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The State of the Science: Forage Fish in the California Current

Executive Summary

In the California Current (CC), a diverse group of forage fishes play an important and often underappreciated role in the "middle" of the food web. These species, such as Pacific sardine and northern anchovy, eat plankton and support predators such as whales, sea lions, seabirds, sharks, salmon, and tuna. The availability—abundance, size, timing, and location—of forage fish has been shown to affect predators with declines in productivity and survival when availability decreases. Meanwhile, fisheries targeting forage fishes may indirectly or directly compete with predator needs. Although some forage fish are consumed by humans, many are used for nonfood products such as animal feed, pet food, and fishing bait.

Forage fish populations are influenced by environmental variation, natural processes, and human activities such as fishing, coastal development, and pollution. They are also subject to natural population cycles. These factors are not always well-understood and are difficult to incorporate into most management approaches.

Many forage fisheries are not managed, and of those that are, management rarely considers such factors as predator needs and environmental fluctuations. Traditional fisheries management based on maximum sustainable yield, or the largest catch that can be taken from a species' stock over an indefinite period, is not appropriate for prey populations like forage fish because it does not account for the larger role they play in ecosystems.

Ecosystem-based fisheries management (EBFM), which focuses on the role of fisheries in the context of an overall ecosystem rather than on single species, has been proposed as a way to, among other things, emphasize the role of forage fish in the ecosystem and consider catch on a secondary basis. Some federal and state agencies are starting to implement EBFM, although movements are slow. Complementary approaches include precautionary management, fisheries closures, and forage reserves for predators, which may be tailored to predator needs in terms of prey diversity, abundance, distribution, size, seasonality, and/or interannual variability.

There is economic and ecosystem research that indicates leaving more forage fish in the environment to support predator fisheries may be more valuable than removing them in forage fisheries. In upwelling systems like the CC, forage fish may be more valuable as prey than as catch.

Several large-scale studies have also recently suggested thresholds of forage fish biomass that should remain in the ocean for predators. Under the increasing array of threats to forage fish, efforts should be made to control those factors that we can, such as fishing, to enable the maximum resilience possible to factors that we cannot easily control, such as climate change. This approach is important for the health of forage fish stocks themselves as well as the predators that rely on those fish.

Introduction

The California Current, which runs from Baja California in Mexico to Canada's British Columbia, may be the world's most storied sliver of ocean. In the early 1940s, sardine boats out of Monterey, California hauled in 700,000 tons a year and provided the backdrop for John Steinbeck's nostalgic *Cannery Row*. The Pacific sardine fishery subsequently suffered a spectacular crash by the late 1940s.

Globally, forage fishes are some of the most abundant and well-known in the world, including species like sardine and anchovy, but also many other important, though less well-known, species. Forage fishes play an important role in marine food webs, occupying the "middle" of the food web (Figure 1); they largely eat plankton, and are in turn eaten by larger predators. Forage species can also include invertebrates such as squid and krill and juveniles of some predatory fish such as rockfish. Although there are various ways to define forage species, for this document, we consider small open-ocean schooling fish that remain at the same level in the food web for their entire life cycle, and due to their size and abundance are important as forage during their adult life-phase.

Forage fishes often undergo population cycles, the most famous of which is the decadal-scale fluctuations, or 'boom-bust' cycling, of sardine and anchovy (Schwartzlose *et al.* 1999, Chavez *et al.* 2003). For this reason, as well as other factors dictating forage availability, many types of forage fishes are necessary to sustain important predators such as salmon and seabirds that rely on them (Thayer and Sydeman 2009, Daly *et al*).

Fisheries targeting forage fish may compete with predators, either directly for the same fish or indirectly by altering food webs and ecosystem functioning (Trites *et al.* 1997, Coll *et al.* 2008). Many forage fisheries are not managed, and of those that are, the larger forage community, predator needs, or environmental fluctuations are rarely taken into account. This is despite concerns researchers have raised about the effects of fishing on seabirds (Jahncke *et al.* 2004, Fredericksen *et al.* 2008, Pichegru

Figure 1. Forage fish play an important role in marine food webs, occupying the "middle" of the food web. They largely eat plankton and in turn support a diverse group of predators, including commercially important species like salmon and tuna.

et al. 2010), pinnipeds (DeMaster *et al*. 2001, Matthiopoulos *et al*. 2008), and cetaceans (Constable *et al*. 2000, Bearzi *et al*. 2008). Recent studies have suggested forage thresholds needed to sustain predators that would necessitate reductions in current levels of fishing (Smith *et al*. 2011, Cury *et al*. 2011, Pikitch *et al*. 2012).

THE ROLE OF FORAGE FISH IN THE CALIFORNIA CURRENT

The California Current (Figure 2) is characterized by a narrow continental shelf with a steep slope, along which the main current flows and across which winds cause coastal upwelling (Figure 3), particularly important near capes and headlands (Chavez *et al*. 2002, Checkley and Barth 2009). Interannually, the timing of upwelling is variable but generally strongest during the spring and summer, leading to nutrient enrichment and cool temperatures in the ocean's surface layer as water rises from the depths (Chavez *et al*. 2002, Bograd *et al*. 2009). High nutrient levels fuel plankton photosynthesis and growth, providing the base for the food web. The effect of upwelling is altered during El Niño Southern Oscillation (ENSO) events when the ocean surface mixed layer deepens, leading to warm, nutrient-poor surface waters and an influx of subtropical or tropical species (Chavez *et al*. 2002). There are also longer-term ocean fluctuations driving marine productivity, represented by the warm or cool phases of the Pacific Decadal Oscillation (PDO) (Mantua and Hare 2002, Checkley and Barth 2009).

There are many forage fishes in the CC, including the northern anchovy (*Engraulis mordax*; see anchovy case study), Pacific sardine (*Sardinops sagax*; see sardine case study), Pacific herring (*Clupea pallasii*; see

Figure 2. The California Current (CC) spans temperate waters from Baja California to British Columbia.

herring case study), Pacific saury (*Cololabis saira*), lanternfish (Myctophidae), Pacific sandlance (*Ammodytes hexapterus*), and smelt (Osmeridae; see smelt case study), along with many other less-well-known species. These forage fishes support a diverse predator assemblage of whales and dolphins, seals and sea lions, seabirds and sea turtles, sharks and rays, and large fishes such as salmon and tuna. Some forage fishes occur throughout the CC, while others are more important in the north (*e.g.*, sandlance in Washington) or south (*e.g.*, grunion in Southern California). Some other ecosystems, such as the Humboldt Current off Peru, are dominated by a few or even just one forage fish species and have a mid-food web bottleneck, or "wasp-waist," structure (see Cury *et al*. 2000). The degree of forage diversity in the CC arguably precludes such a structure, although sardine and anchovy are dominant species.

