplankton, bottomfish, flatfish, invertivores, kelp, seastar abalone urchin, halibut + small flatfish, forage fish:jellyfish, zooplankton, piscivore:planktivore, piscivore, sablefish, shallow large rockfish prop. mature, shortbelly rockfish prop. mature, groundfish mean weight at maturity, piscivores, forage fish, krill, pinnipeds |
| Groundfish prop. mature | Positive | Phytoplankton, bottomfish, flatfish, invertivores, kelp, seastar abalone urchin, halibut + small flatfish, forage fish:jellyfish, zooplankton, piscivore:planktivore, piscivore, invertivore:herbivore, sablefish, shallow large rockfish prop. mature, shortbelly rockfish prop. mature, piscivores, forage fish, krill, salmon, pinnipeds |
| | Negative | Noncommercial species, roundfish, rockfish, rockfish:flatfish, habitat structure, shallow large + midwater + shortbelly rockfish, shallow + midwater + canary rockfish, lingcod + yelloweye + midwater + large shallow rockfish, zooplanktivorous fish, benthic:pelagic, marine mammal + birds, seabird, marine mammal, finfish:crustacean, cetacean, immature groundfish spp., immature assessed spp., habitat structure, zooplanktivorous fish, noncommercial species B, diving + migratory birds, baleen whales, sea otters |

Table A-10. MPAs (based on three scenarios). Indicators that were significantly ($P < 0.05$) and strongly ($|r| > 0.5$) correlated to each attribute in greater than or equal to 20 of 23 simulations.

| Attribute | Correlation | Indicator |
|---|---|---|
| NPP | Positive | Phytoplankton, bottomfish, shallow small rockfish, zooplankton, piscivore:planktivore, piscivore, sablefish, lingcod prop. mature, shallow large rockfish prop. mature, assessed spp. weight at maturity, piscivores, krill |
| | Negative | Rockfish, shallow + midwater + canary rockfish, zooplanktivorous fish, zooplankton:phytoplankton, zooplanktivorous fish |
| NPP:B | Negative | Benthic invertebrates |
| Mean trophic level of B | Positive | Benthic invertebrates |
| Shannon Diversity Index | Positive | Benthic invertebrates |

Table A-10 continued. MPAs (based on three scenarios). Indicators that were significantly ($P < 0.05$) and strongly ($|r| > 0.5$) correlated to each attribute in greater than or equal to 20 of 23 simulations.

| Attribute | Correlation | Indicator |
|---|---|---|
| Shannon Diversity Index (cont.) | Negative | Phytoplankton |
| Total living biomass | Positive | Phytoplankton, benthic invertebrates |
| No. nonassessed below B40 | Positive | Mean trophic level catch, noncommercial species, scavengers, herbivores, habitat structure, Dungeness crab + seastar, shallow large rockfish, Dungeness + crab, marine mammal + birds, seabird, finfish:crustacean, midwater rockfish prop. mature, immature groundfish spp., immature assessed spp., habitat structure, noncommercial species B, diving + migratory birds, baleen whales, sea otters |
| | Negative | Flatfish, invertivores, kelp, seastar abalone urchin, lingcod, halibut + small flatfish, forage fish:jellyfish, piscivore:scavenger, invertivore:herbivore, shortbelly rockfish prop. mature, forage fish, pinnipeds |
| No. nonassessed below B25 | Positive | Mean trophic level catch, noncommercial species, scavengers, herbivores, roundfish, rockfish:flatfish, habitat structure, shallow large + midwater + shortbelly rockfish, Dungeness crab + seastar, shallow large rockfish, Dungeness + crab, lingcod + yelloweye + midwater + large shallow rockfish, marine mammal + birds, seabird, finfish:crustacean, midwater rockfish prop. mature, immature groundfish spp., immature assessed spp., reeftop invertebrates, habitat structure, noncommercial species B, diving + migratory birds, baleen whales, sea otters |
| | Negative | Flatfish, invertivores, kelp, seastar abalone urchin, lingcod, halibut + small flatfish, forage fish:jellyfish, piscivore:planktivore, piscivore:scavenger, invertivore:herbivore, shortbelly rockfish prop. mature, forage fish, pinnipeds |
| Target group biomass | Positive | Flatfish, invertivores, kelp, seastar abalone urchin, lingcod, halibut + small flatfish, forage fish:jellyfish, piscivore:planktivore, piscivore:scavenger, invertivore:herbivore, shortbelly rockfish prop. mature, forage fish, pinnipeds |
| | Negative | Noncommercial species, scavengers, roundfish, rockfish:flatfish, habitat structure, shallow large + midwater + shortbelly rockfish, Dungeness crab + seastar, shallow large rockfish, Dungeness + crab, lingcod + yelloweye + midwater + large shallow rockfish, penthic:pelagic, marine mammal + birds, seabird, finfish:crustacean, midwater rockfish prop mature, immature groundfish spp., immature assessed spp., habitat structure, noncommercial species B, diving + migratory birds, baleen whales, sea otters |
| Total catch | Positive | Scavengers, Dungeness crab + seastar, shallow large rockfish, shallow small rockfish, Dungeness + crab, lingcod prop. mature, midwater rockfish prop. mature, assessed spp. weight at maturity, reeftop invertebrates, krill, sea otters |
| | Negative | Piscivore:scavenger, invertivore:herbivore |
| Rockfish | Positive | No. assessed below B25, noncommercial species, roundfish, rockfish, rockfish:flatfish, shallow large + midwater + shortbelly rockfish, shallow + midwater + canary rockfish, lingcod + yelloweye + midwater + large shallow rockfish, zooplanktivorous fish, benthic:pelagic, marine mammal, finfish:crustacean, cetacean, immature groundfish spp., immature assessed spp., zooplanktivorous fish, noncommercial species B, baleen whales |

Table A-10 continued. MPAs (based on three scenarios). Indicators that were significantly ($P < 0.05$) and strongly ($|r| > 0.5$) correlated to each attribute in greater than or equal to 20 of 23 simulations.

| Attribute | Correlation | Indicator |
|---|---|---|
| Rockfish (cont.) | Negative | Phytoplankton, flatfish, kelp, seastar abalone urchin, halibut + small flatfish, forage fish:jellyfish, piscivore:planktivore, piscivore, sablefish, shallow large rockfish prop. mature, groundfish mean weight at maturity, piscivores, forage fish, krill |
| Groundfish prop. mature | Positive | Phytoplankton, bottomfish, flatfish, invertivores, kelp, seastar abalone urchin, halibut + small flatfish, forage fish:jellyfish, zooplankton, piscivore:planktivore, piscivore, sablefish, shallow large rockfish prop. mature, shortbelly rockfish prop. mature, piscivores, forage fish, salmon, pinnipeds |
| | Negative | Noncommercial species, roundfish, rockfish, rockfish:flatfish, habitat structure, shallow large + midwater + shortbelly rockfish, shallow + midwater + canary rockfish, lingcod + yelloweye + midwater + large shallow rockfish, zooplanktivorous fish, benthic:pelagic, marine mammal + birds, seabird, finfish:crustacean, immature groundfish spp., habitat structure, zooplanktivorous fish, noncommercial species B, diving + migratory birds, baleen whales, sea otters |

metrics of groundfish populations rather than other functional groups. Similarly, detecting impacts of the nutrient scenarios appeared to require more monitoring of mammal and bird groups, with less emphasis on rockfish age structure.

## Spatial Scaling of Indicators

For MPA, nutrients, and fishing hotspot scenarios, we tested the strength of attribute-indicator relationships, varying whether the attributes and indicators were calculated from local or coast-wide data. In general, we found the largest number of significant, strong correlations when correlating coast-wide attributes with coast-wide indicators (Table A-8 through Table A-10).

Comparing local indicators with local attributes or mixing the scale of attributes and indicators generally reduced the number of significant, strong correlations (Table A-11 through Table A-19). However, the indicators identified were mostly a subset of the indicators identified in the coast-wide × coast-wide case. The winnowing of indicators from coast-wide attributes × coast-wide indicators to the other scales was the most pronounced for the MPA scenario, where the coast-wide × coast-wide case identified 119 positive and 89 negatively correlated indicators × attribute combinations, while the local × local case identified only 6 positively and 7 negatively correlated combinations. Mixing the scales of indicators and attributes (local × coast-wide and vice versa) led to an intermediate number of both positive and negative correlations. For the nutrient and the fishing hotspots scenarios, the local attribute × local indicator scale had 23% and 14% fewer attribute-indicator combinations than did the coast-wide × coast-wide scale, and mixed scales had an intermediate number of attribute-indicator combinations. The winnowing of indicators may be due to that fact that many of them reflect our (NMFS) orientation toward coast-wide monitoring efforts and management, while local applications require a different set of indicators.

Table A-11. MPAs scenarios, coast-wide attributes × local indicators. Indicators that were significantly ($P < 0.05$) and strongly ($|r| > 0.5$) correlated to each attribute in greater than or equal to 20 of 23 simulations.

| Attribute | Correlation | Indicator |
|---|---|---|
| NPP | Positive | Shallow large rockfish prop. mature, assessed spp. weight at maturity |
| NPP:B | Negative | Benthic invertebrates |
| Mean trophic level of B | Positive | Benthic invertebrates |
| Shannon Diversity Index | Positive | Benthic invertebrates |
| Total living biomass | Positive | Benthic invertebrates |
| No. nonassessed below B40 | Positive | Sea otters |
| | Negative | Kelp, seastar abalone urchin, pinnipeds |
| No. nonassessed below B25 | Positive | Habitat structure, habitat structure, sea otters |
| | Negative | Kelp, seastar abalone urchin, lingcod, pinnipeds |
| Target group biomass | Positive | Invertivores, kelp, seastar abalone urchin, pinnipeds |
| | Negative | Roundfish, habitat structure, shallow large + midwater + shortbelly rockfish, lingcod + yelloweye + midwater + large shallow rockfish, finfish:crustacean, habitat structure, sea otters |
| Total catch | Positive | Assessed spp. weight at maturity, sea otters |
| Rockfish | Positive | Roundfish, rockfish, shallow large + midwater + shortbelly rockfish, shallow + midwater + canary rockfish, lingcod + yelloweye + midwater + large shallow rockfish, zooplanktivorous fish, marine mammal, finfish:crustacean, cetacean, zooplanktivorous fish |
| | Negative | Invertivores, kelp, seastar abalone urchin, piscivore:planktivore, shallow large rockfish prop. mature, groundfish mean weight at maturity |
| Groundfish prop. mature | Positive | Invertivores, kelp, piscivore:planktivore, shallow large rockfish prop. mature, pinnipeds |
| | Negative | Roundfish, habitat structure, shallow large + midwater + shortbelly rockfish, shallow + midwater + canary rockfish, lingcod + yelloweye + midwater + large shallow rockfish, zooplanktivorous fish, finfish:crustacean, habitat structure, zooplanktivorous fish, sea otters |

Table A-12. MPAs, local attributes × coast-wide indicators. Indicators that were significantly ($P < 0.05$) and strongly ($|r| > 0.5$) correlated to each attribute in greater than or equal to 20 of 23 simulations.

| Attribute | Correlation | Indicator |
|---|---|---|
| NPP | | [None] |
| NPP:B | Negative | Benthic invertebrates |
| Mean trophic level of B | Positive | Benthic invertebrates |
| Shannon Diversity Index | | [None] |
| Total living biomass | | [None] |
| No. nonassessed below B40 | | [None] |

Table A-12 continued. MPAs, local attributes × coast-wide indicators. Indicators that were significantly ($P < 0.05$) and strongly ($|r| > 0.5$) correlated to each attribute in greater than or equal to 20 of 23 simulations.

| **Attribute** | **Correlation** | **Indicator** |
|---|---|---|
| No. nonassessed below B25 | Positive | Mean trophic level catch, noncommercial species, scavengers, herbivores, habitat structure, Dungeness crab + seastar, shallow large rockfish, Dungeness + crab, marine mammal + birds, seabird, finfish:crustacean, midwater rockfish prop. mature, immature groundfish spp., immature assessed spp., habitat structure, noncommercial species B, diving + migratory birds, baleen whales, sea otters |
| | Negative | Flatfish, invertivores, kelp, seastar abalone urchin, lingcod, halibut + small flatfish, forage fish:jellyfish, piscivore:scavenger, invertivore:herbivore, shortbelly rockfish prop. mature, forage fish, pinnipeds |
| Target group biomass | | [None] |
| Total catch | | [None] |
| Rockfish | Positive | Roundfish, rockfish, shallow + midwater + canary rockfish, zooplanktivorous fish, benthic:pelagic, zooplanktivorous fish |
| | Negative | Piscivore:planktivore, shallow large rockfish prop. mature |
| Groundfish prop. mature | | [None] |

Table A-13. MPAs, local attributes × local indicators. Indicators that were significantly ($P < 0.05$) and strongly ($|r| > 0.5$) correlated to each attribute in greater than or equal to 20 of 23 simulations.

| **Attribute** | **Correlation** | **Indicator** |
|---|---|---|
| NPP | | [None] |
| NPP:B | Negative | Benthic invertebrates |
| Mean trophic level of B | Positive | Benthic invertebrates |
| Shannon Diversity Index | | [None] |
| Total living biomass | | [None] |
| No. nonassessed below B40 | | [None] |
| No. nonassessed below B25 | Positive | Sea otters |
| | Negative | Kelp, seastar abalone urchin, lingcod, pinnipeds |
| Target group biomass | | [None] |
| Total catch | | [None] |
| Rockfish | Positive | Roundfish, rockfish, shallow + midwater +canary rockfish, zooplanktivorous fish |
| | Negative | Piscivore:planktivore, shallow large rockfish prop. mature |
| Groundfish prop. mature | | [None] |

Table A-14. Nutrient scenarios, coast-wide attributes × local indicators. Indicators that were significantly ($P < 0.05$) and strongly ($|r| > 0.5$) correlated to each attribute in greater than or equal to 20 of 23 simulations.

| Attribute | Correlation | Indicator |
|---|---|---|
| NPP | Positive | Total catch |
| | Negative | Noncommercial species, noncommercial species B |
| NPP:B | Negative | Benthic invertebrates |
| Mean trophic level of B | Positive | Benthic invertebrates |
| Shannon Diversity Index | | [None] |
| Total living biomass | Positive | Benthic invertebrates |
| | Negative | Noncommercial species, noncommercial species B |
| No. nonassessed below B40 | Positive | Shallow large rockfish |
| | Negative | Noncommercial species, noncommercial species B, pinnipeds |
| No. nonassessed below B25 | Positive | Kelp |
| | Negative | Kelp |
| Target group biomass | Positive | Phytoplankton, scavengers, invertivores, kelp, seastar abalone urchin, piscivore:planktivore, seabird, shallow large rockfish prop. mature, reeftop invertebrates, diving + migratory birds, pinnipeds |
| | Negative | Gelatinous zooplankton, marine mammal, cetacean, sea otters |
| Total catch | | [None] |
| Rockfish | Positive | Bottomfish, roundfish, rockfish, shallow large + midwater + shortbelly rockfish, shallow + midwater + canary rockfish, Dungeness + crab, lingcod + yelloweye + midwater + large shallow rockfish, gelatinous zooplankton, zooplanktivorous fish, marine mammal, finfish:crustacean, cetacean, immature groundfish spp., zooplanktivorous fish, sea otters |
| | Negative | Phytoplankton, scavengers, invertivores, kelp, seastar abalone urchin, piscivore:planktivore, seabird, reeftop invertebrates, diving + migratory birds, pinnipeds |
| Groundfish prop. mature | Positive | Phytoplankton, scavengers, invertivores, kelp, seastar abalone urchin, piscivore:planktivore, seabird, reeftop invertebrates, diving + migratory birds, pinnipeds |
| | Negative | Bottomfish, roundfish, rockfish, shallow large + midwater + shortbelly rockfish, shallow + midwater + canary rockfish, lingcod + yelloweye + midwater + large shallow rockfish, gelatinous zooplankton, zooplanktivorous fish, piscivore:scavenger, marine mammal, finfish:crustacean, cetacean, immature groundfish spp., zooplanktivorous fish, sea otters |

Table A-15. Nutrient scenarios, local attributes × coast-wide indicators. Indicators that were significantly ($P < 0.05$) and strongly ($|r| > 0.5$) correlated to each attribute in greater than or equal to 20 of 23 simulations.

| **Attribute** | **Correlation** | **Indicator** |
|---|---|---|
| NPP | Positive | Scavengers, habitat structure, Dungeness crab + seastar, Dungeness + crab, marine mammal + birds, seabird, reeftop invertebrates, habitat structure, diving + migratory birds, baleen whales, sea otters |
| | Negative | Piscivore:scavenger, shortbelly rockfish prop. mature, pinnipeds |
| NPP:B | Positive | Habitat structure, habitat structure |
| Mean trophic level of B | Positive | Benthic invertebrates |
| Shannon Diversity Index | Negative | Benthic invertebrates |
| Total living biomass | Positive | Benthic invertebrates |
| No. nonassessed below B40 | Positive | Scavengers, Dungeness crab + seastar, shallow large rockfish, Dungeness + crab, marine mammal + birds, seabird, midwater rockfish prop. mature, diving + migratory birds, baleen whales |
| | Negative | Seastar abalone urchin, lingcod, piscivore:scavenger, pinnipeds |
| No. nonassessed below B25 | Positive | Scavengers, Dungeness crab + seastar, shallow large rockfish, Dungeness + crab, marine mammal + birds, seabird, midwater rockfish prop. mature, diving + migratory birds, baleen whales |
| | Negative | Flatfish, invertivores, seastar abalone urchin, halibut + small flatfish, forage fish:jellyfish, piscivore:scavenger, forage fish, pinnipeds |
| Target group biomass | Positive | Roundfish, rockfish, rockfish:flatfish, shallow large + midwater + shortbelly rockfish, shallow + midwater + canary rockfish, lingcod + yelloweye + midwater + large shallow rockfish, zooplanktivorous fish, marine mammal, cetacean, immature groundfish spp., zooplanktivorous fish |
| | Negative | Kelp, piscivore:planktivore, lingcod prop. mature, assessed spp. weight at maturity, forage fish, krill |
| Total catch | Positive | Phytoplankton, bottomfish, lingcod prop. mature, krill |
| Rockfish | Positive | Roundfish, rockfish, rockfish:flatfish, shallow large + midwater + shortbelly rockfish, shallow + midwater + canary rockfish, lingcod + yelloweye + midwater + large shallow rockfish, zooplanktivorous fish, benthic:pelagic, marine mammal + birds, seabird, marine mammal, finfish:crustacean, cetacean, immature groundfish spp., immature assessed spp., zooplanktivorous fish, diving + migratory birds, sea otters |
| | Negative | Invertivores, kelp, seastar abalone urchin, forage fish:jellyfish, zooplankton, piscivore:planktivore, piscivore, sablefish, piscivores, forage fish, krill, pinnipeds |
| Groundfish prop. mature | | [None] |

Table A-16. Nutrient scenarios, local attributes × local indicators. Indicators that were significantly ($P < 0.05$) and strongly ($|r| > 0.5$) correlated to each attribute in greater than or equal to 20 of 23 simulations.

| Attribute | Correlation | Indicator |
|---|---|---|
| NPP | Positive | Habitat structure, shallow large rockfish, habitat structure, sea otters |
| | Negative | Piscivore:planktivore, marine mammal + birds, pinnipeds |
| NPP:B | Positive | Habitat structure, habitat structure |
| Mean trophic level of B | Positive | Benthic invertebrates |
| Shannon Diversity Index | Negative | Benthic invertebrates |
| Total living biomass | Positive | Benthic invertebrates |
| No. nonassessed below B40 | Negative | Noncommercial species, lingcod, noncommercial species B, pinnipeds |
| No. nonassessed below B25 | Positive | Shallow large rockfish |
| | Negative | Phytoplankton, noncommercial species, invertivores, seastar abalone urchin, reeftop invertebrates, noncommercial species B, pinnipeds |
| Target group biomass | Positive | Roundfish, rockfish, shallow large + midwater + shortbelly rockfish, shallow + midwater + canary rockfish, Dungeness + crab, lingcod + yelloweye + midwater + large shallow rockfish, gelatinous zooplankton, zooplanktivorous fish, marine mammal, finfish:crustacean, cetacean, immature groundfish spp., zooplanktivorous fish |
| | Negative | Total catch, kelp, zooplankton, zooplankton:phytoplankton, piscivore:planktivore, seabird, assessed spp. weight at maturity, krill, diving + migratory birds |
| Total catch | Positive | Zooplankton, zooplankton:phytoplankton, midwater rockfish prop. mature, krill |
| | Negative | Noncommercial species, immature groundfish spp., noncommercial species B |
| Rockfish | Positive | Bottomfish, roundfish, rockfish, shallow large + midwater + shortbelly rockfish, shallow + midwater + canary rockfish, Dungeness + crab, lingcod + yelloweye + midwater + large shallow rockfish, gelatinous zooplankton, zooplanktivorous fish, marine mammal, finfish:crustacean, cetacean, immature groundfish spp., zooplanktivorous fish, sea otters |
| | Negative | Scavengers, invertivores, kelp, seastar abalone urchin, piscivore:planktivore, seabird, reeftop invertebrates, diving + migratory birds, pinnipeds |
| Groundfish prop. mature | | [None] |

Table A-17. Fishing hotspots, coast-wide attributes × local indicators. Indicators that were significantly ($P < 0.05$) and strongly ($|r| > 0.5$) correlated to each attribute in greater than or equal to 20 of 23 simulations.

| Attribute | Correlation | Indicator |
|---|---|---|
| NPP | Positive | Total catch, shallow large rockfish, zooplankton, assessed spp. weight at maturity, krill |
| | Negative | Zooplanktivorous fish, zooplanktivorous fish |
| NPP:B | Negative | Benthic invertebrates |
| Mean trophic level of B | Positive | Benthic invertebrates |
| Shannon Diversity Index | Positive | Benthic invertebrates |
| | Negative | Mean trophic level catch |
| Total living biomass | Positive | Benthic invertebrates |
| No. nonassessed below B40 | Positive | Mean trophic level catch, scavengers, Dungeness crab + seastar, Dungeness + crab, marine mammal + birds, seabird, diving + migratory birds, baleen whales, sea otters |
| | Negative | Flatfish, invertivores, seastar abalone urchin, halibut + small flatfish, piscivore:scavenger, piscivore, invertivore:herbivore, sablefish, shortbelly rockfish prop. mature, piscivores, forage fish, pinnipeds |
| No. nonassessed below B25 | Positive | Mean trophic level catch, scavengers, Dungeness crab + seastar, Dungeness + crab, gelatinous zooplankton, marine mammal + birds, seabird, reeftop invertebrates, diving + migratory birds, baleen whales, sea otters |
| | Negative | Flatfish, invertivores, kelp, seastar abalone urchin, lingcod, halibut + small flatfish, forage fish:jellyfish, piscivore:scavenger, piscivore, invertivore:herbivore, sablefish, shortbelly rockfish prop. mature, immature groundfish spp., immature assessed spp., piscivores, forage fish, pinnipeds |
| Target group biomass | Positive | Bottomfish, flatfish, invertivores, kelp, seastar abalone urchin, lingcod, halibut + small flatfish, shallow small rockfish, forage fish:jellyfish, piscivore:planktivore, piscivore:scavenger, piscivore, invertivore:herbivore, sablefish, shallow large rockfish prop. mature, shortbelly rockfish prop. mature, immature groundfish spp., immature assessed spp., piscivores, forage fish, pinnipeds |
| | Negative | Scavengers, rockfish:flatfish, shallow large + midwater + shortbelly rockfish, Dungeness crab + seastar, shallow + midwater + canary rockfish, Dungeness + crab, lingcod + yelloweye + midwater + large shallow rockfish, gelatinous zooplankton, zooplanktivorous fish, benthic:pelagic, marine mammal + birds, seabird, marine mammal, finfish:crustacean, cetacean, reeftop invertebrates, zooplanktivorous fish, diving + migratory birds, baleen whales, sea otters |
| Total catch | Positive | Noncommercial species, herbivores, shallow large rockfish, zooplankton:phytoplankton, lingcod prop. mature, midwater rockfish prop. mature, groundfish mean weight at maturity, assessed spp. weight at maturity, krill, noncommercial species B |

Table A-17 continued. Fishing hotspots, coast-wide attributes × local indicators. Indicators that were significantly ($P < 0.05$) and strongly ($|r| > 0.5$) correlated to each attribute in greater than or equal to 20 of 23 simulations.

| Attribute | Correlation | Indicator |
|---|---|---|
| Rockfish | Positive | Scavengers, rockfish, rockfish:flatfish, shallow large + midwater + shortbelly rockfish, Dungeness crab + seastar, shallow + midwater + canary rockfish, Dungeness + crab, lingcod + yelloweye + midwater + large shallow rockfish, gelatinous zooplankton, zooplanktivorous fish, marine mammal + birds, seabird, marine mammal, finfish:crustacean, cetacean, zooplanktivorous fish, diving + migratory birds, sea otters |
| | Negative | Bottomfish, flatfish, invertivores, kelp, seastar abalone urchin, halibut + small flatfish, shallow small rockfish, forage fish:jellyfish, piscivore:planktivore, piscivore:scavenger, piscivore, sablefish, lingcod prop. mature, shallow large rockfish prop. mature, shortbelly rockfish prop. mature, immature groundfish spp., immature assessed spp., groundfish mean weight at maturity, piscivores, forage fish, krill, pinnipeds |
| Groundfish prop. mature | Positive | Bottomfish, flatfish, invertivores, kelp, seastar abalone urchin, halibut + small flatfish, shallow small rockfish, forage fish:jellyfish, piscivore:planktivore, piscivore:scavenger, piscivore, invertivore:herbivore, sablefish, shallow large rockfish prop. mature, shortbelly rockfish prop. mature, immature groundfish spp., piscivores, forage fish, salmon, pinnipeds |
| | Negative | Scavengers, rockfish, rockfish:flatfish, shallow large + midwater + shortbelly rockfish, Dungeness crab + seastar, shallow + midwater + canary rockfish, Dungeness + crab, lingcod + yelloweye + midwater + large shallow rockfish, gelatinous zooplankton, zooplanktivorous fish, marine mammal + birds, seabird, marine mammal, finfish:crustacean, cetacean, reeftop invertebrates, zooplanktivorous fish, diving + migratory birds, sea otters |

Table A-18. Fishing hotspots, local attributes × coast-wide indicators. Indicators that were significantly ($P < 0.05$) and strongly ($|r| > 0.5$) correlated to each attribute in greater than or equal to 20 of 23 simulations.

| Attribute | Correlation | Indicator |
|---|---|---|
| NPP | Positive | Shallow large rockfish prop. mature |
| | Negative | Shallow large rockfish, marine mammal + birds, seabird, midwater rockfish prop. mature, diving + migratory birds |
| NPP:B | Negative | Benthic invertebrates |
| Mean trophic level of B | Positive | Benthic invertebrates |
| Shannon Diversity Index | Negative | Benthic invertebrates |
| Total living biomass | Positive | Benthic invertebrates |

Table A-18 continued. Fishing hotspots, local attributes × coast-wide indicators. Indicators that were significantly ($P < 0.05$) and strongly ($|r| > 0.5$) correlated to each attribute in greater than or equal to 20 of 23 simulations.

| Attribute | Correlation | Indicator |
|---|---|---|
| No. nonassessed below B40 | Positive | Mean trophic level catch, noncommercial species, roundfish, rockfish, rockfish:flatfish, habitat structure, shallow large + midwater + shortbelly rockfish, Dungeness crab + seastar, shallow large rockfish, shallow + midwater + canary rockfish, Dungeness + crab, lingcod + yelloweye + midwater + large shallow rockfish, zooplanktivorous fish, benthic:pelagic, marine mammal + birds, seabird, marine mammal, finfish:crustacean, cetacean, midwater rockfish prop. mature, immature groundfish spp., immature assessed spp., habitat structure, zooplanktivorous fish, noncommercial species B, diving + migratory birds, baleen whales, sea otters |
| | Negative | Flatfish, invertivores, kelp, seastar abalone urchin, lingcod, halibut + small flatfish, forage fish:jellyfish, piscivore:planktivore, piscivore:scavenger, piscivore, invertivore:herbivore, shallow large rockfish prop. mature , shortbelly rockfish prop. mature, piscivores, forage fish, pinnipeds |
| No. nonassessed below B25 | Positive | Mean trophic level catch, noncommercial species, rockfish:flatfish, shallow large + midwater + shortbelly rockfish, shallow large rockfish, lingcod + yelloweye + midwater + large shallow rockfish, benthic:pelagic, marine mammal + birds, seabird, marine mammal, finfish:crustacean, cetacean, midwater rockfish prop. mature, immature groundfish spp., immature assessed spp., noncommercial species B, diving + migratory birds, baleen whales, sea otters |
| | Negative | Flatfish, invertivores, kelp, seastar abalone urchin, lingcod, halibut + small flatfish, forage fish:jellyfish, piscivore:scavenger, ivertivore:herbivore, shallow large rockfish prop. mature, Shortbelly rockfish prop. mature, forage fish, pinnipeds |
| Target group biomass | Positive | Flatfish, invertivores, kelp, seastar abalone urchin, lingcod, halibut + small flatfish, forage fish:jellyfish, piscivore:planktivore, piscivore:scavenger, piscivore, invertivore:herbivore, shallow large rockfish prop. mature, shortbelly rockfish prop. mature, piscivores, forage fish, pinnipeds |
| | Negative | Noncommercial species, scavengers, roundfish, rockfish, rockfish:flatfish, habitat structure, shallow large + midwater + shortbelly rockfish, Dungeness crab + seastar, shallow large rockfish, shallow + midwater + canary rockfish, Dungeness + crab, lingcod + yelloweye + midwater + large shallow rockfish, zooplanktivorous fish, benthic:pelagic, marine mammal + birds, seabird, marine mammal, finfish:crustacean, cetacean, midwater rockfish prop. mature, immature groundfish spp., immature assessed spp., habitat structure, zooplanktivorous fish, noncommercial species B, diving + migratory birds, baleen whales, sea otters |
| Total catch | Positive | Phytoplankton, bottomfish, scavengers, Dungeness crab + seastar, shallow large rockfish, shallow small rockfish, Dungeness + crab, sablefish, lingcod prop. mature, groundfish mean weight at maturity, assessed spp. weight at maturity, reeftop invertebrates, krill |

Table A-18 continued. Fishing hotspots, local attributes × coast-wide indicators. Indicators that were significantly ($P < 0.05$) and strongly ($|r| > 0.5$) correlated to each attribute in greater than or equal to 20 of 23 simulations.

| Attribute | Correlation | Indicator |
|---|---|---|
| Rockfish | Positive | Roundfish, rockfish, rockfish:flatfish, shallow large + midwater + shortbelly rockfish, shallow + midwater + canary rockfish, lingcod + yelloweye + midwater + large shallow rockfish, zooplanktivorous fish, benthic:pelagic, marine mammal, finfish:crustacean, cetacean, immature groundfish spp., immature assessed spp., zooplanktivorous fish |
| | Negative | Kelp, forage fish:jellyfish, piscivore:planktivore, piscivore, shallow large rockfish prop. mature, groundfish mean weight at maturity, piscivores, forage fish |
| Groundfish prop. mature | Negative | Shallow large rockfish, midwater rockfish prop. mature |

Table A-19. Fishing hotspots, local attributes × local indicators. Indicators that were significantly ($P < 0.05$) and strongly ($|r| > 0.5$) correlated to each attribute in greater than or equal to 20 of 23 simulations.

| Attribute | Correlation | Indicator |
|---|---|---|
| NPP | Positive | Phytoplankton, piscivore:scavenger, shallow large rockfish prop. mature |
| | Negative | Zooplankton:phytoplankton |
| NPP:B | Positive | Phytoplankton |
| | Negative | Benthic invertebrates |
| Mean trophic level of B | Positive | Benthic invertebrates |
| | Negative | Phytoplankton |
| Shannon Diversity Index | Negative | Phytoplankton, benthic invertebrates |
| Total living biomass | Positive | Benthic invertebrates |
| No. nonassessed below B40 | Positive | Mean trophic level catch, scavengers, rockfish:flatfish, shallow large + midwater + shortbelly rockfish, Dungeness crab + seastar, shallow + midwater + canary rockfish, Dungeness + crab, lingcod + yelloweye + midwater + large shallow rockfish, gelatinous zooplankton, zooplanktivorous fish, benthic:pelagic, marine mammal + birds, seabird, marine mammal, cetacean, zooplanktivorous fish, diving + migratory birds, baleen whales, sea otters |
| | Negative | Bottomfish, flatfish, invertivores, kelp, seastar abalone urchin, lingcod, halibut + small flatfish, shallow small rockfish, forage fish:jellyfish, piscivore:planktivore, piscivore:scavenger, piscivore, invertivore:herbivore, sablefish, shallow large rockfish prop. mature, shortbelly rockfish prop. mature, immature groundfish spp., immature assessed spp., piscivores, forage fish, pinnipeds |
| No. nonassessed below B25 | Positive | Mean trophic level catch, scavengers, rockfish:flatfish, shallow large + midwater + shortbelly rockfish, Dungeness crab + seastar, Dungeness + crab, lingcod + yelloweye + midwater + large shallow rockfish, gelatinous zooplankton, benthic:pelagic, marine mammal + birds, seabird, marine mammal, cetacean, diving + migratory birds, baleen whales, sea otters |

Table A-19 continued. Fishing hotspots, local attributes × local indicators. Indicators that were significantly ($P < 0.05$) and strongly ($|r| > 0.5$) correlated to each attribute in greater than or equal to 20 of 23 simulations.

| Attribute | Correlation | Indicator |
|---|---|---|
| No. nonassessed below B25 (cont.) | Negative | Bottomfish, flatfish, invertivores, kelp, seastar abalone urchin, lingcod, halibut + small flatfish, shallow small rockfish, forage fish:jellyfish, piscivore:planktivore, piscivore:scavenger, piscivore, invertivore:herbivore, sablefish, shallow large rockfish prop. mature, shortbelly rockfish prop. mature, immature groundfish spp., immature assessed spp., piscivores, forage fish, pinnipeds |
| Target group biomass | Positive | Bottomfish, flatfish, invertivores, kelp, seastar abalone urchin, lingcod, halibut + small flatfish, shallow small rockfish, forage fish:jellyfish, piscivore:planktivore, piscivore:scavenger, piscivore, invertivore:herbivore, sablefish, shallow large rockfish prop. mature, shortbelly rockfish prop. mature, immature groundfish spp., immature assessed spp., piscivores, forage fish, pinnipeds |
| | Negative | Scavengers, rockfish:flatfish, shallow large + midwater + shortbelly rockfish, Dungeness crab + seastar, shallow + midwater + canary rockfish, Dungeness + crab, lingcod + yelloweye + midwater + large shallow rockfish, gelatinous zooplankton, zooplanktivorous fish, benthic:pelagic, marine mammal + birds, seabird, marine mammal, finfish:crustacean, cetacean, reeftop invertebrates, zooplanktivorous fish, diving + migratory birds, baleen whales, sea otters |
| Total catch | Positive | Noncommercial species, herbivores, shallow large rockfish, zooplankton:phytoplankton, lingcod prop. mature, midwater rockfish prop. mature, groundfish mean weight at maturity, assessed spp. weight at maturity, krill, noncommercial species B |
| Rockfish | Positive | Roundfish, rockfish, rockfish:flatfish, shallow large + midwater + shortbelly rockfish, shallow + midwater + canary rockfish, lingcod + yelloweye + midwater + large shallow rockfish, zooplanktivorous fish, marine mammal, finfish:crustacean, cetacean, zooplanktivorous fish |
| | Negative | Kelp, seastar abalone urchin, shallow small rockfish, piscivore:planktivore, piscivore, sablefish, lingcod prop. mature, shallow large rockfish prop. mature, groundfish mean weight at maturity, piscivores, forage fish |
| Groundfish prop. mature | | [None] |

The nutrient scenarios were a partial exception to this winnowing effect. Though the total number of selected attribute-indicator pairs did decrease at the local and mixed spatial scales, relative to the coast-wide × coast-wide case, analysis of these scales identified several additional indicator-attribute combinations. Comparing the local attributes × local indicators scale to the coast-wide attributes × coast-wide indicators scale, the former added the following positively correlated indicators that were not selected at all in the coast-wide case: krill, habitat structure, zooplankton, zooplankton:phytoplankton, and gelatinous zooplankton. Negatively correlated indicators included in the local × local case but not coast-wide included total catch, noncommercial species, scavengers, reeftop invertebrates, and assessed species' mean weight at maturity. Twenty other indicators were correlated with at least one attribute at both scales, but gained significant attribute-indicator pairings at the local scale. As described above in the

Analysis of Scenario Types subsection, the nutrient scenarios had a larger sample size than the MPA or fishing hotspot scenarios and better ability to filter indicators from the larger set identified in the full analysis of all scenarios. Thus the trends seen in the nutrient scenarios—addition of some new indicator-attribute pairs as we move from coast-wide to local scales—should be given more weight than the pure reduction in indicators seen for MPAs and fishing hotspots.

