Monterey Bay National Marine Sanctuary
Conservation Working Group White Paper:

Forage Species Science and Management in the Monterey Bay National Marine Sanctuary

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About the Conservation Working Group

The mission of the Conservation Working Group is to help promote and achieve comprehensive and long-lasting stewardship of the Sanctuary by identifying resource protection and management needs, and making recommendations on priorities, strategies, and policies to Sanctuary staff, the Sanctuary Advisory Council and associated working groups. This white paper has been generated, reviewed, vetted, and unanimously endorsed by the current members of Conservation Working Group at the time of this writing.

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Executive Summary

In this white paper, we examine the role of forage species in the California Current marine ecosystem, the natural and human-caused threats to forage species populations, and the management structures currently in place, with a geographic focus on the Monterey Bay National Marine Sanctuary. In any ecosystem – on land or sea – food availability is a critical factor directly affecting the health and biodiversity of the system. This is especially true for the California Current Large Marine Ecosystem and in particular the key foraging areas in the West Coast National Marine Sanctuaries. Sometimes referred to as the "Blue Serengeti of the Pacific", this wild ocean ecosystem supports a phenomenal diversity of life. It also contributes to the regulation of our climate and supports a major part of the U.S. and world economy.

One pillar to the long-term sustainability of this ocean ecosystem is healthy populations of forage species that provide the food supply for larger animals. Forage species, such as Pacific herring, Pacific sardine, Northern anchovy, market squid, lanternfish, and krill, are critical prey for whales, dolphins, sea lions, many types of fish, and millions of seabirds. The abundance and availability of these small schooling fish and invertebrates are key to a vibrant food web and a healthy ecosystem.

On a global scale, a recent report by the Lenfest Forage Fish Task Force provided new analysis describing the importance of forage fish and issued a series of management recommendations tailored to the level of information available for each forage species and their role in the ecosystem.

Given the increasing global demand for seafood, and in particular wild-caught fish used as feed for the growing aquaculture industry, proactive actions taken now may avert a future crisis. The first step is to manage forage species differently than other commercial fish species, to account for their unique ecological role. There has been some progress. West Coast states, regional fishery managers, the National Marine Sanctuaries, and the federal government have already prevented directed fisheries for krill off the U.S. West Coast, citing the importance of these species as a keystone prey in the California Current marine ecosystem food web. Many other important forage species, however, remain unmanaged and fisheries could develop at any time and with little warning. While in some respects, management of some forage species on the U.S. west coast is progressive of other parts of the world, new science is now making it possible for management to move toward a more ecosystem-based approach.

There are societal trade-offs among economic sectors inherent in forage species management, as forage species have economic value not only as landed catch, but also if left in the water due to their supportive role of other species that benefit different economic sectors. The goal is to provide a balanced approach taking into account the needs of all sectors, hence providing the greatest overall benefit to the Nation. This requires a paradigm shift in fisheries management away from the traditional single-species maximum sustainable yield approach toward a more holistic ecosystem-based approach. However, this requires further tools, data, and frameworks.

As commercial landings of larger fish species have declined off the U.S. West Coast (e.g., tunas, salmon, and rockfish) for various reasons in recent decades, the relative contribution of the smaller forage species to commercial landings and value has increased. Yet the supportive value of forage species to recreational and commercial fisheries, tourism, recreation, wildlife viewing, and healthy ecosystems has not been fully assessed.

This document is intended to provide background on the science and management of West Coast forage species of importance to the MBNMS ecosystem and resources, to help facilitate appropriate engagement between this Sanctuary and state and federal fishery managers.

Introduction and Background

> *"Forage is the heartbeat of the ocean, the life giving sustenance that keeps the thousands of species of large food and sport fish alive and robust. Nothing, no other category of fish, determines the fate of our favorite seafood as much as the availability of sufficient forage to keep them healthy and reproductive."*
>
> -Darrell Ticehurst, Coastside Fishing Club. April 15, 2011 article in *Pacific Coast Sportfishing Magazine*.

The health and biodiversity of fish species, marine mammals, sea turtles, and seabirds of the California marine sanctuaries are dependent on the base of the food web. Small schooling fish and invertebrates like sardines, herring, squid, anchovy, smelts and krill are vital prey or "forage" for many larger species of fish and wildlife.

Precise definitions of forage species with clear thresholds do not exist in the scientific literature. The Lenfest Task Force defined forage species in terms of their functional role in providing a critically important route for energy transfer from plankton to higher trophic levels in marine ecosystems[1]. The Pacific Fishery Management Council's Ecosystem Plan Development Team adopted the following working definition: "species that are often present in high abundance, forming dense schools or aggregations, and which are generally plankton feeders for a large part of their life cycle".[2] In coastal upwelling systems in particular, the vast majority of trophic transfer takes place through a small number of key forage species. For purposes of this document, the term forage species refers to *lower trophic-level fish or invertebrate species that contribute significantly to the diets of other fish, birds, mammals, or sea turtles, or otherwise contribute disproportionately to ecosystem function and resilience due to its role as prey*.

While this definition could be interpreted broadly, considerations should include the importance to multiple predators, particularly those of economic importance, broad geographic range throughout the California Current, and the relative abundance of the species in the main habitat types found in the California Current. The California Current is a highly dynamic system that undergoes short and long-term changes in oceanographic conditions, food web structure, and the relative abundance of both predators and forage species. Furthermore, as climate change proceeds over the next century, abundances and distributions of many species will change in unpredictable ways.

There are several major commercial fisheries targeting forage species in the Pacific Ocean waters off the U.S. west coast, as well as several species that are currently not subject to significant fishing pressure. Existing fisheries on forage species are managed by a combination of state and federal fishery management under a suite of laws and regulations, described in detail in the Management Section. However, some forage species are currently unmanaged. Given the increasing global demand for seafood, and in particular the explosion of finfish and shrimp aquaculture that depends on wild fish as aquafeeds, there is an increasing interest in how forage species are managed.[3] West Coast states and the federal government have stepped forward by preventing directed fisheries for krill, yet fisheries could develop at any time for a wide suite of other important forage species. Some forage species stocks, like Pacific sardines, are fished by multiple nations[4], highlighting the need for international management and cooperation.

Traditional, single-species fisheries management tends to focus on maximizing long-term yields for the benefit of the fishing sector that targets the species in question. As a result, traditional approaches do not explicitly consider how much prey needs to be left in the ocean to support valuable fisheries and wildlife, or the effects of fishing on ecosystem functioning or on other economic sectors that rely indirectly on forage species. There has been some progress at the state and federal levels of fishery management, and this white paper intends to recognize and document those progressive steps. For example, several Fishery Management Councils are developing Fishery Ecosystem Plans and their Scientific and Statistical Committees are working on ways to better account for forage considerations in assessment models. However, there is a paucity of practical tools for fishery managers to explicitly consider this trade-off in management decisions. In particular, there is an inadequate accounting for the needs of predators dependent on abundant populations of forage species. The National Marine Sanctuary Program is unique within NOAA in that it has a mandate to consider broad ecosystem protection in a multi-sectoral, holistic way. Therefore, there is an opportunity for the Sanctuaries to contribute data, tools, and information into the fishery management process to help address these gaps.

The purpose of this document is to provide background on the science and management of forage species relevant to the Monterey Bay National Marine Sanctuary, to provide a basis for additional engagement between the Sanctuary and fishery managers on forage species fishery management decisions that affect the broader Sanctuary ecosystem.

California Current Marine Ecosystem: Foraging Destination of the Pacific

One of ten major Large Marine Ecosystems in the United States, the California Current Large Marine Ecosystem (LME) is considered globally important for its high productivity and the large numbers of species it supports.[5] The California Current extends 3,000 km from the northern end of Vancouver Island to Baja California Sur, and includes the Pacific Ocean waters off Washington, Oregon, and California from shore to the 200 mile Exclusive Economic Zone. The California Current LME is influenced by a series of four currents and is one of five[6] Large Marine Ecosystems in the world that is characterized by its productive upwelling. When strong winds blow alongshore towards the equator, warm surface waters are carried offshore and are replaced by deep, cold, nutrient-rich waters.[7] This upwelling fuels phytoplankton blooms and in turn, zooplankton and euphausiids (krill) flourish. These tiny plants and animals create a solid foundation for a food web that supports marine mammals including blue and humpback whales; elephant seals; millions of seabirds; endangered sea turtles; slow growing fragile deep sea corals; and species such as salmon, halibut, and crab that are vitally important for commercial, recreational, and subsistence harvest.

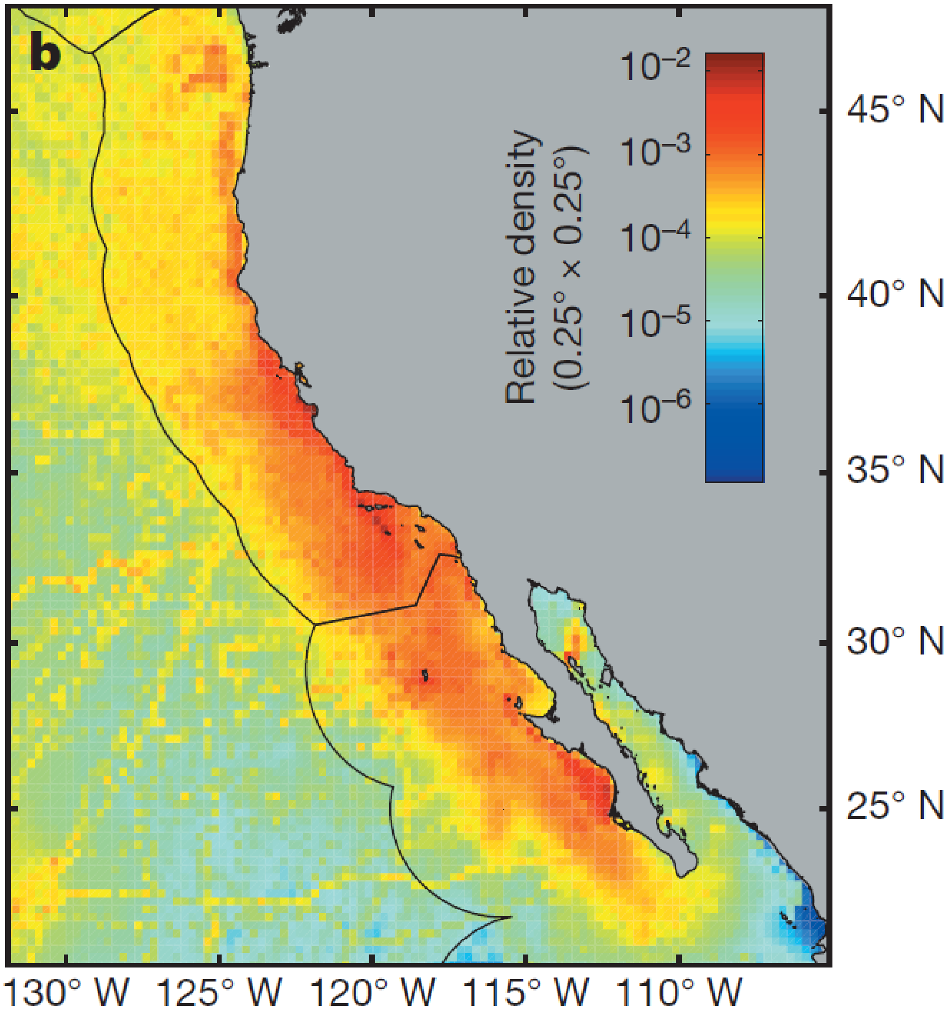


Figure 1: Density of apex predators in the California Current. Source: Block et al. 2011, *Nature*.

The California Current LME is one of the most productive ocean systems in the world, attracting a disproportionately high abundance and diversity of pelagic fish, turtles, seabirds, whales, and pinnipeds. According to the Census of Marine Life, the California Current LME has among the highest numbers of species of fish, seabirds and marine mammals of all 11 LMEs in the North Pacific Ocean. A recent study[8] summarizing the results of 10 years of telemetry work on 23 species of tunas, sharks, whales, pinnipeds, seabirds and sea turtles through the Tagging of Pacific Predators initiative highlights the California Current Large Marine Ecosystem (CCS) as one of two most critical foraging zones for wide-ranging marine predators in the Pacific (Figs. 1 and 2). The study stated:

> *"All species tagged outside the CCLME spent significantly more time on average in the CCLME than expected on the basis of null model simulations. The retention within and attraction to the CCLME is consistent with the high productivity of this region, which supports large biomasses of krill, sardines, anchovies, salmon, groundfish and squid that provide a predictable forage base for top predators."*

The California Current LME is clearly integral to the economy, culture, and well-being of the west coast states as well as the American way of life. These waters provide opportunities for millions of Americans, for recreational activities, commercial fishing, critical commerce supply links, subsistence and personal use, and a variety of economic activities including tourism. In 2004, ocean sectors contributed over $57 billion to the combined Gross Domestic Product of California, Oregon, and Washington. [9] The ocean sector includes construction, living resources, minerals, ship and boat building, transportation, tourism and recreation.