Although little is known about many of the forage fishes in the CC, some species such as sardine and anchovy support commercially important fisheries and are managed and studied extensively. There is considerably less data on noncommercial species such as sandlance, smelt, and lanternfish. Even for the more well-understood species, much is still unknown about mechanisms driving population dynamics and the extent to which predators depend on them. In part this is due to sampling difficulties and the considerable seasonal and year-to-year variability of these species.

Availability of forage fishes has been shown to directly affect marine predators. For instance, prey availability influences distribution, diet, foraging behavior, offspring growth, breeding success, adult body condition and survival, and population change in seabirds (Anderson *et al.* 1982, Rindorf *et al.* 2000, Jahncke *et al.* 2004, Davis *et al.* 2005, Crawford *et al.* 2006, Crawford *et al.* 2007, Piatt *et al.* 2007, Thayer and Sydeman 2007, Frederiksen *et al.* 2008, Field *et al.* 2010, Pichegru *et al.* 2010) and marine mammals (Kieckhefer 1992, Aguilar 2000, Jaquet *et al.* 2003, Soto *et al.* 2004, Soto *et al.* 2006, Womble *et al.* 2005, Womble and Sigler 2006, Hlista *et al.* 2009, Sigler *et al.* 2009, Winter *et al.* 2009, Patrician and Kenney 2010, Miller *et al.* 2011). For salmon, prey availability influences growth and survival (Brodeur 1991, Daly *et al.* 2009, Weitkamp and Sturdevant 2008). Tuna distributions vary widely and track forage fish (Laurs *et al.* 1984, Polovina 1996, Kitagawa *et al.* 2007).

Prey availability refers to not only forage abundance, but also size classes, timing, and geographic considerations that may determine predators' ability to find and consume prey. Salmon, for example, rely on different forage fishes—including anchovy, sardine, herring, sandlance, and smelt—at different times of the year and at various stages of their life cycle (Daly *et al.* 2009, Merkel 1957). Salmon have prey size limitations as small smolts entering the ocean, yet this may be one of the most important periods determining young salmons' survival (Koslow *et al.* 2002, Logerwell *et al.* 2003, MacFarlane 2010). Seasonal availability of forage may also be key for other predators (Willson and Womble 2006); herring has been found to occur in 90 percent of Steller sea lions' diet at certain locations during the herring spawning period (Womble and Sigler 2006). Migration of surf scoters parallels the northward progression of herring spawning events along the West Coast (Lok *et al.* 2012).

Predator-prey mismatch, when the timing or spatial distribution of forage availability differs from that of predator needs, is becoming common with climate change (Bertram *et al.* 2001, Edwards and Richardson 2004, Durant *et al.* 2007, Sydeman and Bograd

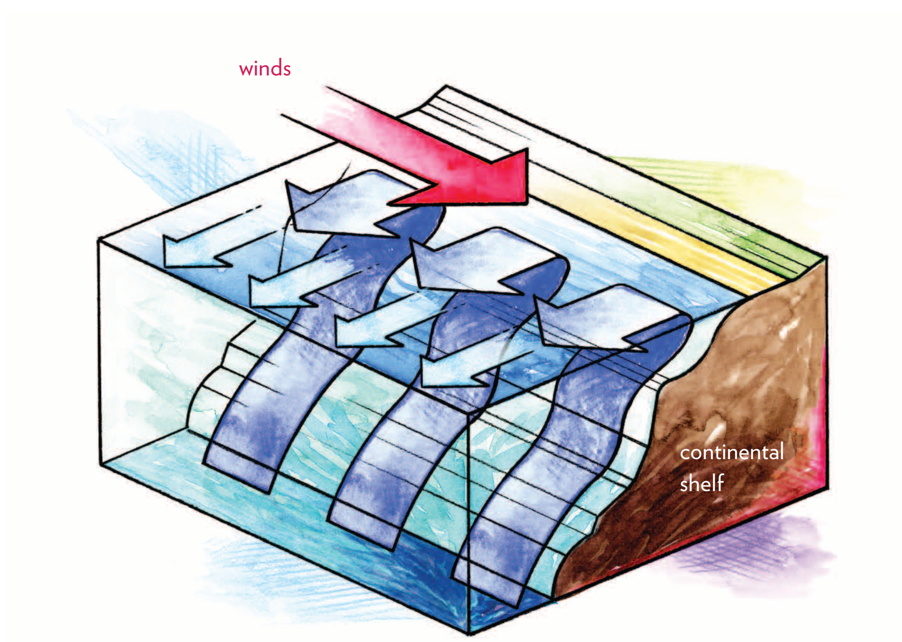


Figure 3. Upwelling occurs when wind drives cooler, dense, and nutrient-rich water towards the ocean surface, replacing the warmer surface water. Coastal upwelling in the CC is variable but generally strongest during the spring and summer, often leading to nutrient enrichment and cool temperatures in the ocean's surface layer. High nutrient levels can fuel plankton growth.

2009, Watanuki *et al.* 2009, Dorman *et al.* 2011). Temporal examples include variation in herring spawning initiation of more than three months, leaving predators such as Steller sea lions with fewer or lower-quality prey options during the lean winter months or during spring, when preparing for breeding (Willson and Womble 2006). Localized depletion of forage fishes due to fishing is also a concern (Tasker *et al.* 2000). Spatially, breeding seabirds, seals, and sea lions return to offspring at land-based colonies and thus have limited foraging ranges, during which time localized prey depletions could be deleterious (Croll and Tershy 1998, Wanless *et al.* 1998, Daunt *et al.* 2008, Wolf and Mangel 2008, Plagányi and Butterworth 2012). More research is needed in this area.