In terms of downscaling coast-wide indicators (e.g., trawl survey data) to local attributes (e.g., state or NMS waters), we identified only three attributes that were good candidates for this: mean trophic level of biomass, number of unassessed species below B25, and rockfish biomass. Across the three types of spatial scenarios, mean trophic level of biomass was only consistently correlated with benthic invertebrates and we will not discuss it further. The attribute rockfish was consistently negatively related to the piscivore:planktivore ratio and positively related to roundfish, rockfish, zooplanktivorous fish, the benthic:pelagic ratio, and shallow + midwater + canary rockfish biomass.

Overall, the results for the rockfish attribute are not surprising, since all of these selected indicators are direct metrics of rockfish stocks and local population dynamics are partially driven by coast-wide processes (recruitment). The attribute number of unassessed species below B25 was positively related to shallow large rockfish, marine mammals, seabirds, midwater rockfish percent mature, baleen whales, and diving and migratory birds. This attribute was also negatively correlated with flatfish, invertivores, seastar + abalone + urchins, halibut + small flatfish, forage fish, piscivores:scavengers, and pinnipeds. The implication is that when coast-wide stocks of flatfish, some invertebrates, forage fish, pinnipeds, and piscivores are high, unassessed species are likely to be locally abundant. Conversely, when some mammal and bird groups are abundant coast wide, unassessed groups are more likely to be locally depleted.

Our analysis does not support attempts to gain information about coast-wide attributes of ecosystem health by scaling up local indicators. Overall, only a few attribute × indicator combinations appeared suited to this upscaling. The attribute mean trophic level of biomass was only (positively) correlated to benthic invertebrate abundance. Total living biomass was also only (positively) correlated to benthic invertebrate abundance, and NPP:B was therefore negatively related to benthic invertebrates (since the former attribute is the denominator of the latter). No indicator was consistently suitable for upscaling to inform NPP or the Shannon Diversity Index. The number of nonassessed species below B40 was only negatively related to pinniped abundance. The number of nonassessed species below B25 was positively related to sea otter abundance and negatively related to pinniped abundance, lingcod (*Ophiodon elongatus*), seastar + abalone + urchins, and kelp.

Thus of all the attributes of ecosystem health, the strongest possibility of appropriate upscaling might be that when local (e.g., nearshore) monitoring of a group such as kelp or pinnipeds revealed changes in abundance, we might expect changes in abundance in the same direction for unassessed species. Overall, many of the components and species involved in our ecosystem health metrics are sessile and the modeled population dynamics of invertebrates in particular are inherently local; therefore, extrapolating ecosystem health to a large region from local monitoring is risky.

The analysis does support the scaling up of certain local indicators to inform the status of coast-wide attributes related to groundfish. Eighteen indicators appeared suitable for upscaling, meaning the use of local indicators (e.g., scuba or remotely operated vehicle monitoring) as a proxy for coast-wide attributes. Many of these 18 indicators were direct metrics of groundfish populations. Target group biomass and groundfish proportion mature had similar sets of relevant indicators at the coast-wide × coast-wide scale; here for upscaling they both showed positive correlations for invertivores, kelp, and pinnipeds, and negative correlations for sea otters. Coast-wide groundfish proportion mature was also negatively correlated with local indices of total rockfish abundance, as it had been with coast-wide indices of total rockfish abundance. These included lingcod + yelloweye + midwater + large shallow rockfish, finfish:crustaceans, zooplanktivorous fish, shallow + midwater + canary rockfish, and shallow large + midwater + shortbelly rockfish. As might be expected a priori, the coast-wide rockfish attribute was positively correlated with seven metrics of local rockfish abundance and negatively correlated to piscivore:planktivore ratio (most rockfish are categorized as planktivores).

Coast-wide rockfish was also positively correlated with local crustaceans, marine mammals, and cetaceans, and negatively correlated with invertivores, kelp, and seastars + abalone + urchins. The attribute total catch did not appear to have any indicators suitable for this sort of upscaling; one factor contributing to this may be that much of the total catch occurred in the boxes deeper than 50 m, while many of the local boxes for the nutrient, fishing, and hotspot scenarios were in the 0–50 m zone. The appropriateness of extrapolating information from the local scale to the regional for groundfish is not surprising, since in some sense all sampling programs (e.g., Keller et al. 2007) only capture a subset of the domain inhabited by a species, and must be scaled up to stock-wide estimates (e.g., generalized linear mixed model in Kaplan and Helser 2007). Clearly this sort of extrapolation is most appropriate for metrics related to mobile species, for which migration, dispersal, and recruitment link local cells.

Ignoring which particular attributes were significantly related to the indicators, 12 indicators provided information for downscaling and upscaling. This means that for all three types of spatial scenarios, these indicators were significantly and consistently correlated with at least one coast-wide attribute when calculated from local data, and with at least one local attribute when calculated from coast-wide data. Positive correlations included the indicators rockfish, shallow + midwater + canary rockfish, zooplanktivorous fish, finfish:crustaceans, and sea otters. Negative correlations included the indicators invertivores, kelp, seastar + abalone + urchins, lingcod, piscivores:planktivores, and pinnipeds. Benthic invertebrates provided downscaling and upscaling information, and were positively correlated to some attributes and negatively correlated with others.

The importance of 9 of these 12 indicators might be anticipated, since they are based on fish and mammal abundances that respond in similar ways across the model domain, driven by stock-wide population dynamics (e.g., recruitment and migration) in addition to local processes. Less intuitively, indicators involving sessile species such as kelp and invertebrates show spatial synchrony; this is partly driven by trends in most scenarios that echo the status quo (Horne et al. 2010). In status quo, kelp (macroalgae), sea urchins (benthic grazers), and bivalves (other benthic filter feeders) decline sharply and crabs (megazoobenthos) increase sharply.

# Discussion

We found that most of the attributes of interest had one or more strongly correlated indicators ($|r| > 0.5$). Our correlation testing identified 17 of 75 indicators that were positively correlated to attributes of ecosystem health and 12 that were negatively related. Attributes of groundfish were positively related to 29 indicators and negatively related to 31 indicators (Table A-5). The disparity between the number of suitable indicators for these two types of attributes is likely due to the fact that many indicators we tested are currently collected as part of monitoring programs focused on groundfish. However, our correlation analysis also identified suitable indicators of groundfish status that are derived from other groups, such as forage fish, invertebrates, and biomass ratios such as piscivores:planktivores. We found that very strong correlations ($|r| > 0.7$) between indicators and attributes were rare, limited to benthic invertebrates (as an indicator of ecosystem health) and direct measures of rockfish abundance (as indicators of rockfish and groundfish proportion mature).

Detecting the impacts of particular types of drivers and pressures may require tailoring the subset of indicators calculated. For instance, detecting impacts of the fishing scenarios on groundfish required more indicators that were direct metrics of groundfish populations rather than other functional groups. Similarly, detecting impacts of the nutrient scenarios on groundfish appeared to require more monitoring of mammal and bird groups, with less emphasis on rockfish age structure. Table A-6 and Table A-8 present these tailored sets of indicators and attributes. The set of indicators related to attributes of ecosystem health did not change substantially as we altered the type of driver or pressure.

The consideration of spatial scaling of indicators in three sets of spatially heterogeneous scenarios identified five main conclusions:

1. The analysis suggested that many attribute-indicator relationships that are strong at a coast-wide scale break down at local scales and are not appropriate for downscaling or upscaling (a winnowing effect).
2. Results from the nutrient scenario, which was the only case with nonfishing perturbations, identified additional indicators that could be used to monitor local attributes, but were poorly correlated with regional attributes. This is particularly important since the nutrient scenario had the highest sample size of the scenarios considered here for spatial scaling.
3. Downscaling from coast-wide indicators (e.g., trawl survey) to local attributes (e.g., state waters or sanctuaries) led to low and inconsistent correlations between attributes and indicators. Only 3 attributes and 20 indicator-attribute pairs showed potential for downscaling, compared to 126 pairs for the coast-wide × coast-wide analysis.
4. For attributes related to groundfish, upscaling from local indicators to regional attributes commonly resulted in consistent significant relationships, particularly with indicators related to species groups that had somewhat synchronous coast-wide dynamics. Attempts at upscaling to inform attributes related to ecosystem health were less successful.
5. A subset of nine indicators, primarily related to fish and mammal populations, showed the potential for downscaling and upscaling of monitoring.

In a prior analysis (Kaplan and Levin 2009), we qualitatively evaluated four indicators and their response to fishing intensity, using an earlier version of the California Current Atlantis model (Brand et al. 2007). Three indicators tested in Kaplan and Levin (2009) and in the present document were responsive to the perturbations in ecosystem state in both cases. These were the biomass ratio indicators of piscivore:scavenger, piscivore:planktivore, and benthic:pelagic fish. These indicators were well correlated to attributes related to groundfish and the number of assessed species below B25 and B40, but not to other ecosystem health attributes.

As with Fulton et al. (2005) work in Australia, we found that a suite of indicators was necessary to capture changes to groundfish and ecosystem health and impacts of fishing and nutrient scenarios. In our analysis, no single indicator was well correlated with more than 2 of the 11 attributes. There is much overlap between the indicators selected by Fulton et al. (2005) and our set for the California Current. Both contain direct metrics of primary producers, benthos, top predators, and target species, as well as biomass ratios of particular functional groups. Spatially explicit simulation testing of indicators for southeast Australia (Smith et al. 2010) also found that the best set of indicators proved sensitive to scale. For instance, as for southeast Australia, we found that the ratio of benthic:pelagic fish was a suitable indicator at coast-wide scales, but was not suitable at intermediate scales such as our local zones in the nutrient enrichment scenarios (which covered all nearshore areas <50 m in depth).

Our results suggest a subset of indicators that can be broadly useful as metrics of ecosystem state in the context of NMFS's California Current IEA. These indicators can be used to assess the status and trends in groundfish resources and ecosystem health (Status of the California Current Ecosystem: Major EBM Components section). The approach used here can be extended to identify indicators that are useful in assessing other ecosystem components, such as salmon or forage fish. The present correlation analysis suggests further investigation of the existing monitoring programs that can inform these indicators (Selecting and Evaluating Indicators for the California Current section) and the cost feasibility of increased monitoring in the future. Our analysis of spatial scale suggests a subset of indicator-attribute pairs that can be used at local scales, and a smaller subset of indicator-attribute pairs that can be used to downscale and upscale monitoring and indicators. In the California Current, the data available for indicator calculation are from a variety of spatial scales (Selecting and Evaluating Indicators for the Califoria Current section) and will require careful decisions about their applicability within the IEA. In the context of decision support tools for fishery managers, indicators at the correct scale can be used as metrics to score the performance of alternative policy scenarios tested in a simulation setting (Kaplan et al. in prep.), or to evaluate the performance of management actions in the field.

# Appendix B: Emerging Analyses Using Moving Window Multivariate Autoregressive Models for Leading Indicators of Regime Shifts

A major challenge to forecasting the relationships between exogenous pressures (climate change, harvest, coastal development, etc.) and state variables (populations, food webs, oceanographic conditions, etc.) is the additive effects of these pressures, which conspire to threaten wholesale regime change in large marine ecosystems. Ecosystem responses to environmental change can be gradual and linear or sudden and nonlinear, wherein a slight change in environmental conditions beyond a specific threshold level can induce a shift from the current state to a new, often wholly different state located at a separate equilibrium point (Figure B-1a, Scheffer et al. 2001). Similar shifts can occur following a disturbance or perturbation to the system (Figure B-1b). The propensity of an ecosystem to move from one equilibrium point to another is directly related to system stability (Scheffer et al. 2001). Researchers and managers are challenged to identify the circumstances under which ecosystems will cross critical thresholds and settle into alternate states, and metrics for calculating ecosystem stability are key to this endeavor. The analysis of time series data offers one of the best opportunities to assess such trends and transitions, and is therefore a critical part of the California Current Integrated Ecosystem Assessment process (Fluharty et al. 2006).

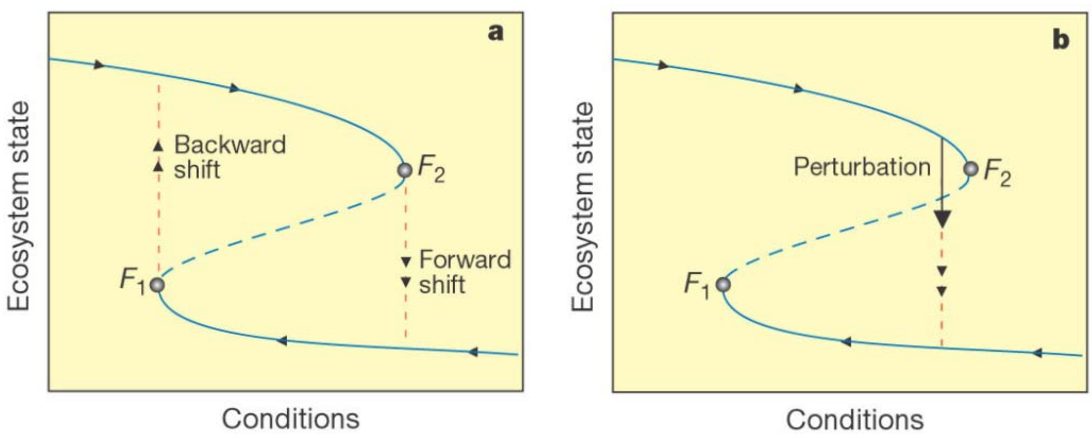


Figure B-1. Panel a, for an ecosystem on the upper branch, close to the bifurcation point $F_2$, a small change in environmental conditions may shift the system beyond the bifurcation and induce a catastrophic shift to the lower alternate stable state (forward shift). A backward shift to the previous state occurs only if conditions are reversed far enough to reach the other bifurcation point, $F_1$. This process is known as hysteresis. Panel b, a perturbation (arrow) or disturbance can also induce a shift to the alternate stable state. An ecosystem's propensity to shift between alternate stable states is dependent on system stability. (Adapted by permission from Macmillan Publishers Ltd., Scheffer et al. in Nature, copyright 2001.)

Predicting ecosystem responses to climate is complicated by the fact that indirect interactions and individual behaviors can stymie expectations about biotic responses to abiotic conditions. Marine population dynamics are tightly linked to environmental conditions such as climate (Walther et al. 2002). However, because ecological communities are more than the sum of their parts, climate change effects cannot be predicted from studies of single species or even pairs of species (Walther 2010). In particular, long-term studies of marine communities are needed to identify nonlinear responses to anthropogenic climate change, including the location of critical thresholds and potential for regime shift (Hoegh-Guldberg and Bruno 2010). Zooplankton are the foundation of the ocean food web, linking oceanographic conditions and primary production to upper trophic levels and fueling the delivery of ocean ecosystem services. As such, zooplankton may provide the best opportunity to understand marine food web responses to climate change.

Given the colinearity among environmental variables and variation in zooplankton abundance at multiple time scales, a multivariate time series approach provides the best opportunity to assess community interactions and the influence of exogenous drivers on trends in abundance over time. We are using multivariate autoregressive (MAR) models (Ives et al. 2003) to quantify zooplankton community interactions and the impact of climate on zooplankton abundance along the Newport Hydrographic Line at Station 5 (NH05). MAR models are multivariate, stochastic models based on a simple linear equation describing change in species abundance through time under density dependence. MAR models are written in matrix form as

$$X_t = A + BX_{t-1} + CU_t + E_t \qquad (6)$$

where, for $P$ interacting species and $q$ environmental covariates, $X_t$ is a $P \times 1$ vector of log-transformed population abundances at time $t$; $A$ is a $P \times 1$ vector of constants, representing intrinsic growth rates; $B$ is a $P \times P$ matrix whose elements are species interactions coefficients, representing the effect, such as predation or competition, of each species on each other species, where diagonal elements are autoregressive coefficients; $X_{t-1}$ is a $P \times 1$ vector of log-transformed species abundances at time $t–1$; $C$ is a $P \times q$ matrix whose elements are the coefficients describing the effects of environmental covariates on species abundance; $U_t$ is a $q \times 1$ vector of environmental covariates at time $t$; and $E_t$ is a $P \times 1$ vector of process error at time $t$, representing environmental variation.

MAR models describe changes in species abundances through time and can be thought of as multiple linear regressions that are solved simultaneously. MAR models allow for simultaneous quantification of species interaction strength and the effects of environmental covariates on species abundance through time, while accounting for temporal autocorrelation and density dependence. Community stability can also be described with MAR models in several ways, all of which are based on the relationship between variance in the environment (process error) and variance in species interactions. We are developing the use of these stability metrics as leading indicators of regime change in the context of a "moving window" MAR model (MWMAR). We can generate a continuous time series of community stability of length $k$, by estimating community stability within a time window of size $m$ time steps (t), as

$$\text{Stability}(t_i) = \text{Stability}(t_i : t_{i+m}) \qquad (7)$$

for *i* equals 1 to *k*, where *k* equals total length of the time series minus window size *m* (Figure B-2).

Between 1996 and 2009, the northern CCLME experienced at least two major regime shifts. From August 1998 to February 2002, the northern CCLME experienced a “cold” period, where both the Pacific Decadal Oscillation (PDO) and El Niño/Southern Oscillation (ENSO) indices showed negative anomalies; and from August 2002 to August 2005, the system was in a “warm” phase, where the PDO and ENSO indices were in positive phases. Using a MWMAR model, we generated time series of five separate metrics of stability (Figure B-3), indicating how much species interactions exacerbate or amplify environmental variance (maxEigen, det(B)2/p), how quickly the community is likely to return to its stable state (maxLB⊗B), how much the system reacts to perturbations (t-b react), and the worst-case reaction to perturbation (w-c react) (see Ives et al. 2003 for complete description of stability metrics). We can use these metrics to identify whether the ecosystem becomes more or less susceptible to perturbation and being pushed into an alternate stable state when approaching a regional regime shift.

Following generation of stability time series with the MWMAR model, we parsed each stability time series into unique periods corresponding to periods before, during, and after a regime shift in the northern California Current Large Marine Ecosystem, and analyzed trends in each metric during each period to determine whether the system was becoming increasingly or decreasingly stable leading up to a regime shift (Figure B-4). While these results are preliminary and need to be further developed, it appears that system stability increased leading up to a shift to a cold regime, and that stability decreased as the shift to a warm regime approached (Figure B-4). Further analyses will include comparison of stability trends estimated using more or fewer interacting species, variations in moving window size (*m*), and more detailed analyses of the trends in the resulting stability time series, including calculating moving averages.

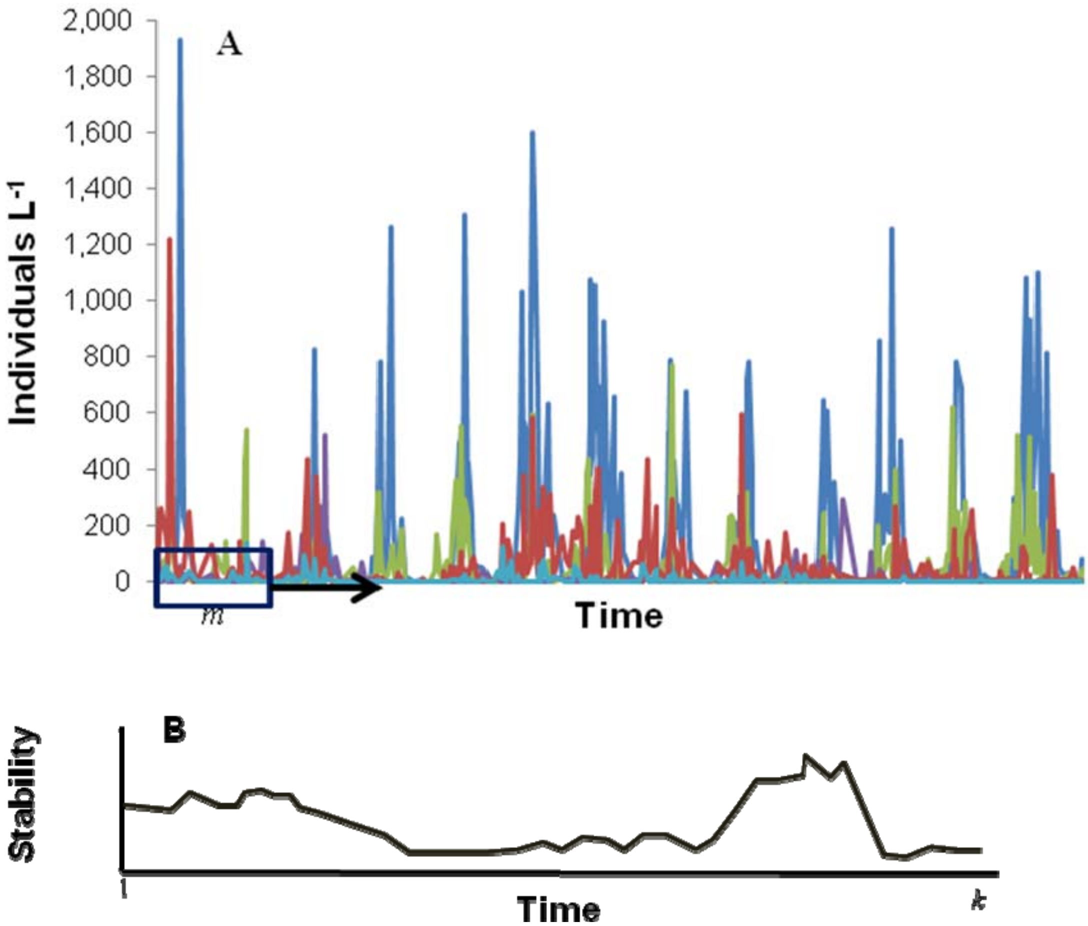


Figure B-2. Chart A, time series of abundance for several zooplankton groups sampled at NH05, showing a moving window of size *m*; Chart B, time series, of length *k*, of stability calculated for moving window *m*.

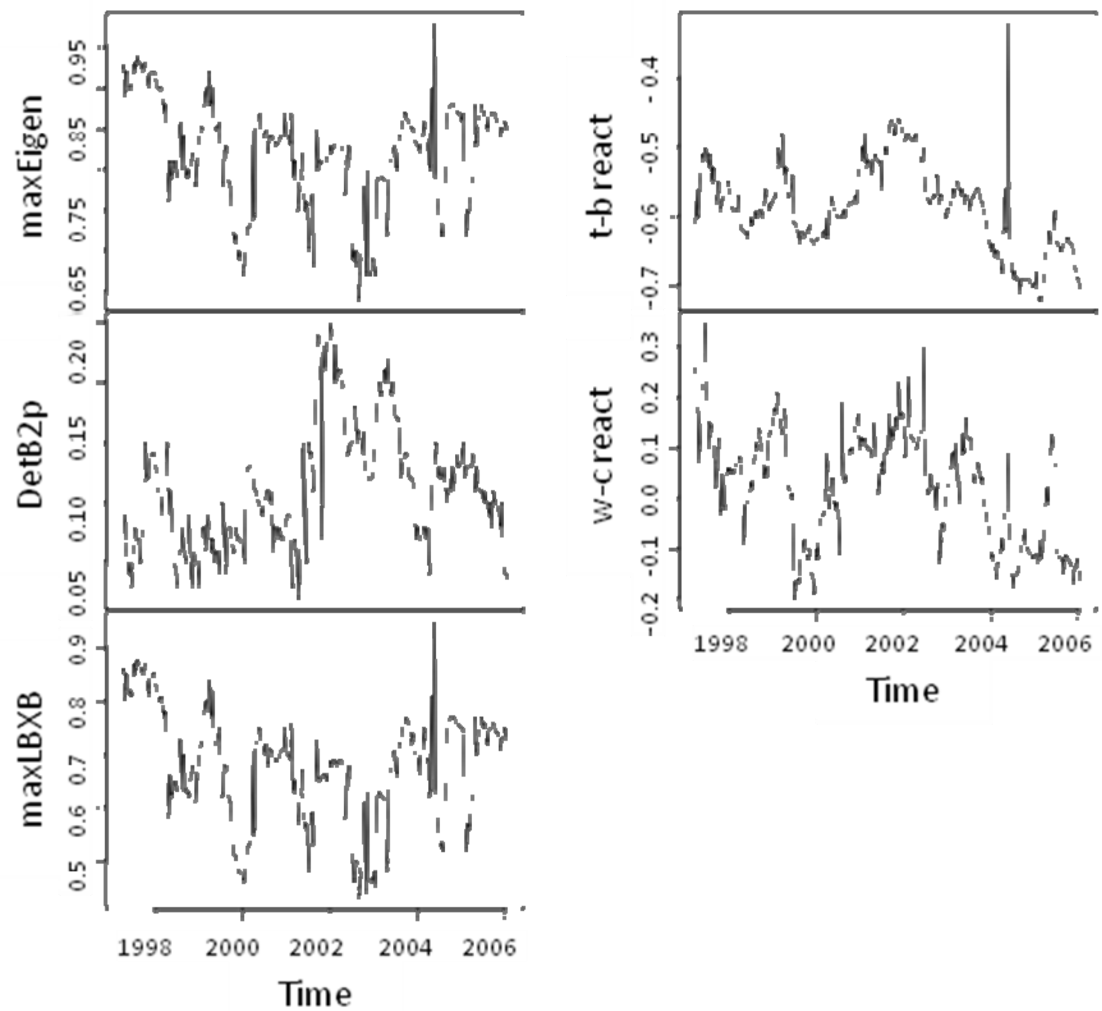


Figure B-3. Five different stability metrics calculated for the eight strongest-interacting species in the NH05 community, using a MWMAR. Y-axis: maxEigen is maximum Eigen value, DetB2p is determinant$(B)^{2p}$, maxLBXB is maximum lambda of $B \otimes B$, t-b react is trace-based reactivity, w-c react is worst-case reactivity.

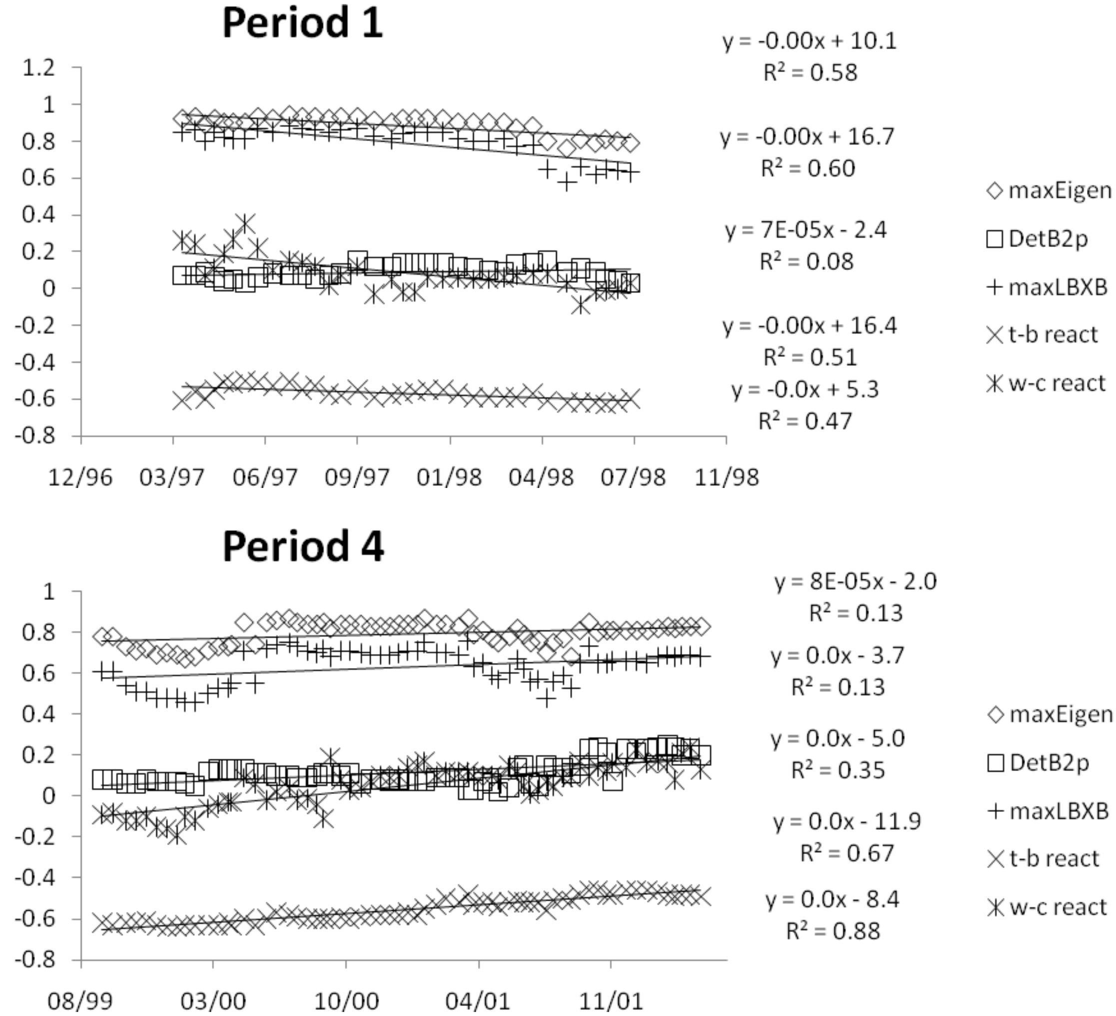


Figure B-4. Trends in five stability metrics calculated using MWMAR for two different periods in the full time series. Period 1 (21 March 1997 to 20 July 1998) corresponds to a period of neutral regime, that is, neither cold nor warm, but approaching a shift to a cold regime. Period 4 (29 July 1999 to 20 March 2002) corresponds to a period between the cold and warm regimes in the run-up to the warm regime. Shown are regression lines, equations, and $R^2$ values for the significant trends in stability with time. Equations correspond to regression lines in order, top to bottom. Smaller stability values indicate greater stability. Legend: maxEigen is maximum Eigen value, DetB2p is $\mathrm{Det}(B)^{2/p}$, maxLBXB is maximum lambda of $B \otimes B$, t-b react is trace-based reactivity, and w-c react is worst-case reactivity. For a full explanation of each stability metric, see Ives et al. 2003.

# Appendix C: Data Sources

## EBM Component: Groundfishes

Data for groundfish abundance come from two sources: 1) the Alaska Fisheries Science Center's (AFSC) Pacific West Coast bottom trawl survey of groundfish resources (Weinberg et al. 2002) and 2) the Northwest Fisheries Science Center's (NWFSC) U.S. West Coast bottom trawl survey of groundfish resources off Washington, Oregon, and California (Keller et al. 2008). Important differences exist between the two surveys (e.g., trawl speed, trawl duration, net type) making them not directly comparable (Table 7 and Table 8). Triennial trawl survey data are courtesy of Mark Wilkins, AFSC; NWFSC trawl survey data are courtesy of Beth Horness, NWFSC.

The AFSC survey was conducted triennially from 1977 to 2004 and is generally referred to as the triennial survey. Due to changing objectives, sampling effort with regard to depth and latitude differed among years for the survey (Table 9). The survey was initiated with the goal of providing fishery-independent data on a number of commercially important species including Pacific hake (*Merluccius productus*), sablefish (*Anoplopoma fimbria*) and shelf and slope rockfishes (*Sebastes* spp.). In 1977 sampling occurred between lat 34°00′N and the U.S.-Canada border at 91 to 457 m with sampling stratified by depth. The emphasis of the survey shifted in 1980 to providing better information for two rockfishes: canary (*Sebastes pinniger*) and yellowtail (*S. flavidus*). Effort shifted to the north from lat 36°48′N to 50°00′N. The depth range remained similar at 55–366 m. In 1986 the survey extent was similar but stopped at lat 49°15′N and concentrated on 92–219 m. In 1989 the survey was extended to the south as the objectives of the survey shifted to monitoring a broad range of demersal species and the survey extent shifted to the south (Table 8).