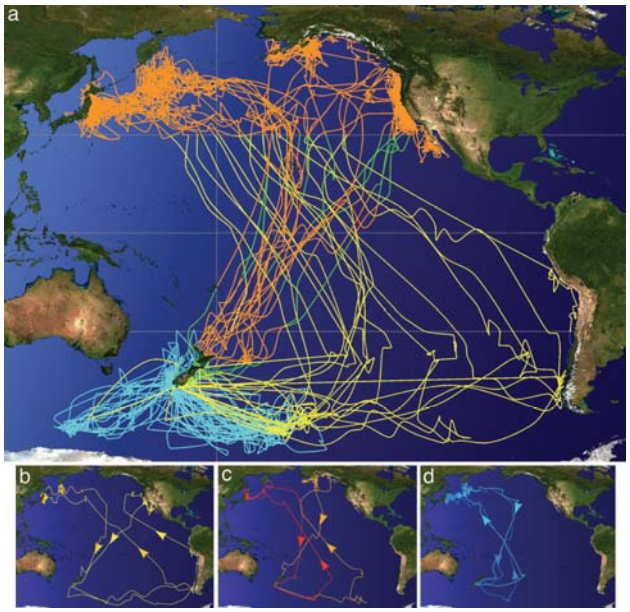


Figure 2: Satellite tag tracks of Sooty Shearwater tagged at their breeding colonies in New Zealand. Source: Shaffer et al. (2006)[10]

Monterey Bay National Marine Sanctuary: A Hotspot within a Hotspot

Within the CCLME, Monterey Bay, Gulf of the Farallones and Cordell Bank National Marine Sanctuaries are of elevated importance as foraging areas for apex predators. The MBNMS was established for the purpose of resource protection, research, education, and public use of this national treasure. Stretching from Marin to Cambria, the MBNMS encompasses a shoreline length of 276 miles and 6,094 square miles of ocean. Supporting one of the world's most diverse marine ecosystems, it is home to numerous mammals, seabirds, fishes, invertebrates and plants in a remarkably productive coastal environment. The MBNMS is part of a system of 13 National Marine Sanctuaries and one marine national monument, administered by the National Oceanic and Atmospheric Administration. The California Current passes through the MBNMS, which, along with areas of strong coastal upwelling, makes this one of the most productive ocean systems in the world. Topographic breaks in the shelf such as the Monterey Submarine Canyon bring water depths in excess of 1,000 m within 10 miles of shore, downstream from upwelling centers such as Pt. Año Nuevo. High euphausiid densities appear to result from the habitat provided by the proximity of the deep canyon to an upstream coastal upwelling center.

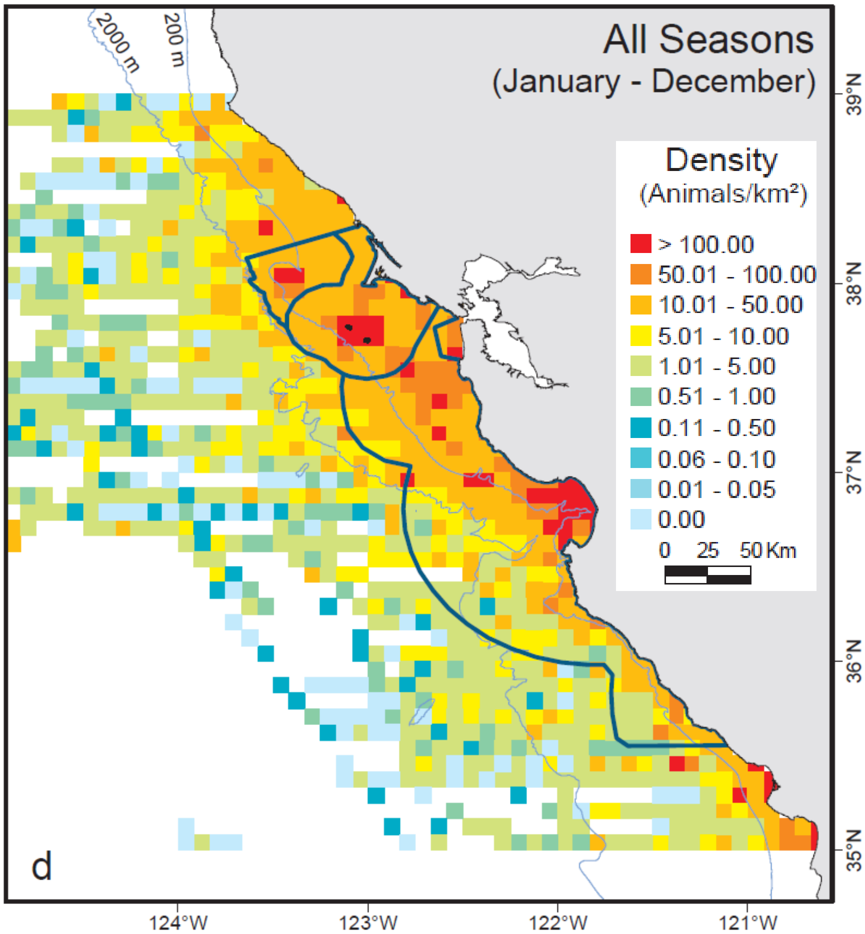


Figure 3: Marine Bird Density. Source: NOAA National Centers for Coastal Ocean Science (NCCOS) 2007. At-sea data from the CDAS Central California Data Set (1980-2001), 2003.

Because of this productive environment, the study area contains a rich fauna of marine mammals, as evidenced in marine mammal abundance and species richness. The Monterey Bay canyon complex is a seabird and marine mammal hotspot. Greater Monterey Bay is “the restaurant that is always open” to pelagic marine predators in the CCS in years of overall poor ocean conditions. Over 100 seabirds/km^2 occur consistently over seasons, as well as the highest marine mammal species richness in California. Over 29 species of marine mammals occur here: 22 cetaceans (whales, dolphins, and porpoises), six pinnipeds (seals and sea lions), and one fissiped species (the sea otter).

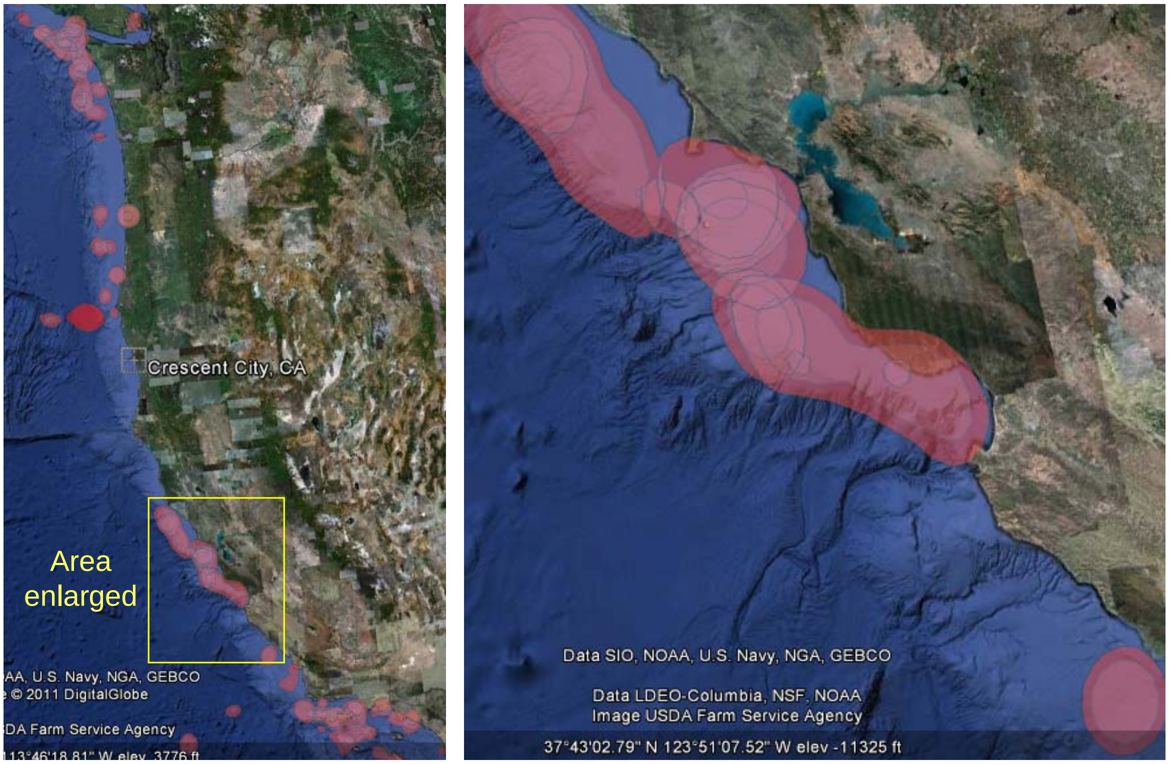


Figure 4: (Left) Seabird hotspots in the north-central part of the California Current. (Right) Seabird hotspots in the region of the Monterey Bay National Marine Sanctuary, based on at-sea surveys for 21 commonly occurring breeding and visiting species. Represents top 10% of seabird density in the entire California Current for individual species. In prep. Farallon Institute for Advanced Ecosystem Research. 2012.

There may be identifiable "super hot spots" within MBNMS: Pacific predators aggregating to feed in greater Monterey Bay (Ano Nuevo through Carmel Canyon) include sooty shearwater, [11] ashy storm-petrel,[12] marbled murrelet,[13] black-footed albatross[14] and blue whales, which congregate on the Monterey Canyon slopes exploit extremely dense patches of euphausiids aggregated on the edge of the Monterey Bay Submarine Canyon.[15] (Figs. 3 and 4) The unique topography of Monterey Bay serves to enhance primary and secondary productivity even in years of poor overall productivity in the California Current System (CCS).[16] Further offshore yet still within MBNMS, Davidson Seamount has a different yet still highly diverse seabird and marine mammal species assemblage.[17] Forage species populations are preyed upon by important commercial and recreational fisheries like Chinook salmon, albacore tuna, yelloweye rockfish, white seabass, barred sand bass, kelp bass, and California halibut (Fig.6).[18,19,20] Forage species are also critical to supporting marine wildlife including humpback whales, sea lions, dolphins, porpoises, seabirds[21,22,23] and therefore support associated recreation and tourism.

Fisheries on Forage Species

Because of their short lifespan and dependence on plankton, many forage species populations fluctuate widely simply due to changing environmental conditions, more so than most other commercial fish species.[24] This dependence on the environment has led to an erroneous perception that fishing poses less risk on forage species populations or the availability of forage. Conversely, scientists have recently concluded that forage species are just as likely, if not more likely, to experience fishery collapses than larger fish, often because managers tend to set more aggressive harvest rates for these species.[25] Throughout the world, fishing on small pelagic fish and invertebrates has been linked to declines in their predators (e.g. [26,27,28]) and on the U.S. West Coast, simulations of Pacific sardine populations show drastic differences in the amount of years of low abundance and average biomass resulting from subtle changes in fishing rates.[29] In particular, the effects of fishing of forage species are more severe in times of low natural productivity, such as that caused during El Niño conditions.[30] While climate-mediated stressors will take unilateral international action to address, fishing pressure on forage species is within the realm of regional management.

While there remains debate whether certain declines in forage species are caused by fishing pressure or environmental conditions, it is likely the compounding effect of low natural productivity and fishing pressure that determines the rate of collapse and the speed of recovery[31]. Therefore predicting and responding to natural fluctuations in forage species populations is critical to maintaining the resilience of ocean food webs in the face of the many threats to forage species.

Over the last century, California landings of commercial fish have varied dramatically, and forage species have varied in their importance.[32] For example, small pelagics (also referred to as “wetfish”) dominated landings in the 1930s and 1940s. Since the 1980s, the relative importance of forage species in commercial fishery landings both by value and by weight has increased dramatically, as landings of larger commercial species like salmon, rockfish, and tunas have decreased for both biological and regulatory reasons, as well as the shift in tuna landings fisheries to other areas (Fig. 5). As such, the portfolio of fishery landings has become much less diverse, and fishing communities are becoming more dependent on a group of species whose populations tend to have higher variance.

Traditional single-species fishery management historically emphasized maximizing the catch of individual fish stocks over the consideration of maintaining a healthy ocean ecosystem. Based on the concept of “Maximum Sustainable Yield” (MSY), fishery managers seek to maintain high fishery catches by regulating the number or weight of fish caught, the size of the fish caught, and/or the time and space where fishing is allowed to take place.[33] MSY is the largest long-term average catch or yield that can be taken from a stock under prevailing conditions.[34] This focus on maximizing yield can lead to overfishing in years of unfavorable environmental conditions, poor recruitment, and low productivity.[35] In addition, even if MSY can be achieved in practice, the widespread application of MSY policies is predicted to cause severe deterioration of ecosystem structure particularly the loss of top predator species[36]. Since 1996, the federal Magnuson-Stevens Act has included a concept of Optimum Yield intended to account for ecological factors (see Management Sections). Some scientists have observed that the progression of fishery activity may “fish down” marine food webs, yet there remains debate on the extent of this phenomenon.[37] Fishing down the food web is described as fisheries target lower and lower trophic level fish stocks as species in higher trophic levels are sequentially depleted.