Forage species richness is key in local marine communities. A diverse forage assemblage can provide the redundancy needed for prey-switching opportunities, especially given variability in abundance, size, distribution, or time as discussed above. Despite this, the specific forage needs of top predators have not been adequately addressed in management. The diets of some dependent predators have not been sufficiently studied, particularly if such studies are logistically challenging, as is often the case for cetaceans (e.g., Stroud *et al.* 1981). Nevertheless, there is an abundance of predator-diet data available for the CC (*e.g.*, Sydeman *et al.* 2001, Dufault *et al.* 2009, Orr *et al.* 2011).

FORAGE FISHERIES IN THE CALIFORNIA CURRENT

The schooling behavior of forage fish allows them to be easily caught, translating into relatively low operating costs for fisheries and thus relatively cheap fish and fish products for consumers. Forage fish are caught within the exclusive economic zones (EEZ) of Canada, Mexico, and the United States, as well as in international waters outside these EEZs. Forage fish are generally targeted with "round-haul" gear including purse seines, drum seines, and lampara nets (Figure 4). These species are also taken incidentally with trawls, gillnets, trammel nets, trolls, pots, hook-and-line, and jigs.

Although some forage fish are consumed by humans, many are used for nonfood products such as animal feed, pet food, aquaculture, and bait for fishing. More than 36 percent of the global fish catch is destined for nonfood uses (Tacon and Metian 2009), and demand is increasing (Naylor *et al.* 2000). The exact proportions of forage fish usage in the CC are not well-documented.

Historically, most fish that could be caught were used as human food sources globally; the reduction of fish to fishmeal and oil for indirect use is a relatively recent development. The fish oil industry began in the 19th century when seasonally abundant catches of herring and sardines could not be absorbed by local markets in Europe and North America (Watson *et al.* 2006). The oil was used for lubricating machinery, leather tanning, soap production, and other nonfood products, and the byproducts of fish oil production were used as fertilizer. The production of fishmeal for animal feed began in the early 20th century, including from sardines in California (Watson *et al.* 2006).

Pacific sardine (see sardine case study) is currently one of the most lucrative fisheries in California. It is also caught off the coasts of Oregon and Washington in significant amounts (California Department of Fish and Game [CDFG] 2012, Hill *et al.* 2010b). However, sardine abundance may be declining (Wespestad and Maguire 2012, Zwolinski and Demer 2012). The status of anchovy (see anchovy case study) populations is largely unknown, although limited data suggest that populations of these fish are depressed (Brodeur *et al.* 2006, Bjorkstedt *et al.* 2011, Fissel *et al.* 2011).

Herring (see herring case study) also support very high-value fisheries in the CC, much of it for roe destined for the Japanese market. Herring populations, however, are also at a low level, probably due to a combination of human and environmental factors (Landis *et al.* 2004, CDFG 2012, Wespestad and Maguire 2012).

There are economic and ecosystem arguments that favor leaving more forage fish in the environment to support predator fisheries versus removing them in forage fisheries. Sardines, for example, are valuable as food for commercially important predators in the CC, particularly salmon. The ecosystem value of forage fish would increase with consideration of predator species such as seabirds and marine mammals that are not exploited but have extraordinary aesthetic and ecotourism value (Hanneson *et al.* 2009, Hannesson and Herrick 2010). Therefore, in upwelling systems such as the CC, forage fish are generally more valuable as support to other valuable fisheries than as catch themselves (Pikitch *et al.* 2012).

CHALLENGES FOR FORAGE FISH IN THE CALIFORNIA CURRENT

Environmental variability

The CC has historically had large natural fluctuations in oceanographic factors and related forage fish abundance (Baumgartner *et al.* 1992, Chavez *et al.* 2003). The biological mechanisms causing these population cycles are still unclear but probably are related to current flows, upwelling, and associated sea surface temperature (MacCall 2009). The cyclical pattern of abrupt changes in forage fish populations suggests that the driver is a combination of several physical and ecological factors (MacCall 2009). For example, anchovies and sardines have long been considered to ecologically replace each other as the environment fluctuates. However, recent research suggests that the ecological mechanisms behind out-of-phase fluctuations may be much more complex than a simple replacement (Barange *et al.* 2009).

Climate change

Climate change is distinct from environmental variability in that it refers to changes in the mean and/or variability of ecosystem properties (such as temperatures and sea levels) that persist for an extended period, typically decades or longer (Intergovernmental Panel on Climate Change [IPCC] 2007). Effects can be seen on physical ocean processes and habitats, as well as on species interactions, including cycles of forage fish dynamics and predator responses.