The triennial survey used the standard AFSC Resource Assessment and Conservation Engineering (RACE) Division high-opening Nor'easter trawl with rubber bobbin roller gear. The trawl had a 27.2 m headrope and a 37.4 m foot rope. All trawls were rigged consistently to RACE survey gear standards employing triple 55 m dandy lines (1.59 cm steel cable) connected to each wing and fished with 2.1 × 1.5 m steel V-doors weighing approximately 567 kg each. Nets were hauled at 1.5 m $sec^{-1}$ (3 knots) for 30 minutes. Sampling followed a systematic-random design with tracklines placed across the survey area. Stations were randomly placed along the tracklines at the rate of approximately one station per 7.4 km. For a more detailed description see Weinberg et al. (2002).

The NWFSC survey has been conducted annually since 1998. From 1998 to 2002 the survey covered only the continental slope (≈200–1,200 m). Starting in 2003 the sampling was expanded to include the shelf with the survey covering approximately the area from the U.S.-Mexico border (lat 32°30′N) to Cape Flattery, Washington (lat 48°10′N), depths from 55 to 1,280 m. The most recently available data were for 2009.

The trawls were carried out on four different vessels and used an Aberdeen-style net with a small-mesh liner (5 cm stretched measure) in the cod end to retain smaller specimens. Trawl duration was approximately 15 min at approximately 1.1 m $sec^{-1}$ (2.2 knots).

As of 2003, the NWFSC survey has used a depth-stratified (three zones) random sampling design with trawl locations selected randomly prior to the initiation of the survey. There has been some minor change in the survey design with regard to allocation of sampling effort (Table 10). For a more detailed description, see Keller et al. (2008).

## Key Attribute: Population Size

Numbers derived from the trawl surveys are the sole indicator for groundfish population size. Because of differences in sampling design, trawl duration, and net mesh size, the two surveys are not directly comparable. Here the annual means for various metrics (groundfish numbers, size distributions) from the two surveys are plotted on the same figures to allow for comparison, but statistically the two surveys are treated separately. There is overlap between the two surveys in 2004. Comparison of the two surveys in this year reveals wide discrepancies in estimates.

To provide similar coverage of latitudes and depths from the two surveys, a subset of the data was chosen to include trawls falling between lat 34°N–48°N and 50–350 m bottom depth. The first year (1977) of the AFSC survey is generally considered unreliable and not used in stock assessment. These data were not used here. The 1980 data are also somewhat unreliable and though used here should be interpreted with some caution. Since earlier years of the NWFSC survey were limited to the continental slope, only data from 2003 to 2009 were used for consistency in depth coverage between the two surveys. A total of 6,287 trawls (4,017 triennial, 2,270 NWFSC) were used in the following analyses.

Annual coast-wide mean catch per unit effort (CPUE, measured as number per $km^2$) for each species within survey was estimated using a generalized additive model (GAM) (Hastie and Tibshirani 1999). In the model, year was treated as a categorical, parametric factor while bottom depth, latitude (starting latitude of the trawl), and their interaction were modeled as smoothed terms (continuous, nonlinear covariates). Thin-plate regression splines were used as the base for depth and latitude (Wood 2006a). A tensor product smooth was used to estimate the interaction term since the two variables differed substantially in scale (Wood 2006b). Data were log(x+1) transformed prior to analysis. Display time series are the back transformed estimates of the year intercept + year coefficients.

## Key Attribute: Population Condition

### Indicator: Size structure

In order to investigate whether size structure of groundfish populations have changed, we compared years within each of the two surveys. We did not make comparisons across surveys because the two surveys used different methods and different-sized nets. These differences will bias the size structure available to be collected and the catchability of many species. However, within each survey, we are able to look for changes in size structure over time.

Similar to population abundance, we investigate changes in size structure in 17 species. These species represent one member from each of the fish functional groups found in the spatially explicit Atlantis ecosystem model of the central California Current (Horne et al. 2010). These species provide insight across a wide range of foraging guilds and trophic levels.

For each species, we calculated the quartiles for length of all individuals collected during the first year of each survey. For the triennial survey, we used 1980, as it is generally accepted that 1977 is not appropriate to use for abundance and biomass estimates. We used 2003 for the NWFSC annual survey. In instances when there were less than 20 individuals of a species measured during a year, we used the first year in which there were greater than 20 individuals.

Next we used these quartiles from the first year's survey for each species to categorize all length measurements for that species into its respective quartile. Counts of individuals in each quartile were summed for each year. We then calculated the proportion of individuals in each quartile each year by dividing the sum of individuals in each quartile by the total number of individuals collected for that year for that species. The proportion of individuals in each quartile was then plotted against year and shown in Figure 13 through Figure 16. In the first year (generally 1980 for triennial and 2003 for NWFSC), the proportion of individuals should be close to 0.25 for each of the quartiles, because each quartile represents 25% of the data for that species. Some values differ from 0.25 in the first year because of the location of the quartile. For example, if 100 sablefish were collected in 2003 and the value of the upper quartile was 52 cm but there were 20 more 52 cm individuals that fell below the quartile line, these individuals would be calculated in the proportion as being in the upper quartile (Quartile 4 on the figures). Thus in this example, Quartile 4 would have a larger proportion of individuals during the first year.

These calculations were then repeated using only data collected in each of the four national marine sanctuaries (figures in Appendix D). In some cases, there was not enough data for some of the 14 species in some national marine sanctuaries to make useful comparisons over time.

### Indicator: Spatial structure

Data selection in terms of year, depth, and latitude ranges followed that for estimation of groundfish number time series above. Note that from 1980 to 1986, the triennial survey did not sample south of lat 36°N (Table 9).

Annual distributions were estimated for 1° latitude bins (rounding down) separately for each year and separately for each survey. Thus there are two estimates of distribution for 2004 when the two surveys overlapped temporally. For each year and survey, a separate GAM (Hastie and Tibshirani 1999) was run with latitude as a categorical, parametric variable and depth of the trawl as a continuous nonlinear covariate. A thin-plate regression spline was used to smooth the depth term. All models used an identity link and Gaussian error distribution. Data were log(x+1) transformed prior to analysis, and annual means for each time series are the back-transformed estimates of the intercept + latitude coefficients from the model.

# EBM Component: Ecosystem Health

## Key Attribute: Community Composition

### Indicator: Diversity

**Shannon Diversity**—The Shannon Diversity Index takes into account the number of species and the evenness of the species. The index is increased either by having additional unique species or by having a more even representation of species (greater evenness).

Data for groundfish diversity come from two sources: 1) the AFSC Pacific West Coast bottom trawl survey of groundfish resources (Weinberg et al. 2002), and 2) the NWFSC U.S. West Coast bottom trawl survey of groundfish resources off Washington, Oregon, and California (Keller et al. 2008). While important differences exist between the two surveys, both contain taxa identified to varying taxonomic levels (some to species, some to family). The analyses here include only those taxa identified to species. A subset of the available data was used including trawls between 50–350 m and lat 34–38°N. Triennial data included the years 1980–2004 (every third year), while NWFSC data included 2003–2009 data. A total of 349 taxa identifiable to the species level was used in the following analyses.

After calculating Shannon Diversity for each trawl, annual means were derived using a GAM (Hastie and Tibshirani 1999) in which year was a parametric, categorical effect. Depth and latitude were included as nonlinear covariates to account for variation with these parameters. Depth and latitude smooths used thin-plate regression splines (Wood 2006a). A tensor product smooth was used for the interaction between depth and latitude because the two variables differed greatly in scale (Wood 2006a, Wood 2006b). GAMs used an identity link and Gaussian error structure. The results shown are the coefficients for year effect derived from the models. Separate GAM models were run for the triennial and NWFSC data because of differing sampling methodologies.

**Taxonomic distinctness for groundfishes**—West Coast groundfishes: Taxonomic distinctness quantifies diversity as the relatedness of the species within a sample, based on the distances between species in a classification tree (Clarke and Warwick 2001a). Average taxonomic distinctness (Δ+ or AvTD) is the mean of all species-to-species distances through the tree for all pairs of species within a sample and represents the taxonomic breadth of the sample. The variation in taxonomic distinctness (Λ+ or VarTD) is the variation in branch lengths among all pairs of species (it is not the variance of AvTD among samples) and is a measure of the irregularities and divergences in the distribution of branch lengths within a sample. Both indices are appealing because they are based on presence/absence data and, unlike many biodiversity measures, neither is affected by the number of species or the sampling effort (Clarke and Warwick 1998b, Clarke and Warwick 2001c).

Data for groundfish come from two sources: 1) the AFSC Pacific West Coast bottom trawl survey of groundfish resources (Weinberg et al. 2002), and 2) the NWFSC West Coast bottom trawl survey of groundfish resources off Washington, Oregon, and California (Keller et al. 2008). While differences exist between the two surveys, both contain taxa identified to varying taxonomic levels (some to species, some to family). For the analyses here, only taxa identified to species were included. A subset of the available data was used including trawls between 50–350 m and lat 34–38°N. Triennial data included the years 1980–2004 (every third year), while NWFSC data included 2003–2009 data. A total of 349 taxa identifiable to the species level was used in the following analyses. A total of 6,287 trawls (4,017 triennial, 2,270 NWFSC) were used in the following analyses.

Equations for the calculation of average taxonomic distinctness and variation in taxonomic distinctness are given by Clarke and Warwick (1998a) and Clarke and Warwick (2001b), respectively. Taxonomic information was derived from (Nelson 2006). The taxonomic hierarchy had eight levels including species, genus, family, order, class, grade, taxa.1, and subphylum. The group taxa.1 distinguished hagfishes and lamprey from the vertebrates. Step lengths in the classification tree varied according to the relative proportional loss of the number of distinct classes.

After calculating AvTD and VarTD for each trawl, annual means were derived using a GAM (Hastie and Tibshirani 1999) in which year was a parametric, categorical effect. Depth and latitude were included as nonlinear covariates to account for variation with these parameters. Depth and latitude smooths used thin-plate regression splines (Wood 2006a). A tensor product smooth was used for the interaction between depth and latitude because the two variable differed greatly in scale (Wood 2006a, Wood 2006b). GAMs used an identity link and Gaussian error structure. The results shown are the coefficients for year effect derived from the models. Separate GAM models were run for the triennial and NWFSC data because of differing sampling methodologies.

**Taxonomic distinction for zooplankton**—Data for zooplankton are courtesy of Bill Peterson, NWFSC, Newport, Oregon. Also see Peterson et al. (unpubl. manuscr.). Data were collected off Oregon at NH05.

Equations for the calculation of average taxonomic distinctness and variation in taxonomic distinctness for zooplankton are given by Clarke and Warwick (1998a) and Clarke and Warwick (2001b), respectively. The taxonomic hierarchy had seven levels including species, genus, family, order, class, subphylum, and phylum. Step lengths in the classification tree varied according to the relative proportional loss of the number of distinct classes. There were 162 taxa of which 55 were identified to species. Future analyses may wish to more selectively choose those taxa used to calculate taxonomic distinctness metrics.

Seasonal averages for AvTD and VarTD were calculated by first calculating the AvTD or VarTD for each sample and then taking the average of those samples by season. Seasonal averages were then plotted. Seasons were 1) winter: December, January, February; 2) spring: March, April, May; 3) summer: June, July, August; and 4) fall: September, October, November. Winter means include December data from the previous calendar year, that is, winter 1997 is the average of data from December 1996, January 1997, and February 1997.

### Indicator: Seabird reproduction indices

**Point Reyes Bird Observatory (PRBO) conservation science**—Colony based data contain information collected at major seabird colonies and marine mammal rookeries including the Farallon Islands, Alcatraz Island, Año Nuevo Island, and Vandenberg Air Force Base. Information includes annual mean productivity for Ashy storm-petrel (*Oceanodroma homochroa*), Brandt's cormorant (*Phalacrocorax penicillatus*), Cassin's auklet (*Ptychoramphus aleuticus*), common murre (*Uria aalge*), pelagic cormorant (*Phalacrocorax pelagicus*), pigeon guillemot (*Cepphus columba*), rhinoceros auklet (*Cerorhinca monocerata*), and western gull (*Laurus occidentalis*) breeding on the Farallon Islands. See California Avian Data Center; online at http://data.prbo.org/cadc2/index.php?page=marine-data. Data collected by PRBO Conservation Science in collaboration with the U.S. Fish and Wildlife Service.

**Bird Research Northwest (formerly Columbia Bird Research)**—Ongoing research program investigating the ecology of piscivorous colonial waterbirds (primarily, Caspian terns [*Hydroprogne caspia*], double-crested cormorants [*Phalocrocorax auritis*], American white pelicans [*Pelecanus erythrorhynchos*], and several gull [*Larus*] species) and their impacts on the survival of juvenile salmonids in the Columbia Basin and elsewhere along the Pacific Coast. This research project is a joint, collaborative project between Oregon State University, Real Time Research Inc., and the U.S. Geological Survey's Oregon Cooperative Fish and Wildlife Research Unit. Support for this research project has come from the Bonneville Power Administration; U.S. Army Corps of Engineers, Walla Walla District; U.S. Army Corps of Engineers, Portland District; U.S. Fish and Wildlife Service, Pacific Region, Migratory Birds and Habitat Programs; NMFS; and the Northwest Power and Conservation Council. Bird Research Northwest is online at http://www.birdresearchnw.org/Project-Info/Project-Data/default.aspx.

**Triangle Island bird data**—Research mainly focuses on Cassin's and rhinoceros auklets, but key demographic parameters are also monitored for pelagic cormorants, Leach's stormpetrels (*Oceanodroma leucorhoa*), glaucous-winged gulls (*Larus glaucescens*), black oystercatchers (*Haematopus bachmani*), tufted puffins (*Fratercula cirrhata*), and common murres. Situated near the northern limits of the California Current oceanographic zone and within the territorial boundaries of the Kwakiutl District Council, the Anne Vallée Ecological Reserve at Triangle Island supports the largest and most diverse seabird colony in British Columbia. During 1994–2003, breeding success (here measured as fledgling production, the mean mass of fledged chick produced per egg laid) of both Cassin's and rhinoceros auklets was lower in years with higher ocean temperatures (SST, sea surface temperature). The birds were affected at all stages of breeding: in warm years, females were less likely to lay eggs, those that did were less likely to hatch their eggs, fewer of the chicks survived to fledge, and the few chicks that did fledge were light in mass (which does not bode well for subsequent survival).

Over the years, the research program at Triangle Island has been funded by the Baillie Foundation, the Canadian Wildlife Service, the Climate Change Action Fund, the Important Bird Areas Community Action Fund, NOAA, the Natural Sciences and Engineering Research Council of Canada, the Nestucca Trust Fund, Simon Fraser University, the Science Horizons Program of Environment Canada, the Vancouver Foundation, and the World Wildlife Fund Canada. Research information is online at http://www.sfu.ca/biology/wildberg/bertram/triangle /climatechange.html. The contact for data is constans@sfu.ca; mark.hipfner@ec.gc.ca.

**Washington coastal islands**—Rhinoceros auklet reproductive success from three islands for the following years are: Protection Island from 2006 to 2010 (plus published data from the

1970s), Tatoosh Island from 2005 to 2009, and Destruction Island from 2008 to 2010 (plus published data from the 1970s). The contact for data is Dr. Scott Pearson, senior research scientist, Washington Department of Fish and Wildlife, Wildlife Research Division, 1111 Washington Street SE, 5th Floor, Olympia, Washington 98501-2283, telephone (360) 902-2524.

**Oregon coast**—Central Oregon coast breeding colony reproductive success data for pelagic cormorants were collected over 38 years during the summer by students, and approximately 9 years (1998–2002, 2007–present) on common murres from the Yaquina Head colony. The contacts for data are Rob Suryan, rob.suryan@oregonstate.edu, and Jan Hodder, jhodder@uoregon.edu.

### Indicator: The northern copepod biomass anomaly

Data is courtesy of Bill Peterson. Also see Peterson et al. (unpubl. manuscr.). Data were collected off Oregon at NH05.

### Indicator: Top predator biomass

Annual means for top predator biomass were derived using a GAM (Hastie and Tibshirani 1999) in which year was a parametric, categorical effect. Depth and latitude were included as nonlinear covariates to account for variation with these parameters. Depth and latitude smooths used thin-plate regression splines (Wood 2006a). A tensor product smooth was used for the interaction between depth and latitude because the two variables differed greatly in scale (Wood 2006a, Wood 2006b). GAMs used an identity link and Gaussian error structure. The results shown are the coefficients for year effect derived from the models. Separate GAM models were run for the triennial and NWFSC data because of differing sampling methodologies.

## Key Attribute: Energetics and Material Flows

### Indicator: Nutrient levels

Usage permissions: CalCOFI database data is accessible in the CCE LTER data repository supported by the Division of Ocean Sciences, NSF Grant OCE-0417616. Contact: Jim Wilkinson. Data set 82: Conductivity temperature depth bottle data. The survey cruise data set (CalCOFI–SIO) has 800,605 records spanning 1949–2009; parameters are from discrete samples taken from bottles on a hydrographic CTD (conductivity temperature depth) cast. Parameters include depth, temperature, salinity, density (sigma theta), specific volume anomaly, wave height, oxygen, chlorophyll, primary productivity, and nutrients phosphate, nitrate, nitrite, and ammonia.

Filters to CalCOFI data download are: Year, limited to data collected since 1983 (previous to that there are missing years); depth, limited to samples less than 6 m; and seasons, with data binned as 1 equals winter (Jan-Mar), 2 equals spring (Apr-Jun), 3 equals summer (Jul-Sep), and 4 equals fall (Oct-Dec). Geographically the stations are 66.7–136.7 (CalCOFI north to IMECOCAL).

**Indicator: Chlorophyll *a***

Chlorophyll *a* (chl *a*) data were collected from the Orbview-2 SeaWiFS and Aqua MODIS (online at http://coastwatch.pfeg.noaa.gov/erddap/index.html). Winter and summer spatial patterns of chl *a* are averages of long-term means from 1999 to 2008 using chl *a* data from SeaWiFS. The time series are constructed from area averages of chl *a* data from MODIS. The area used in the averages is centered on NDBC buoys 46050, 46014, and 46025; the areas have widths extending 50 km from the coast and lengths of 200 km.

Satellite remotely sensed chlorophyll concentration (mg $m^{-3}$) data were obtained from the Sea-viewing Wide Field-of-View Sensor (SeaWiFS, online at http://oceancolor.gsfc.nasa.gov/SeaWiFS/). Monthly Level 3 mapped 9 km resolution data were provided by the NASA Goddard Space Flight Center (online at http://oceancolor.gsfc.nasa.gov/). We used monthly composites of 9 x 9 km pixels to assess changes in chl *a*; data were processed by Rob Suryan of Oregon State University. Here, we report on chlorophyll concentrations in a 9 x 9 km pixel over the period 1998–2006.

# EBM Driver and Pressure: Climate

Several long-term observing programs provide time series of physical, biological, chemical, and fisheries variables within the California Current Large Marine Ecosystem (CCLME) (Peña and Bograd 2007). These include: CalCOFI (Hewitt 1988, Bograd et al. 2003, http://www.calcofi.org/), Line P (Freeland 2007, http://www.pac.dfo-mpo.gc.ca/science/oceans/data-donnees/line-p/index-eng.htm), and U.S. GLOBEC Northeast Pacific Program (Batchelder et al. 2002, http://globec.coas.oregonstate.edu). An abbreviated description of each data set in this IEA is included below.

## Large-scale Climate Forcing

### PDO

Computation of the Pacific Decadal Oscillation (PDO) index was developed by Zhang et al. (1997). Data were downloaded from the University of Washington Joint Institute for the Study of the Atmosphere and Ocean. Methods and details of computation are online at http://jisao.washington.edu/pdo/PDO.latest. The PDO reflects SST for the entire North Pacific, including the CCLME, from greater than lat 20°N.

### MEI

The Multivariate ENSO Index (MEI) is based on six observed variables over the tropical Pacific. Negative values of the MEI represent the cold ENSO phase, (La Niña), while positive MEI values represent the warm ENSO phase (El Niño). Data were obtained online at http://www.cdc.noaa.gov/people/klaus.wolter/MEI/table.html from NOAA's Earth System Research Laboratory. In the CCLME, warm ENSO phases (positive MEI values) are associated with strong advection from the south and cold ENSO phases (negative MEI values) with weak northward transport.

### NPGO

The North Pacific Gyre Oscillation (NPGO) index, data online at http://eros.eas.gatech.edu/npgo/data/NPGO.txt, emerges from analyses of anomalies of Northeast Pacific SSTs and sea-surface height (Di Lorenzo et al. 2008). Positive values indicate a strong North Pacific gyre and advective transport from the north into the CCLME; negative values indicate a weak gyre and decreased southward transport.

### NOI

The Northern Oscillation Index (NOI) is an index of indices of mid-latitude climate fluctuations that show interesting relationships with marine ecosystems and populations. The NOI reflects the variability in equatorial and extratropical teleconnections and represents a wide range of local and remote climate signals (data online at http://coastwatch.pfeg.noaa.gov/erddap/griddap/erdlasNoix.graph).

### CUI

The Cumulative Upwelling Index (CUI) is calculated by NOAA's Environmental Research Division from estimates of the magnitude of the offshore component of the Ekman transport driven by wind stress. Positive values indicate upwelling while negative values indicate downwelling (methods and details of computation online at http://www.pfeg.noaa.gov/products/PFEL/modeled/indices/upwelling/NA/how_computed.html).

## Large-scale Physical and Biological Conditions

### SST

Sea surface temperature (SST) data were collected from the Pathfinder satellite. Area averages were constructed from long term mean from 1999 to 2008 (data online at http://coastwatch.pfeg.noaa.gov/erddap/griddap/erdPHsstamday.html).

### Winds

Meridional winds (north/south) data were collected from the QuikSCAT satellite. Area averages were constructed from long-term mean from 1999 to 2008 (data online at http://coastwatch.pfeg.noaa.gov/erddap/griddap/erdQSstressmday.html).

SST and meridional winds from buoys were collected from NDBC buoys. We used data from buoys 46023, 46014, 46050 (data online at http://www.ndbc.noaa.gov/).

### Sea level

Sea level measurements (mm), compiled by the National Water Level Observation Network, were obtained from the Center for Operational Oceanographic Products and Services (NOS 2008). We used data from San Diego and San Francisco, California, and South Beach, Oregon. Methods and data were downloaded from the University of Hawaii Sea Level Center (http://uhslc.soest.hawaii.edu/).

## Hypoxia

The collection and processing of dissolved oxygen data on the shelf off Newport, Oregon, are done by Bill Peterson of NOAA. The data are from the hydrographic sampling station Newport Line (NH) 05 that is located 5 miles off the coast at a depth of 50 m. The dissolved oxygen data taken from a location off the coast of San Diego, California, are from the CalCOFI program (data online at http://www.calcofi.org/data.html). The data are from hydrographic station 93.30 at a depth of 200 m.

## OPI

The Oregon Production Index (OPI) is an index to the ocean survival (based on smolt-to-adult returns) for coho salmon (*Oncorhynchus kisutch*) in Oregon. Data were obtained from tables in the Pacific Fishery Management Council's preseason report (http://www.pcouncil.org/salmon/stock-assessment-and-fishery-evaluation-safe-documents/preseason-reports/2010-preseason-report-i/). The percent smolt-adult returns were calculated by the formula SAR $= a/(b \times 1{,}000) \times 100$, where SAR is the percent smolt-adult return, $a$ is the adult OPIH (thousands), and $b$ is the total hatchery smolts released (millions).

## CVI

The Central Valley Index (CVI) for Chinook salmon (*O. Tshawytscha*) was obtained from the Pacific Fishery Management Council (http://www.pcouncil.org/salmon/background/document-library/historical-data-of-ocean-salmon-fisheries/). Escapement values for the CVI extend through 2007, but were replaced with a similar Sacramento Index in 2008. Because the two indices are highly correlated, we use a data set compiled of fall escapement values from the CVI from 1970 to 2007, and the fall escapement value from the Sacramento Index for 2008.

# Appendix D: National Marine Sanctuaries

In cases where data were available, we repeated analysis of the groundfish and ecosystem health EBM components for each of NOAA's national marine sanctuaries (NMSs) north of Point Conception.

## Olympic Coast NMS

Groundfish numbers: Only 3 of the 15 species examined showed declining 5-year trends (Figure D-1 through Figure D-4), namely, shortbelly rockfish (*Sebastes jordani*), yelloweye rockfish (*S. ruberrimus*), and spiny dogfish (*Squalus acanthias*). Eleven of the species showed no change, while 1 (redstripe rockfish [*S. proriger*]) showed an increasing trend over the last 5 years.

Groundfish size class distribution: Most species show variation in the proportion of individuals in four size classes through time (Figure D-5 through Figure D-8). Some groups like canary rockfish (*Sebastes pinniger*) showed an aging population with an increase in the proportion of large individuals but an overall decrease in their numbers. Several species like lingcod (*Ophiodon elongatus*) and sablefish (*Anoplopoma fimbria*) showed an increase in the proportion of small fish in the population. Some species do not have size estimates in all years.

Shannon Diversity Index: This showed a declining 5-year trend (Figure D-9).

Taxonomic distinctness: Average taxonomic distinctness declined over the last 5 years of the time series while variation in taxonomic distinctness did not (Figure D-10).

Top predator biomass (groundfishes): The 5-year trend showed a sharp decline from 2003 levels but no change over the last 5 years in the biomass of top predators (Figure D-11).

## Cordell Bank NMS

Groundfish numbers: Four of 17 fishes showed declines over the last 5 years (Figure D-12 through Figure D-15). These included Dover sole (*Microstomus pacificus*), splitnose rockfish (*Sebastes diploproa*), rex sole (*Glyptocephalus zachirus*), and longnose skate (*Raja rhina*). Five species showed increases including redstripe rockfish, chilipepper (*Sebastes goodei*), arrowtooth flounder (*Atheresthes stomias*), canary rockfish, and yelloweye rockfish. Hake (*Merluccius productus*), stripetail rockfish (*Sebastes saxicola*), sablefish, spiny dogfish, shortbelly rockfish, darkblotched rockfish (*S. crameri*), white croaker (*Genyonemus lineatus*), and lingcod showed no change over the last 5 years relative to the overall time series.

Groundfish size class distribution: Most species show variation in the proportion of individuals in four size classes through time (Figure D-16 through Figure D-19). Some species do not have size estimates in all years.

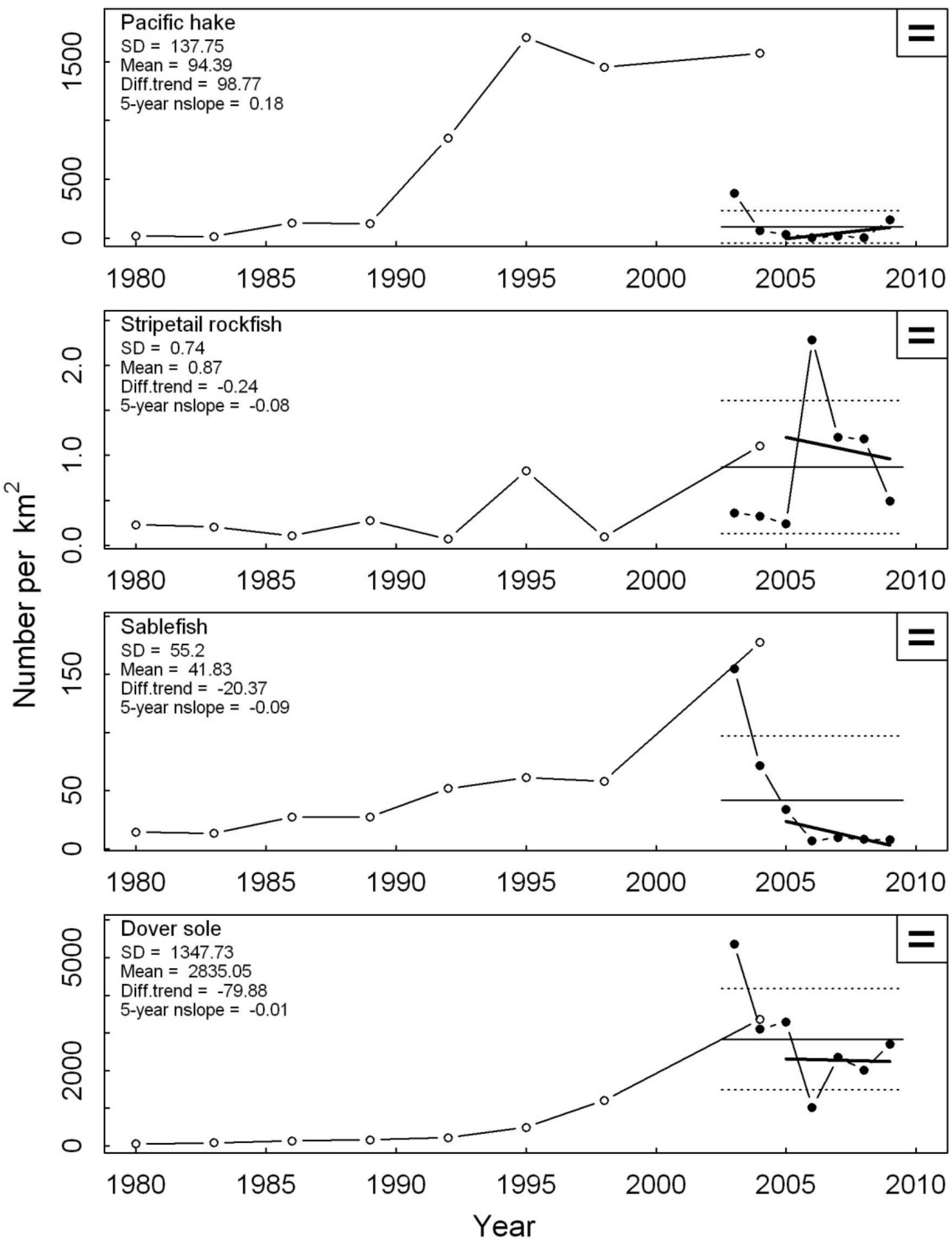


Figure D-1. CPUE (number per km$^2$) for four groundfishes within the Olympic Coast NMS from 1980 to 2009 for the triennial trawl survey (open circles, data courtesy of Mark Wilkins, AFSC) and the NWFSC trawl survey (closed circle, data courtesy of Beth Horness, NWFSC). Mean and SD are the mean and standard deviation of the NWFSC time series, Diff.trend is the absolute change in the predicted trend over 5 years, 5-year nslope is the slope of normalized data for comparison across species. The solid line is the mean for the 7-year NWFSC data. Dotted lines are ±1 SD. The trend line (thick black) is the 5-year trend. Symbols in the upper right indicate that the 5-year trend showed no change relative to 1 SD of NWFSC data. Data are the year effect from the GAM model and not absolute estimates of abundance.

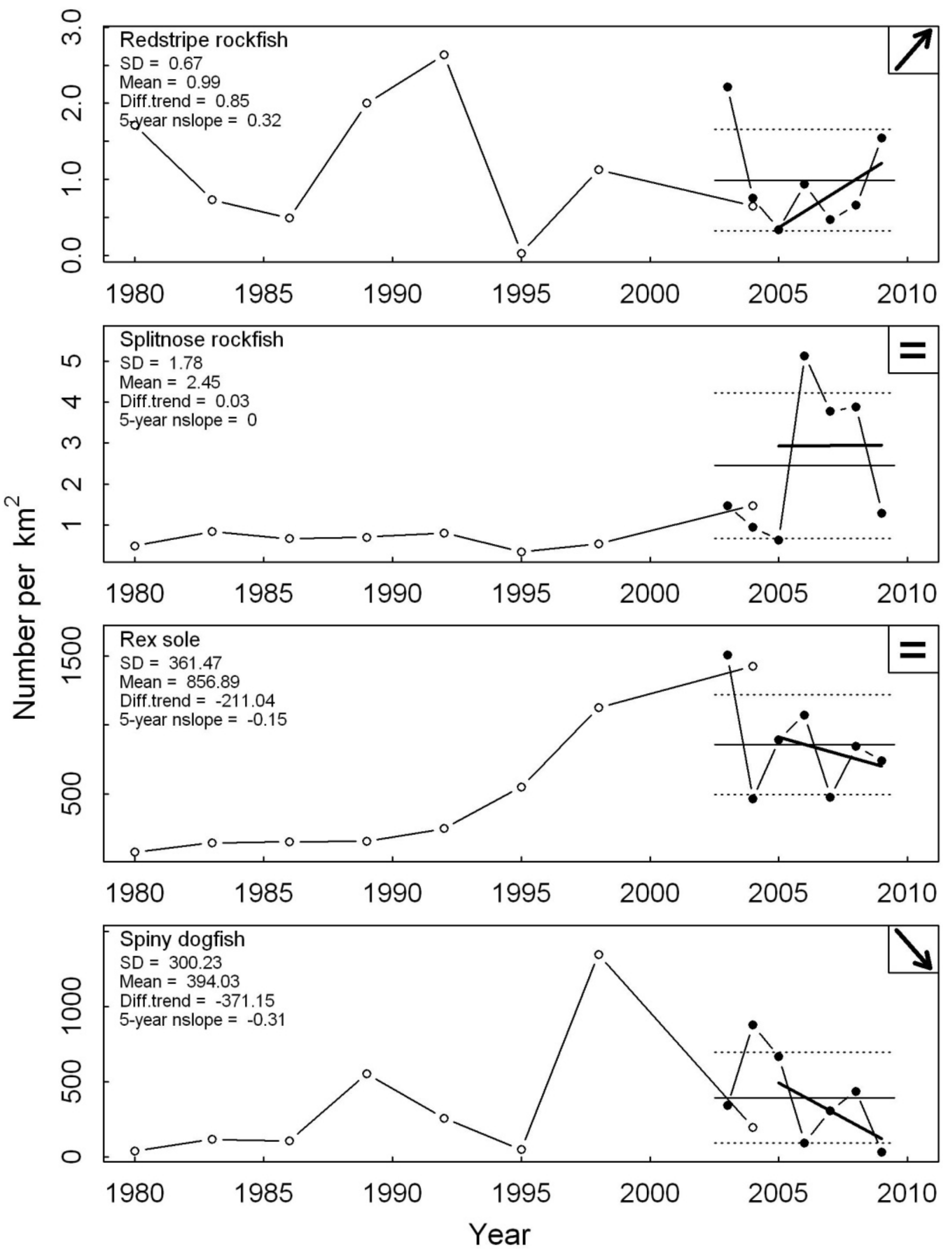


Figure D-2. CPUE (number per km$^2$) for four groundfishes within the Olympic Coast NMS from 1980 to 2009 for the triennial trawl survey (open circles, data courtesy of Mark Wilkins, AFSC) and the NWFSC trawl survey (closed circle, data courtesy of Beth Horness, NWFSC). Mean and SD are the mean and standard deviation of the NWFSC time series, Diff.trend is the absolute change in the predicted trend over 5 years, 5-year nslope is the slope of normalized data for comparison across species. The solid line is the mean for the 7-year NWFSC data. Dotted lines are ±1 SD. The trend line (thick black) is the 5-year trend. Symbols in the upper right indicate whether the 5-year trend increased, decreased, or showed no change relative to 1 SD of NWFSC data. Data are the year effect from the GAM model and not absolute estimates of abundance.