Some have suggested the concept of Ecologically Sustainable Yield where the full impacts of fishing on the ecosystem are evaluated and considered.[38] Fishery scientists and ecologists agree that a wide range of exploitation rates result in catch levels close to maximum levels, yet setting exploitation at the lower end of this range reduce ecosystem impacts, rebuilds total biomass, prevents species collapse, reduces the costs of fishing, and increases profit margins over the long term.[39,40] An alternative, but complementary way to begin accounting for forage considerations is to incorporate predator-prey relationships into stock assessments.[41]

Specific to forage species, a recent study found widespread impacts of harvesting forage species across 5 different ecosystems, including the California Current. Authors recommended maintaining forage biomass levels much greater than MSY biomass levels (over 75% of their unfished levels) and fishing rates less than half of MSY rates.[42] The Lenfest Forage Fish Task Force[43] echoed these recommendations, and further recommended establishing a “hockey stick” control rule (e.g., inclusion of a “cutoff” as in Pacific sardine management) for forage species that sets a minimum biomass level at 40% of the unfished biomass. They also recommend using spatial management to protect predators likely to be adversely affected by localized forage depletion.

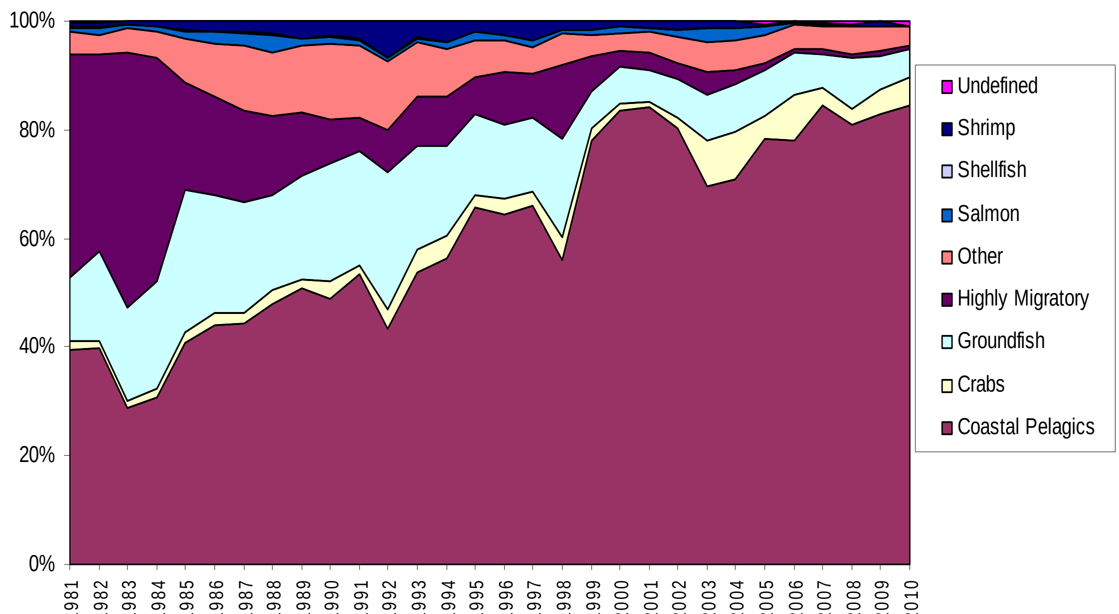
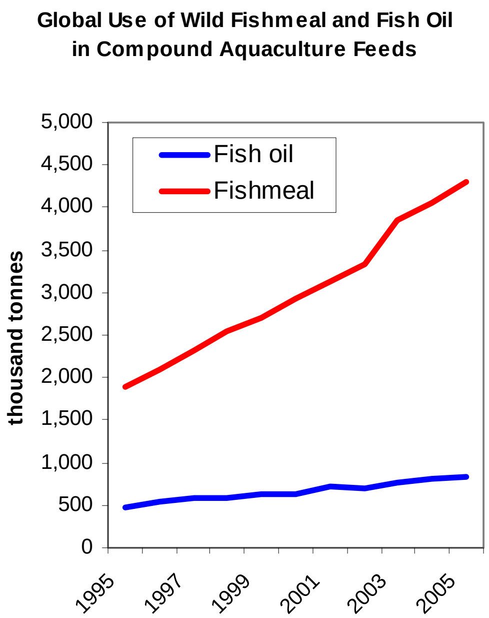


Figure 5: Relative contribution of species groups to total California landings by weight. Data source: Pacific Fisheries Information Network (PacFIN).

End Uses of Commercially Fished Forage Species

Globally, only about 10% of forage species landings are sold for direct human consumption. The remaining 90% goes primarily to bait and feeds for livestock or farmed fish[44]. Despite marked increases in feed efficiency, aquaculture's share of global fishmeal and fish oil consumption more than doubled over the past decade to 68% and 88%, respectively (Fig. 6).[45] Total production of farmed fish and shellfish increased threefold from 1995 to 2007 and a greater share of farmed fish now use compound feeds derived from wild fish. While feed conversion ratios (amount of fish feed required per quantity of farmed fished produced) are improving, the growth in the industry has resulted in the total increase of fish feeds used. This growth in the aquaculture sector will likely drive prices higher, creating incentives for higher catch rates in existing fisheries and making once uneconomical fisheries feasible.[46]



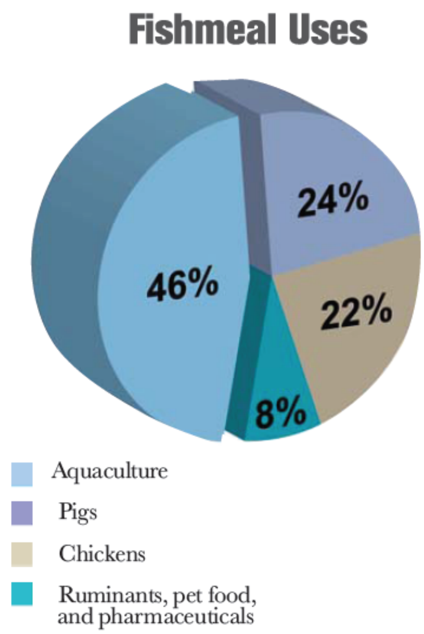


Figure 6. (Left) Global use of wild fishmeal and fish oil in compound aquaculture feeds. Source: Tacon and Metian 2008. (Right) Global fishmeal end uses by category. Source: Campbell and Alder, 2008.

For several decades, 20 million to 30 million metric tons of fish (1/4 to 1/3 of the global fish catch) have been removed from the marine food web each year to produce fishmeal and fish oil for animal feeds and other industrial purposes. The percentage of forage species catch landed and consumed directly by humans has ranged from 10-20% since the 1960s.[47] Another 5-9 million metric tons of ''low value/trash fish'' and other forage fish are used for nonpelleted (farm-made) aquafeeds.[48] While there are readily available substitutes to fish meal, substitutes for fish oil are not readily available, which is a key limiting factor in the aquaculture production of shrimp and finfish.

In 2002, 46% fishmeal and fish oil were primarily used for aquaculture, followed by 24% for pigs, and 22% for poultry.[49] Despite improvements in feed efficiency, overall demand particularly for fish oil is increasing due to the expansion of aquaculture production.[50] In 2008, 27.2 million tons of the 89.7 million tons (over 30%) of capture fisheries production went to non-food uses. Of this, 20.8 million tons went to fishmeal and fish oil.[51] The remainder went as a combination of bait, pharmaceuticals, and direct feeding in aquaculture and livestock.

Off California, the Coastal Pelagic Finfish (sardines, anchovy, mackerel) are sold as relatively high volume/low value products (e.g., Pacific mackerel canned for pet food, Pacific sardine frozen and shipped to Australia to feed penned tuna or sold as bait for Asian longline tuna fisheries, and northern anchovy as bait or tuna feed).[52] In recent years, 75-95% of market squid and Pacific sardine landings have been exported.[53] Market squid and some larger Pacific sardines (caught off Oregon and Washington) are sold for direct human consumption. Small quantities of these species are also sold locally as live or dead bait to recreational fishermen. Additional historical information on the economics and end uses of California "wetfish" fisheries has been summarized elsewhere.[54]

Supportive Value of Forage Species

Fish that are used for supplying feed to fish farming or animal farming are also a source of food for wild fish that in turn are captured and used for direct human consumption, or as food for animals that are in demand for non-consumptive reasons (marine mammals or sea birds). It is highly likely, therefore, that the capture of feed fish will be at the expense of other wild fish or animals that mankind utilizes, directly or indirectly.

The value of forage fish left in the ocean is an externality to the directed fisheries for forage species. Forage fish left in the ocean can be parsed into two components. On the one hand, they contribute to the spawning stock and hence the recruitment to the fishery in future years (as is the case with sardines, where there is a stock-recruitment relationship). On the other hand, the forage fish contribute to the overall abundance and productivity of their predators. Economists would refer to this tradeoff between harvest and the ecosystem, as the "opportunity cost" of removing forage fish from the sea. The Lenfest Forage Fish Task Force compared the global value of the direct catch of forage fish with the value of allowing them to remain in the ocean as prey for other commercially valuable fish. Globally, the supportive value to other commercial fish catch alone was $11.3 billion while their direct value as forage landings totaled $5.6 billion[55].

While fishermen may target multiple species throughout the year, those who target forage species may not necessarily receive benefits from increases in other species of fish or seabirds or mammals that consume forage species. Hence they have little incentive to take into account or internalize how their activities affect the availability of forage. However, depending on the value of sardine predators, for example, and the transfer efficiency of sardine biomass into predator biomass, sardines may ultimately be more valuable to the coastal economy if left in the water unfished (Fig. 7). One conclusion of Hannesson and Herrick's study[56] of the value of Pacific sardines as forage fish is that:

> *…taking the opportunity cost of sardines as forage fish into consideration could quite possibly mean closing down the sardine fishery altogether,*

> *and at the very least would have an appreciable impact on how much of sardines should be caught in any particular year.*

However, the authors point out that existing models underlying such an exercise remain highly uncertain in a predictive sense.

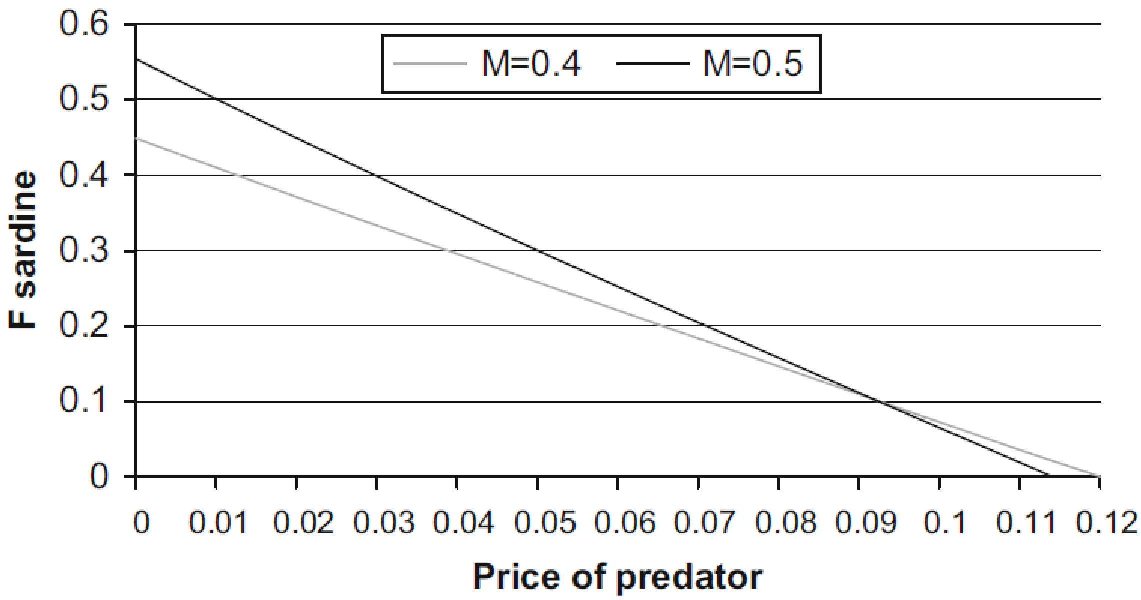


Figure 7. The dependence optimal fishing mortality on Pacific sardines (F sardine) and the net price of sardine predators, with a net sardine price of 0.02, for two different levels of natural mortality (M). When the price of predator exceeds the level in which the curve intersects the x-axis, it is economically optimal to cease all sardine fishing. Source: Hannesson & Herrick 2010. *Marine Policy.*

Other Threats to California Current Forage Species

Climate Change

Climate change can impact species populations both through gradual warming, changes in oceanographic conditions, and the frequency, intensity, and location of extreme events. Due to their known sensitivity to temperature and oceanographic conditions, forage species may respond differently to climate change than more long-lived species. The impacts of climate change on forage species depend on changes to primary productivity, transfer through the food chain, and the effects on oceanographic conditions that determine reproduction and survival. Some studies have predicted significant changes in fishery production based on the effects of climate change on species distribution.[57] Fishing makes fish populations more sensitive to the stresses of climate change.[58] To increase the resilience of ocean ecosystems to the effects of climate change, the Food and Agriculture Organization of the United Nations recommends taking an ecosystem-based approach to fisheries management.[59]