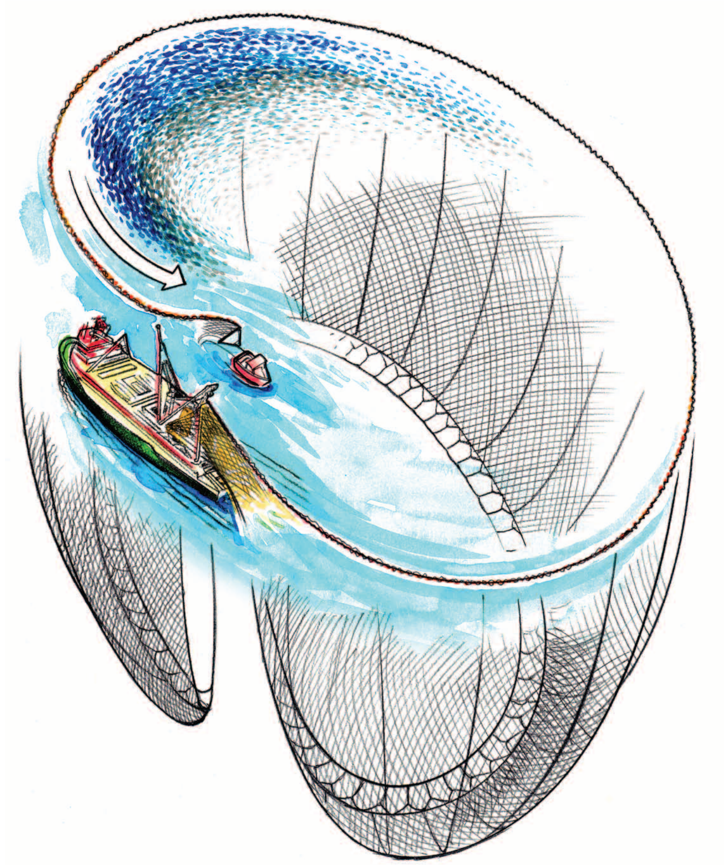
Species interactions

Incidence of nonnative species is increasing and can also have a powerful effect on coastal food webs and fundamentally alter fish distributions. For example, an introduced clam (*Corbula amurensis)* in the San Francisco Bay eliminated summer-long phytoplankton blooms starting in 1987, causing a shift in anchovy distribution out of the estuary that was a direct response to reduced food availability (Kimmerer 2006). A more pervasive example in the CC is the jumbo squid (*Dosidicus gigas)* from tropical waters, which has been observed in substantial numbers in the subtropical CC since the 1998 ENSO warm-water event (Pearcy 2002, Brodeur *et al.* 2006, Field *et al.* 2007). It is a voracious predator of many forage fishes such as anchovies and sardines (Field *et al.* 2007).

Fishing

Improvements in fishing technology such as acoustics and modernized gear have increased the vulnerability of schooling forage fish (Beverton 1990). Furthermore, fishing makes fish populations more variable than would occur naturally and more susceptible to climate perturbations (Hsieh *et al.* 2006, Anderson *et al.* 2008). Susceptibility may increase because fish populations are less abundant, have truncated age structures (fewer older individuals), or are depleted locally. The latter two factors are potentially just as important as abundance in maintaining long-term sustainable population levels (Berkeley *et al.* 2004, Anderson *et al.* 2008).

Sardines provide one example. At less than 5,000 tons (MacCall 1979), sardine abundance was probably lower after the 1960s population crash than at any time in the previous 2000 years, even during periods of natural low abundance, which were historically on the order of roughly 400,000 tons (Baumgartner *et al.* 1992; see sardine case study). Another example comes from herring along the Pacific coast, which are experiencing truncated age structure and localized depletions of subpopulations (Stick and Lindquist 2009, CDFG 2012; see herring case study). These changes may threaten the ability of the overall herring metapopulation to respond to harmful changes, because it has lost valuable genetic and behavioral diversity. For



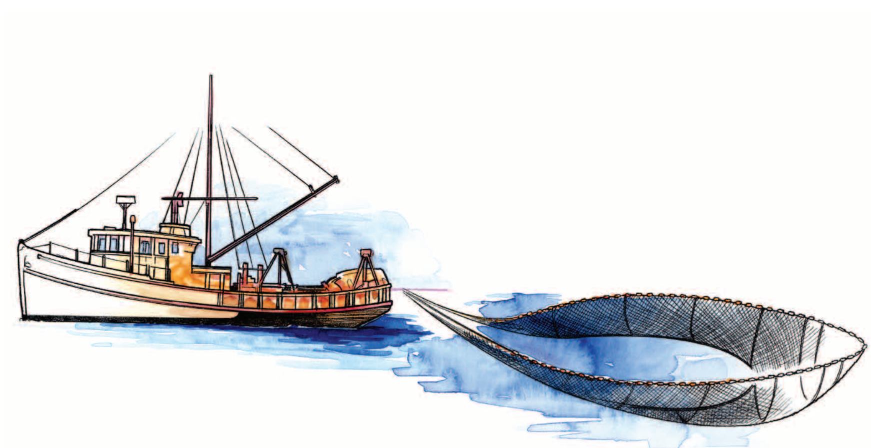


Figure 4. Forage fish are generally targeted with "round-haul" gear including purse seines (top), drum seines, and lampara nets (bottom).

example, remaining subpopulations may be at a genetic disadvantage for certain types of adaptation, may be more susceptible to disease or parasites, or may not have the ability to shift spawning times to account for climate changes or spawning locations in response to local habitat degradation. These could compromise herring at a metapopulation level or even eventually render the metapopulation obsolete. The benefit of diversity among subpopulations, which allows some to persist in the face of change, is termed the "portfolio effect" (Berkeley *et al.* 2004, Anderson *et al.* 2008, Schindler *et al.* 2010, Carlson and Satterthwaite 2011).

Coastal development

Urban, industrial, agricultural, or aquaculture development may directly degrade coastal habitat. This may have particularly negative influences on species that spawn in beach, intertidal, or subtidal areas (see smelt case study). Offshore renewable energy and desalination projects are also increasing rapidly off the West Coast. For example, desalination projects may result in changes to local water flow and salinity levels, and entrainment of larvae, eggs, and plankton in pumps and turbines (San Francisco Bay Conservation and Development Commission 2005).

Pollution

Oil spills, ocean dumping, industrial discharge, and other chemical pollution are continuing threats for fisheries (Colodey and Wells 1992, Sindermann 1996, Carls *et al.* 1999, Landis *et al.* 2004, Incardona *et al.* 2012; see herring case study). Increases in runoff are anticipated due to expanding human populations, coastal development, and agriculture. Noise pollution could also be a problem; trauma from high-intensity, low-frequency sounds has been observed recently in cephalopods (André *et al.* 2011) and in fish (McCauley *et al.* 2003).

Together, these influences may threaten the whole forage base (all species combined) or just specific species, cause widespread or local effects. They could increase variation in forage fish dynamics, by further reducing population numbers, diversity, and the ability of fish to withstand harm.

FORAGE FISH MANAGEMENT IN THE CALIFORNIA CURRENT

Forage fishes are managed within the U.S. EEZ, spanning the jurisdictions of federal or state agencies and Native American tribes. Federally, the Coastal Pelagic Species Fishery Management Plan (CPS FMP) includes sardines and anchovies. The Pacific Fishery Management Council (PFMC) and the National Marine Fisheries Service (NMFS) have federal jurisdiction in the CC.

Sardines are actively managed, meaning landings and markets are substantial enough to warrant annual assessment of stock status and fishery management. Anchovies are monitored only for potential elevation to active management, because they are assumed to now be landed in low numbers. Herring was recently added to the CPS FMP as a new designation, "ecosystem component" species. While this designation initiates monitoring of herring as incidental catch, there are still no federal restrictions on fishing for ecosystem-component species. Therefore, herring management is left to the states of California, Oregon, and Washington. Except for species listed under the Endangered Species Act (*e.g.*, the threatened smelt species eulachon [*Thaleichthys pacificus*]), most forage fishes in the CC are not federally or even actively managed at the state level. Examples include most smelts, sandlance, lanternfishes, saury, and others.