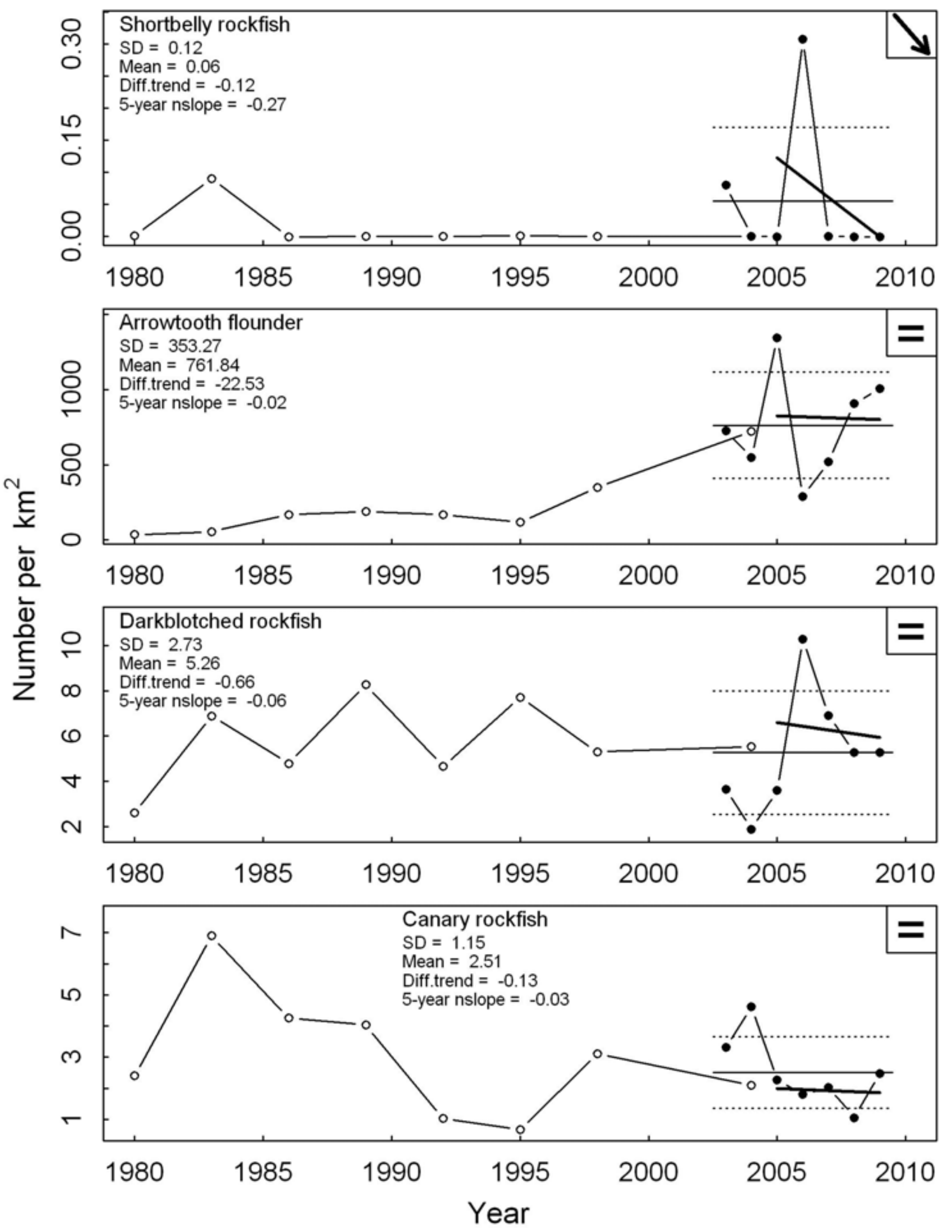


Figure D-3. CPUE (number per km$^2$) for four groundfishes within the Olympic Coast NMS from 1980 to 2009 for the triennial trawl survey (open circles, data courtesy of Mark Wilkins, AFSC) and the NWFSC trawl survey (closed circle, data courtesy of Beth Horness, NWFSC). Mean and SD are the mean and standard deviation of the NWFSC time series, Diff.trend is the absolute change in the predicted trend over 5 years, 5-year nslope is the slope of normalized data for comparison across species. The solid line is the mean for the 7-year NWFSC data. Dotted lines are ±1 SD. The trend line (thick black) is the 5-year trend. Symbols in the upper right indicate whether the 5-year trend decreased or showed no change relative to 1 SD of NWFSC data. Data are the year effect from the GAM model and not absolute estimates of abundance.

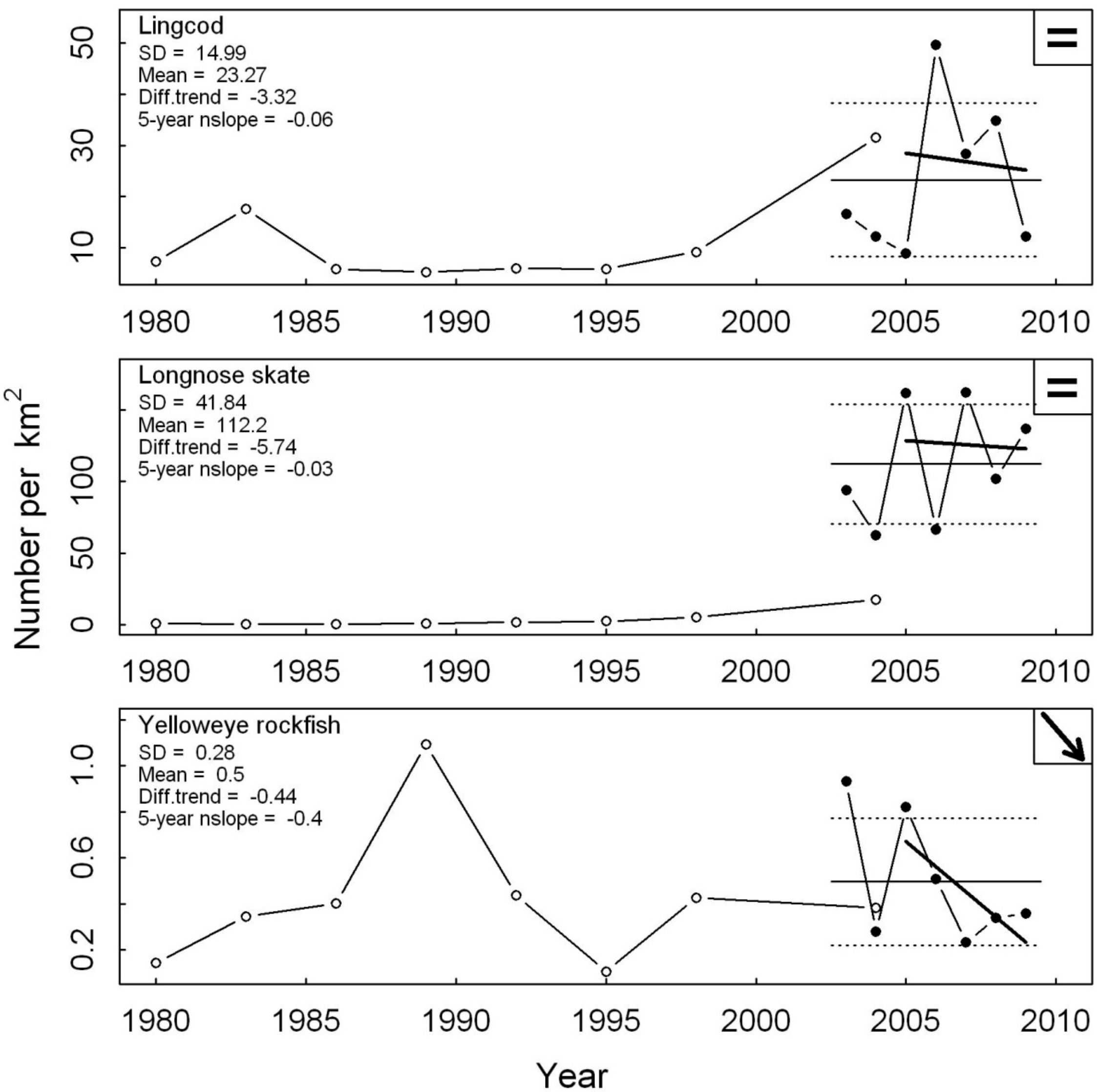


Figure D-4. CPUE (number per km$^2$) for three groundfishes within the Olympic Coast NMS from 1980 to 2009 for the triennial trawl survey (open circles, data courtesy of Mark Wilkins, AFSC) and the NWFSC trawl survey (closed circle, data courtesy of Beth Horness, NWFSC). Mean and SD are the mean and standard deviation of the NWFSC time series, Diff.trend is the absolute change in the predicted trend over 5 years, 5-year nslope is the slope of normalized data for comparison across species. The solid line is the mean for the 7-year NWFSC data. Dotted lines are ±1 SD. The trend line (thick black) is the 5-year trend. Symbols in the upper right indicate whether the 5-year trend decreased or showed no change relative to 1 SD of NWFSC data. Data are the year effect from the GAM model and not absolute estimates of abundance.

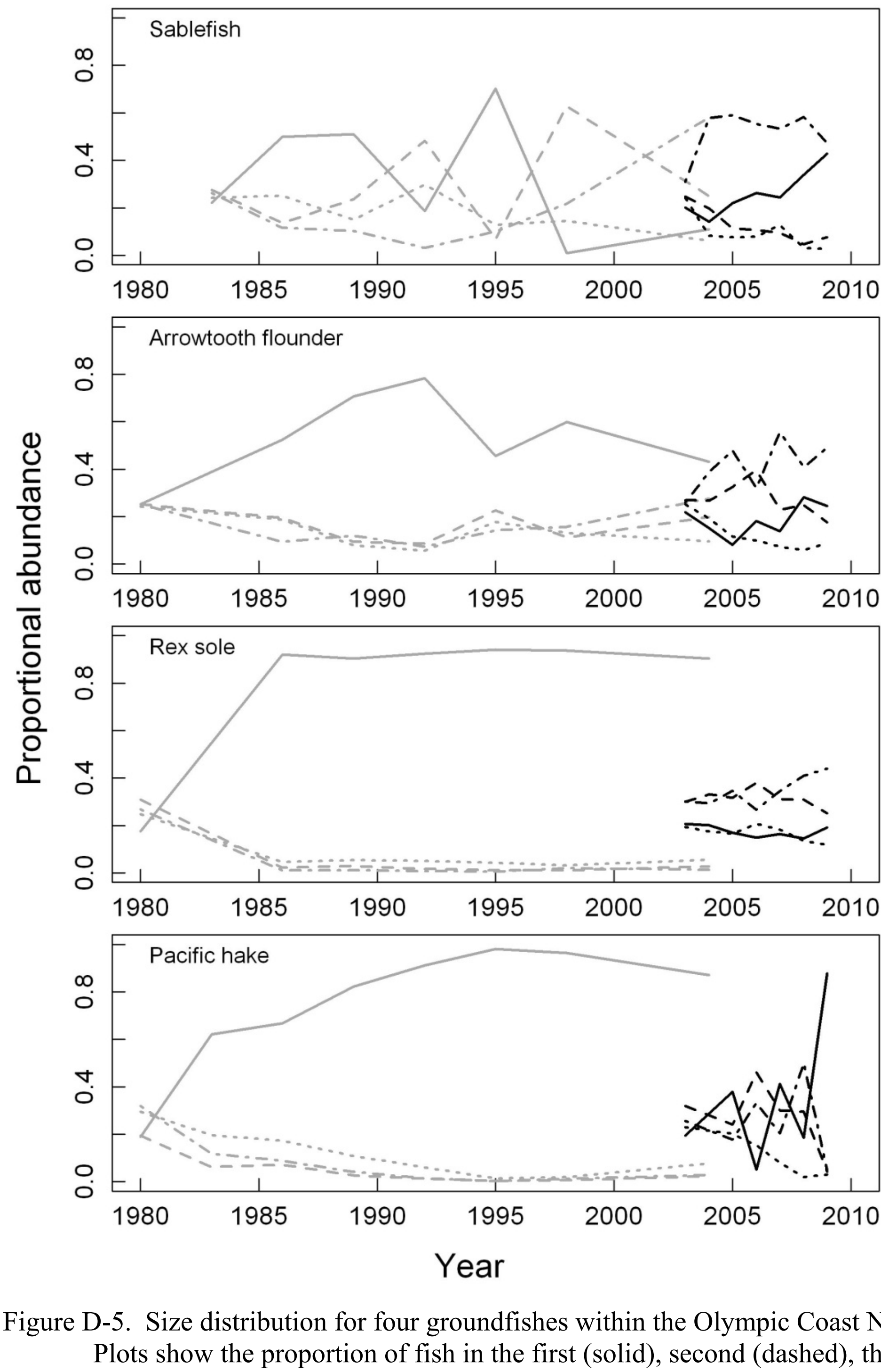


Figure D-5. Size distribution for four groundfishes within the Olympic Coast NMS from 1980 to 2009. Plots show the proportion of fish in the first (solid), second (dashed), third (dotted), and fourth (dot-dash) quartiles. Gray lines are the triennial survey data (courtesy of Mark Wilkins, AFSC), and black lines are the NWFSC survey data (courtesy of Beth Horness, NWFSC). To show change in size structure through time, size cutoffs for the quartiles were established based on the first year in each time series (1980 and 2003). Subsequent years show proportion of fishes in those size classes.

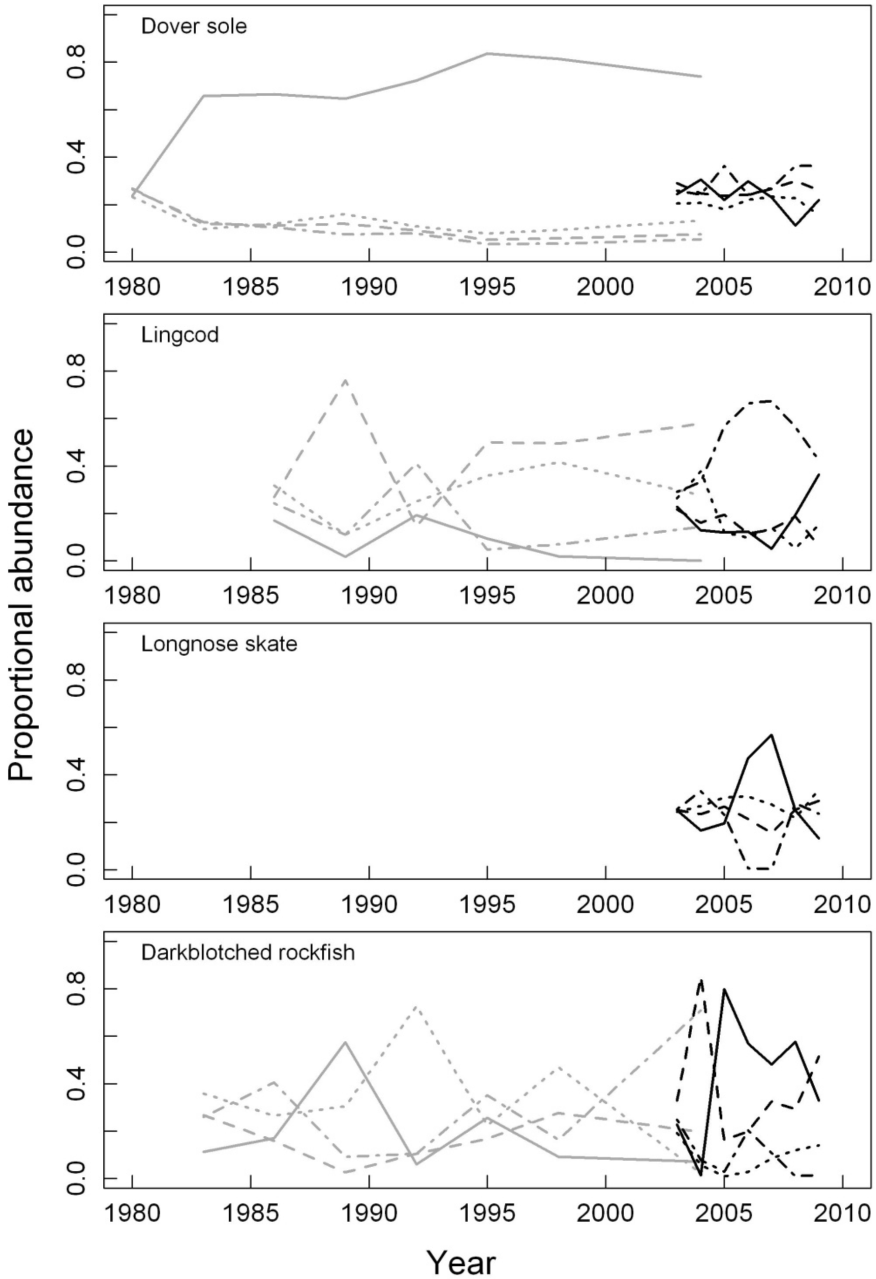


Figure D-6. Size distribution for four groundfishes within the Olympic Coast NMS from 1980 to 2009. Plots show the proportion of fish in the first (solid), second (dashed), third (dotted), and fourth (dot-dash) quartiles. Gray lines are the triennial survey data (courtesy of Mark Wilkins, AFSC), and black lines are the NWFSC survey data (courtesy of Beth Horness, NWFSC). To show change in size structure through time, size cutoffs for the quartiles were established based on the first year in each time series (1980 and 2003). Subsequent years show proportion of fishes in those size classes.

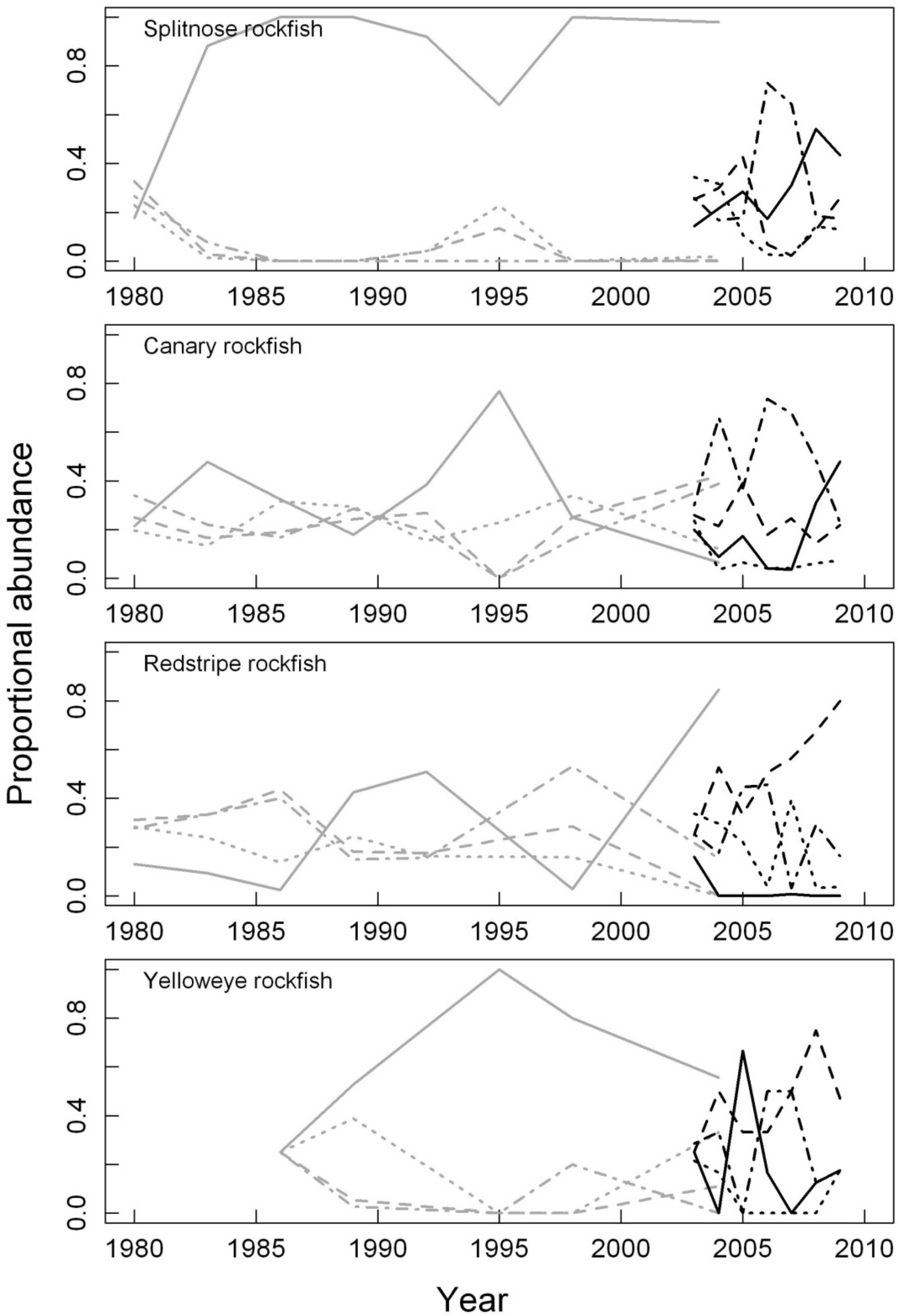


Figure D-7. Size distribution for four groundfishes within the Olympic Coast NMS from 1980 to 2009. Plots show the proportion of fish in the first (solid), second (dashed), third (dotted), and fourth (dot-dash) quartiles. Gray lines are the triennial survey data (courtesy of Mark Wilkins, AFSC), and black lines are the NWFSC survey data (courtesy of Beth Horness, NWFSC). To show change in size structure through time, size cutoffs for the quartiles were established based on the first year in each time series (1980 and 2003). Subsequent years show proportion of fishes in those size classes.

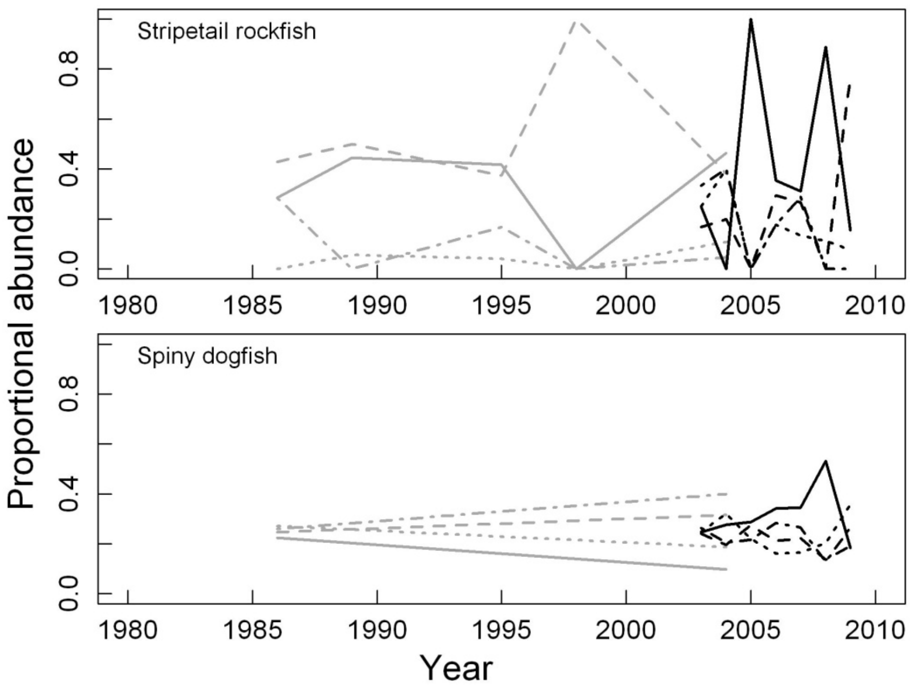


Figure D-8. Size distribution for two groundfishes within the Olympic Coast NMS from 1980 to 2009. Plots show the proportion of fish in the first (solid), second (dashed), third (dotted), and fourth (dot-dash) quartiles. Gray lines are the triennial survey data (courtesy of Mark Wilkins, AFSC), and black lines are the NWFSC survey data (courtesy of Beth Horness, NWFSC). To show change in size structure through time, size cutoffs for the quartiles were established based on the first year in each time series (1980 and 2003). Subsequent years show proportion of fishes in those size classes.

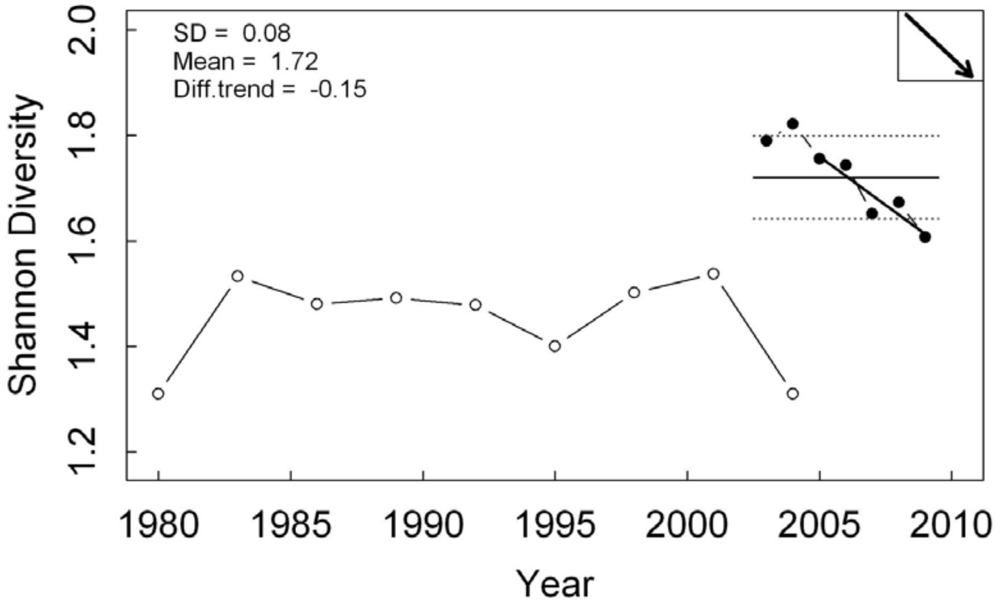


Figure D-9. Annual mean Shannon Diversity within the Olympic Coast NMS. Open circles show yearly averages calculated from the triennial trawl survey (data courtesy of Mark Wilkins, AFSC). Closed circles show results for the NWFSC trawl survey (data courtesy of Beth Horness, NWFSC). Mean and SD are the mean and standard deviation of the NWFSC time series, Diff.trend is the absolute change in the predicted trend over 5 years. The solid line is the mean for the NWFSC data. Dotted lines are ±1 SD. The trend line (thick black) is the 5-year trend. Symbol in the upper right indicates that the 5-year trend decreased relative to 1 SD of NWFSC data. Data are the year effect from the GAM model and not absolute estimates of Shannon Diversity.

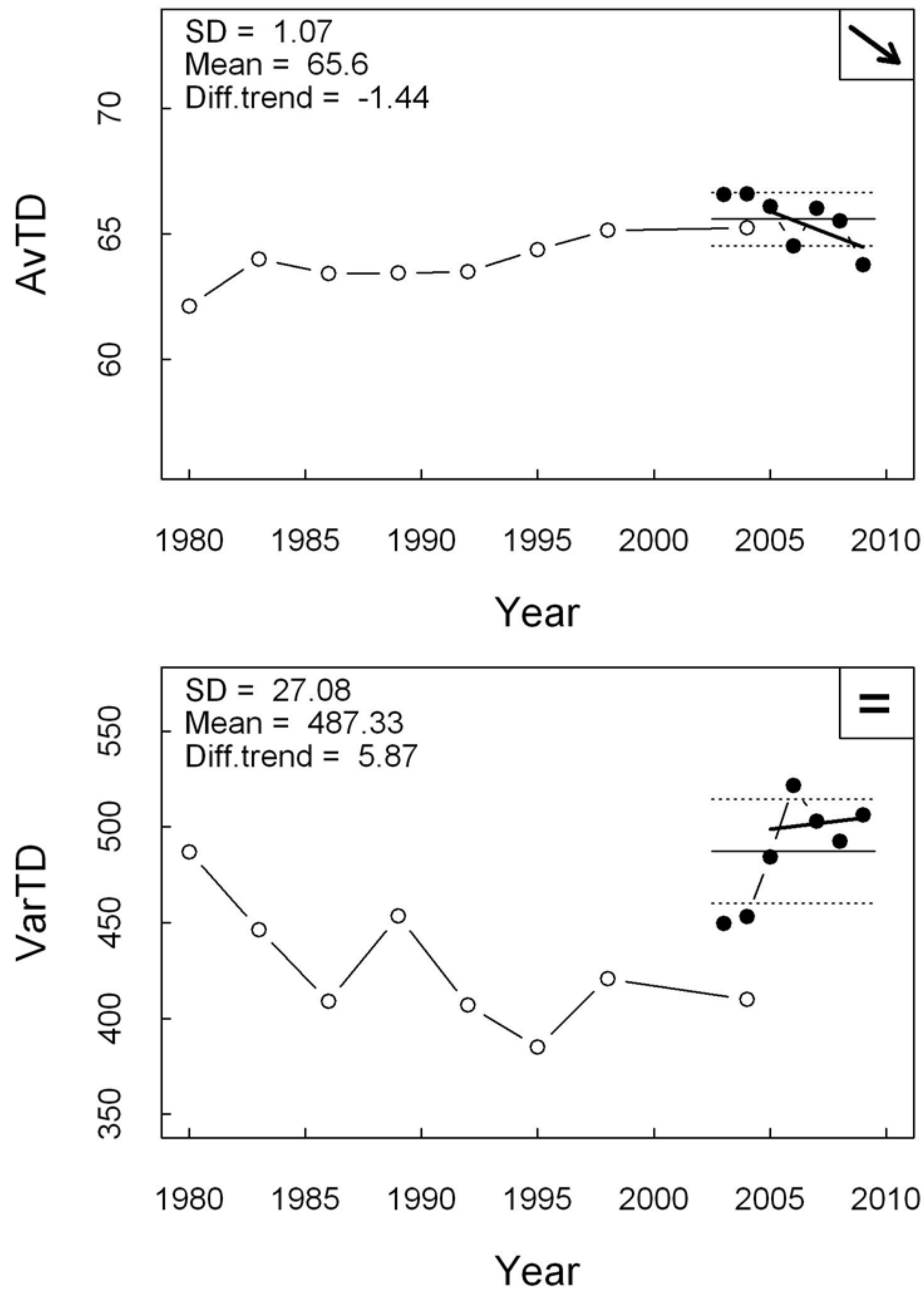


Figure D-10. Average taxonomic distinctness (AvTD) and variation in taxonomic distinctness (VarTD) for West Coast groundfishes from 1980 to 2009 within the Olympic Coast NMS for 50–350 m bottom depth. Closed circles show results for the NWFSC trawl survey (data courtesy of Beth Horness, NWFSC). Mean and SD are the mean and standard deviation of the combined time series, Diff.trend is the absolute change in the predicted trend over 5 years. The solid line is the mean for the NWFSC data. Dotted lines are ±1 SD. The trend line (thick black) is the five-year trend. Symbols in the upper right indicate whether the 5-year trend decreased or showed no change relative to 1 SD of NWFSC data. Data are the year effect from the GAM model and not absolute estimates of the metrics.

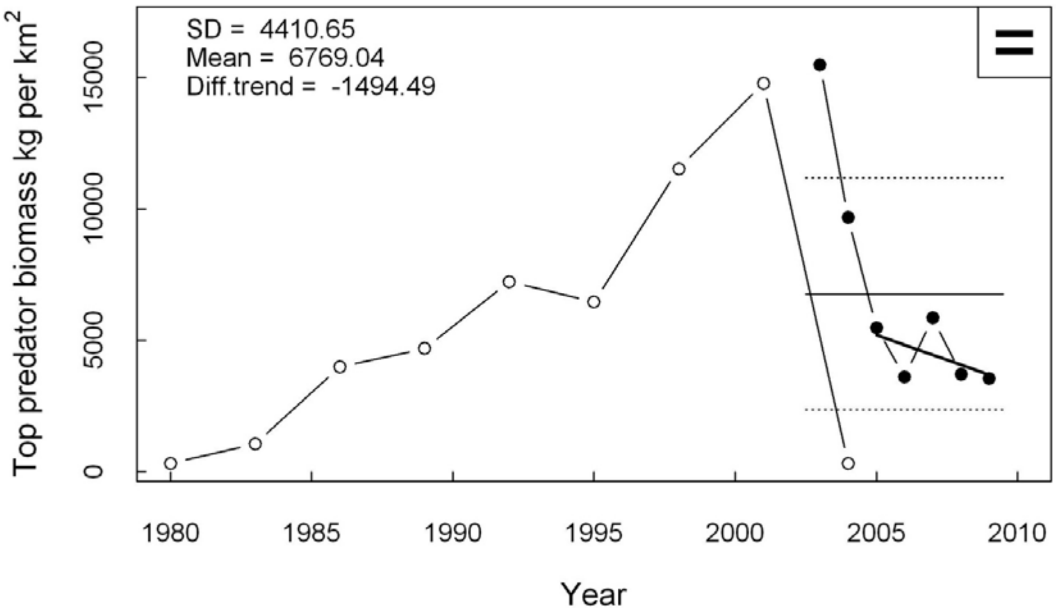


Figure D-11. Top predator biomass within the Olympic Coast NMS. Closed circles show results for the NWFSC trawl survey (data courtesy of Beth Horness, NWFSC). Mean and SD are the mean and standard deviation of the NWFSC time series, Diff.trend is the absolute change in the predicted trend over 5 years. The solid line is the mean for the NWFSC data. Dotted lines are ±1 SD. The trend line (thick black) is the 5-year trend. Symbol in the upper right indicates that the 5-year trend showed no change relative to 1 SD of NWFSC data. Data were log(x+0.1) transformed prior to analysis and back-transformed for presentation. Data are the year effect from the GAM model and not absolute estimates of abundance.