Ocean Acidification

The emerging literature on ocean acidification has highlighted a major threat to forage species caused by anthropogenic carbon dioxide emissions. In particular, the shells of small planktonic organisms like pteropods, which are consumed by krill, herring, and other forage species, may be experience difficulty forming their calcium carbonate shells under projected pH conditions.[60] Ocean acidification may also have unexpected impacts on the physiology of larger species. For example, increased ocean acidity was found to inhibit a the Humboldt squid's (*Dosidicus gigas*) ability to transport such large amounts of oxygen, which could inhibit important activities like hunting and avoiding predators, and ultimately imperil their populations.[61] One recent study forecasted that habitats along the California Current seafloor will become exposed to year-round undersaturation of aragonite (i.e., oceanic calcium carbonate) within the next 20 to 30 years, with potentially major implications for the entire marine food web.[62]

Pollution

Pollution such as oil spills can have catastrophic effects on forage species, through developmental effects and acute toxicity.[63] The *Exxon Valdez* oil spill caused the collapse of Prince William Sound herring populations, which has still not recovered over twenty years later and this has also likely affected the recovery of seabirds that feed on herring.[64,65] In 2007, the container ship Cosco Busan released 54,000 gallons of bunker fuel oil into San Francisco Bay, causing unexpectedly high mortality in Pacific herring embryos.[66]

Potential Consequences of Reduced Forage Species Availability

Establishing a definitive causal link between fishing on forage species, effects on forage species abundance, and effects on predators remains an empirical challenge, yet such effects are widespread in ecosystem models.[67] However, various studies have examined the linkage between predator populations and their forage, irrespective of fishing effects. Overall, the Pacific Fishery Management Council, which has jurisdiction over fisheries occurring in federal waters between 3 to 200 miles from shore, lists 19 species of marine mammals, 33 species of marine birds, and over 40 different species of marine fish that prey on forage species managed under the federal Coastal Pelagic Species Fishery Management Plan.[68] For example, diets of some salmon, rockfish, and tuna species overlap, in that they all contain large proportions of small planktivores (Fig. 8) A few of these predators are endangered salmon stocks, endangered birds, depleted rockfish populations, and eight species of whales. However, lack of forage did not lead to the original endangered species listings. While not clearly linked to fishing pressure, insufficient ocean food supply has been linked to the loss of Sacramento River fall Chinook salmon[69] and substantial declines of coho salmon off Oregon[70].

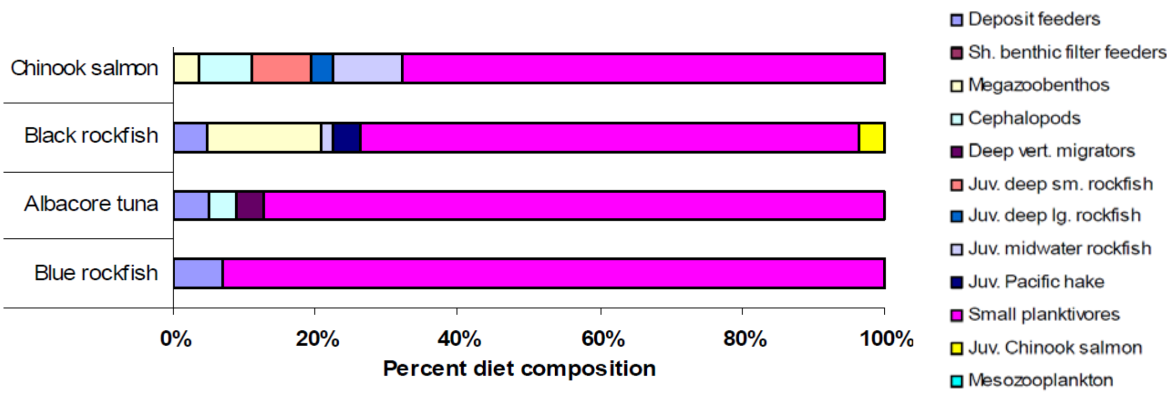


Figure 8. Percent diet composition of various prey groups for four economically important fish species on the U.S. West Coast, for which small plantivores (herring, sardine, and anchovy) are the primary dietary component. Source: Dufault et al. 2009. NOAA Technical Memorandum NMFS-NWFSC-103.

Seabirds and marine mammals are long-lived, and have adapted to variability in prey availability related to shifting oceanographic conditions and/or fisheries pressure by undergoing periods of consistently high or low breeding success, or occasional complete breeding failures. Regardless of the cause of decreased prey resources, seabird and marine mammal responses have been documented in many regions. In California:

- In 2005 unusual ocean climate conditions led to mass starvation deaths of Brandt's Cormorant and Common Murres in Monterey Bay and the CCS. [71] At Southeast Farallon Island (SEFI), these conditions caused unprecedented breeding failures in Cassin's Auklet.[72]

- A recent study estimated that fisheries for rockfish have decreased breeding success of Common Murre, Pigeon Guillemot, and Rhinoceros Auklet at SEFI by 10-30%. [73]

- In 2009, reproductive success of Common Murres at SEFI was among the lowest observed in the last 38 years and the lowest ever recorded during a year that did not contain an El Niño.[74]

- At Southeast Farallon Island (SEFI), there is a significant long-term relationship between juvenile rockfish abundance and breeding productivity for Rhinoceros Auklets, Common Murres and Pigeon Guillemots. [75] Common Murre reproductive success at SEFI is showing a declining trend, reflecting declines in the availability of rockfish *(Sebastes spp*.) their preferred prey item. [76]

- Decreased prey resources over the past 100 years have caused central coast marbled murrelets feeding in the MBNMS to fish further down on the food web, contributing to poor reproduction (see Marbled Murrelet profile below).

- The breeding success of the endangered brown pelican has been linked with the abundance and availability of Northern anchovy.[77]

Globally, a recent meta-analysis published in *Science* [78] detected a common metric for the relationship of food availability with seabird breeding success. The study quantified the effect of fluctuations in food abundance on seabird breeding success, including the effect of reduced availability of rockfish to three breeding birds foraging in the MBNMS: rhinoceros auklets, pigeon guillemots and common murre (Fig 9). It identified a threshold in prey abundance below which seabirds experience consistently reduced and more variable productivity. This response was common to all seven ecosystems and 14 bird species examined within the Atlantic, Pacific, and Southern Oceans. The threshold approximated one-third of the maximum prey biomass observed in long-term studies. Other examples are the declines in Bering Sea populations of northern fur seals (*Callorhinus ursinus*) and kittiwakes (*Rissa* spp.), which are also most likely due to declines in prey (Pacific herring, juvenile pollock, capelin). [79]

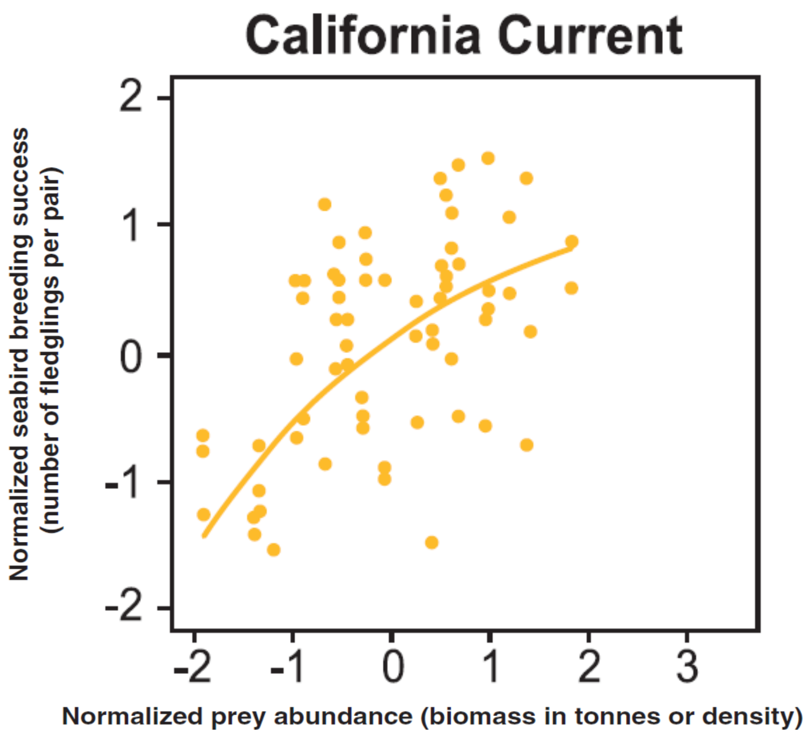


Figure 9. Observed relationship between seabird breeding success and prey abundance in the California Current LME. Source: Cury et al. 2011, *Science*.

While it may be tempting to ignore species specific trends of individual forage species and instead consider only the overall forage base as a whole, it may be inaccurate to assume all forage species are equally substitutable with respect to their predators. When preferred forage species are absent or depleted, marine predators are forced to switch to less desirable prey. Forage species may vary both in their spatio-temporal availability and energy content (Table 1). Preying on species with lower energy content may directly adversely affect the health of the predators' populations. The elegant tern (*Sterna elegans*) is a seabird whose limited geographic range and specialized diet make it particularly vulnerable to changes in prey abundance. Northern anchovy (*Engraulis* *mordax*) and Pacific sardine (*Sardinops sagax*) are the bird's preferred prey, but changes in the abundance of these species in California led to the tern relying on lower-energy forage species such as topsmelt (*Atherinops affinis*).[80] Over the long term, such dietary changes might decrease survival and reproductive success of this seabird.[81] Recent studies of juvenile albacore tuna diets indicate a consistent specialization on Northern anchovy over decades despite massive fluctuations in the relative abundance of anchovy.[82] Furthermore, prey densities necessary to support consumption by top predators require prey abundances that are many times that of prey consumption alone.[83]

Table 1: Energy density of common prey of juvenile albacore tuna in the California Current System (from Glaser 2010).

Prey category	**Energy Density (kJ/g) ± SD**
Cololabis saira (Pacific saury)	7.5 ± 1.0
Sardinops sagax (Pacific sardine)	7.3 ± 0.6
Myctophidae (Lanternfish)	7.1 ± 0.6
Paralepididae (Barracudinas)	7.1 ± 0.6
Engraulis mordax (Northern anchovy)	6.6 ± 0.5
Fishes (other)	6.6 ± 0.6
Trachurus symmetricus (Jack mackerel)	6.4 ± 0.5
Merluccius productus (Pacific whiting)	5.9 ± 1.3
Vinciguerria lucetia (lightfish)	5.2 ± 0.4
Cephalopods (squid)	4.4 ± 0.5
Sebastes spp. (rockfish)	4.2 ± 0.3
Crustaceans (other)	3.2 ± 1.1
Euphausiids (krill)	3.1 ± 1.1
Pleuroncodes planipes (pelagic red crab)	3.0 ± 1.3
Amphipods	2.5 ± 0.9

Federal Fishery Management of California Current Forage Species

In the U.S., the Magnuson-Stevens Fishery Management and Conservation Act (MSFMCA) is the primary statute governing federal fishery management. The heart of this statute is the requirement that fisheries achieve "optimum yield", defined as the catch providing the "greatest overall benefit to the nation", which operationally is to be calculated as maximum sustainable yield "as reduced by any relevant economic, social, or ecological factor."[84] Further guidance on implementing this statute by NOAA includes "maintaining adequate forage for all components of the ecosystem" and "managing forage stocks for higher biomass than Bmsy to enhance and protect the marine ecosystem" (CFR 600.310 (e)(3)). The MSFMCA also requires NMFS to minimize to the extent practicable adverse impacts to essential fish habitat caused by fishing[85]. In the context of fishing removals of forage species, "Loss of prey may be an adverse effect on Essential Fish Habitat".[86]

The National Marine Fisheries Service (NMFS) is the lead federal agency responsible for the stewardship of the nation's offshore living marine resources and their habitat, through implementation of the MSFMCA. The Pacific Fishery Management Council (PFMC) advises the agency on all federal fisheries management occurring off the U.S. West Coast. However, final authority to approve and implement PFMC recommendations rests with the Secretary of Commerce. In addition to a NMFS representative, the PFMC includes representatives from the States of Washington, Oregon, California, Idaho, Tribes, plus appointed members of the public who generally represent various commercial and recreational fishing interests. National Marine Sanctuary staff participate in PFMC sub-committees and may also engage through the NMFS representatives on the PFMC. NMFS and the PFMC manage fisheries that directly target key forage species like sardine, Pacific mackerel, and market squid, and they manage some important forage species that have no directed fishery, like shortbelly rockfish and krill. Fisheries for forage species are generally managed by NMFS in one of two federal plans; the Coastal Pelagic Species Fishery Management Plan (FMP) and the Groundfish FMP.

The PFMC and NMFS have taken some precautionary actions to protect forage species and their role in the marine ecosystem. In 2006, recognizing the importance of krill as a key prey for blue whales, salmon, seabirds and many other species, the PFMC unanimously voted to recommend NOAA prohibit krill harvest off the U.S West Coast. After much delay, in July 2009, NOAA officially adopted the ban on krill harvest throughout the U.S. West Coast Exclusive Economic Zone (EEZ).

In 2010, the PFMC voted to set the 2011-2012 catch levels for shortbelly rockfish at less than 1% of the allowable biological catch. They also greatly reduced the catch levels of Pacific mackerel due to a high degree of uncertainty in the stock assessment. These precautionary measures recognize the role of these forage species as prey in the ecosystem.