Challenges of forage fish management

Traditional stock assessment techniques are often used with the forage fish that are managed in the CC; however, these assessments do not perform well for pelagic forage fish. For example, basic management information, such as reliable estimates of population size, is not available for most forage fishes, even species with active fisheries. In addition, most fisheries management focuses on individual species and does not consider multiple species simultaneously, which is problematic given the critical ecological role of forage fish as prey.

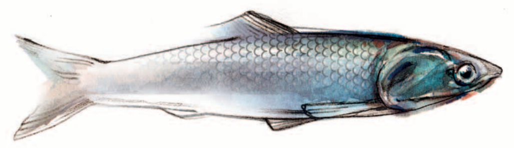
Furthermore, populations of short-lived forage fish can grow or decline quickly in response to climatic shifts, but mechanisms driving these dynamics are not well-understood (MacCall 2009). Fishing itself also increases populations' susceptibility to climate changes (Hsieh *et al.* 2006, Anderson *et al.* 2008), yet management response often lags behind these biophysical changes.

The "catchability" of forage fish may increase or remain constant even as a stock declines rapidly, due to their schooling nature and their vulnerability to modern fishing technology (Beverton 1990). Thus, declines in stock size may not be apparent based on commonly used catch-per-unit-effort statistics.

Traditional fisheries management focuses on maximum sustainable yield through time, yet this concept is not appropriate for prey populations, for populations that undergo natural cyclical fluctuations, or when considering effects to other species in the ecosystem (Larkin 1977, Legovic *et al.* 2010, Zwolinski and Demer 2012). High catch rates on short-lived species also mean that errors or uncertainty in setting catch rates can have particularly severe consequences (Pinsky *et al.* 2010). "Pretty good yield" has been recently suggested as an alternative and is defined as 80 percent of maximum sustained yield (Hilborn 2010), although this still does not account for any interactions with other species.

Natural mortality (e.g., predation, disease, starvation) is notoriously difficult to estimate reliably; yet inaccurate natural mortality rates may result in very misleading estimates of stock status provided to managers (Vetter 1998, Lee *et al.* 2011). Specifically, traditional assessment approaches that underestimate the magnitude and dynamic nature of natural mortality for forage fishes lead to biomass and yield projections that are overly optimistic (Tyrrell *et al.* 2011). Moreover, different survey methods result in size selectivity of forage fish, or bias towards certain size classes, that is difficult to establish and can introduce additional error into stock assessments (see Hill *et al.* 2010a). Finally, predator needs are not adequately addressed in most current management scenarios (Pikitch *et al.* 2004, Tyrrell *et al.* 2010).

CASE STUDY: NORTHERN ANCHOVY *Engraulis mordax*



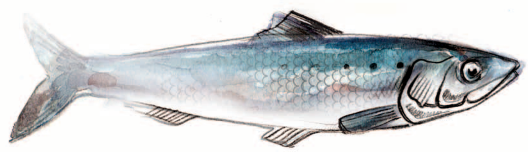
Anchovies consist of two subspecies in the CC: *Engraulis mordax mordax,* which ranges from British Columbia to Baja California and was recently also found in the Gulf of California; and *E.mordax nanus,* which is found in the bays of California. Usually seen in coastal waters within about 18 miles (30 kilometers) from shore, anchovies form large, tightly packed schools. *E. mordax mordax* is divided into northern, central, and southern subpopulations. The central subpopulation was once the focus of large, commercial fisheries in the U.S. and Mexico. Most of this subpopulation is located in the Southern California Bight. Those found north of Cape Mendocino, California, are considered the northern stock, and the southern stock is found entirely in Mexican waters.

Anchovies have the ability to spawn throughout the year. In California, peak spawning occurs from February to April and in Washington from mid-June to mid-August (Hunter and Macewicz 1980, Laroche and Richardson 1980). The last comprehensive stock estimates for the central subpopulation were made in 1995, after population declines and the downturn of the fishery (Jacobson *et al.* 1995). Recent population estimates, although limited by available data types and survey and analysis methods (see Jacobson *et al.* 1994, Fissel *et al.* 2011, Simmonds 2011), indicate a generally depressed anchovy population (Fissel *et al.* 2011). Only two scientific assessments have been completed for the northern stock, the second of which suggests there was a significant decline by 1995 (Richardson 1981, Emmett *et al.* 1997). Other data sources also suggest that these anchovy populations remain low (Brodeur *et al.* 2006, Bjorkstedt *et al.* 2011).

Despite limited information, commercial catch in the CC increased in the mid-2000s (PFMC 2010). Furthermore, catch outside of commercial fisheries is poorly documented and underreported (PFMC 2010). In 2005, for example, anchovy mortality from bycatch, live bait, recreational, incidental, and international fisheries totaled at minimum more than 65 percent of commercial U.S. landings (California, Oregon, and Washington [calculated from PFMC 2010]).

Anchovies are of high importance to predators due their relatively small size, inshore distributions, and almost year-round availability. More than 50 predator species in the CC consume anchovies, including important commercial and recreational species. The seasonal diet of Chinook salmon, for example, can be as much as 90 percent anchovy in some years (Merkel 1957).