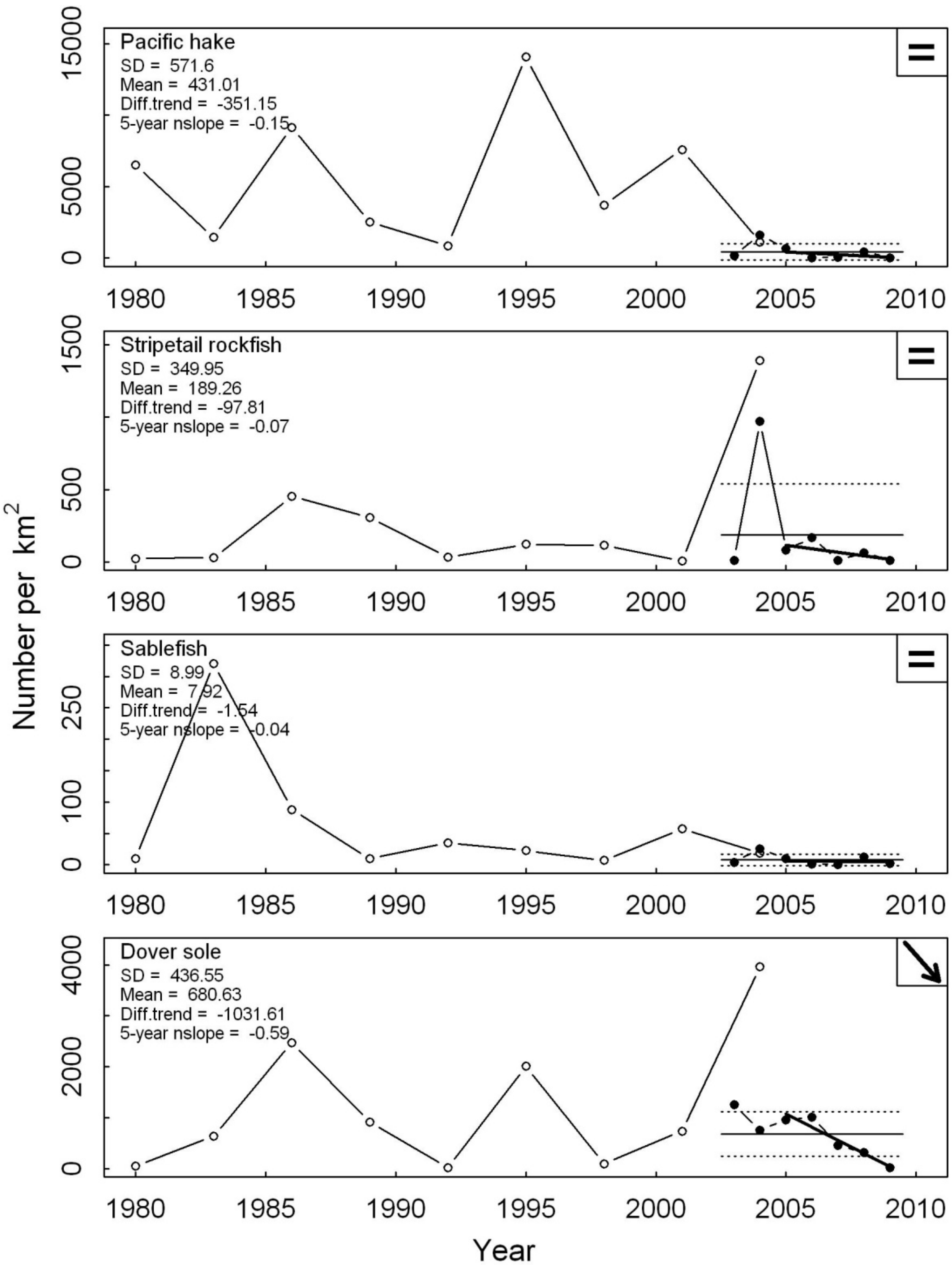


Figure D-12. CPUE (number per km$^2$) for four groundfishes within the Cordell Bank NMS from 1980 to 2009 for the triennial trawl survey (open circles, data courtesy of Mark Wilkins, AFSC) and the NWFSC trawl survey (closed circle, data courtesy of Beth Horness, NWFSC). Mean and SD are the mean and standard deviation of the NWFSC time series, Diff.trend is the absolute change in the predicted trend over 5 years, 5-year nslope is the slope of normalized data for comparison across species. The solid line is the mean for the 7-year NWFSC data. Dotted lines are ±1 SD. The trend line (thick black) is the 5-year trend. Symbols in the upper right indicate whether the 5-year trend decreased or showed no change relative to 1 SD of NWFSC data. Data are the year effect from the GAM model and not absolute estimates of abundance.

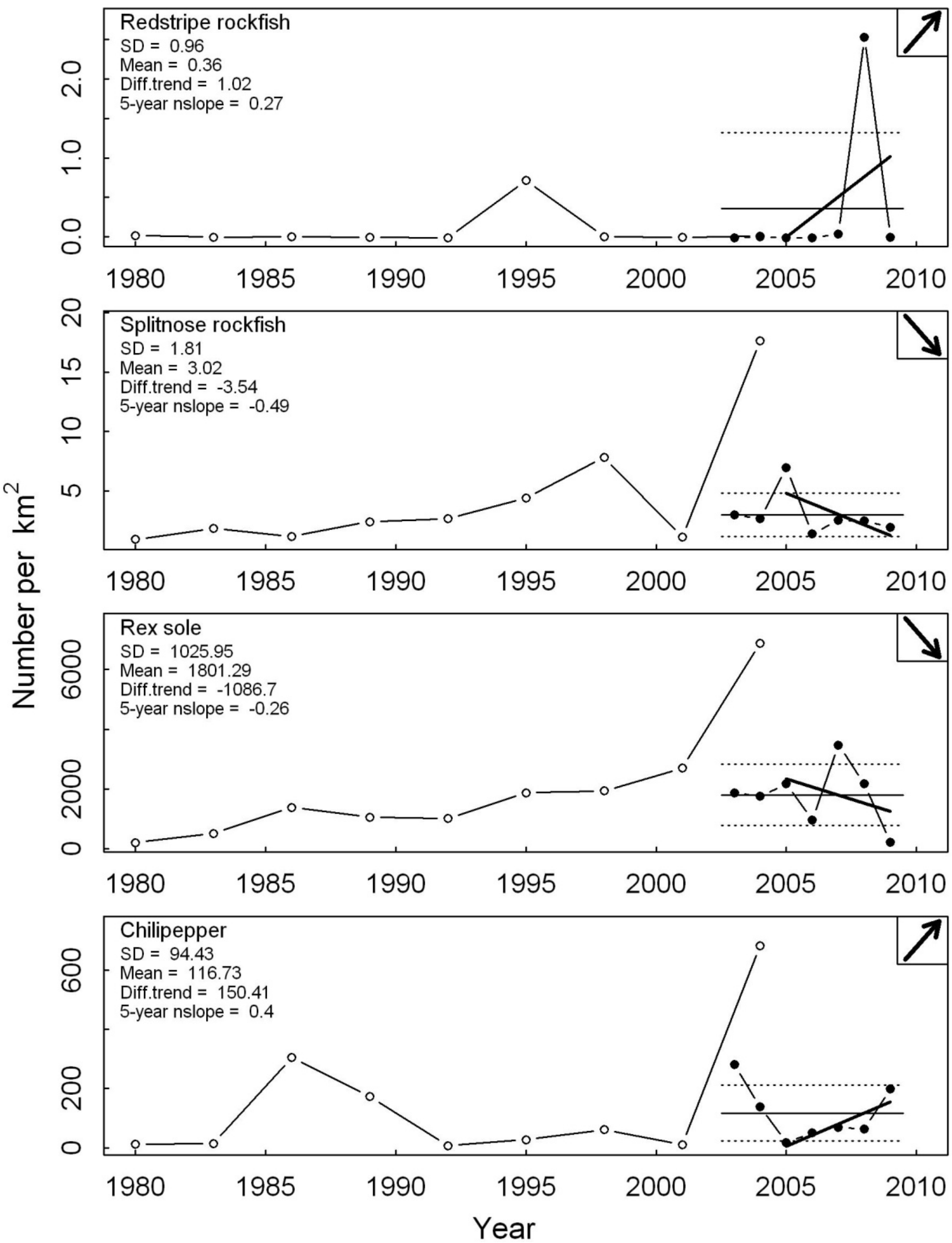


Figure D-13. CPUE (number per km$^2$) for four groundfishes within the Cordell Bank NMS from 1980 to 2009 for the triennial trawl survey (open circles, data courtesy of Mark Wilkins, AFSC) and the NWFSC trawl survey (closed circle, data courtesy of Beth Horness, NWFSC). Mean and SD are the mean and standard deviation of the NWFSC time series, Diff.trend is the absolute change in the predicted trend over five years, 5-year nslope is the slope of normalized data for comparison across species. The solid line is the mean for the 7-year NWFSC data. Dotted lines are ±1 SD. The trend line (thick black) is the 5-year trend. Symbols in the upper right indicate whether the 5-year trend increased or decreased relative to 1 SD of NWFSC data. Data are the year effect from the GAM model and not absolute estimates of abundance.

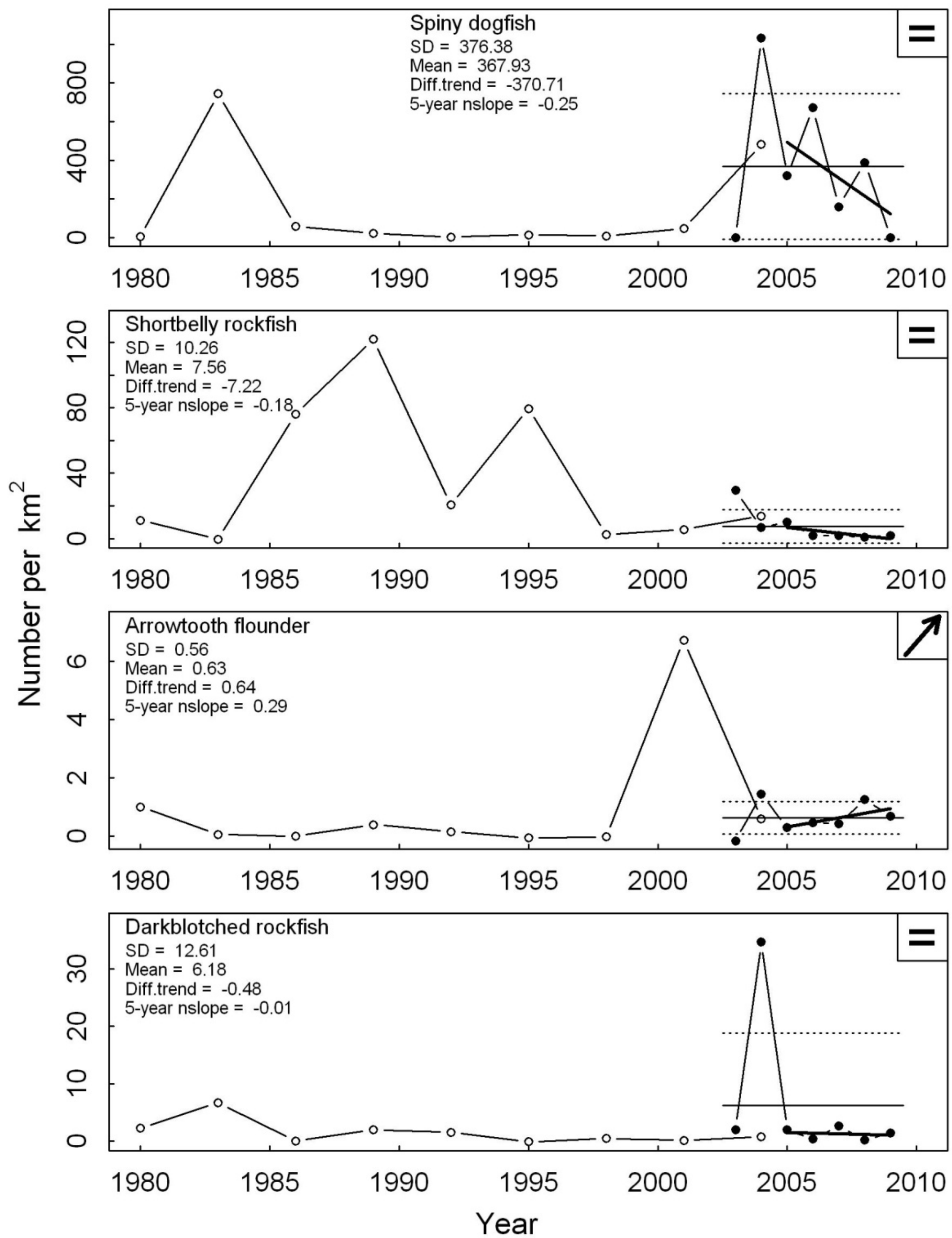


Figure D-14. CPUE (number per km$^2$) for four groundfishes within the Cordell Bank NMS from 1980 to 2009 for the triennial trawl survey (open circles, data courtesy of Mark Wilkins, AFSC) and the NWFSC trawl survey (closed circle, data courtesy of Beth Horness, NWFSC). Mean and SD are the mean and standard deviation of the NWFSC time series, Diff.trend is the absolute change in the predicted trend over 5 years, 5-year nslope is the slope of normalized data for comparison across species. The solid line is the mean for the 7-year NWFSC data. Dotted lines are ±1 SD. The trend line (thick black) is the 5-year trend. Symbols in the upper right indicate whether the 5-year trend increased or showed no change relative to 1 SD of NWFSC data. Data are the year effect from the GAM model and not absolute estimates of abundance.

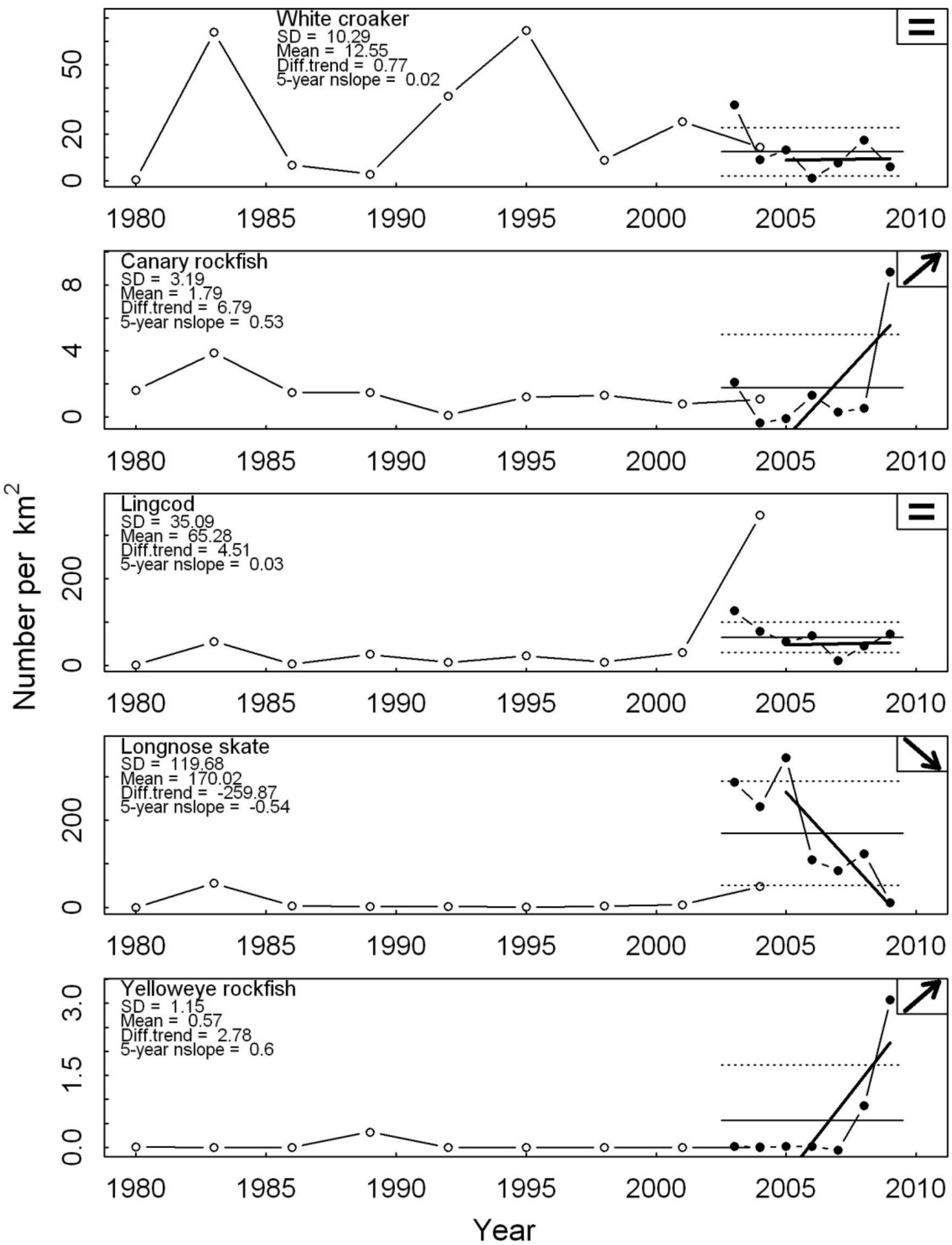


Figure D-15. CPUE (number per km$^2$) for five groundfishes within the Cordell Bank NMS from 1980 to 2009 for the triennial trawl survey (open circles, data courtesy of Mark Wilkins, AFSC) and the NWFSC trawl survey (closed circle, data courtesy of Beth Horness, NWFSC). Mean and SD are the mean and standard deviation of the NWFSC time series, Diff.trend is the absolute change in the predicted trend over 5 years, 5-year nslope is the slope of normalized data for comparison across species. The solid line is the mean for the 7-year NWFSC data. Dotted lines are ±1 SD. The trend line (thick black) is the 5-year trend. Symbols in the upper right indicate whether the 5-year trend increased, decreased, or showed no change relative to 1 SD of NWFSC data. Data are the year effect from the GAM model and not absolute estimates of abundance.

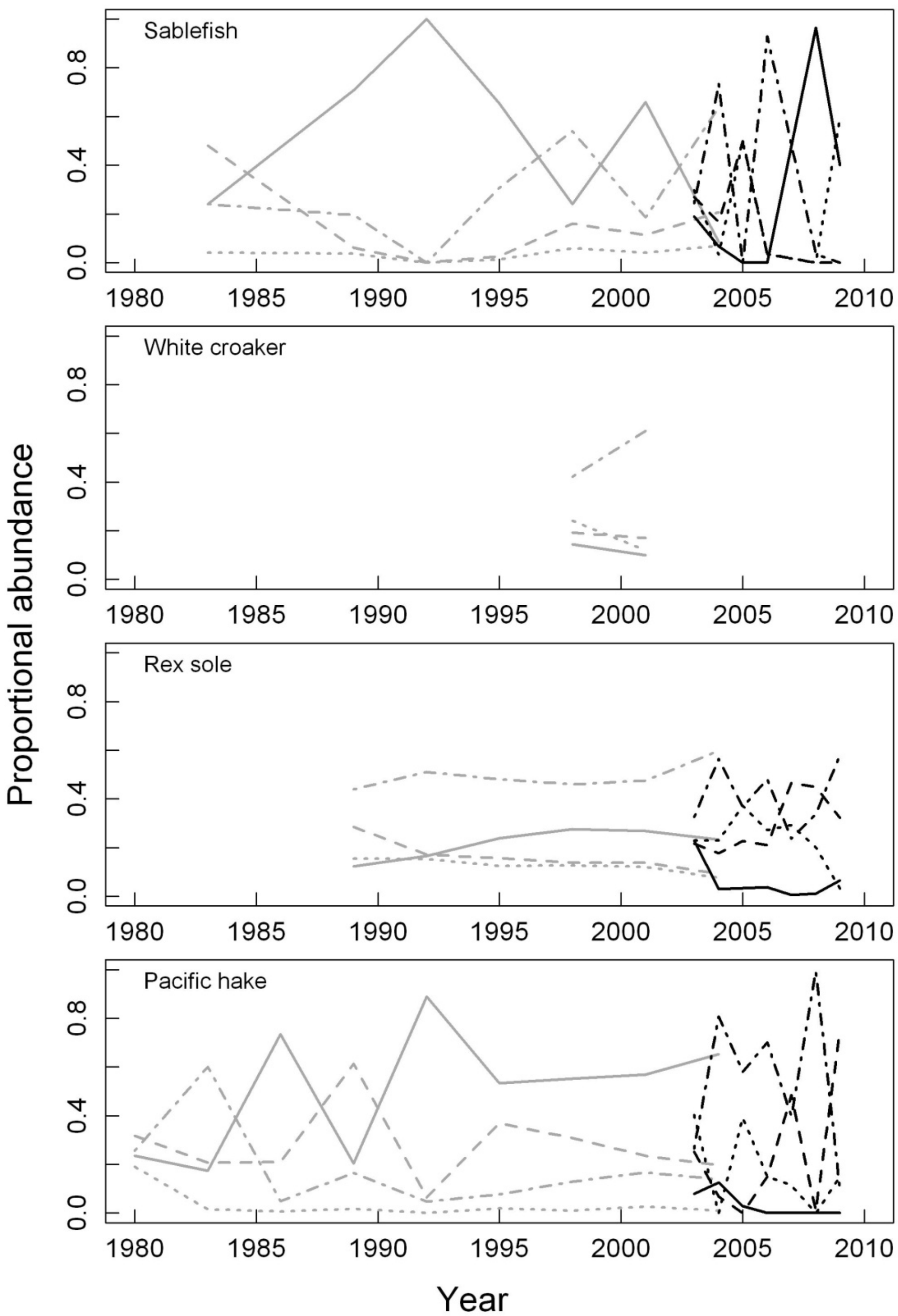


Figure D-16. Size distribution for four groundfishes within the Cordell Bank NMS from 1980 to 2009. Plots show the proportion of fish in the first (solid), second (dashed), third (dotted), and fourth (dot-dash) quartiles. Gray lines are the triennial survey data (courtesy of Mark Wilkins, AFSC), and black lines are the NWFSC survey data (courtesy of Beth Horness, NWFSC). To show change in size structure through time, size cutoffs for the quartiles were established based on the first year in each time series (1980 and 2003). Subsequent years show proportion of fishes in those size classes.

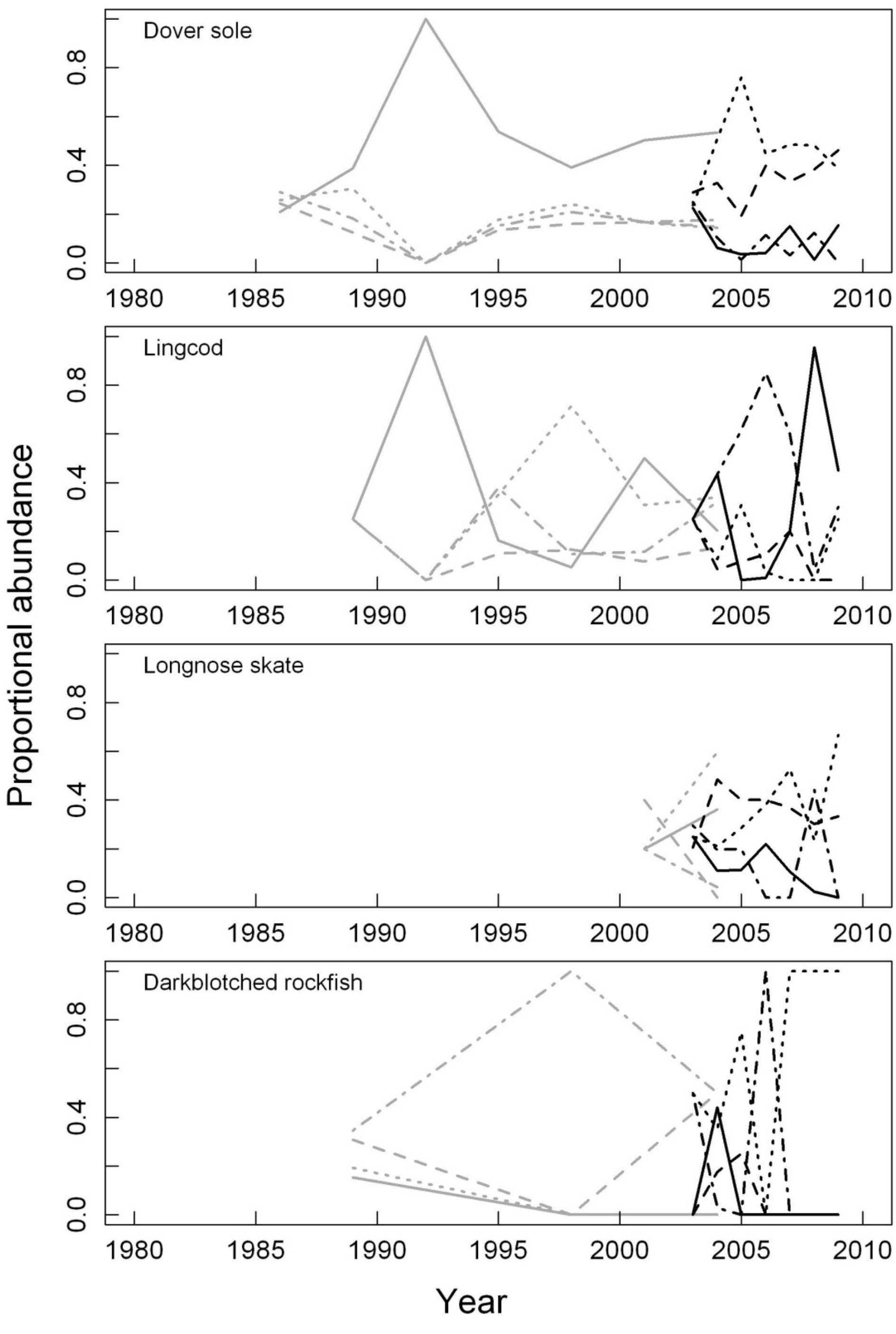


Figure D-17. Size distribution for four groundfishes within the Cordell Bank NMS from 1980 to 2009. Plots show the proportion of fish in the first (solid), second (dashed), third (dotted), and fourth (dot-dash) quartiles. Gray lines are the triennial survey data (courtesy of Mark Wilkins, AFSC), and black lines are the NWFSC survey data (courtesy of Beth Horness, NWFSC). To show change in size structure through time, size cutoffs for the quartiles were established based on the first year in each time series (1980 and 2003). Subsequent years show proportion of fishes in those size classes.

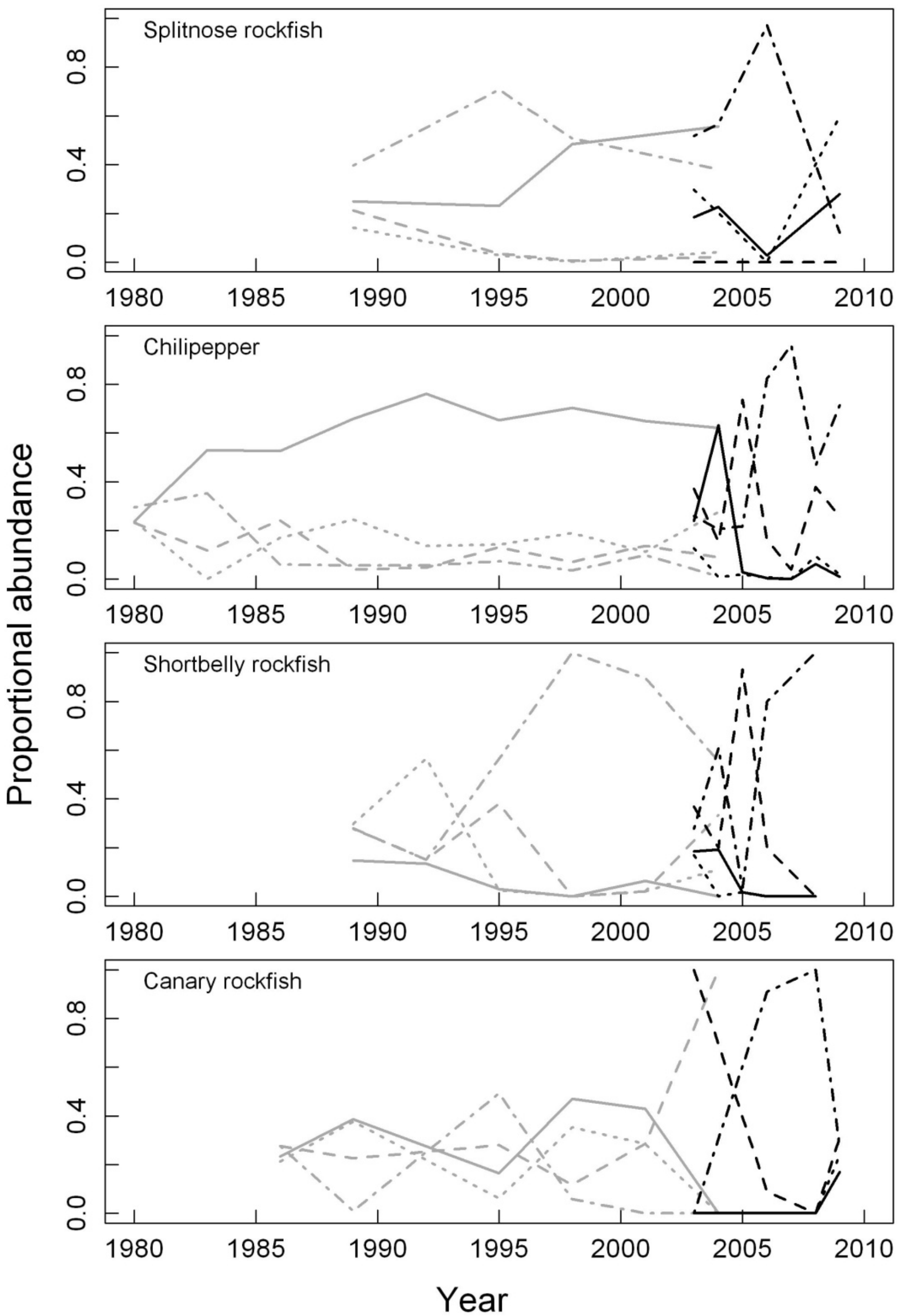


Figure D-18. Size distribution for four groundfishes within the Cordell Bank NMS from 1980 to 2009. Plots show the proportion of fish in the first (solid), second (dashed), third (dotted), and fourth (dot-dash) quartiles. Gray lines are the triennial survey data (courtesy of Mark Wilkins, AFSC), and black lines are the NWFSC survey data (courtesy of Beth Horness, NWFSC). To show change in size structure through time, size cutoffs for the quartiles were established based on the first year in each time series (1980 and 2003). Subsequent years show proportion of fishes in those size classes.

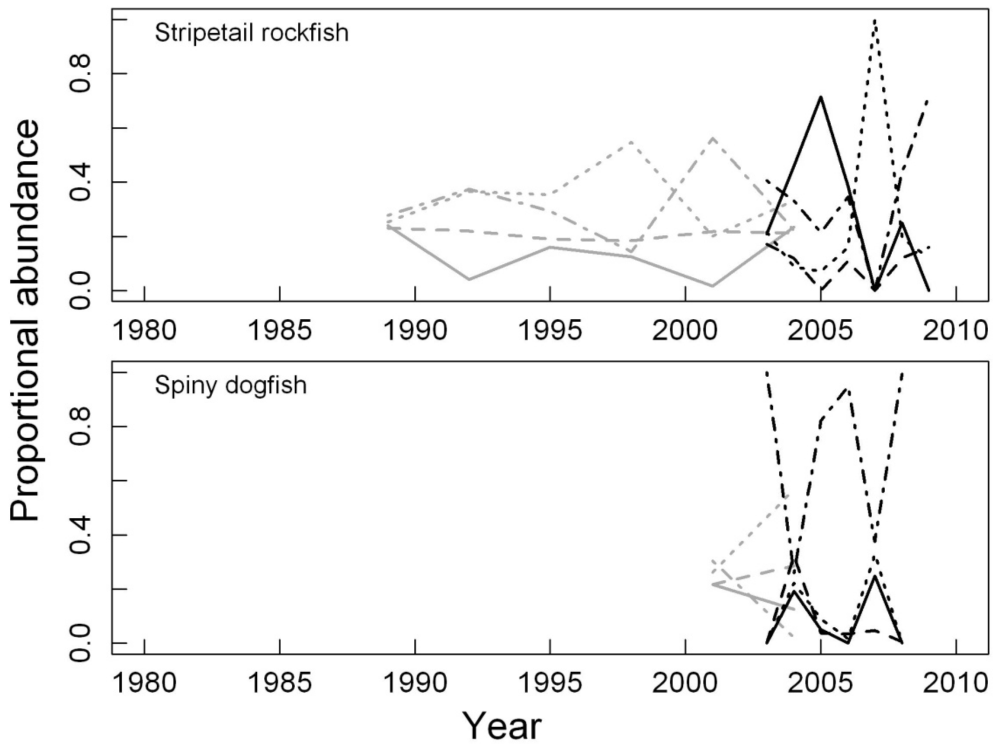


Figure D-19. Size distribution for two groundfishes within the Cordell Bank NMS from 1980 to 2009. Plots show the proportion of fish in the first (solid), second (dashed), third (dotted), and fourth (dot-dash) quartiles. Gray lines are the triennial survey data (courtesy of Mark Wilkins, AFSC), and black lines are the NWFSC survey data (courtesy of Beth Horness, NWFSC). To show change in size structure through time, size cutoffs for the quartiles were established based on the first year in each time series (1980 and 2003). Subsequent years show proportion of fishes in those size classes.

Shannon Diversity Index: This showed high variability and a trend towards an increase over the last 5 years of the time series (Figure D-20). However, the increase was just less than 1 SD of the NWFSC time series.

Taxonomic distinctness: Average taxonomic distinctness (AvTD) and variation in taxonomic distinctness (VarTD) showed a declining 5-year trend with a decline greater than 1 SD of the NWFSC time series (Figure D-21). For AvTD this result was due largely to the final data point, prior to which AvTD had been trending up.

Top predator biomass (groundfishes): This declined over the final 5 years of the NWFSC time series (Figure D-22). The total change was almost twice the SD of the NWFSC time series.