Many other important forage species are currently unmanaged by state or federal governments. In June 2012, the PFMC unanimously adopted the following management objective for these species:[87]

> *It is the Council's intent to recognize the importance of forage fish to the marine ecosystem off our coast, and to provide adequate protection for forage fish. We declare that our objective is to prohibit the development of new directed fisheries on forage species that are not currently managed by our Council, or the States, until we have an adequate opportunity to assess the science relating to the fishery and any potential impacts to our existing fisheries and communities.*

To accomplish this objective, the Council set out a pathway including amending the list of allowable fisheries on the US west coast, such that any new fishery would be required to submit notification to the Council before operating, and adding a list of currently unmanaged forage species into one or more federal Fishery Management Plans for the purpose of implementing long term regulatory protections.[88]

California Management of Forage Species

The California Department of Fish and Game (CDFG) is responsible for most state-managed fisheries off California and the California Fish and Game Commission is the decision-making body. Fisheries are managed under the state's Marine Life Management Act (MLMA). The California legislature still has authority over certain species that had been subject to legislative action prior to the 1998 passage of the MLMA and have not had management authority delegated since then to the Commission. The State of California does not have a comprehensive Forage Fish Management Plan, nor does it have any formal recognition of forage species in the MLMA or in state policy. However, the MLMA does contain an equivalent definition of Optimum Yield and also requires Fishery Management Plans to summarize readily available information about "the ecosystem role of the target species and the relationship of the fishery to the ecosystem role of the target species".[89] Furthermore the California Fish and Game Commission is currently considering establishing its own policy on forage species management.

Under the MLMA, Fishery Management Plans were envisioned to be the primary tool for fishery management. However, due to chronic underfunding and the comprehensive requirements of FMPs, only 3 have been completed in the last decade. While the three FMPs stated an intention to move toward "ecosystem-based management", neither the MLMA or the FMPs have stated what "ecosystem-based management" means in the context of the managed species or provide a framework for evaluating whether management is ecosystem-based.[90] While FMPs are required to summarize existing information on the ecological role of target species, the effect of the fishery on their ecological role, and the influence of oceanographic conditions on the target species, the Commission is not required to account for these factors in management decisions.

Some California based fisheries for forage species, such as Pacific sardine and northern anchovy are managed primary by the National Marine Fisheries Service and the state of California enforces those management decisions for the component of the fishery that occurs in state waters, and monitors landings. Market squid and Pacific herring are the two main forage species currently managed by the CDFG. Market squid is managed through the Market Squid Fishery Management Plan, while Pacific herring is managed through an annual Supplemental Environmental Document by CDFG and the Fish and Game Commission. In addition, there are some regulations on fishing gear and monitoring of landings for smelts and silversides.

The MLMA contains provisions for the development of new fisheries that do not currently exist, termed "Emerging Fisheries". The state's current policy is to promote the development of such fisheries and not to regulate them until they have emerged (e.g., landings and participation have increased).[91] However, new fishing gears typically require an Experimental Gear Permit from the California Fish and Game Commission[92]. Therefore, it is unclear whether California can prevent new fisheries from developing on forage species under current law.

On November 7, 2012, the California Fish and Game Commission adopted a policy on forage species management[1]. This policy defines forage species, recognizes their important ecological role, specifies that their ecological benefits will be accounted for in their management, specifies the types of Essential Fishery Information (EFI) relevant to forage species, and describes a suite of management goals for forage species. Of particular relevance is the goal to "Prevent the development of new or expanded forage fisheries until EFI is available and applied to ensure the sustainability of target forage species and protection of its benefits as prey". This policy sets a new course for forage species management by the Commission, providing the basis for additional protections and improved ecosystem-based management.

California is currently concluding the initial implementation of the Marine Life Protection Act, creating a new, improved network of marine protected areas (including several no-take marine reserves) in state waters. Protecting key foraging areas was not a specific objective of the scientific guidelines used in developing the network. The marine protected areas, however, do protect some key nearshore spawning areas for market squid and other forage species, and several areas in the vicinities of seabird colonies and marine mammal haulouts received additional protections.

Profiles of Selected Predators of California Current Forage Species

The following brief profiles are intended to provide additional context through local examples that highlight the broader trends discussed in this white paper. This section is not intended to be a comprehensive description of predator-prey relationships in the California Current.

California Brown Pelicans (*Pelecanus occidentalis californicus*)

Forage fish availability is likely the most important factor influencing brown pelican breeding success.[93] Brown pelican productivity is associated with the abundance and availability of northern anchovy, which in some years, makes up over 92% of their diet.[94]

Marbled murrelet (*Brachyramphus marmoratus*)

The marbled murrelet is a small threatened seabird that nests in coastal old growth forests from central California to Alaska and feeds on forage fish in coastal nearshore waters. In California's Monterey Bay ecosystem, marbled murrelets historically fed on sardine.[95] The

[1] Available at: http://www.fgc.ca.gov/policy/p2fish.aspx#FORAGE

collapse of the California sardine fishery in the late 1940s reduced the availability of sardine for the marbled murrelet. Over time, these birds made a fundamental prey switch, from sardine, to smaller forage species like krill. This prey switch, however, requires spending more time and energy foraging, having to catch 80 krill to match the energy found in a single Pacific sardine.[96] Foraging hotspots for marbled murrelets within the MBNMS have recently been identified (Fig. 10).

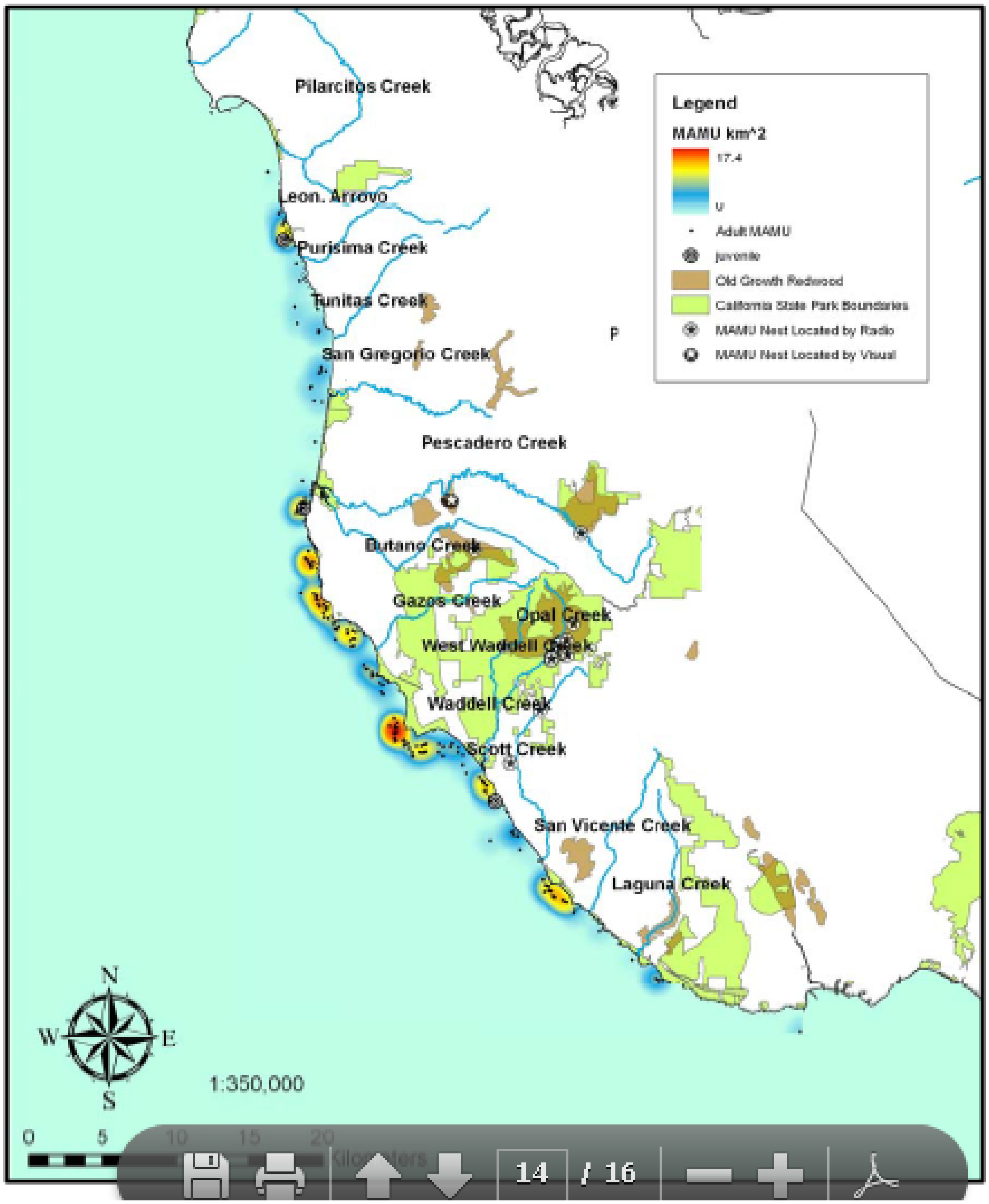


Figure 10: Foraging hotspots for the highly endangered central coast marbled murrelet. Source: Peery, Z. and B. Henry. 2010. Abundance and productivity of marbled murrelets off central California during the 2009 breeding season. Final report submitted to California State Parks.

Common murre (*Uria aalge*)

The common murre is one of the most abundant seabird species in the California Current. During the breeding season, Pacific hake and northern anchovy comprise the majority of adult murre diets, yet market squid dominate their diet in the wintering season.[97] However, chicks consume primarily (>80%) northern anchovy, Pacific sardine, and juvenile rockfish. In 2004, adult common murres from Cape Blanco, OR to Point Conception, CA were estimated to consume 225,000 mt of prey[98], rivaling the largest commercial fisheries off the West Coast.

Blue Whale (*Balaenoptera musculus*)

Endangered blue whales, which are the largest animals to have ever lived on earth, feed exclusively on tiny krill (Euphausids) at rates of up to two metric tons per day.[99] With their great size (up to 33 meters and 172 metric tons), blue whales have the highest average daily energy requirements of any species.[100] Therefore blue whales feed only in exceptionally productive areas like the northern Channel Islands, Monterey Bay Canyon, and Gulf of the Farallones, around the Farallon Islands off San Francisco.

Chinook Salmon (*Oncorhynchus tshawytscha)*

The chinook salmon is the largest of the Pacific Ocean salmon species and has great cultural, economic and ecological value. These fish are renowned for their great migrations from the streams where they are born, north to Alaska, and back to their natal rivers as adults to spawn. In the California Current ecosystem, juvenile and adults chinook salmon prey heavily on Pacific sardine, herring, northern anchovy, krill and juvenile rockfish. Pacific herring, Pacific sardine and northern anchovy make up roughly 48%, by weight, of the diet of chinook salmon.[101] Nine chinook salmon stocks in Washington, Oregon and California are listed as threatened or endangered under the U.S. Endangered Species Act.[102]

California sea lions (*Zalophus californicus*)

California sea lions have increased in number since the cessation of hunting in the 1940s.[103] In the United States, the major breeding areas are located in the Channel Islands off Southern California. However, in 2010, as a result of shifts in their prey, a record number of yearling sea lions were stranded on California beaches, while adults from Southern California migrated north to Monterey and Oregon in search of food. The top 5 prey items for California sea lions are Northern anchovy, market squid, Pacific hake, jack mackerel, and shortbelly rockfish.[104]

Yelloweye rockfish (*Sebastes ruberrimus*)

Yelloweye rockfish are an exceptionally long-lived and slow growing rockfish species that has been overfished. Living over 100 years old, this is one of the longest lived rockfishes.[105,106] The current low population size is a result of overfishing and the species is now in a rebuilding plan managed by NMFS. The primary food source of yelloweye rockfish are small planktivores (32% of diet) like Northern anchovy and Pacific sardine.[107] Other rockfish, like black rockfish and blue rockfish also prey heavily on these forage species.[108] The population of yelloweye rockfish is not estimated to recover until the year 2074.

Albacore tuna (*Thunnus alalunga*)

Albacore tuna is one of the most prized and lucrative fish on the west coast, both commercially and recreationally. In 2009, the commercial fishery for albacore tuna was worth over $27 million, about 90% of the total value of highly migratory species (e.g., tunas, swordfish, sharks).[109] Over 80% of albacore tuna diet is composed of small planktivores[110], making it among the species most dependent on these forage fish. A recent study found that Northern anchovy is consistently the primary component of albacore tuna diets despite oceanic regime changes and wide changes in anchovy abundance, suggesting that albacore specialize on eating anchovy.[111]

Pacific Bluefin Tuna (*Thunnus orientalis*)

A new line of evidence combining physiological, tagging, and diet studies of Pacific bluefin tuna suggests that this species may specialize on Pacific sardine.[112] Bluefin have recently been found to possess higher expression of genes allowing high cardiac performance at lower temperatures. Furthermore, electronic tagging allowing comparison of habitat use shows this species is entering depths with lower temperatures than other tunas. The diet studies show Pacific sardine to be the primary prey item and that bluefin tuna prey diversity is lower than for other species. Sardines have greater energy content per gram (density) than many other forage species (e.g., squid, krill) [113]. The current hypothesis is that sardine occupy these colder, deeper waters in an attempt to avoid predation by many predators, and that the unique adaptations of bluefin tuna allow them to exploit this prey niche.