Increases in commercial and other landings despite 15 years of low anchovy productivity and high dependence of predators could put the anchovy stock, valuable predators, and the larger ecosystem at risk. ■

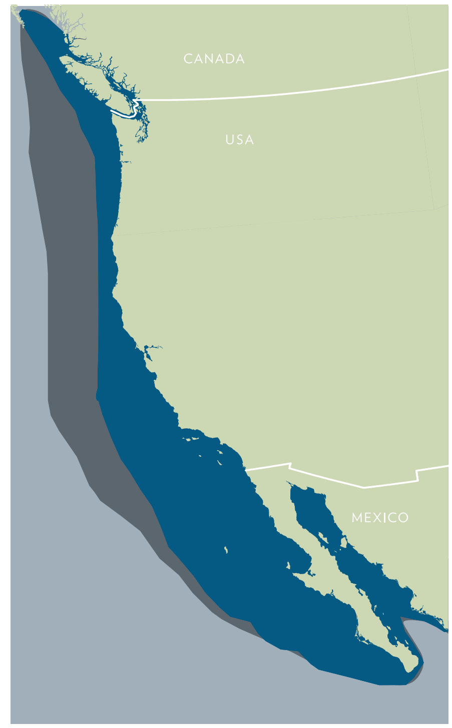


When the population of Pacific sardines is large, this fish is abundant from the tip of Mexico's Baja California to southeastern Alaska and throughout the Gulf of California. There are three Pacific sardine subpopulations in the CC with spawning centers in the Gulf of California, Baja California inshore and southern to central California offshore (Smith 2005, Hill *et al.* 2010b). The central California subpopulation is most relevant to the CC as a whole. This population spawns from January to June, and larger adults migrate in the spring to Washington and British Columbia.

Sardine populations naturally fluctuate in abundance roughly every 50 years (Baumgartner *et al.* 1992), driven mainly by large-scale climate fluctuations (Chavez *et al.* 2003, MacCall 2009), but these natural up and downs in population are also exacerbated by fishing pressure (MacCall 2009, Zwolinski and Demer 2012). Geologic records of fish scales deposited in the Southern California Bight indicate that unfished sardine populations fluctuated naturally between a low of 400,000 tons to many millions of tons (up to 16 million tons [Baumgartner *et al.* 1992]). In the 1930s and 1940s, sardines were the largest single-species fishery in the Western Hemisphere and were largely unregulated (Zwolinski and Demer 2012). The population went from more than 3 million tons in the 1930s to less than 5,000 tons in the 1960s (MacCall 1979). Sardine biomass did not increase again until the 1980s and 1990s, and the fishery resumed; biomass peaked at more than 1.5 million tons in 2000 and has subsequently trended downward to roughly 500,000 tons in 2010 (Hill *et al.* 2010b), with renewed fears of a population crash (Zwolinski and Demer 2012).

The sardine fishery has been federally regulated since 2000. Some management measures are relatively progressive, such as an environmental harvest-control rule, although there are opportunities to further improve management (Jacobson *et al.* 2001, Smith *et al.* 2005, Emmett *et al.* 2005, Hill *et al.* 2010b, McClatchie *et al.* 2010, PFMC 2010, Zwolinski and Demer 2012). For example, within the U.S. EEZ, sardines are caught by commercial, live bait, and recreational fisheries in California, Oregon, and Washington. Sardines are also taken as incidental catch in the Pacific mackerel, squid, and anchovy fisheries. The federal harvest quota for sardine includes set-asides for research, incidental catch, and management uncertainty. The set-aside for incidental catch (3,000 tons) does not appear to have been exceeded recently in squid, anchovy or Pacific mackerel fisheries (PFMC 2010); however, there are no set-asides for live bait and recreational fisheries. California live bait fisheries alone regularly exceeded 3,000 tons annually in the past decade (PFMC 2010). Thus the cumulative human removal of sardines from the ecosystem is not fully addressed in the commercial harvest quota.

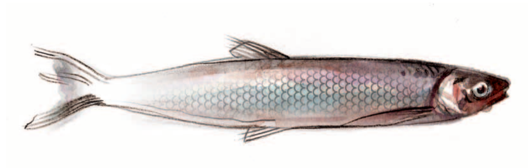
Beyond the U.S. EEZ, sardines are caught in Mexican and Canadian fisheries. International catch pushed total sardine harvest above the federal overfishing limit in 2009 (Hill *et al.* 2010b), highlighting the difficulty of managing



RANGE
HIGH CONCENTRATION RANGE

fish populations spanning international boundaries. Furthermore, overfishing measures specified in the CPS FMP were not implemented, despite the fact that this occurred during the recent sardine population decline.

Many predators rely on sardines, including Chinook and coho salmon, Pacific hake, and jack mackerel (Merkel 1957, Emmett *et al.* 2005). Seabirds, seals, sea lions, whales, dolphins, and sharks also forage extensively for sardines (Baltz and Morejohn 1977, Stroud *et al.* 1981,



Velarde *et al.* 1994, Clapham *et al.* 1997, Emmett *et al.* 2005, Becker and Beissinger 2006, Weise and Harvey 2008). California sea lions alone, for example, may consume the equivalent of roughly 10 percent of total sardine biomass in central California (Weise and Harvey 2008). Federal sardine management for the U.S. West Coast includes a harvest cut-off of 150,000 tons, which theoretically includes stock for potential rebuilding at low population sizes, as well as sardines as forage for dependent predators (PFMC 2010) for each year under all environmental conditions. Further synthesis of CC predator forage requirements is much needed to determine the adequacy of this threshold, given the importance of sardines as forage.

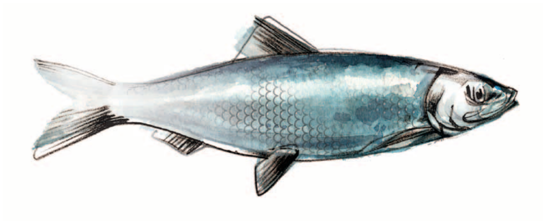
There are very few fisheries stock assessments or harvest policies that incorporate any measure of environmental variability (except see Schirripa *et al.* 2009). The sardine federal harvest policy is relatively unique because a proxy for environmental variability, a three-year average of sea surface temperature at the Scripps Institution of Oceanography pier in La Jolla, California, is used as one parameter in the formula for establishing the harvest quota (Hill *et al.* 2010b). Although a recent study suggested problems with this specific approach (McClatchie *et al.* 2010), environmental factors are clearly important for sardine stocks. Thus, this general approach should continue to be pursued, even if the specifics need to be modified. ■

The "true" smelts (Osmeridae) are several species of small silvery fish, including whitebait smelt, surf smelt, night smelt, longfin smelt, and eulachon. Smelt are common year-round residents in many nearshore areas from California to Alaska; however, their full ranges are not well-documented. They are relatively small, short-lived fish, reaching about 8 to 12 inches (20 to 30 centimeters) in length and surviving for three to five years. Some smelt have an entirely marine/estuarine life history (surf, whitebait, night smelt), while others (such as eulachon and longfin smelt) are anadromous. Eulachon is federally listed as threatened under the Endangered Species Act, and there is an active petition to list longfin smelt.