## Gulf of the Farallones NMS

Groundfish numbers: Four of 14 species showed declines within the Gulf of the Farallones NMS. These included stripetail rockfish, Dover sole, rex sole, and longnose skate (Figure D-23 through Figure D-26). Six species showed no change: hake, chilipepper rockfish,

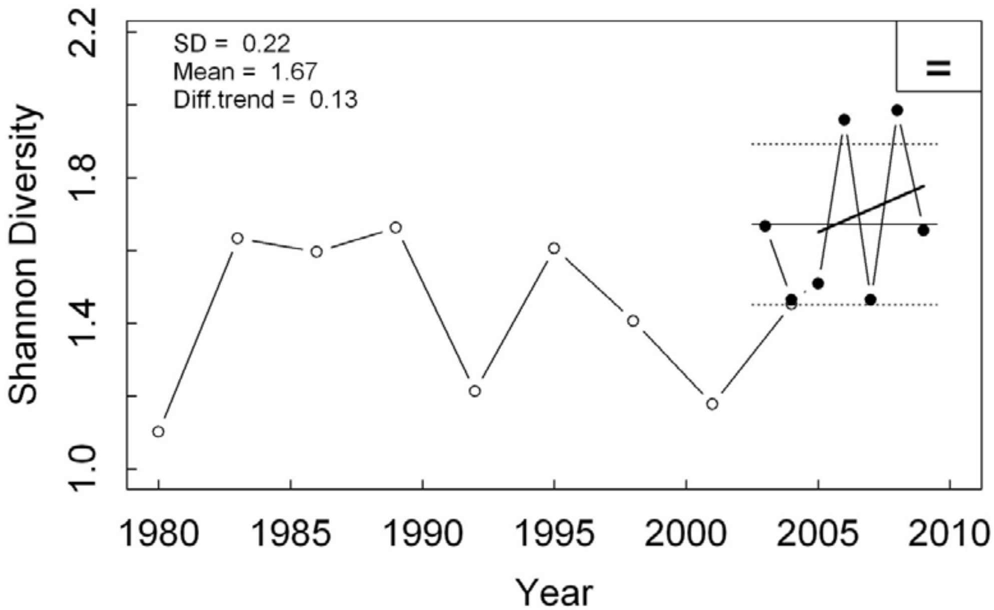


Figure D-20. Annual mean Shannon Diversity within the Cordell Bank NMS for 50–350 m bottom depth. Open circles show yearly averages calculated from the triennial trawl survey (data courtesy of Mark Wilkins, AFSC). Closed circles show results for the NWFSC trawl survey (data courtesy of Beth Horness, NWFSC). Mean and SD are the mean and standard deviation of the NWFSC time series, Diff.trend is the absolute change in the predicted trend over 5 years. The solid line is the mean for the NWFSC data. Dotted lines are ±1 SD. The trend line (thick black) is the 5-year trend. Symbol in the upper right indicates that the 5-year trend showed no change relative to 1 SD of NWFSC data. Data are the year effect from the GAM model and not absolute estimates of Shannon Diversity.

spiny dogfish, shortbelly rockfish, white croaker, and canary rockfish. Four species showed increasing 5-year trends that were greater than 1 SD of the data series: sablefish, splitnose rockfish, arrowtooth flounder, and lingcod.

Groundfish size class distribution: Most species show variation in the proportion of individuals in four size classes through time (Figure D-27 through Figure D-30). Some species such as sablefish showed drastic changes in size structure, especially within the NWFSC time series. For sablefish, larger fish were initially more common, but for the final 3 years small fish dominated the population. Other species such as Dover sole showed an increase in the proportion of large individuals in the population. Some species do not have size estimates in all years.

Shannon Diversity Index: This decreased within the Gulf of Farallones sanctuary over the final 5 years of the time series (Figure D-31). The decrease was due to the final point in the time series, so some caution should be use in interpreting this result. Prior to 2009, the trend in diversity was relatively stable.

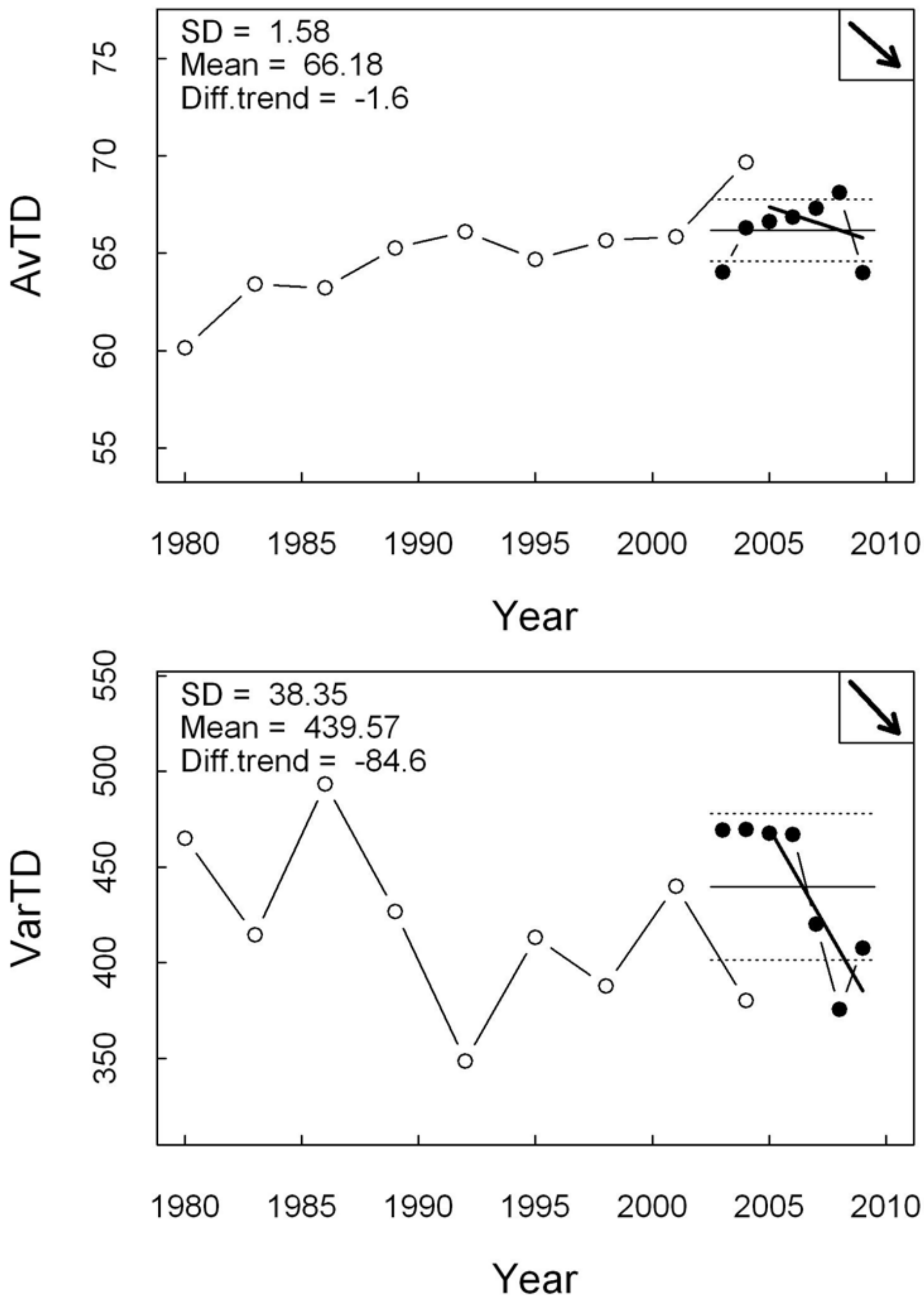


Figure D-21. Average taxonomic distinctness (AvTD) and variation in taxonomic distinctness (VarTD) for West Coast groundfishes from 1980–2009 within the Cordell Bank NMS for 50–350 m bottom depth. Closed circles show results for the NWFSC trawl survey (data courtesy of Beth Horness, NWFSC). Mean and SD are the mean and standard deviation of the NWFSC time series, Diff.trend is the absolute change in the predicted trend over 5 years. The solid line is the mean for the NWFSC data. Dotted lines are ±1 SD. The trend line (thick black) is the 5-year trend. Symbols in the upper right indicate that the 5-year trend decreased relative to 1 SD of NWFSC data. Data are the year effect from the GAM model and not absolute estimates of the metrics.

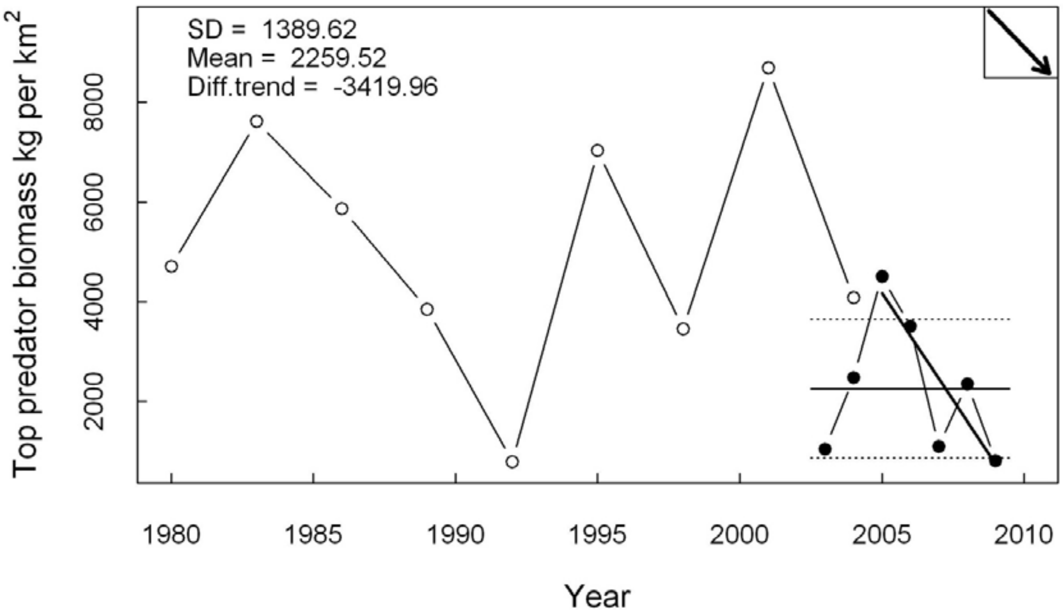


Figure D-22. Top predator biomass within the Cordell Bank NMS. Closed circles show results for the NWFSC trawl survey (data courtesy of Beth Horness, NWFSC). Mean and SD are the mean and standard deviation of the NWFSC time series, Diff.trend is the absolute change in the predicted trend over 5 years. The solid line is the mean for the NWFSC data. Dotted lines are ±1 SD. The trend line (thick black) is the 5-year trend. Symbol in the upper right indicates that the 5-year trend decreased relative to 1 SD of NWFSC data. Data were log(x+0.1) transformed prior to analysis and back-transformed for presentation. Data are the year effect from the GAM model and not absolute estimates of abundance.

Taxonomic distinctness: Neither average nor variation in taxonomic distinctness changed during the final 5 years of the time series (Figure D-32).

Top predator biomass (groundfishes): While variable from year to year, the top predator biomass showed no sign of increase or decrease (Figure D-33).

## Monterey Bay NMS

Groundfish numbers: Eight of 16 species examined in the Monterey Bay NMS showed declining trends over the last 5 years of the time series (Figure D-34 through Figure D-37). These species included hake, stripetail rockfish, Dover sole, rex sole, chilipepper, spiny dogfish, shortbelly rockfish, and white croaker. For 5 species, trends over the last 5 years showed no change: sablefish, splitnose rockfish, darkblotched rockfish, canary rockfish, and longnose skate. Arrowtooth flounder, lingcod, and yelloweye rockfish all showed increasing trends.

Groundfish size class distribution: Most species show variation in the proportion of individuals in four size classes through time (Figure D-38 through Figure D-41). Some groups such as canary rockfish showed an aging population, with an increase in the proportion of large individuals, but an overall decrease in their numbers. Some species do not have size estimates in all years.

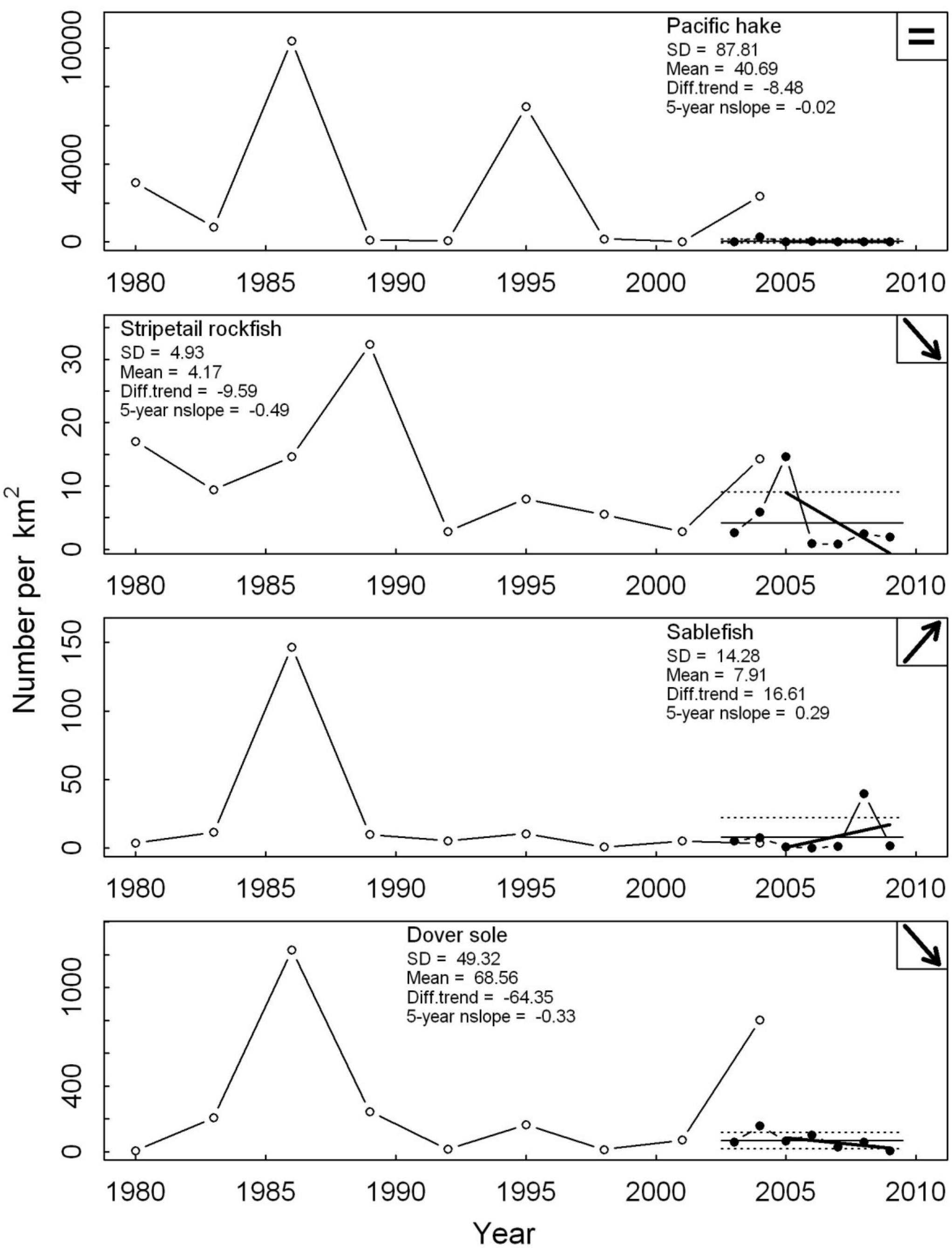


Figure D-23. CPUE (number per $km^2$) for four groundfishes within the Gulf of the Farallones NMS from 1980 to 2009 for the triennial trawl survey (open circles, data courtesy of Mark Wilkins, AFSC) and the NWFSC trawl survey (closed circle, data courtesy of Beth Horness, NWFSC). Mean and SD are the mean and standard deviation of the NWFSC time series, Diff.trend is the absolute change in the predicted trend over 5 years, 5-year nslope is the slope of normalized data for comparison across species. The solid line is the mean for the 7-year NWFSC data. Dotted lines are ±1 SD. The trend line (thick black) is the 5-year trend. Symbols in the upper right indicate whether the 5-year trend increased, decreased, or showed no change relative to 1 SD of NWFSC data. Data are the year effect from the GAM model and not absolute estimates of abundance.

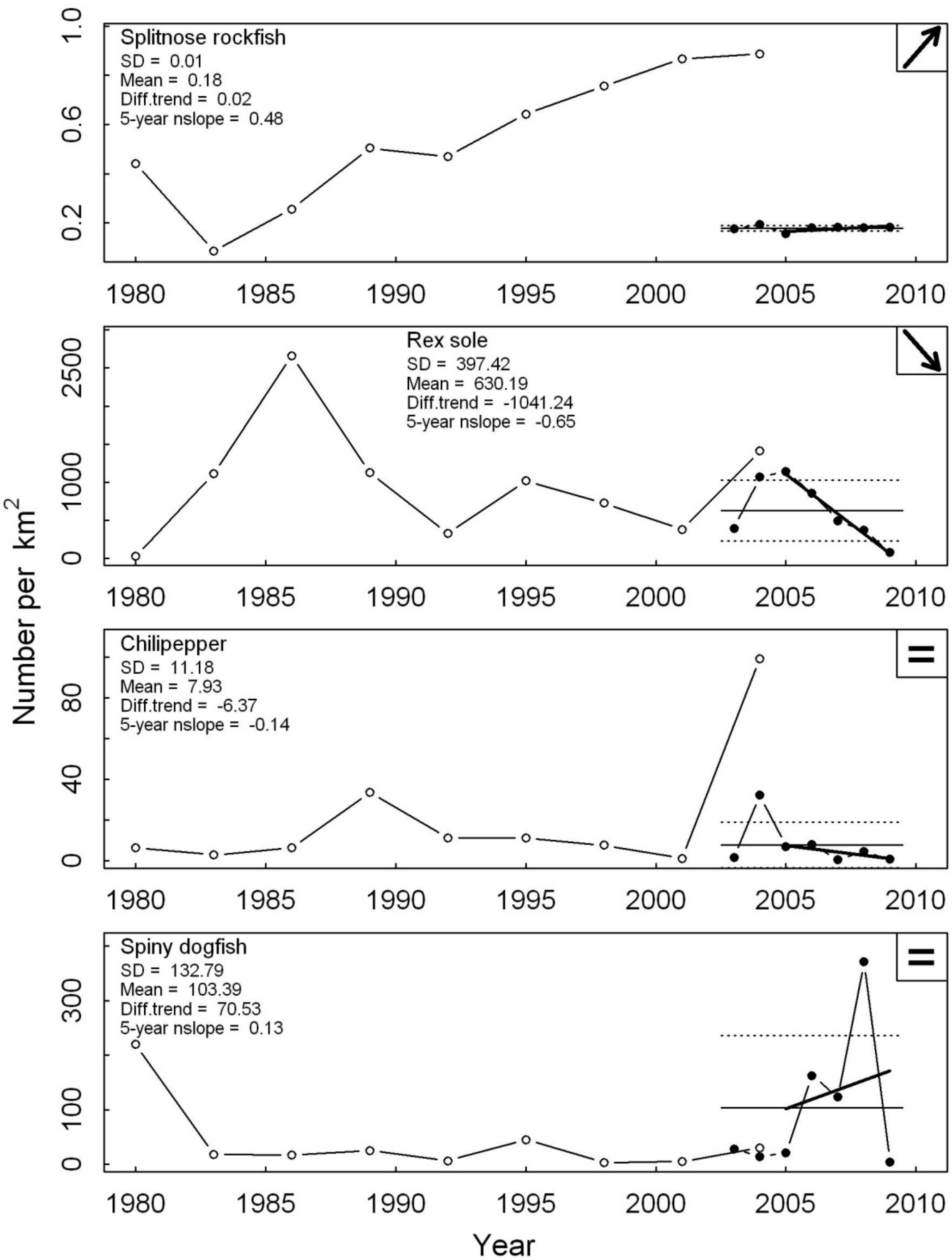


Figure D-24. CPUE (number per km$^2$) for four groundfishes within the Gulf of the Farallones NMS from 1980 to 2009 for the triennial trawl survey (open circles, data courtesy of Mark Wilkins, AFSC) and the NWFSC trawl survey (closed circle, data courtesy of Beth Horness, NWFSC). Mean and SD are the mean and standard deviation of the NWFSC time series, Diff.trend is the absolute change in the predicted trend over 5 years, 5-year nslope is the slope of normalized data for comparison across species. The solid line is the mean for the 7-year NWFSC data. Dotted lines are ±1 SD. The trend line (thick black) is the 5-year trend. Symbols in the upper right indicate whether the 5-year trend increased, decreased, or showed no change relative to 1 SD of NWFSC data. Data are the year effect from the GAM model and not absolute estimates of abundance.

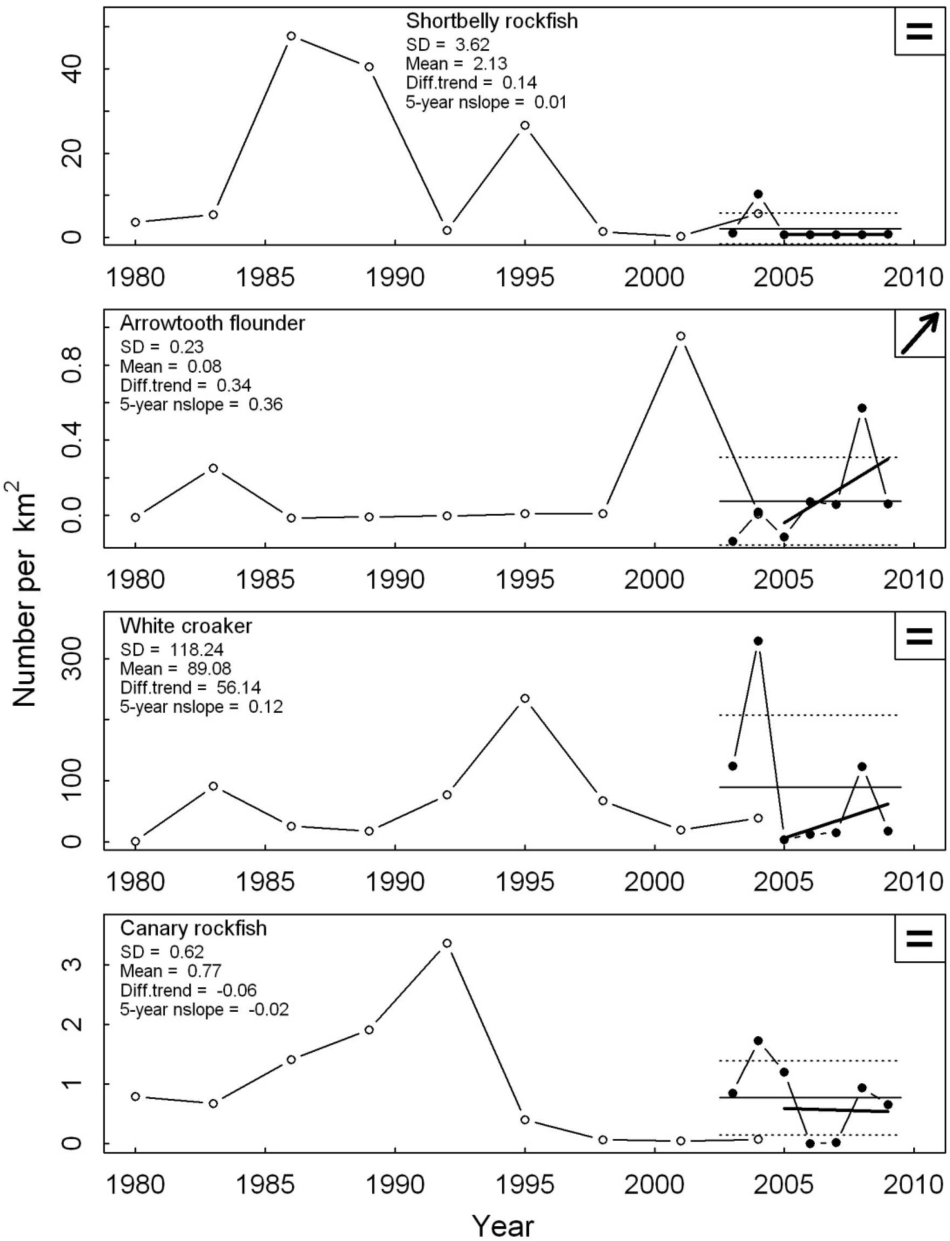


Figure D-25. CPUE (number per km$^2$) for four groundfishes within the Gulf of the Farallones NMS from 1980 to 2009 for the triennial trawl survey (open circles, data courtesy of Mark Wilkins, AFSC) and the NWFSC trawl survey (closed circle, data courtesy of Beth Horness, NWFSC). Mean and SD are the mean and standard deviation of the NWFSC time series, Diff.trend is the absolute change in the predicted trend over 5 years, 5-year nslope is the slope of normalized data for comparison across species. The solid line is the mean for the 7-year NWFSC data. Dotted lines are ±1 SD. The trend line (thick black) is the 5-year trend. Symbols in the upper right indicate whether the 5-year trend increased or showed no change relative to 1 SD of NWFSC data. Data are the year effect from the GAM model and not absolute estimates of abundance.

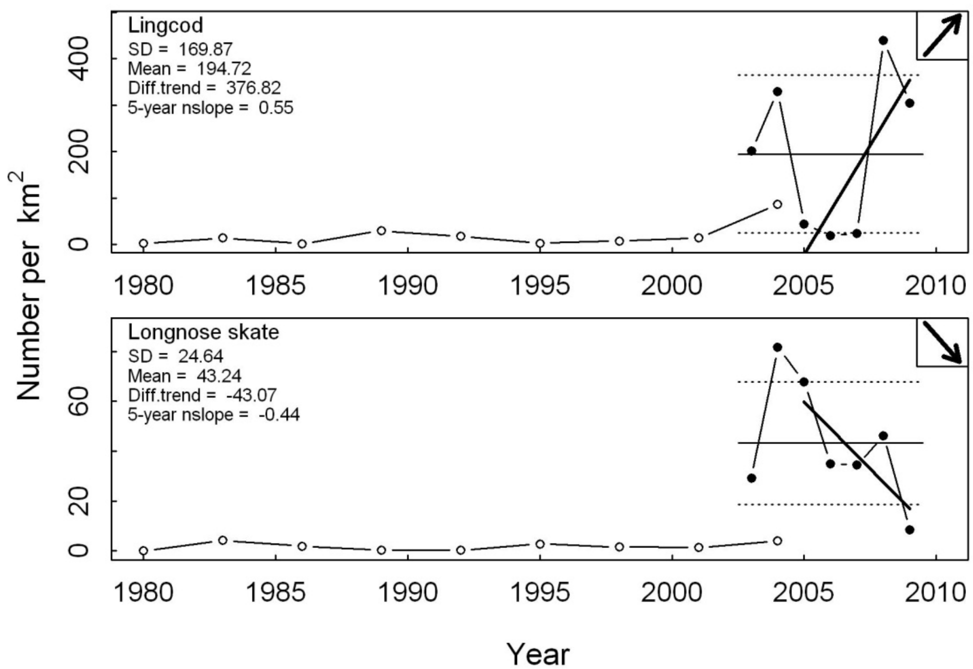


Figure D-26. CPUE (number per km$^2$) for two groundfishes within the Gulf of the Farallones NMS from 1980 to 2009 for the triennial trawl survey (open circles, data courtesy of Mark Wilkins, AFSC) and the NWFSC trawl survey (closed circle, data courtesy of Beth Horness, NWFSC). Mean and SD are the mean and standard deviation of the NWFSC time series, Diff.trend is the absolute change in the predicted trend over 5 years, 5-year nslope is the slope of normalized data for comparison across species. The solid line is the mean for the 7-year NWFSC data. Dotted lines are ±1 SD. The trend line (thick black) is the 5-year trend. Symbols in the upper right indicate whether the 5-year trend increased or decreased relative to 1 SD of NWFSC data. Data are the year effect from the GAM model and not absolute estimates of abundance.

Shannon Diversity Index: This showed a declining 5-year trend with especially steep declines during the last 3 years (Figure D-42).

Taxonomic distinctness: While AvTD appeared to increase from the 1980 to present, the trend over the last 5 years was for a decline greater than 1 SD of the NWFSC time series (Figure D-43). Like other locations, this decline was caused by the 2009 data. Otherwise AvTD had been trending up. VarTD showed substantial variability over the NWFSC time series but no trend over the last 5 years.

Top predator biomass (groundfishes): This declined between 2005 and 2009 (Figure D-44).

Nutrient levels: Mean seasonal peak concentrations of nitrate, silicate, and phosphate were variable at 11 monitoring stations in Monterey Bay National Sanctuary from 2002 to 2007 (Figure D-45).

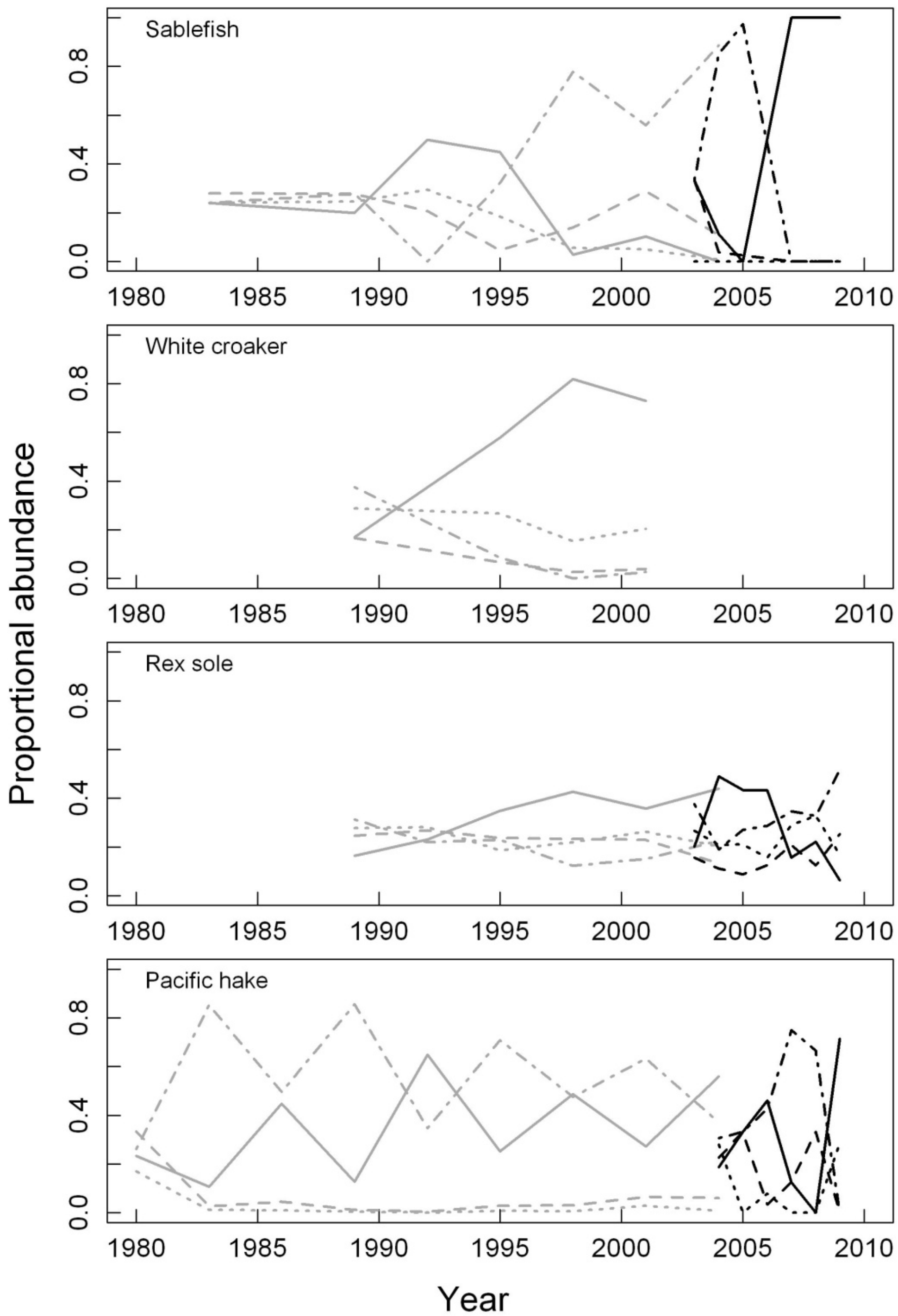


Figure D-27. Size distribution for four groundfishes within the Gulf of the Farallones NMS from 1980 to 2009. Plots show the proportion of fish in the first (solid), second (dashed), third (dotted), and fourth (dot-dash) quartiles. Gray lines are the triennial survey data (courtesy of Mark Wilkins, AFSC), and black lines are the NWFSC survey data (courtesy of Beth Horness, NWFSC). To show change in size structure through time, size cutoffs for the quartiles were established based on the first year in each time series (1980 and 2003). Subsequent years show proportion of fishes in those size classes.