Risso's Dolphin (*Grampus griseus*)

Risso's dolphins are among the larger members of the dolphin family. They migrate up ad down the coast both in small groups up to 30 and in "super-pods" of up to several thousand. These dolphins are squid "specialists" feeding almost exclusively on squid both in inshore and offshore waters.[114] In fact many of the markings on these animals are thought to be scars from interactions with squid.

Leatherback Sea Turtles (*Dermochelys coriacea*)

Leatherback sea turtles migrate from nesting beaches in Indonesia over 6,000 miles to feed on massive aggregations of jellyfish, particularly the brown sea nettle (Chrysaora sp.) off the U.S. West Coast. Recent telemetry and diet information identified the California Current as a foraging hotspot for the Western Pacific population of leatherback sea turtles[115]. Oceana, Turtle Island Restoration Network, and Center for Biological Diversity subsequently submitted a petition to NMFS in 2007 to designate critical habitat under the Endangered Species Act. On January 20, 2012, NMFS finalized designation of two areas totaling over 41,000 square miles of ocean waters based on the importance of the habitat as a foraging area (Fig. 11).

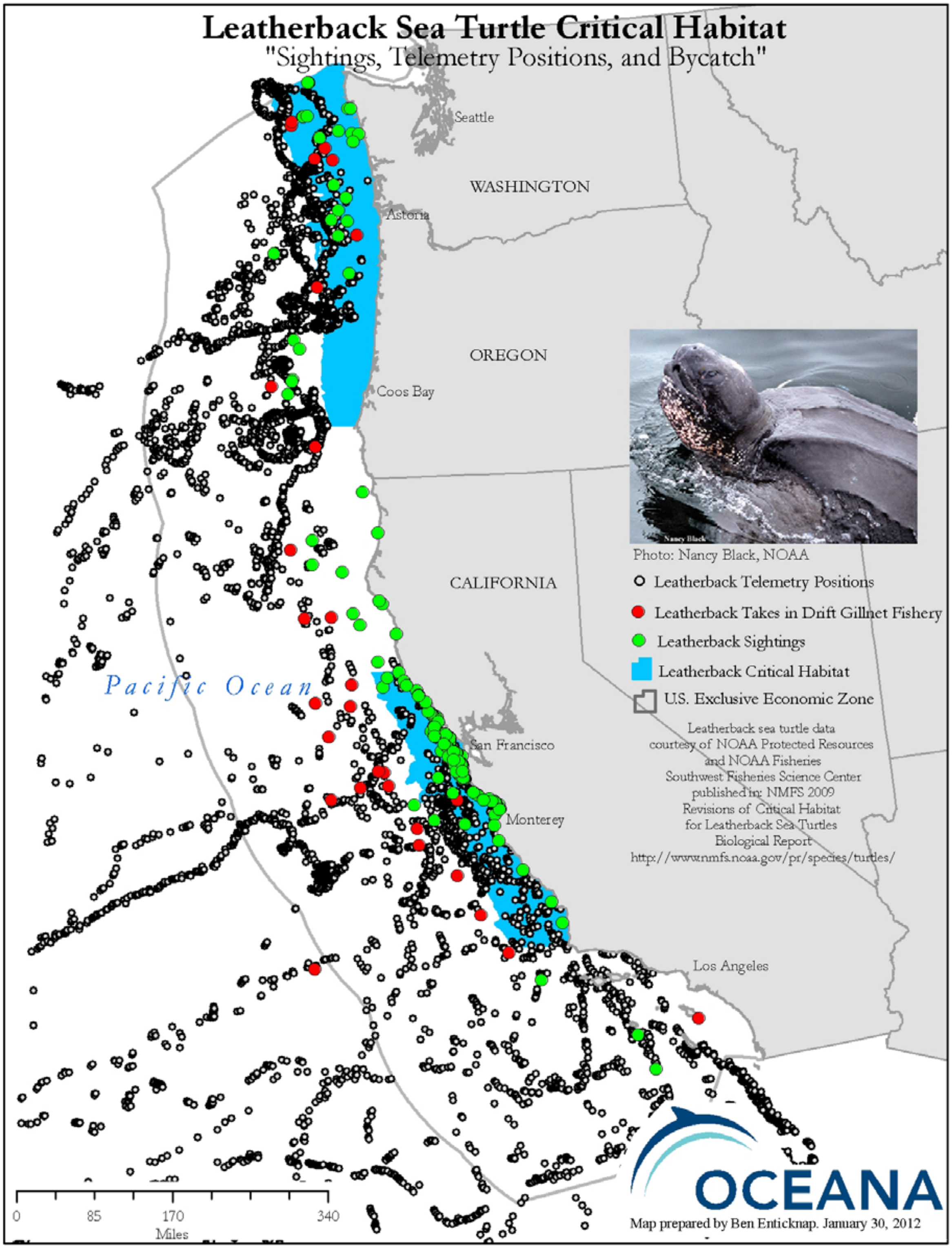


Figure 11: Leatherback critical habitat designated to protect foraging areas off the U.S. West Coast on January 20, 2012 by the National Marine Fisheries Service. Map by Oceana.

Profiles of Selected California Current Forage Species

Pacific sardines (*Sardinops sagax*)

Feeding primarily on plankton, Pacific sardines are a primary forage species for many marine species, transferring energy from low to higher trophic levels. Sardine populations are highly variable, as their recruitment depends largely on oceanographic conditions. Excessive fishing pressure combined with a change to less favorable oceanic conditions caused the collapse of the sardine fishery centered in the 1950s, resulting in the demise of the "Cannery Row" era in Monterey, California.[116,117] Sardine populations undergo wide natural fluctuations in the absence of fishing pressure (Fig. 12). Baumgartner and others defined a collapse threshold as less than 1 million tons and recovery threshold as greater than 4 million tons.[118] The current biomass is approximately 1 million tons.[119] Interestingly, the sardine population in the past 100 years has been within the range estimated over the last 1,700 years.

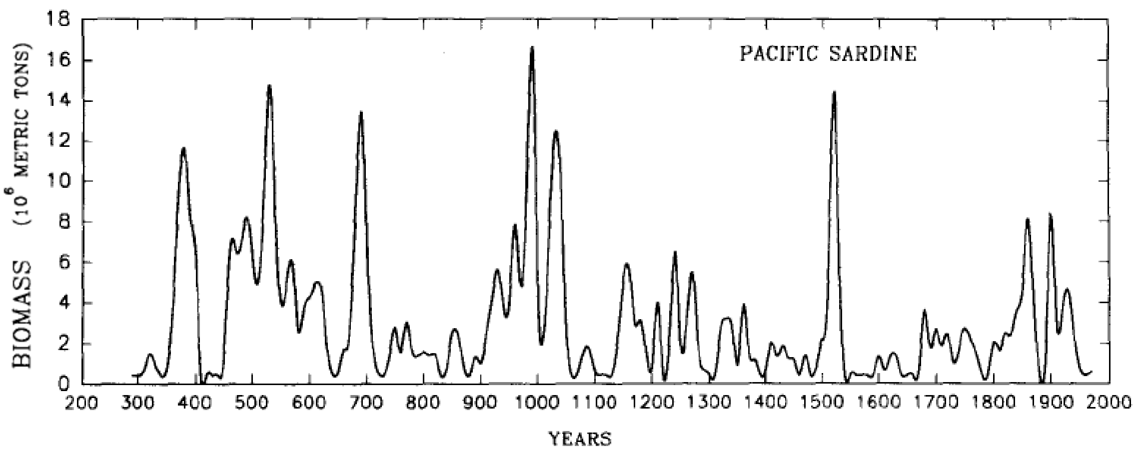


Figure 12. 1700-year hindcast series time series of Pacific sardine biomass using fish scale deposition rates from sediments in the Santa Barbara Basin. Source: Baumgartner et al. 1992.

In the U.S. West Coast and the Peruvian upwelling systems, sardines and anchovy populations appear to have an inverse relationship, where periods of low sardine abundance are marked by dramatic increases in anchovy populations and vice versa (Fig. 13).[120] These fluctuations are thought to be related to different oceanographic regimes including the Pacific Decadal Oscillation.

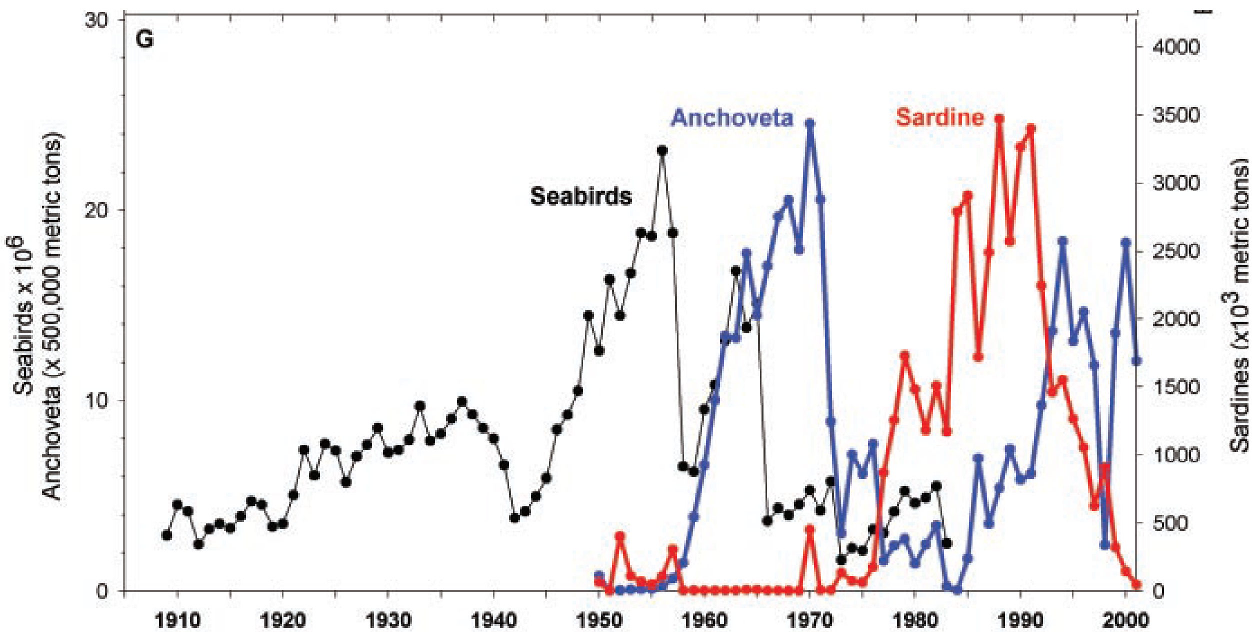


Figure 13: Populations of seabirds, anchoveta, and sardine in the Peruvian upwelling system. Source: Chavez et al. 2003, *Science*.

Pacific sardines are managed by the Pacific Fishery Management Council within the Coastal Pelagic Species (CPS) FMP. Sardine management takes place through an innovative framework originally developed in 1998[121] that offers several potential components of an ecosystem-based forage species management framework (Fig. 14). In current harvest control rule, a minimum CUTOFF biomass is "set-aside" such that fishing quotas are set on a percentage of the biomass above the cutoff and the fishery is closed if the total population drops below the cutoff. The current cutoff for Pacific sardine is 150,000 metric tons. At the time the current harvest control rule was adopted, there was evidence of a relationship between ocean temperature and sardine recruitment, such that warmer temperatures could be used to predict higher recruitment and hence higher productivity of the stock. Accordingly, the percentage (FRACTION) of the remaining biomass above CUTOFF that can be fished increases (to 15%) in warmer ocean conditions where the population is thought to be more productive and decreases (to 5%) in cooler, less favorable conditions. Finally, there is a maximum catch value (MAXCAT) that cannot be exceeded regardless the population size, which prevents overcapitalization and provides a level of precaution when stock assessments are uncertain. The current Pacific sardine harvest control rule currently employs a MAXCAT of 200,000 metric tons but other targeted CPS do not have this control in place. In addition, recent modifications to the sardine management have added a buffer for scientific uncertainty. Finally, since Pacific sardine is a transboundary stock fished in Mexico, Canada, and the U.S., the U.S. harvest guideline is based on the proportion of the stock thought to occur in U.S. waters, which was determined to be 87% based on summer and fall aerial surveys that took place in the 1990s.