Data on smelt life history and particular stocks are largely lacking. There are currently no population size estimates for most smelt species, including whitebait and surf smelt, although these are among the dominant pelagic schooling fishes caught in research surveys in the Oregon-Washington region (Brodeur *et al.* 2003). Environmental influences have been demonstrated for whitebait smelt in Oregon. For example, poor body condition is likely a result of poor ocean conditions, such as reduced upwelling, that result in lower biomass and poor condition of zooplankton prey (Litz *et al.* 2010). It is not known exactly where and when whitebait smelt spawn, but the occurrence of larvae in estuaries during fall suggests that they may be late summer spawners on subtidal banks (reviewed in Litz *et al.* 2010). Smelts are particularly important forage for predators in the central to northern CC.

Commercial and recreational fisheries occur on surf smelt populations at many sites throughout Oregon and Washington (Bargmann 1998). Adequate fishery statistics are lacking for smelts, in spite of their ecologically data-poor status and local importance. Recreational catch may actually exceed that of commercial catch in some instances, perhaps because unlike most other forage fish species, most smelt are used for human consumption (Bargmann 1998). ■

CASE STUDY: PACIFIC HERRING *Clupea pallesi*



Pacific herring have long been exploited by humans and are consumed by natural predators. Herring have been an important resource for Native American groups in the Pacific Northwest for centuries (Hourston and Haegele 1980, Gobalet and Jones 1995, Bargmann 1998). Commercial fisheries have repeatedly sprung up and crashed along the U.S. West Coast. A small commercial sport bait fishery in south Puget Sound (Stick and Lindquist 2009) and small commercial roe, eggs on kelp, and fresh herring fisheries in San Francisco Bay (CDFG 2012) are the only significant fisheries remaining.

Pacific herring are found throughout the coastal zone from northern Baja California around the North Pacific Rim to Korea. They spawn between October and April in shallow parts of bays and inlets, preferably onto marine vegetation or subtidal rocks, but man-made structures are also used.

Threats to herring in the CC include large population declines due to climate and overexploitation, truncated age structure, localized population depletions, degraded spawning habitat, and oil and other chemical pollution (Zebdi and Collie 1995, Toresen and Østvedt 2000, Landis *et al.* 2004, Stout *et al.* 2001, Stick and Lindquist 2009, CDFG 2012, Incardona *et al.* 2012, Wespestad and Maguire 2012). The spawning habitat of what was the largest Washington herring population, Cherry Point in Puget Sound, is now centered in an area of industrial activity and urban development (Stout *et al.* 2001). The largest remaining California population, in urban San Francisco Bay, recently suffered effects of an oil spill (Incardona *et al.* 2012) presumably reducing already depressed numbers (CDFG 2012). Other historically large herring spawning populations in California, such as Tomales Bay, are also significantly reduced (Bartling 2006).

Some herring populations are distinct, not mixing with neighboring populations due to geographic or behavioral differences such as varied spawning times. Where genetic differences have not been established, populations may demographically be characterized as a meta-population. Understanding local population structure, however, is essential for the preservation of spawning potential and genetic and life history diversity (Gustafson *et al.* 2006).

Pacific herring have been documented to live as long as 15 years, though few exceed 9 years (Ware 1985). While CC stocks included long-lived fish in the 1970s, herring older than 4 or 5 are now rare, and the median age is 2 to 3 (Hershberger *et al.* 2005, Gustafson *et al.* 2006, Mitchell 2006, Stick and Lindquist 2009, CDFG 2012). This change is probably largely due to intense fishing. Other factors include predation and increased rates of pathogenic infection in older fish, which may contribute both directly and indirectly (through increased predation) to mortality (Hershberger *et al.* 2002, Stick and Lindquist 2009). Declining longevity may further harm herring populations, for example by reducing the quantity and quality of eggs (Hay 1985, Ware 1985), shortening the spawning season and thus decreasing the populations' overall reproductive potential (Wright and Trippel 2009).

Improving forage fish management

When assessing fish population status for use in management decisions, the inclusion of ecological interactions is central to an ecosystem-based perspective. This is not a new concept (e.g., May *et al.* 1979), yet incorporating basic ecological processes such as predation and competition into fisheries stock assessments is still uncommon (Link 2002, Tyrrell *et al.* 2011). While there are movements toward EBFM at the federal and state levels, they are nascent, slow, or implemented in a piecemeal fashion (Field and Francis 2005, Ruckelshaus *et al.* 2008, Halpern *et al.* 2010). Moreover, the degree to which proposed fisheries ecosystem plans, one of the key approaches to implementing EBFM, are enforceable is unclear. Regardless, a more ecosystem-centric management approach by definition is holistic and includes multiple considerations.

One important consideration in EBFM, a precautionary management approach, emphasizes the role of forage fish in the ecosystem and considers catch secondarily. This effectively shifts the "burden of proof" to show that a given fishing level is safe before allowing it. Such an approach is especially important in data-poor instances or in the face of scientific uncertainty (Pikitch *et al.* 2004, Curtin and Prellezo 2010).

Time and/or spatial fisheries closures can protect spawning fish aggregations or hotspots of predators and prey, and, more generally, life history characteristics and biodiversity (Babcock *et al.* 2005, Field and Francis 2005, Hyrenbach *et al.* 2000, Ruckelshaus *et al.* 2008, Santora *et al.* 2011). Limitations on fishery gear—such as allowable gear types, net length, and mesh size—are important in protecting habitat, minimizing bycatch, and avoiding harvesting of fish before they reach full maturity (Belgrano and Fowler 2011).

The nature, strength, and changes in ecological processes, such as predation and competition, influence single-species population dynamics as well as ecosystem functioning (Field and Francis 2005, Tyrrell *et al.* 2011). Environmental variation further influences single-species dynamics and interactions among species. Environmental effects include long-term (*e.g.*, warm/cool marine decadal regimes) and short-term (e.g., ENSO) fluctuations, as well as trending temperatures and increasing variability associated with climate change (Field and Francis 2005, Curtin and Prellezo 2010, Belgrano and Fowler 2011). Environmental effects, however, are also rarely incorporated into fish population assessments or fisheries management decisions (except see Hill *et al.* 2010b, Schirripa *et al.* 2009; see sardine case study). EBFM should also consider risks to fish populations and the ecosystem from human sources such as habitat destruction and pollution (Pikitch *et al.* 2004, Curtin and Prellezo 2010; see herring and smelt case studies).