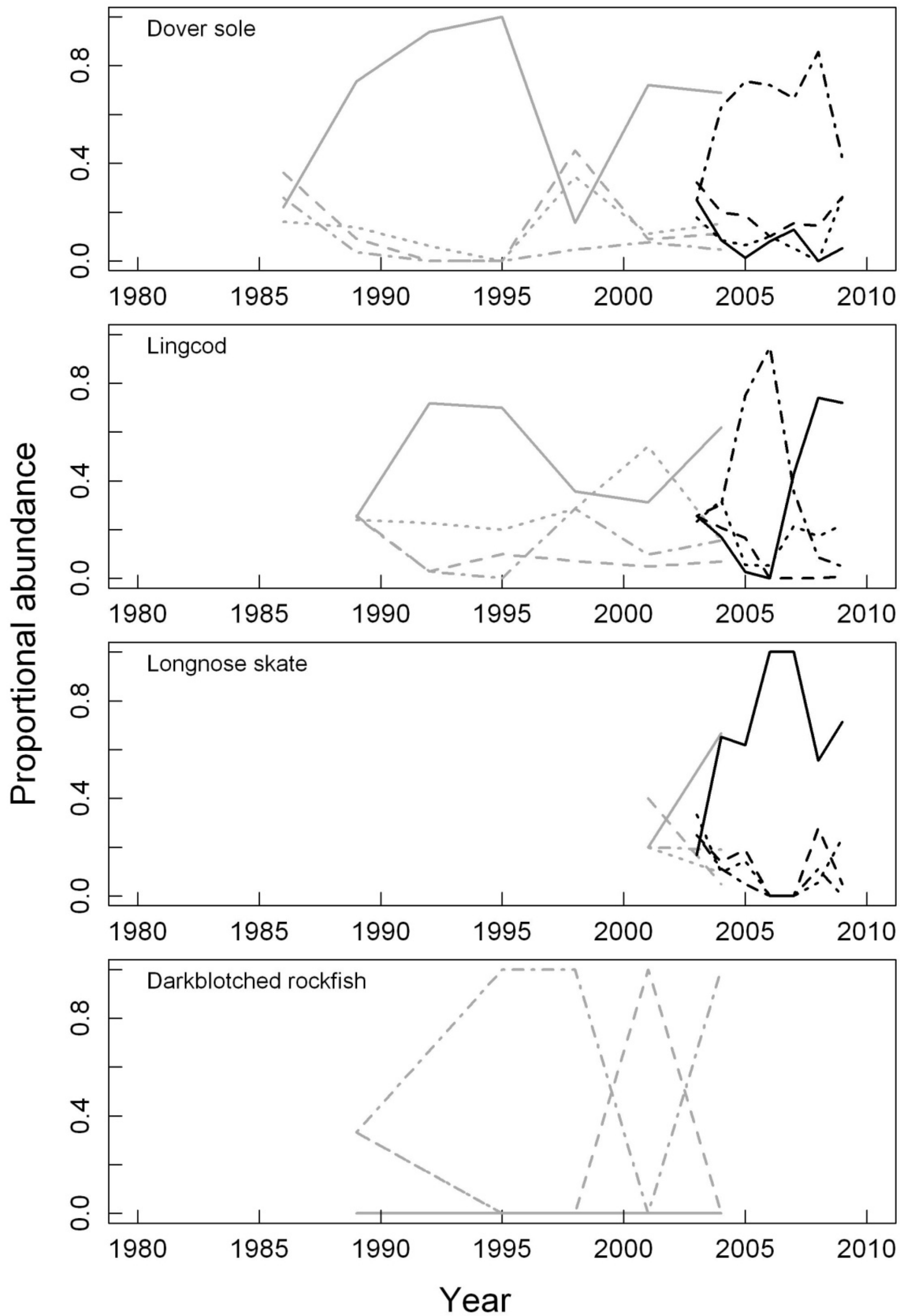


Figure D-28. Size distribution for four groundfishes within the Gulf of the Farallones NMS from 1980 to 2009. Plots show the proportion of fish in the first (solid), second (dashed), third (dotted), and fourth (dot-dash) quartiles. Gray lines are the triennial survey data (courtesy of Mark Wilkins, AFSC), and black lines are the NWFSC survey data (courtesy of Beth Horness, NWFSC). To show change in size structure through time, size cutoffs for the quartiles were established based on the first year in each time series (1980 and 2003). Subsequent years show proportion of fishes in those size classes.

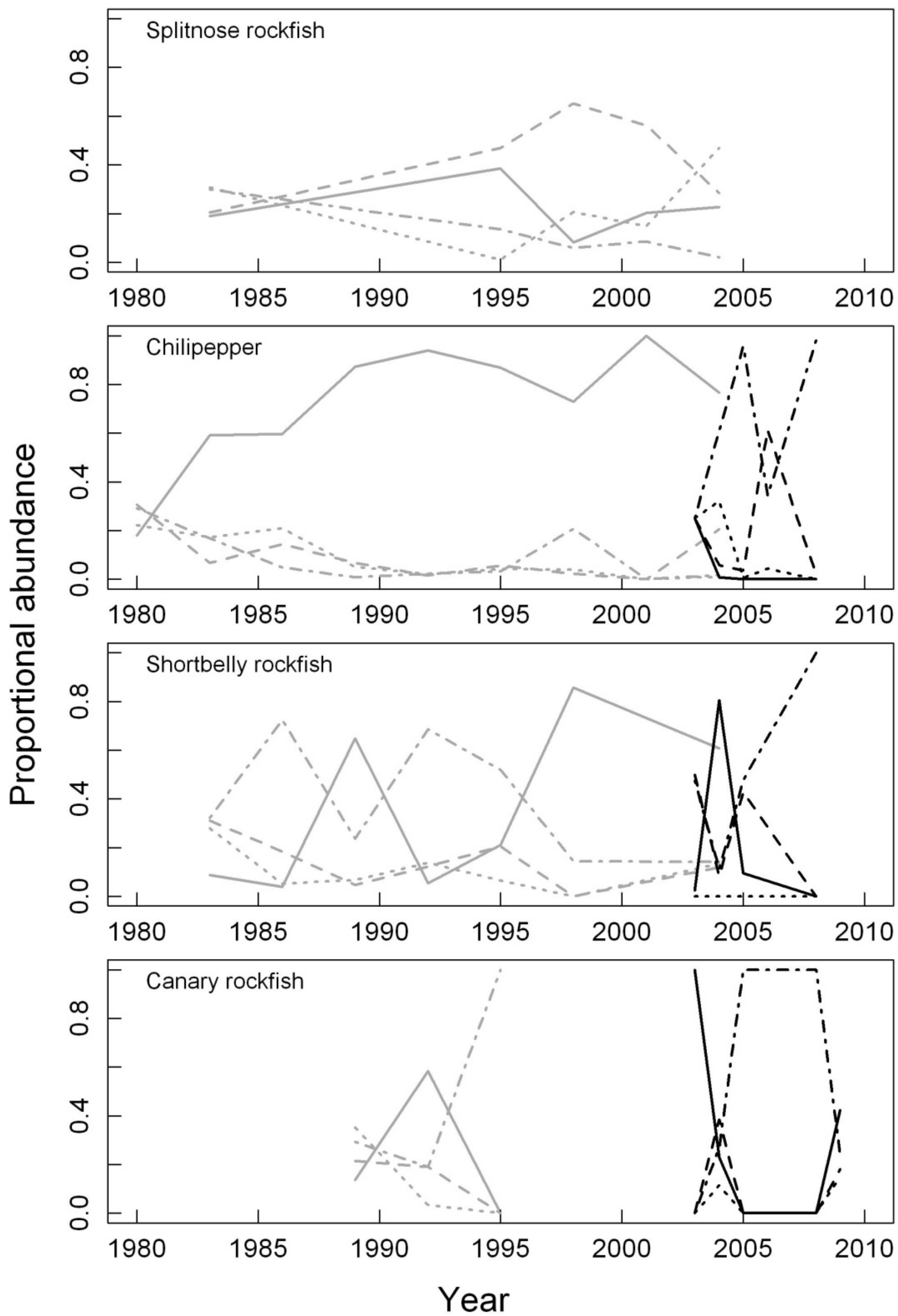


Figure D-29. Size distribution for four groundfishes within the Gulf of the Farallones NMS from 1980 to 2009. Plots show the proportion of fish in the first (solid), second (dashed), third (dotted), and fourth (dot-dash) quartiles. Gray lines are the triennial survey data (courtesy of Mark Wilkins, AFSC), and black lines are the NWFSC survey data (courtesy of Beth Horness, NWFSC). To show change in size structure through time, size cutoffs for the quartiles were established based on the first year in each time series (1980 and 2003). Subsequent years show proportion of fishes in those size classes.

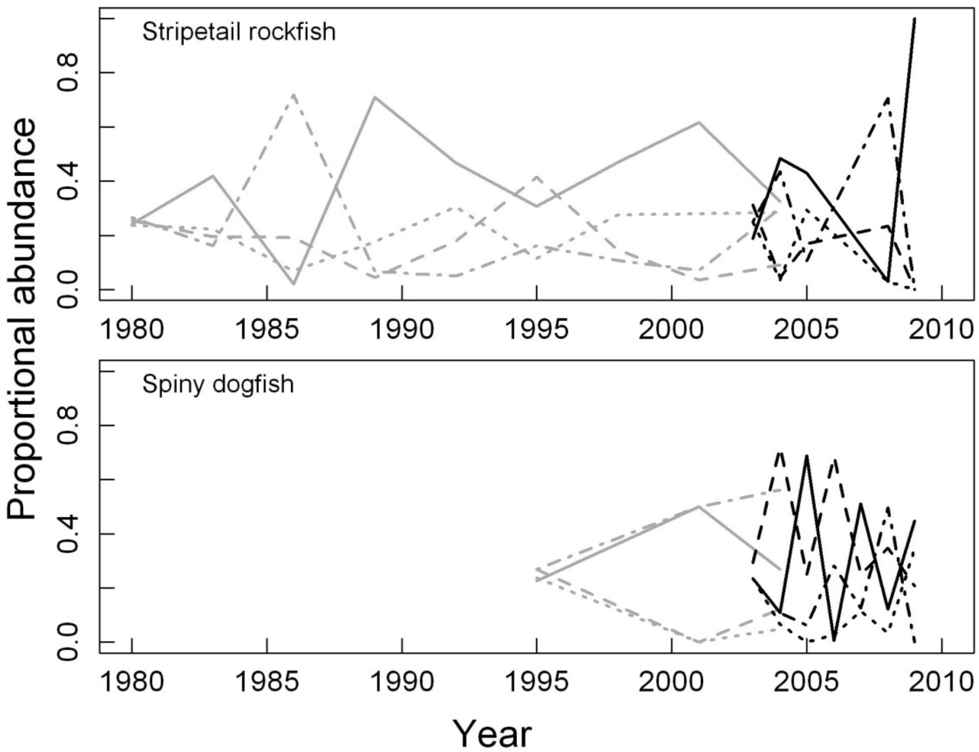


Figure D-30. Size distribution for two groundfishes within the Gulf of the Farallones NMS from 1980 to 2009. Plots show the proportion of fish in the first (solid), second (dashed), third (dotted), and fourth (dot-dash) quartiles. Gray lines are the triennial survey data (courtesy of Mark Wilkins, AFSC), and black lines are the NWFSC survey data (courtesy of Beth Horness, NWFSC). To show change in size structure through time, size cutoffs for the quartiles were established based on the first year in each time series (1980 and 2003). Subsequent years show proportion of fishes in those size classes.

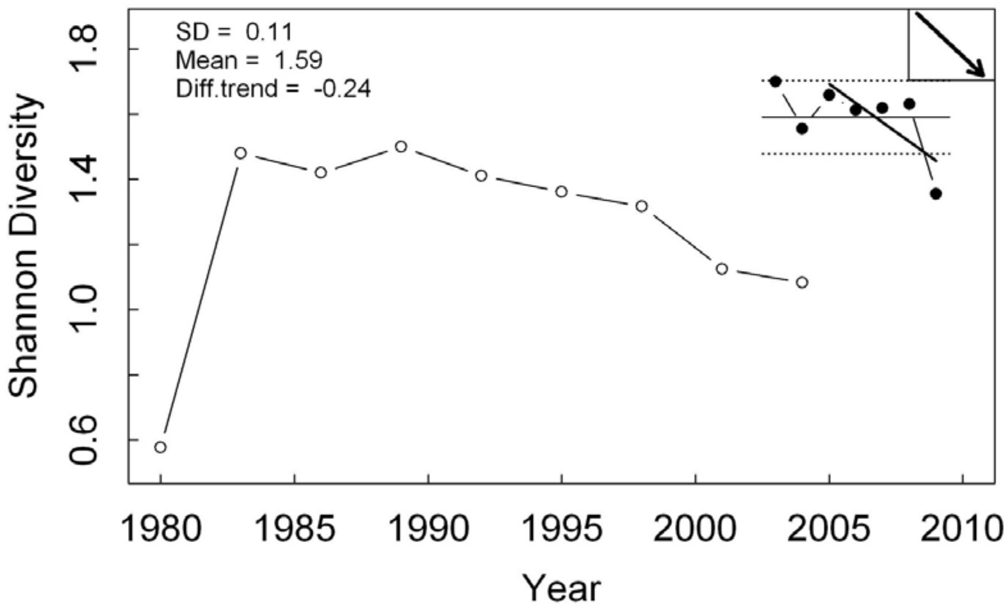


Figure D-31. Annual mean Shannon Diversity within the Gulf of the Farallones NMS for 50–350 m bottom depth. Open circles show yearly averages calculated from the triennial trawl survey (data courtesy of Mark Wilkins, AFSC). Closed circles show results for the NWFSC trawl survey (data courtesy of Beth Horness, NWFSC). Mean and SD are the mean and standard deviation of the NWFSC time series, Diff.trend is the absolute change in the predicted trend over 5 years. The solid line is the mean for the NWFSC data. Dotted lines are ±1 SD. The trend line (thick black) is the 5-year trend. Symbol in the upper right indicates that the 5-year trend decreased relative to 1 SD of NWFSC data. Data are the year effect from the GAM model and not absolute estimates of Shannon Diversity.

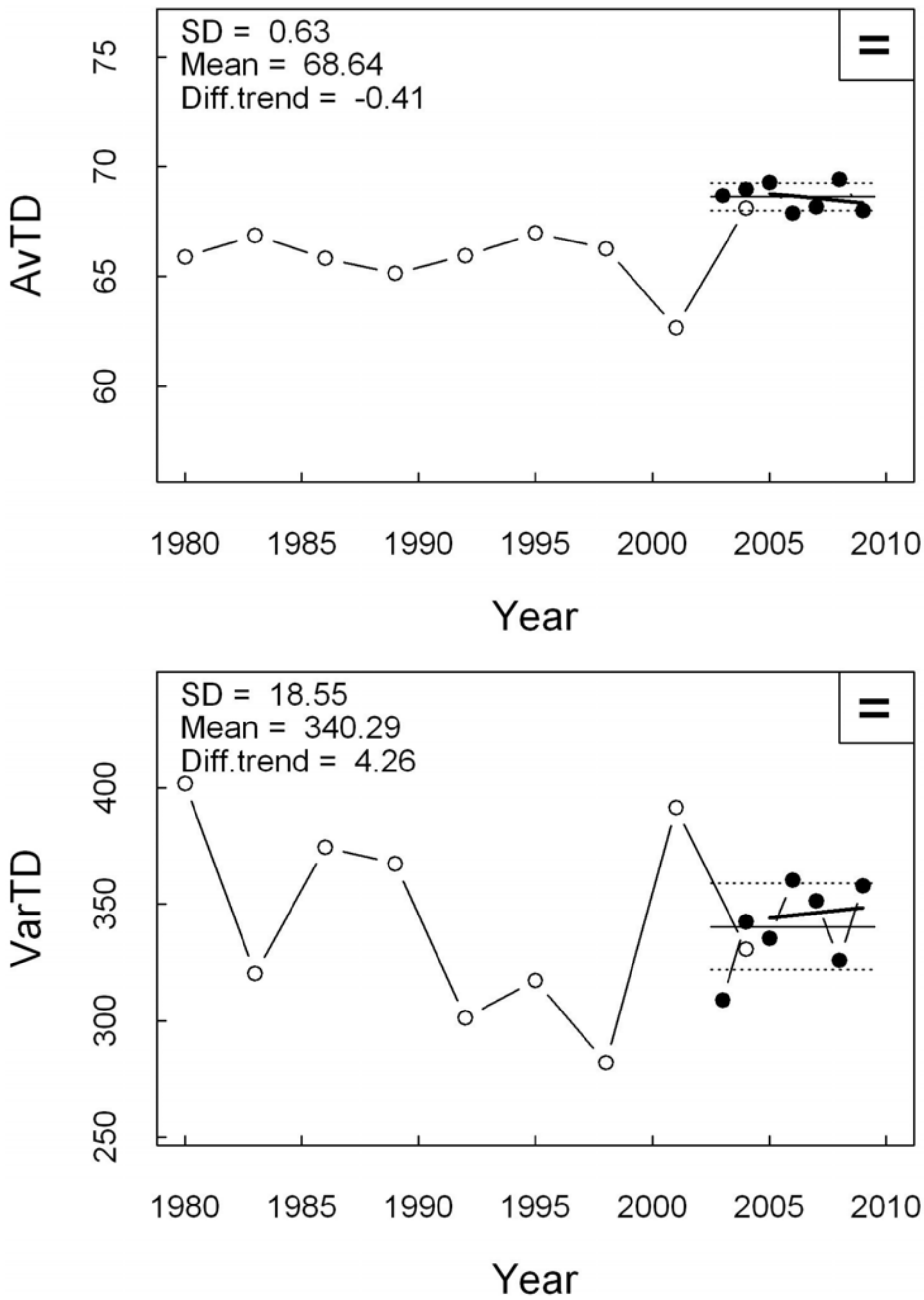


Figure D-32. Average taxonomic distinctness (AvTD) and variation in taxonomic distinctness (VarTD) for West Coast groundfishes within the Gulf of the Farallones NMS from 1980 to 2009 for 50–350 m bottom depth. Closed circles show results for the NWFSC trawl survey (data courtesy of Beth Horness, NWFSC). Mean and SD are the mean and standard deviation of the combined time series, Diff.trend is the absolute change in the predicted trend over 5 years. The solid line is the mean for the NWFSC data. Dotted lines are ±1 SD. The trend line (thick black) is the 5-year trend. Symbols in the upper right indicate that the 5-year trend showed no change relative to 1 SD of NWFSC data. Data are the year effect from the GAM model and not absolute estimates of the metrics.

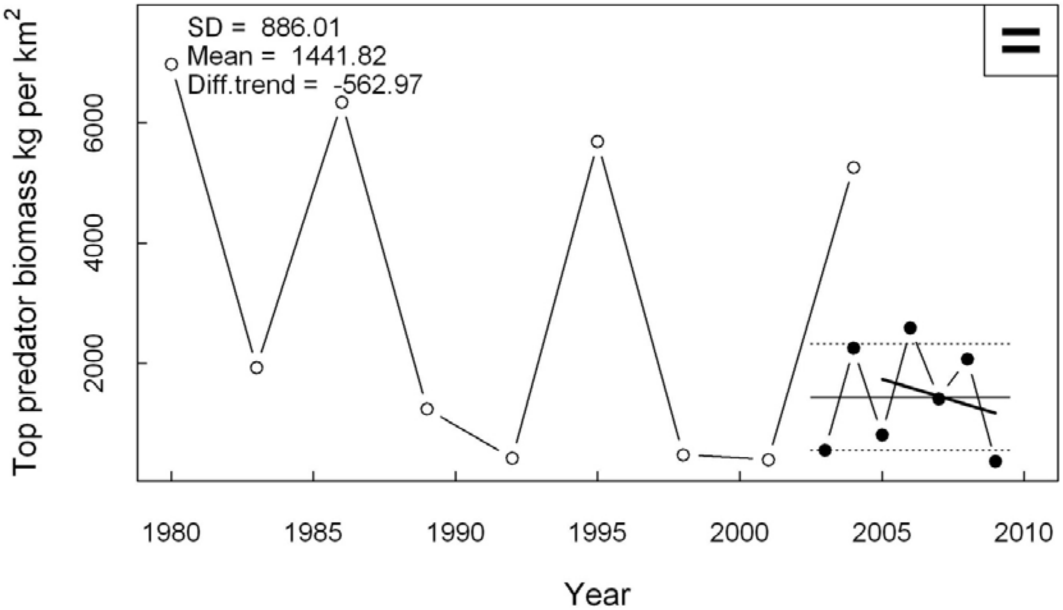


Figure D-33. Top predator biomass within the Gulf of the Farallones NMS. Closed circles show results for the NWFSC trawl survey (data courtesy of Beth Horness, NWFSC). Mean and SD are the mean and standard deviation of the NWFSC time series, Diff.trend is the absolute change in the predicted trend over 5 years. The solid line is the mean for the NWFSC data. Dotted lines are ±1 SD. The trend line (thick black) is the 5-year trend. Symbol in the upper right indicates that the 5-year trend showed no change relative to 1 SD of NWFSC data. Data were log(x+0.1) transformed prior to analysis and back-transformed for presentation. Data are the year effect from the GAM model and not absolute estimates of abundance.

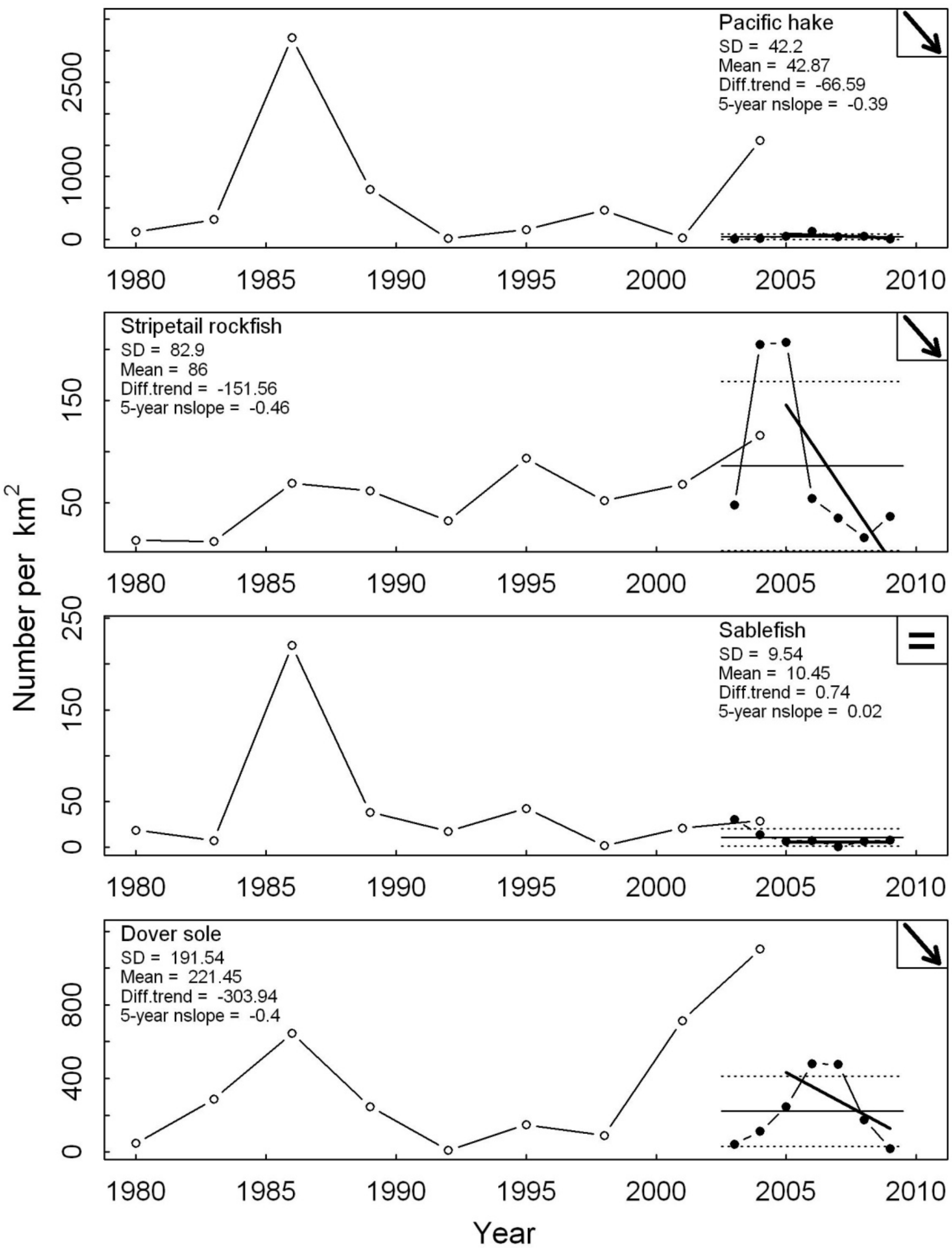


Figure D-34. CPUE (number per km$^2$) for four groundfishes within the Monterey Bay NMS from 1980 to 2009 for the triennial trawl survey (open circles, data courtesy of Mark Wilkins, AFSC) and the NWFSC trawl survey (closed circle, data courtesy of Beth Horness, NWFSC). Mean and SD are the mean and standard deviation of the NWFSC time series, Diff.trend is the absolute change in the predicted trend over 5 years, 5-year nslope is the slope of normalized data for comparison across species. The solid line is the mean for the 7-year NWFSC data. Dotted lines are ±1 SD. The trend line (thick black) is the 5-year trend. Symbols in the upper right indicate that the 5-year trend decreased or showed no change relative to 1 SD of NWFSC data. Data are the year effect from the GAM model and not absolute estimates of abundance.

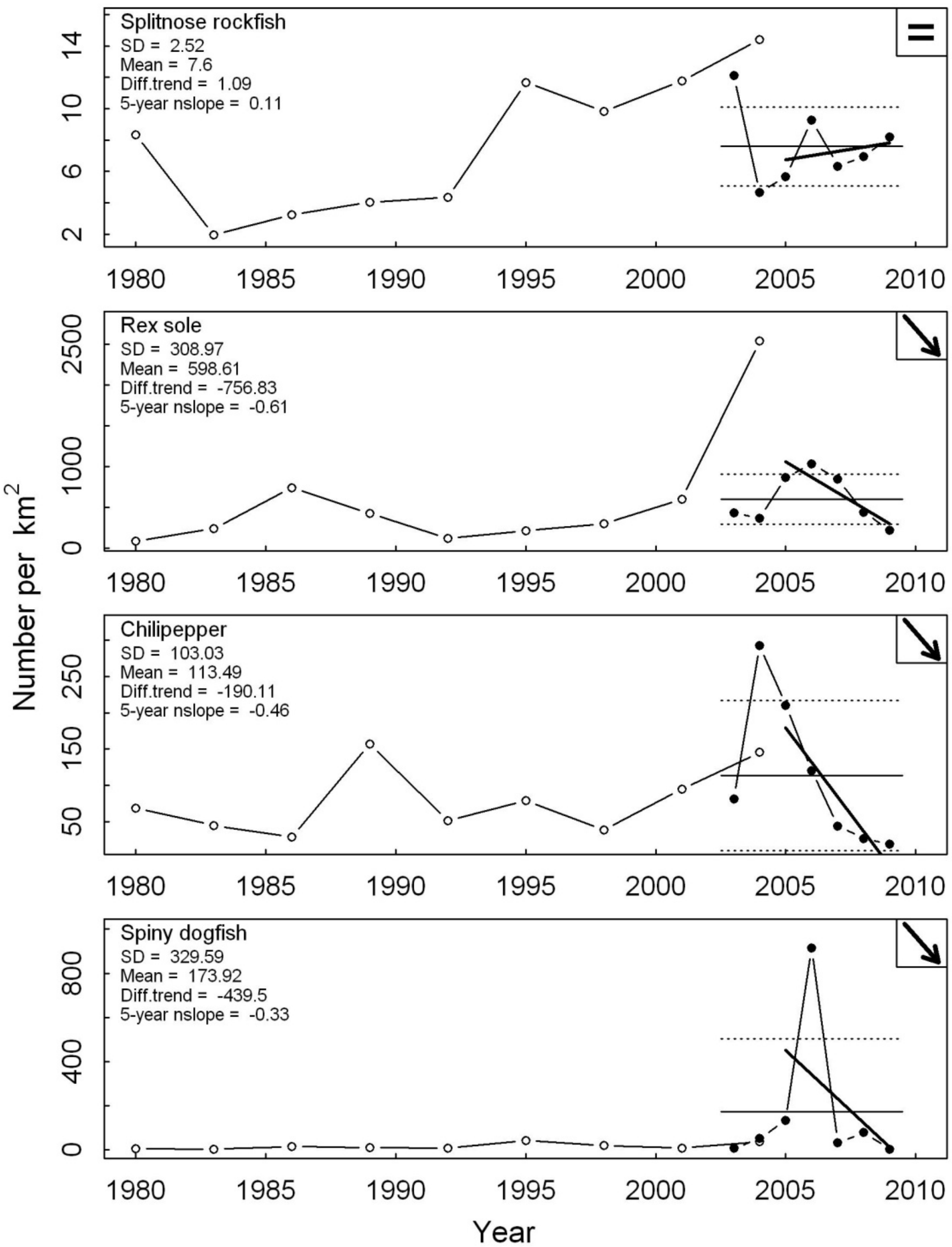


Figure D-35. CPUE (number per km$^2$) for four groundfishes within the Monterey Bay NMS from 1980 to 2009 for the triennial trawl survey (open circles, data courtesy of Mark Wilkins, AFSC) and the NWFSC trawl survey (closed circle, data courtesy of Beth Horness, NWFSC). Mean and SD are the mean and standard deviation of the NWFSC time series, Diff.trend is the absolute change in the predicted trend over 5 years, 5-year nslope is the slope of normalized data for comparison across species. The solid line is the mean for the 7-year NWFSC data. Dotted lines are ±1 SD. The trend line (thick black) is the 5-year trend. Symbols in the upper right indicate that the 5-year trend decreased or showed no change relative to 1 SD of NWFSC data. Data are the year effect from the GAM model and not absolute estimates of abundance.

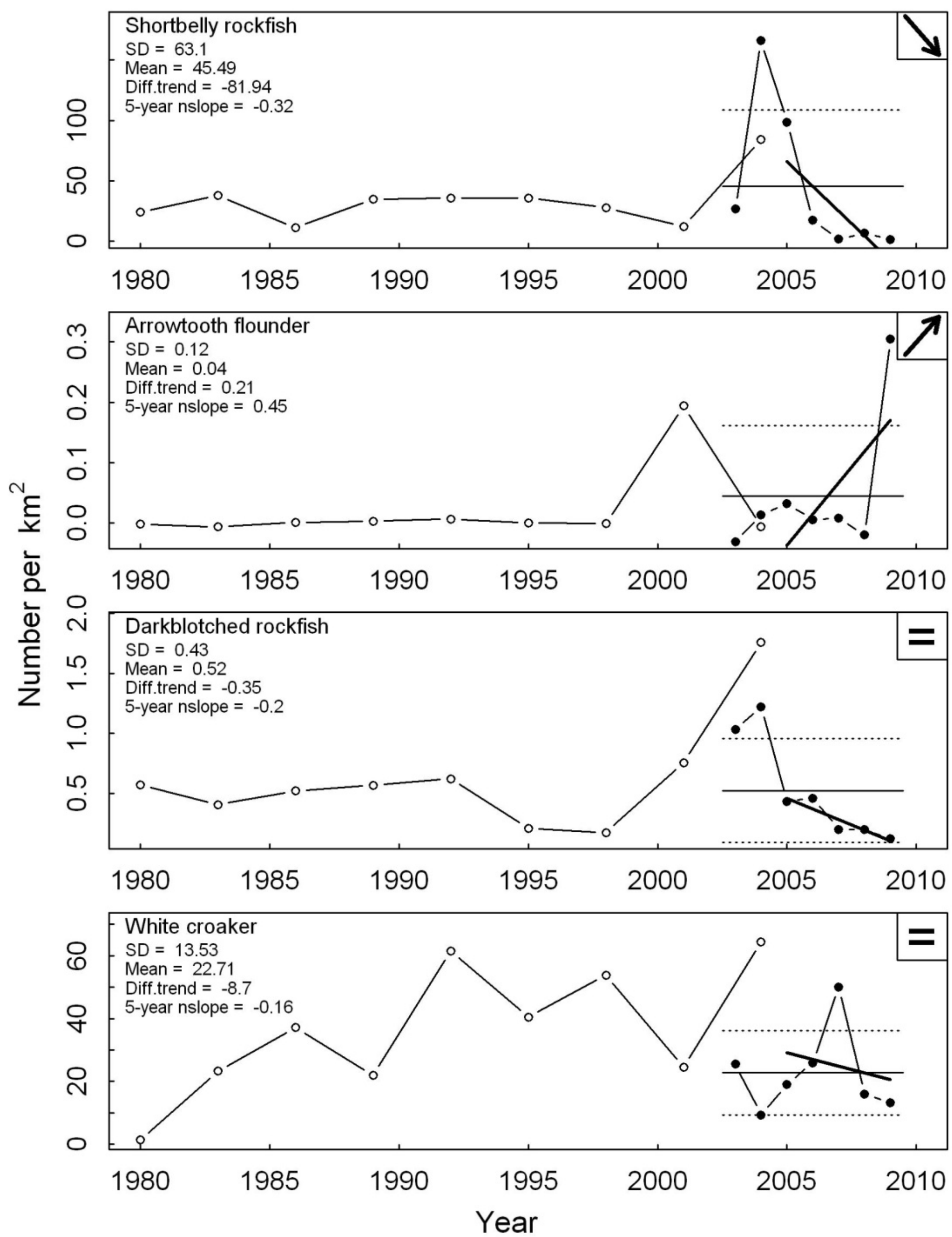


Figure D-36. CPUE (number per km$^2$) for four groundfishes within the Monterey Bay NMS from 1980 to 2009 for the triennial trawl survey (open circles, data courtesy of Mark Wilkins, AFSC) and the NWFSC trawl survey (closed circle, data courtesy of Beth Horness, NWFSC). Mean and SD are the mean and standard deviation of the NWFSC time series, Diff.trend is the absolute change in the predicted trend over 5 years, 5-year nslope is the slope of normalized data for comparison across species. The solid line is the mean for the 7-year NWFSC data. Dotted lines are ±1 SD. The trend line (thick black) is the 5-year trend. Symbols in the upper right indicate that the 5-year trend increased, decreased, or showed no change relative to 1 SD of NWFSC data. Data are the year effect from the GAM model and not absolute estimates of abundance.