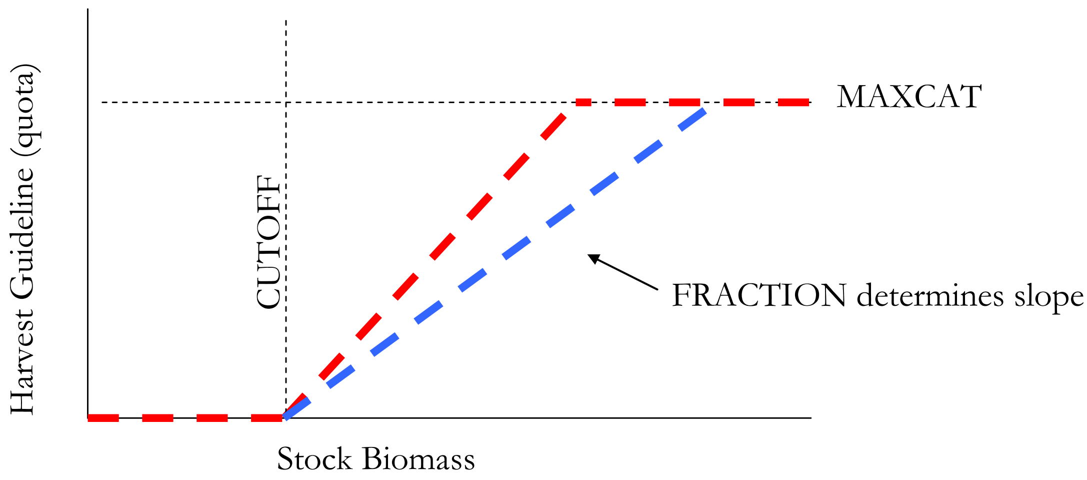


Figure 14: Schematic of the currently employed Pacific Sardine Harvest Control Rule (CPS FMP Amendment 8 (2000)), showing how the CUTOFF, MAXCAT, and FRACTION parameters affect the Harvest Guideline. The temperature at Scripps Institute of Oceanography Pier determines the FRACTION, which ranges from 5-15%. The current CUTOFF is 150,000 metric tons and the MAXCAT is 200,000 metric tons.

Since implementation of the harvest policy in 2000, the temperature-recruitment relationship used to justify the fraction parameter (allowing higher exploitation under favorable environmental conditions) has been shown not to hold.[122] There has also been a scientific debate regarding whether Pacific sardines are currently undergoing a collapse similar to the famous collapse of the 1950s.[123,124,125] As of the time of this writing, the Pacific Fishery Management Council is planning to re-examine the harvest control rule for Pacific sardine in light of the new scientific information in 2012 and 2013.

Pacific hake (*Merluccius productus*)

Pacific hake, also known as Pacific whiting, is among the top three fisheries by volume on the U.S. West Coast (along with market squid and sardine).[126] Pacific hake play an important role in shaping the California Current large marine ecosystem, as they are both a major provider and consumer of forage. Almost 80% of their diet is zooplankton, transferring significant energy up the food web. However, as they grow larger, they consume other forage species, making up the other 20% of their diet are other planktivores like sardines and anchovies.[127] Juvenile Pacific hake provide prey for migrating and surface seabirds, demersal sharks and rockfish. Pacific hake are major prey for large flatfish (37%), pinnipeds (20%), pelagic sharks and sablefish (black cod). Despite sharing many characteristics to other species managed under the CPS FMP (e.g., importance as forage, highly variable recruitment based on oceanographic conditions), they are managed in the Groundfish FMP by the Pacific Fishery Management Council.

Pacific herring (*Clupea pallasii*)

Pacific herring are a critically important forage species in California. Herring are utilized as forage at each stage of their life history from egg to adult, serving as prey for marine mammals and seabirds as well as commercial and recreational fish species. Pacific herring spawning creates a feeding frenzy throughout the marine food web. Animals that prey on herring eggs include ctenophores, chaetognaths, jellyfish, juvenile salmonids, sturgeon, smelt, surfperches, crabs and at least 20 species of birds.[128] Adult herring are also prey for salmon, seals, California sea lions, porpoises, northern fur seals, killer whales, dogfish, stripped bass, steelhead trout, Pacific cod, sablefish, hake, walleye Pollock, lingcod, several species of rockfish (black, yelloweye, quillback and tiger rockfish), northern anchovy, striped bass, pink salmon, cutthroat trout, buffalo sculpin, and sand sole.[129]

Pacific herring are commercially harvested for roe products, bait, pet food, as fresh fish, and the harvest of herring eggs-on-kelp. Pacific herring are managed by individual states, though the species may soon be added as an Ecosystem Component Species to the federal Coastal Pelagic Species FMP, primarily to monitor their populations, to recognize the importance of this species as forage, and to monitor its bycatch in other federally managed fisheries. While California state managers have aimed to harvest between 0-15% of the spawning biomass, the actual exploitation rate was above 20% in the 1990s.[130] The main herring stock in California, the San Francisco Bay herring population, recently crashed in 2007, resulting in managers decreasing the harvest rate and subsequently closing the fishery in 2009 as the biomass fell to a new historic low. The effects of the Cosco Busan oil spill in 2007 have been identified as a contributing factor to this population crash. [131] The stock biomass has subsequently shown signs of recovery, but the long-term trend of a decreasing proportion of older fish in the population remains (Fig 15). As a result, landings have been below 5,000 metric tons in recent years.

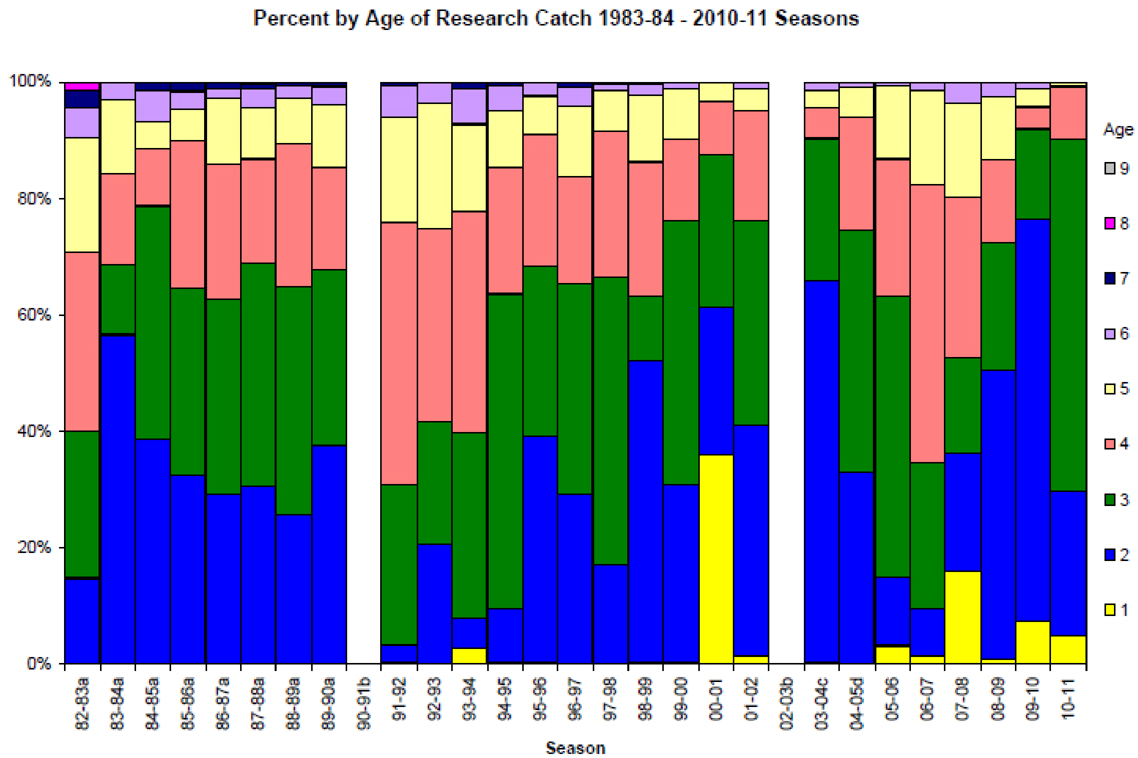


Figure 15: Age composition of Pacific herring. Source: DFG Supplemental Environmental Impact Report: Pacific Herring. 2011.

While fishery managers have recognized the importance of herring as forage and taken measures to recover the stock, there is still no explicit accounting for the needs of predators in herring management. In 2010-2012, CDFG reopened the fishery at a 5% harvest rate; however, the long-term management goals and their ability to provide adequate forage for predators remains unclear.

Juvenile rockfish (*Sebastes spp.*)

Most people do not consider rockfish to be in the same category of important forage species as other species like squid, sardines, or anchovy. However, the juveniles of some rockfish can be extremely abundant and in fact are a primary food source in the California Current. In particular, shortbelly rockfish are the most abundant juvenile rockfish in the California Current and have been recognized for decades as a primary prey item for marine mammals, seabirds, Chinook salmon, and other commercially important fishes.[132,133,134,135,136,137,138] For many breeding California seabirds, as much as 90% of their diet is composed of pelagic stages of juvenile (age-0) rockfish during the late spring and early summer breeding seasons, and unexploited species (such as shortbelly) generally account for more than two thirds of the juvenile rockfish identified.[139,140] Shortbelly rockfish are described as important prey for thresher sharks, longnose skate, and jumbo squid. They are also eaten by other rockfish species, including boccacio and chilipeppers.[141] Furthermore, there is a significant relationship between juvenile rockfish abundance (particularly shortbelly rockfish) and seabird breeding productivity.[142]

While there is no directed fishery for shortbelly rockfish, there is a potential for one to evolve in the future and this species is caught as bycatch in other groundfish fisheries. Until recently, fishery managers set a quota for this species equal to its Acceptable Biological Catch, allowing the potential for development of a fishery without taking into account for its role as a forage species. However, prompted by a request from Oceana, the Pacific Fishery Management Council made a preemptive move in 2010 to set the quota at less than 1% of recent quotas, effectively preventing a fishery for this species solely on the basis of its importance as forage.[143] Building on the precautionary success of krill, this is the first time the PFMC has "frozen the menu" to prevent development of a fishery for a fish species. This is the only groundfish species managed federally or by states in which the importance as forage has been taken into account in management.

Market Squid (*Doryteuthis opalescens*)

Market squid are an important forage species in the California current for a long list of predators including pinnipeds, whales, dolphins, seabirds, marine fish, and over 15 endangered species (Fig. 16).[144] Individuals reproduce and die in 6-9 months, and the population fluctuates massively. The population is highly uncertain and changing rapidly. In recent years, this fishery has been the largest and most valuable commercial fishery in California.

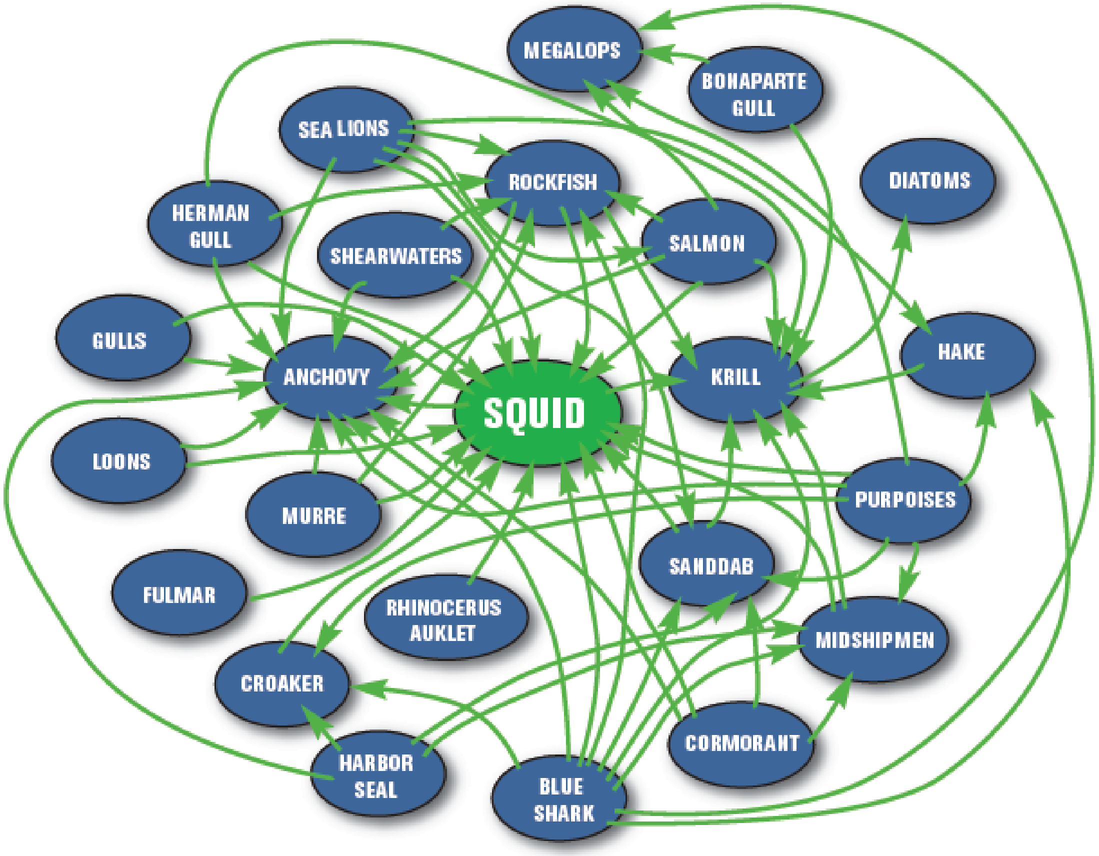


Figure 16. Food web for market squid, Doryteuthus opalescens, involving commercially important fish and key birds and mammals. Adapted from Market Squid Fishery Management Plan (2005).

The Market Squid Fishery Management Plan (MSFMP) repeatedly recognizes the importance of squid as forage. Some precautionary regulations have been implemented to protect the stock (e.g., weekend fishery closures), while recently established marine protected areas are likely to protect a significant portion of squid spawning grounds.