In addition to integrating predator effects into fish population assessments, EBFM should take the needs of predators into account in relation to degree of fishing (Smith *et al.* 2011, Cury *et al.* 2011, Pikitch *et al.* 2012). Approaches include precautionary management, fisheries closures, and forage reserves for predators, which may be apportioned to predator needs in terms of prey diversity, abundance, distribution, size, seasonality, and/or interannual variability due to climate or other factors.

Several large-scale studies have recently suggested thresholds of forage fish biomass that should remain in the ocean for predators. A report of the Lenfest Forage Fish Task Force (Pikitch *et al.* 2012) compared one type of ecosystem model across many systems globally and found that approximately 80 percent of unfished forage fish biomass should remain in the water to avoid a 50 percent reduction in any dependent predator population. A study, partially funded by the Marine Stewardship Council (Smith *et al.* 2011), compared three types of ecosystem models across five systems. Based on the study's results, the authors suggest leaving 75 percent of unfished forage fish biomass in the ocean to maintain ecosystem function. Cury *et al.* (2011) used a different approach, numerical response curves, in seven ecosystems to determine the threshold of roughly 30 percent of the maximum long-term forage fish biomass below which seabirds experience consistently reduced and more variable productivity. Each method has its advantages and difficulties, and additional analysis and synthesis of predator-forage requirements utilizing a combination of these and other approaches will be useful.

When determining catch levels for commercial fisheries, insufficient attention is often paid to the total human removal of forage fish from the ecosystem, both by species and as a forage group. Such removal includes nontarget, or incidental, catch, bycatch, live bait fisheries, recreational fishing, and fishing outside the U.S. EEZ that targets stocks spanning political boundaries (Pikitch *et al.* 2004, Ruckelshaus *et al.* 2008, PFMC 2010). Catch outside of commercial fisheries can be significant in some cases (Pikitch *et al.* 2004), although it is often poorly documented and underreported in the CC (PFMC 2010; see sardine and anchovy case studies). Even after predator needs have been considered, these other types of human removal further reduce the amount of target forage fishes available for commercial fisheries.

Many tools to implement EBFM already exist (Ruckelshaus *et al.* 2008, Lester *et al.* 2010, Tyrrell *et al.* 2011, Pikitch *et al.* 2012). There are some data gaps, such as limited quantification of relationships between fish stocks (Hannesson and Herrick 2010), but modeling tools to address this issue exist or are being developed (see Tyrrell *et al.* 2011 and references therein). Other types of data gaps or stock performance under various conditions might be approximated from other systems that are better studied (Dickey-Collas *et al.* 2010). A wealth of predator diet data exists, although synthesis of forage requirements would enable improved management of fishery resources in an ecosystem manner.

SUMMARY

In the CC, sardines are the most heavily fished forage fish. Sardines are also relatively well-studied and progressively managed, yet there is still much unknown about their populations, and management could be improved, especially in regard to cumulative human removal from the ecosystem, effects of fishing on age structure, West Coast-wide overfishing, the environmental harvest control rule, and quantitative predator needs. Even less is known and little management exists of other forage fishes, despite variable levels of fishing pressure and high importance to predators.

Recent scientific syntheses, although using different methodologies, reach similar conclusions: forage fish management worldwide is important but insufficient (Smith *et al.* 2011, Cury *et al.* 2012, Pikitch *et al.* 2012). Under the increasing array of threats to forage fish, efforts should be made to control the factors we can, such as fishing, to enable the maximum resilience possible to factors that we can't easily control, such as climate change. This approach is important for the health of forage fish stocks themselves as well as fostering continued species diversity and ecosystem functioning in the CC. Public and economic ramifications of sustainable forage fish management are substantial, both for predators with no market value (such as seabirds, marine mammals, and threatened and endangered species) and those with considerable market value (such as commercial fisheries for salmon, tuna, and rockfish).

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901 E Street NW, 10th Floor
Washington, DC 20004
Phone: 202.552.2000
Email: oceanscience@pewtrusts.org

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Cover photo: Two fishermen transfer anchovies, *Engraulis mordax*, from a commercial fishing boat hold to a live bait storage pen, San Francisco Bay, California. Abner Kingman/Getty
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Design: Imaginary Office

SCIENTIFIC CONTRIBUTORS

Julie Thayer, Ph.D.
Dr. Thayer has worked in the California Current marine ecosystem for the past 18 years. She did undergraduate work in marine biology at the University of California, Santa Cruz, and Long Marine Lab, and obtained a doctorate in marine ecology from the University of California, Davis. Dr. Thayer has conducted research on a variety of top marine predators and their prey in relation to ocean climate. Recently she organized a group of researchers from around the North Pacific Rim (Canada, Japan, United States) for a comparative study of forage fish eaten by a seabird, rhinoceros auklet, focusing on spatiotemporal synchronicity in connection with local to basin-scale marine variability (Thayer *et al.* 2008). She has also led a collaborative fisheries research project in which scientific data on the diet of salmon are collected in partnership with local recreational and commercial fishers, synthesizing historical data to help understand the recent salmon population crash.

William Sydeman, Ph.D.
Dr. Sydeman's career spans nearly three decades of ecological research. Starting as an intern marine ornithologist working on the Farallon Islands in 1981, he spent 15 years as the director of marine ecology at PRBO Conservation Science before establishing the Farallon Institute (faralloninstitute.org). Dr. Sydeman obtained his doctorate in ecology from the University of California, Davis. He has conducted a number of plankton-to-predator studies in the California Current large marine ecosystem and has written about seabirds, marine mammals, and various fish species. He serves on many scientific panels, notably as the chair of the Advisory Panel for Marine Birds and Mammals for the North Pacific Marine Science Organization and Scientific Advisory Committee for implementation of the California's Marine Life Protection Act. Dr. Sydeman has presented to state and federal policymakers on the effects of climate change on marine ecosystems and how to best design and use the nation's new ocean observing systems.