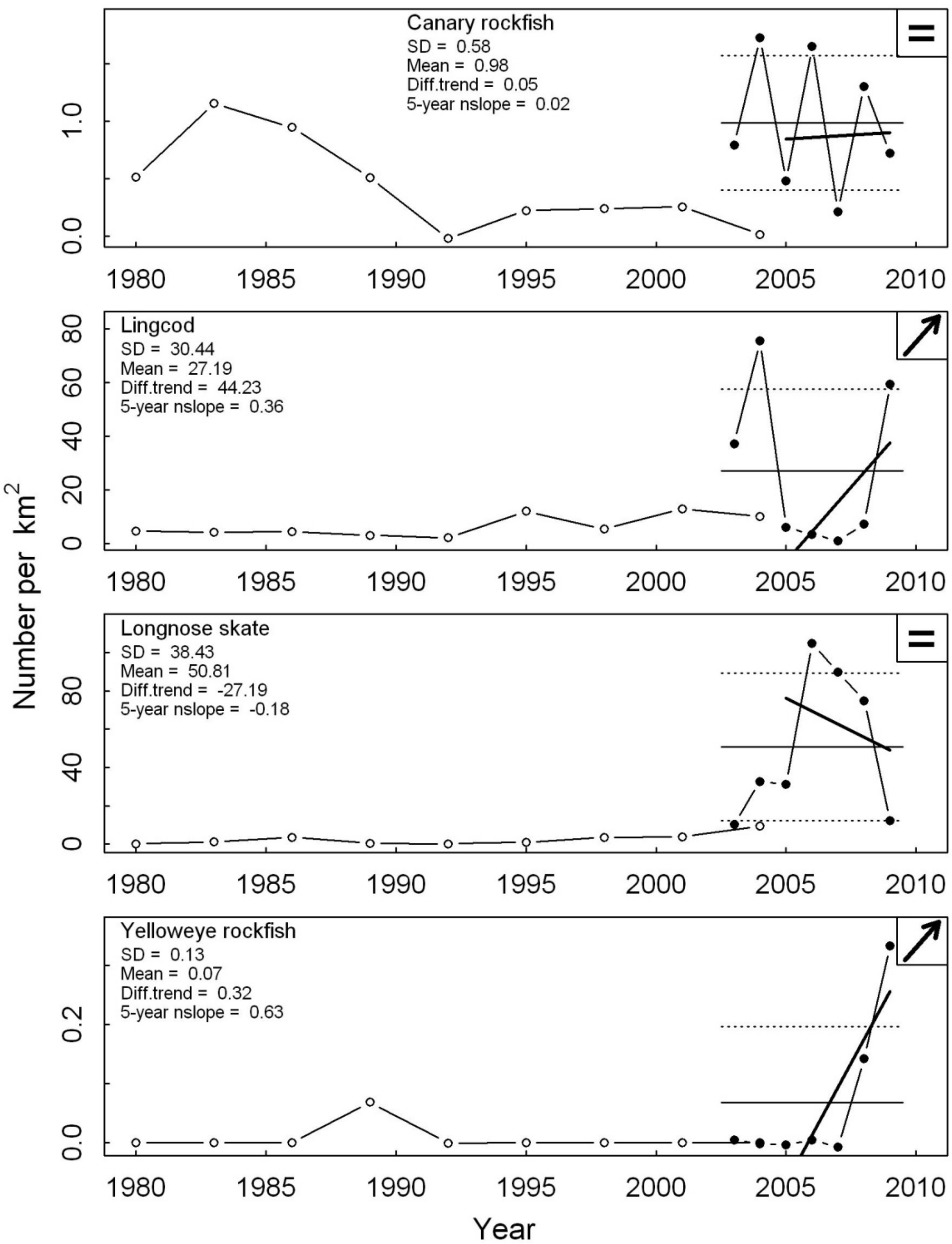


Figure D-37. CPUE (number per km$^2$) for four groundfishes within the Monterey Bay NMS from 1980 to 2009 for the triennial trawl survey (open circles, data courtesy of Mark Wilkins, AFSC) and the NWFSC trawl survey (closed circle, data courtesy of Beth Horness, NWFSC). Mean and SD are the mean and standard deviation of the NWFSC time series, Diff.trend is the absolute change in the predicted trend over 5 years, 5-year nslope is the slope of normalized data for comparison across species. The solid line is the mean for the 7-year NWFSC data. Dotted lines are ±1 SD. The trend line (thick black) is the 5-year trend. Symbols in the upper right indicate that the 5-year trend increased or showed no change relative to 1 SD of NWFSC data. Data are the year effect from the GAM model and not absolute estimates of abundance.

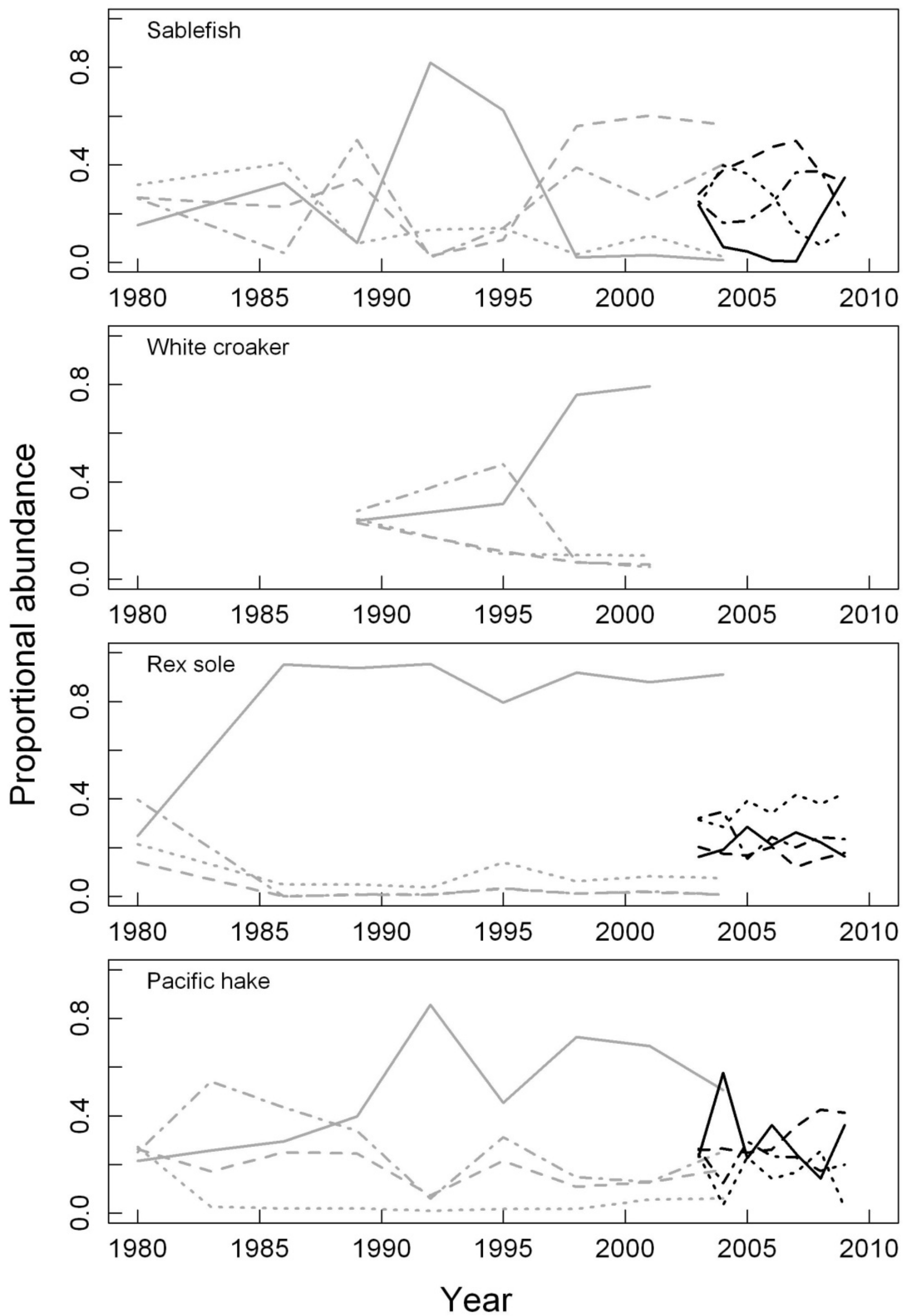


Figure D-38. Size distribution for four groundfishes within the Monterey Bay NMS from 1980 to 2009. Plots show the proportion of fish in the first (solid), second (dashed), third (dotted), and fourth (dot-dash) quartiles. Gray lines are the triennial survey data (courtesy of Mark Wilkins, AFSC), and black lines are the NWFSC survey data (courtesy of Beth Horness, NWFSC). To show change in size structure through time, size cutoffs for the quartiles were established based on the first year in each time series (1980 and 2003). Subsequent years show proportion of fishes in those size classes.

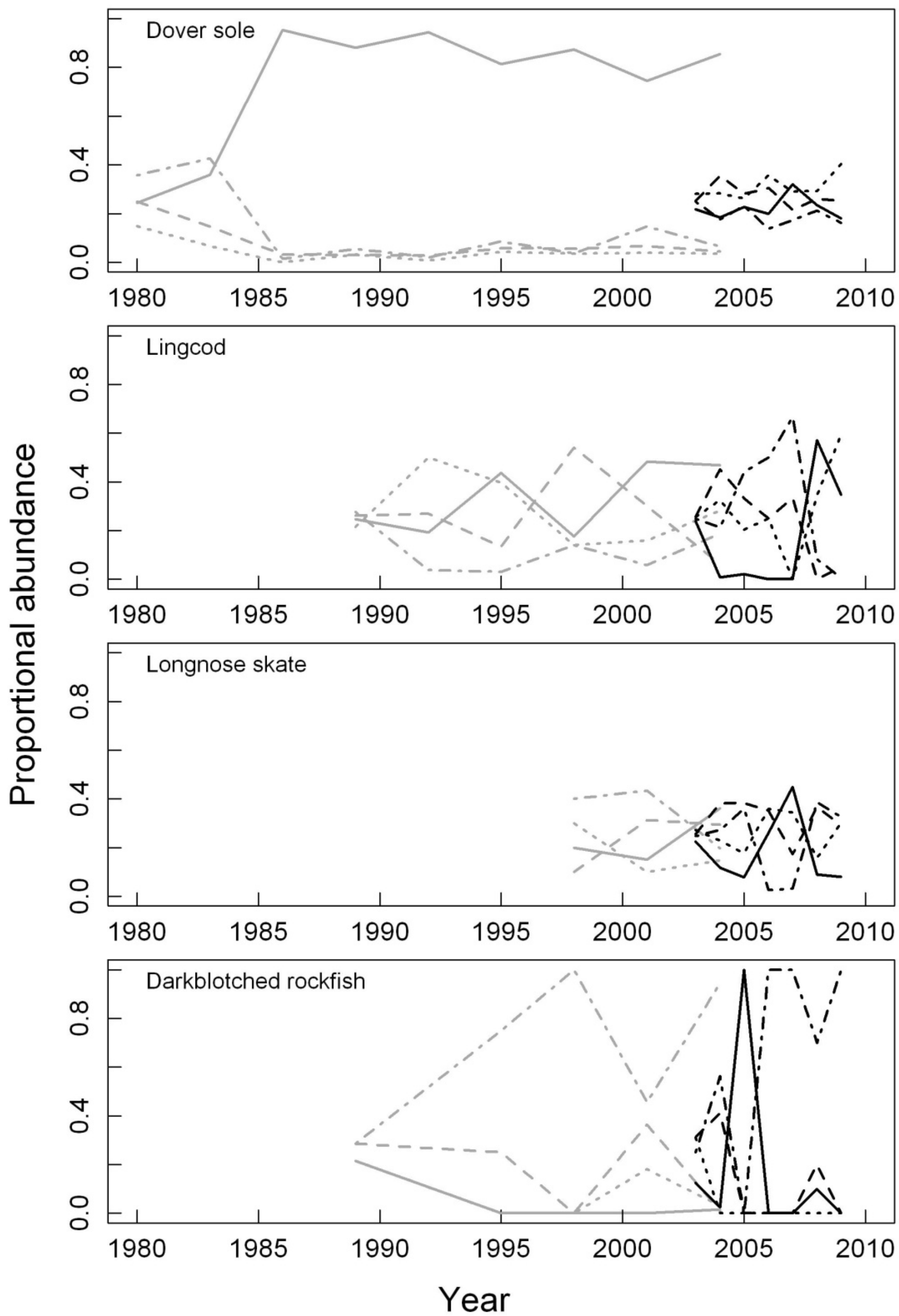


Figure D-39. Size distribution for four groundfishes within the Monterey Bay NMS from 1980 to 2009. Plots show the proportion of fish in the first (solid), second (dashed), third (dotted), and fourth (dot-dash) quartiles. Gray lines are the triennial survey data (courtesy of Mark Wilkins, AFSC), and black lines are the NWFSC survey data (courtesy of Beth Horness, NWFSC). To show change in size structure through time, size cutoffs for the quartiles were established based on the first year in each time series (1980 and 2003). Subsequent years show proportion of fishes in those size classes.

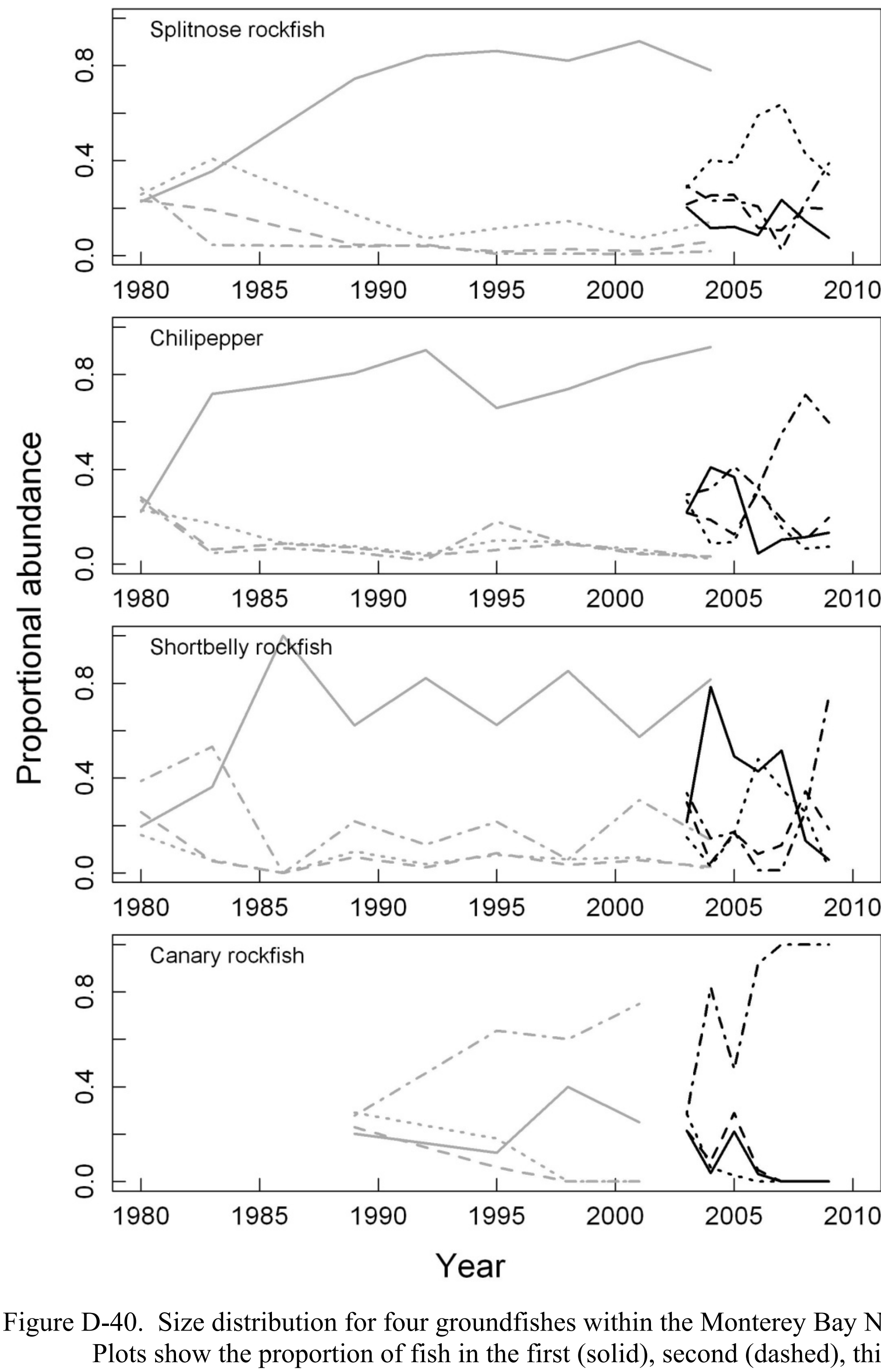


Figure D-40. Size distribution for four groundfishes within the Monterey Bay NMS from 1980 to 2009. Plots show the proportion of fish in the first (solid), second (dashed), third (dotted), and fourth (dot-dash) quartiles. Gray lines are the triennial survey data (courtesy of Mark Wilkins, AFSC), and black lines are the NWFSC survey data (courtesy of Beth Horness, NWFSC). To show change in size structure through time, size cutoffs for the quartiles were established based on the first year in each time series (1980 and 2003). Subsequent years show proportion of fishes in those size classes.

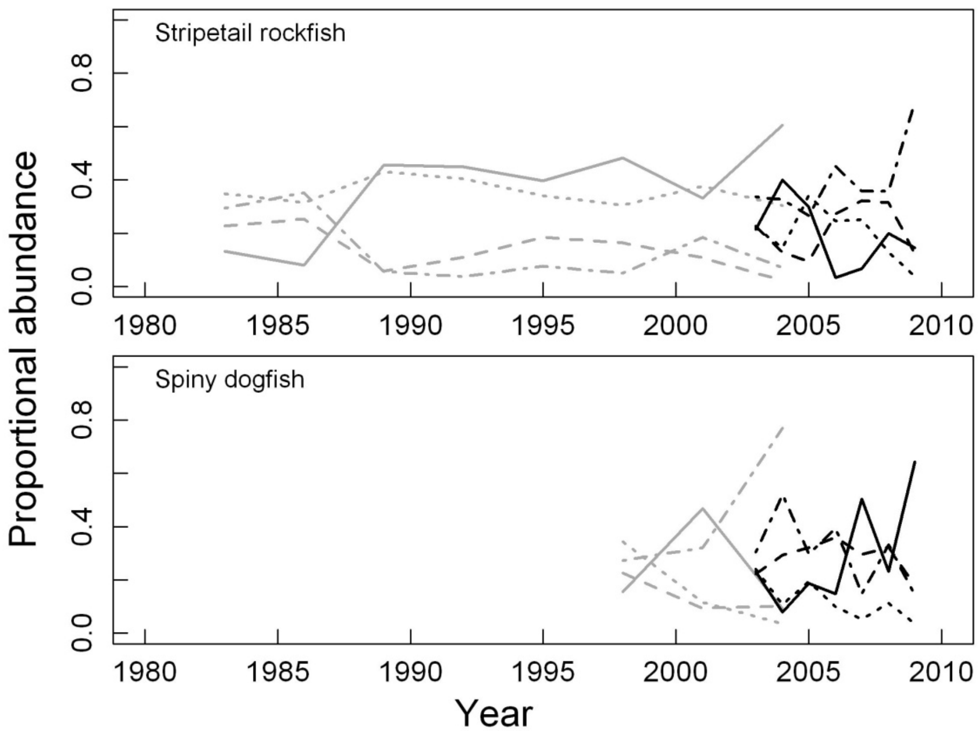


Figure D-41. Size distribution for two groundfishes within the Monterey Bay NMS from 1980 to 2009. Plots show the proportion of fish in the first (solid), second (dashed), third (dotted) and fourth (dot-dash) quartiles. Gray lines are the triennial survey data (courtesy of Mark Wilkins, AFSC), and black lines are the NWFSC survey data (courtesy of Beth Horness, NWFSC). To show change in size structure through time, size cutoffs for the quartiles were established based on the first year in each time series (1980 and 2003). Subsequent years show proportion of fishes in those size classes.

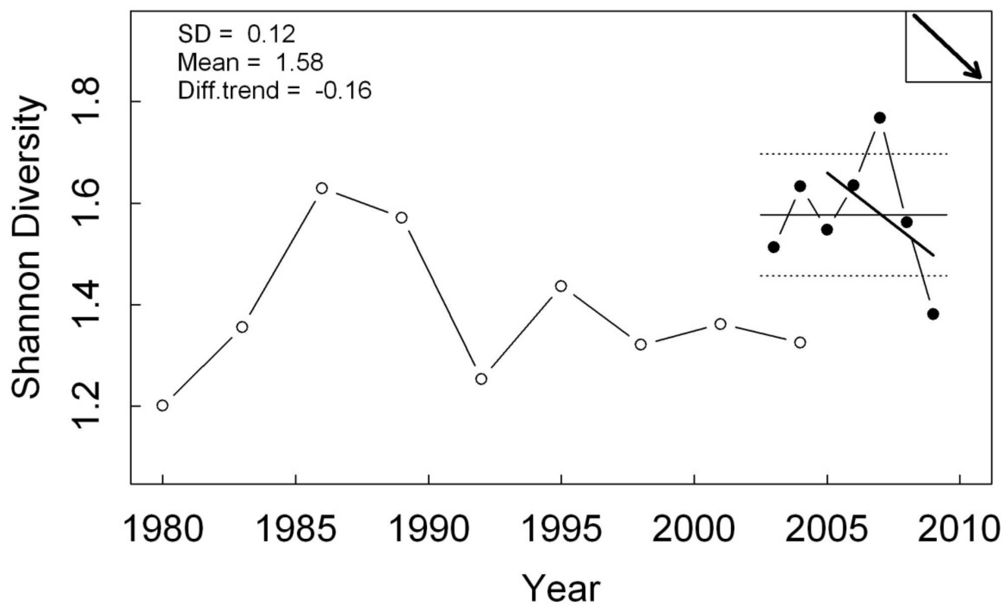


Figure D-42. Annual mean Shannon Diversity within the Monterey Bay NMS for 50–350 m bottom depth. Open circles show yearly averages calculated from the triennial trawl survey (data courtesy of Mark Wilkins, AFSC). Closed circles show results for the NWFSC trawl survey (data courtesy of Beth Horness, NWFSC). Mean and SD are the mean and standard deviation of the NWFSC time series, Diff.trend is the absolute change in the predicted trend over 5 years. The solid line is the mean for the NWFSC data. Dotted lines are ±1 SD. The trend line (thick black) is the 5-year trend. Symbol in the upper right indicates that the 5-year trend decreased relative to 1 SD of NWFSC data. Data are the year effect from the GAM model and not absolute estimates of Shannon Diversity.

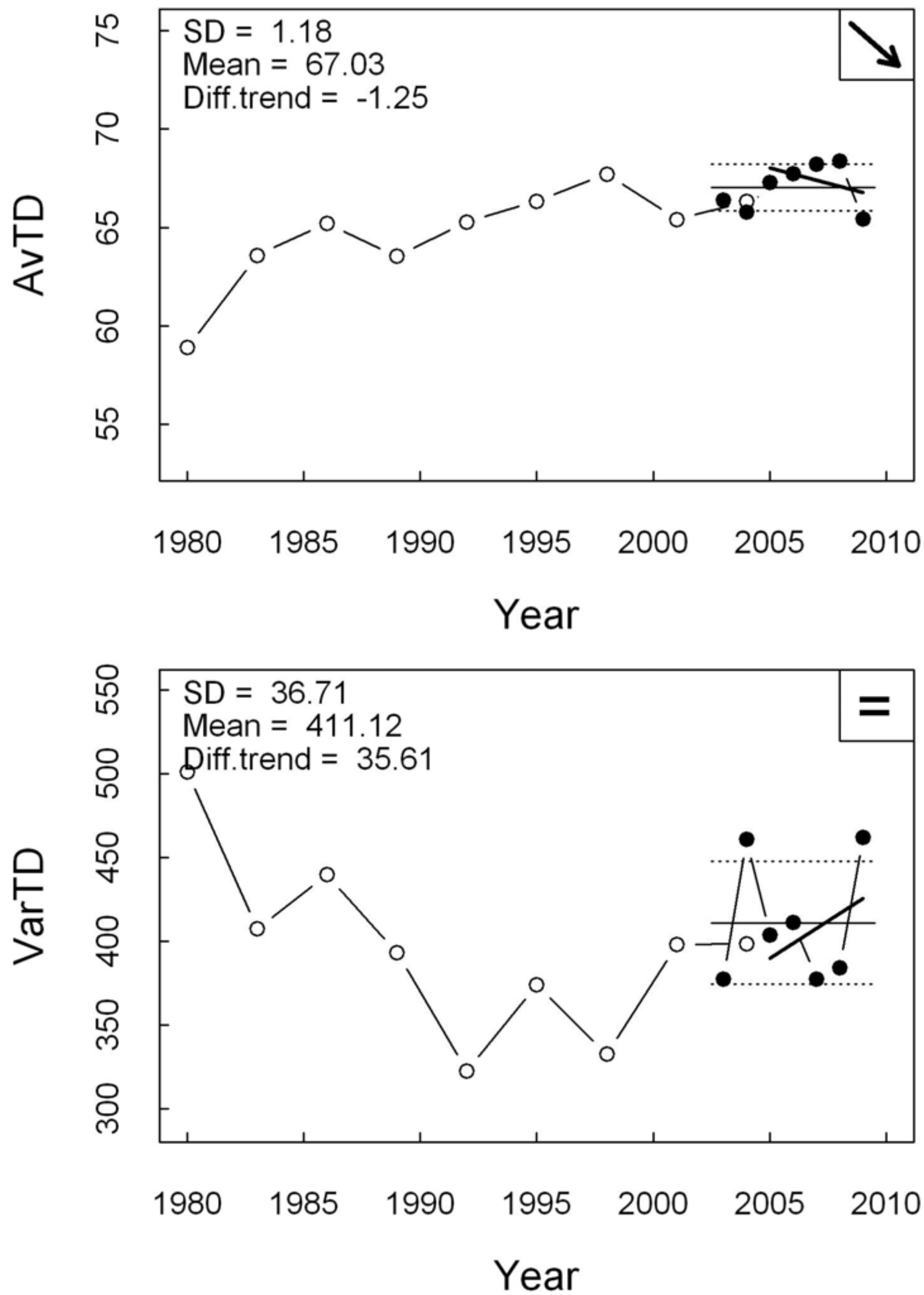


Figure D-43. Average taxonomic distinctness (AvTD) and variation in taxonomic distinctness (VarTD) for West Coast groundfishes from 1980 to 2009 within the Monterey Bay NMS for 50–350 m bottom depth. Closed circles show results for the NWFSC trawl survey (data courtesy of Beth Horness, NWFSC). Mean and SD are the mean and standard deviation of the NWFSC time series, Diff.trend is the absolute change in the predicted trend over 5 years. The solid line is the mean for the NWFSC data. Dotted lines are ±1 SD. The trend line (thick black) is the 5-year trend. Symbols in the upper right indicate that the 5-year trend decreased or showed no change relative to 1 SD of NWFSC data. Data are the year effect from the GAM model and not absolute estimates of the metrics.

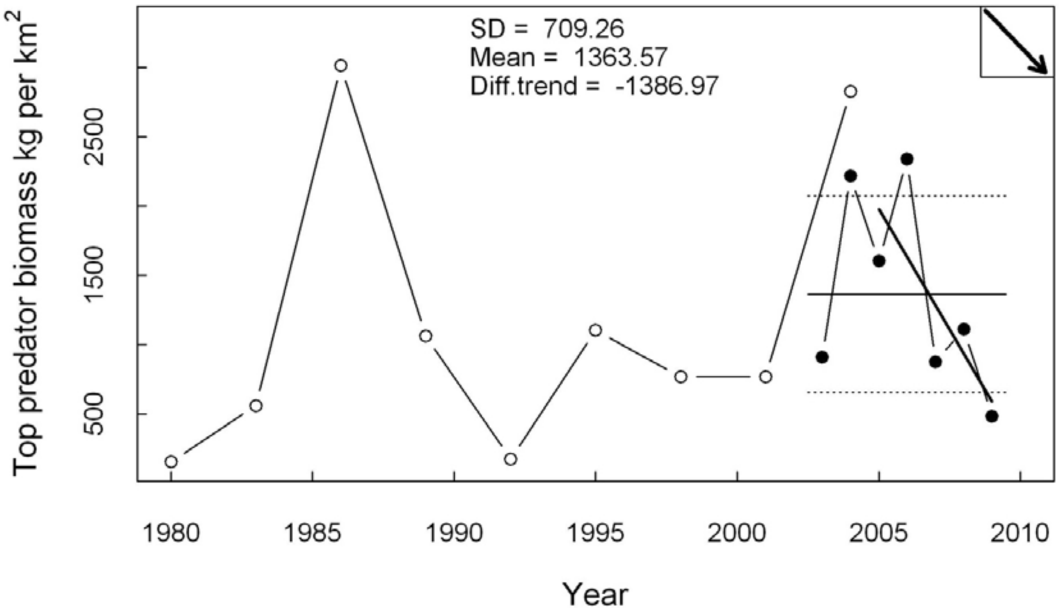


Figure D-44. Top predator biomass within the Monterey Bay NMS. Closed circles show results for the NWFSC trawl survey (data courtesy of Beth Horness, NWFSC). Mean and SD are the mean and standard deviation of the NWFSC time series, Diff.trend is the absolute change in the predicted trend over 5 years. The solid line is the mean for the NWFSC data. Dotted lines are ±1 SD. The trend line (thick black) is the 5-year trend. Symbol in the upper right indicates that the 5-year trend decreased relative to 1 SD of NWFSC data. Data were log(x+0.1) transformed prior to analysis and back-transformed for presentation. Data are the year effect from the GAM model and not absolute estimates of abundance.

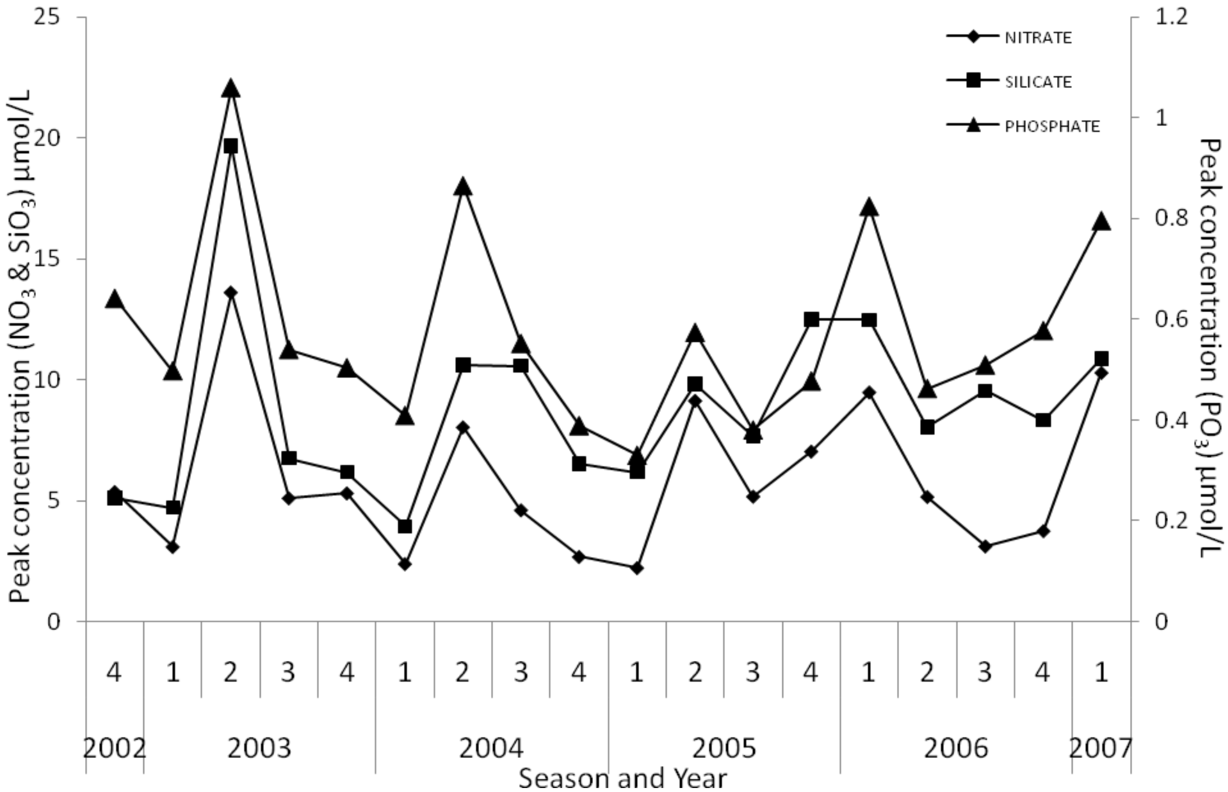


Figure D-45. Mean concentrations (µmol/L) by season. 1 equals winter (Jan–Mar), 2 equals spring (Apr–Jun), 3 equals summer (Jul–Sep), and 4 equals autumn (Oct–Dec) from 2002 to 2007 at 5.0 m depth across 11 sites within the Monterey Bay NMS. (Data accessed on 13 August 2010 at http://cimt.dyndns.org:8080/dods/drds/vNutrients.html.)

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**107** **Lian, C.E. 2010.** West Coast limited entry groundfish trawl cost earnings survey protocols and results for 2004. U.S. Dept. Commer., NOAA Tech. Memo. NMFS-NWFSC-107, 35 p. NTIS number PB2011-102712.

**106** **Harvey, C.J., K.K. Bartz, J. Davies, T.B. Francis, T.P. Good, A.D. Guerry, B. Hanson, K.K. Holsman, J. Miller, M.L. Plummer, J.C.P. Reum, L.D. Rhodes, C.A. Rice, J.F. Samhouri, G.D. Williams, N. Yoder, P.S. Levin, and M.H. Ruckelshaus. 2010.** A mass-balance model for evaluating food web structure and community-scale indicators in the central basin of Puget Sound. U.S. Dept. Commer., NOAA Tech. Memo. NMFS-NWFSC-106, 180 p. NTIS number PB2011-102711.

**105** **Gustafson, R.G., M.J. Ford, D. Teel, and J.S. Drake. 2010.** Status review of eulachon (*Thaleichthys pacificus*) in Washington, Oregon, and California. U.S. Dept. Commer., NOAA Tech. Memo. NMFS-NWFSC-105, 360 p. NTIS number PB2011-102710.

**104** **Horne, P.J., I.C. Kaplan, K.N. Marshall, P.S. Levin, C.J. Harvey, A.J. Hermann, and E.A. Fulton. 2010.** Design and parameterization of a spatially explicit ecosystem model of the central California Current. U.S. Dept. Commer., NOAA Tech. Memo. NMFS-NWFSC-104, 140 p. NTIS number PB2010-110533.

**103** **Dufault, A.M., K. Marshall, and I.C. Kaplan. 2009.** A synthesis of diets and trophic overlap of marine species in the California Current. U.S. Dept. Commer., NOAA Tech. Memo. NMFS-NWFSC-103, 81 p. NTIS number PB2010-110532.

**102** **Reppond, K.D. 2009.** Biochemistry of red king crab (*Paralithodes camtschaticus*) from different locations in Alaskan waters. U.S. Dept. Commer., NOAA Tech. Memo. NMFS-NWFSC-102, 16 p. NTIS number PB2010-110531.

**101** **Sands, N.J., K. Rawson, K.P. Currens, W.H. Graeber, M.H. Ruckelshaus, R.R. Fuerstenberg, and J.B. Scott. 2009.** Determination of independent populations and viability criteria for the Hood Canal summer chum salmon evolutionarily significant unit. U.S. Dept. Commer., NOAA Tech. Memo. NMFS-NWFSC-101, 58 p. NTIS number PB2010-110530.

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