There remains great uncertainty in the management of market squid about the total catch limits established in the MSFMP. The Market Squid Fishery Management Plan (2005) stated "*…it is not currently possible to estimate the total amount of squid used as forage in the California Current ecosystem or the size of squid populations necessary to sustain predator populations…*" The current catch limit of 118,000 short tons was set based on the average of the three highest consecutive catch years (1999-2002) on record (Fig. 17). Without biomass estimates or reference points, it remains unclear the extent to which squid management is meeting its objectives.

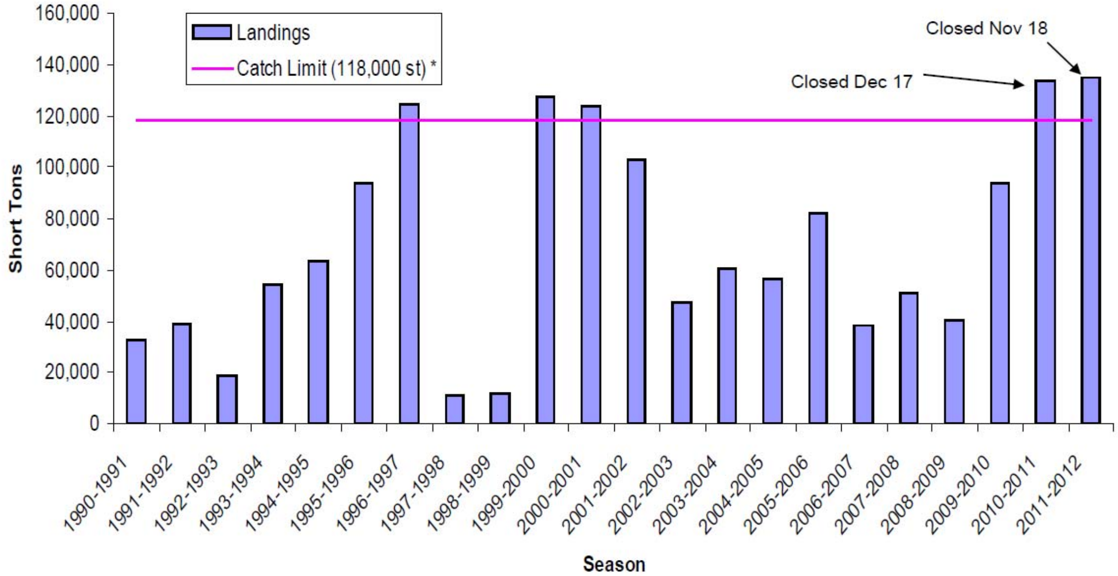
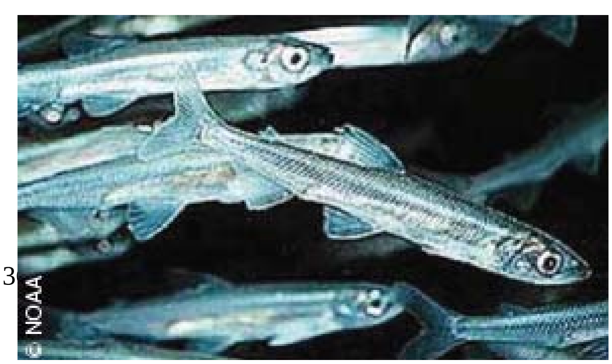


Figure 17. Market Squid Landings in California by Season. *Catch limit was put into place starting with the 2005/2006 season. Source: California Department of Fish and Game.

Northern Anchovy (*Engraulis mordax*)

Northern anchovy are a small schooling pelagic forage fish found along the Pacific coast from Baja California to British Columbia. There is an extensive list of marine fish, birds and mammals in the California Current region that depend on anchovy as prey, including tunas, salmon, sharks, seals, whales and dolphins.[145] Northern anchovy make up over 92% of the diet of nesting brown pelicans off southern California.[146] There are three sub-populations divided into the northern, central, and southern sections of their range. The central subpopulation used to be the focus of large commercial fisheries in the U.S. and Mexico. Anchovies move offshore in winter and are abundant in bays and estuaries in the spring, summer and fall. There have been no stock assessments of the northern anchovy population since 1995, though an assessment is currently being planned by the Southwest Fisheries Science Center.

Smelts (Osmeridae) and Silversides (Atherinidae)



Smelt is a general term used to describe a group of small marine, estuarine and anadromous forage fish in the family Osmeridae.[147] In the California Current, there are two anadromous smelt; eulachon (*Thaleichthys pacificus)* and longfin smelt (*Spirinchus thaleichthys*) which spend most of their lives in marine waters, but spawn in coastal rivers and streams. In 1956 Kelso, Washington was dubbed the "Smelt Capital of the World" for the large runs of eulachon that once traveled up the Columbia River to spawn.[148] Eulachon populations have since crashed off the U.S. West Coast and are now listed as a threatened species. Whitebait smelt **(***Allosmerus elongates*), night smelt (*Spirinchus starksi*) and surf smelt *(Hypomesus pretiosus*) are strictly marine smelt species. The delta smelt (*Hypomesus transpacificus)* is endemic to the Sacramento-San Joaquin estuary of California and is listed as an endangered species. Capelin ***(****Mallotus villosus)* mostly live at higher latitudes, but the southern range of this marine smelt extends into the northern California Current system to approximately the Strait of Juan de Fuca, Washington. Arctic rainbow smelt (*Osmerus mordax dentex*) extend as far south as Vancouver Island, British Columbia. All of these smelt species are important prey for many other fish, birds and mammals in the California Current ecosystem, including recreationally and commercially important species like salmon and cod[149].

Topsmelt (*Antherinops affinis*) and Jacksmelt (*Atherinopsis californiensis)* are also important marine forage fish of the U.S. West Coast. These fish belong to the family Atherinidae (silversides), which includes California grunion.

Krill (Euphausiidae)

Eight-five species of krill (Euphausiids) have been identified throughout the world's oceans, eight of which dominate the krill community in the California Current ecosystem. Many of the fish species that depend on krill directly or indirectly support important recreational and commercial marine fisheries including salmon, rockfish, hake and flatfish. The planet's largest animal, the blue whale, feeds almost exclusively on krill. During the peak summer feeding season off California, blue whales concentrate on large krill schools, with individual whales consuming roughly two tons of krill per day.[150] Two West Coast krill species, *Euphausia pacifica* and *Thysanoessa spinifera*, form large, dense aggregations near the surface. The sub-tropical *Nyctiphanes simplex* is abundant in U.S. West Coast waters during strong El Niño years, and also forms large surface swarms. *Nematocelis difficilis* is very abundant in the California Current, but it does not migrate to the surface, preferring deeper habitats. The other known krill species in the California Current are *T. gregaria*, *E. recurva*, *E. gibboides*, and *E. eximia*.[151]

Krill are fundamental to the trophic structure of the marine life within the Sanctuary, forming a key trophic link in coastal upwelling systems between primary production and higher trophic level consumers. MBNMS took a profoundly important first step toward ecosystem-based management by urging NMFS and the Pacific Fisheries Management Council to use their authority to ban the harvesting of krill in federal waters of the

Sanctuary. This engagement led to the Pacific Fishery Management Council banning on krill harvest in federal water on the west coast in 2006, which went into effect in 2009. The foundational importance of krill to the marine food web in the MBNMS was documented by staff in the "Joint Management Plan Review - Ecosystem Protection – Krill Harvesting Strategy MB-KH1 Ecological and Economic Argument" which was submitted to the Pacific Fisheries Management Council and formed the basis for the Council's and NOAA's eventual ban on krill harvest in federal waters on the west coast. This decision adds upon krill protections already in place in Alaska's state and federal waters, as well as the prohibition on directed harvest of krill in California, Oregon, and Washington state waters.

Pacific Sand Lance (*Ammodytes hexapterus*)

The Pacific sand lance range extends across the Pacific Rim from southern California, north to the Aleutian Islands, and west to Japan. They inhabit relatively shallow depths in bays, estuaries and the open ocean from the intertidal zone to approximately 47 meters. At every stage in its life cycle, sand lance are valuable prey for salmon, seabirds, seals, minke whales and other fish and marine mammals. Thirty-five percent of juvenile salmon diets are composed of sand lance, while juvenile Chinook salmon depend on sand lance for up to 60% of their diet.[152] Pacific sand lance have a highly unusual behavior of burrowing into the seafloor sediment at night for protection from predators. During the day sand lance travel in large schools, feeding on plankton. These large schools are pushed up from below into tight defensive balls by salmon, dog sharks and sea lions. From above, flocks of gulls, cormorants, murres and auklets dive on the balls of sand lance as they approach the surface. Adult sand lance spawn in the upper intertidal zone of sandy-gravel beaches. Some sand lance are taken for recreational purpose and bait off the U.S. West Coast, but presently no commercial fishery exists. In Japan, however, roughly 10,000 tons of sand lance are taken each year by commercial fisheries using trawls and seines.[153]

Mackerels

Pacific mackerel (*Scomber japonicus)* and jack mackerel (*Trachurus symmetricus)* are coastal pelagic fish species that play an important ecological role in the California Current for top predators like bluefin tuna, pelagic sharks, swordfish, marlin, seals and toothed whales.[154,155] Pacific and jack mackerel form large surface schools that are the target of these apex predators, but also targeted by another apex predator - humans. Pacific and jack mackerel fisheries are managed by NMFS and the PFMC as part of the Coastal Pelagic Species Fishery Management Plan. The status of the jack mackerel population off the U.S. West Coast is unknown, and the Pacific mackerel assessment is highly uncertain. Despite this uncertainty, federal managers allow commercial and recreational fisheries, mostly off central and southern California, to take up to 31,000 metric tons of jack mackerel per year and 11,000 metric tons of Pacific mackerel.[156]

List of California Current Forage Species and Management Authorities

The Pacific Fishery Management Council is currently in the process of developing a Fishery Ecosystem Plan for the U.S. West Coast. As part of the process, the Council's Ecosystem Plan Development Team has identified a list of key forage species based the Smith et al. (2011) definition of low trophic level species and a review of existing literature (Table 2).[157] The list of included species is copied directly in the Table below from the November Draft Fishery Ecosystem Plan from the Pacific Fishery Management Council. We recommend the Sanctuary adopt this list initially as a starting point for determining which species meet the definition of forage species. The composition of the list is ongoing and may be modified as additional analyses and information come forward.

Table 2: Important Forage Species in the California Current LME

Common and species name	Relative abundance	Fisheries potential	Role in ecosystem	Managed
Vertebrates				
Northern anchovy (*Engraulis mordax*)	Low frequency (regime scale) variability over time and space, but typically abundant from nearshore to offshore habitats throughout the CCE	Formerly a major fisheries target (100,000s tons), currently a small scale (largely bait) and incidental catch	Key forage species for wide range of HMS, salmon, groundfish, seabird and marine mammals	CPS FMP
Pacific sardine (*Sardinops sagax*)	Low frequency (regime scale) variability over time and space, but often abundant from nearshore to offshore habitats throughout the CCE	Historically, largest fishery in California Current (100,000s tons), currently a major fisheries target	When abundant, a key forage species for wide range of HMS, salmon, groundfish, seabird and marine mammals	CPS FMP
Pacific mackerel (*Scomber japonicus*)	Low frequency (regime scale) variability over time and space, but often abundant from nearshore to offshore habitats throughout the CCE	Historically and currently an important fisheries target (10,000s tons)	When abundant, a moderately important forage species for many HMS and some marine mammals	CPS FMP
Jack mackerel (*Trachurus symetricus*)	Low frequency (regime scale) variability over time and space, but often abundant in offshore habitats (rarely close to shore) throughout the CCE	Occasionally important fisheries target (10,000s tons)	When abundant, a moderately important forage species for many HMS and some marine mammals	CPS FMP
Pacific herring (*Clupea pallasi*)	Abundant to very abundant in nearshore and many estuaries	Fairly high commercial importance (up to 10,000s tons)	Among the more frequently encountered prey in predators such as salmon, hake, rockfish, marine mammals, seabirds	States
Round and thread herrings (*Etrumeus teres* and *Opisthonema libertate*)	Subtropical species that are "reasonably abundant" in the southern part of the CCS. Range likely to expand with global climate change	Unknown in CCS, but in 100,000s tons throughout Eastern Tropical Pacific	Currently key LTL species in core range, could potentially be in CCS with global change	none
American shad (*Alosa sapidissima*)	Anadromous, moderately abundant in rivers, estuaries	CCS landings in 100s tons, com./rec. important elsewhere	An introduced species (Bzero=0!), moderately important prey for some predators	none
Mesopelagic fishes (Myctophidae, Bathylagidae, Paralepididae, Gonosomatidae; 100s of species in CCS)	Likely the most abundant fish assemblage on the planet. Uncommon inshore but tremendously abundant in mesopelagic (offshore, midwater) waters	Currently limited fisheries potential; despite tremendous abundance, technology is historically infeasible	Important prey for entire mesopelagic food web, many large squids, many tunas and HMS, some rockfish (esp. blackgill, bank), rare in mammal or seabird diets	none
Pacific sandlance (*Ammodytes hexapterus*)	Common, but not abundant, in coastal waters of Pacific Northwest	Important fishery target in other regions (particularly North Atlantic)	Moderately important prey for some fishes, seabirds and marine mammals in the Pacific Northwest	none
Pacific saury (*Cololabis saira*)	Low frequency (regime scale) variability over time and space, primarily an offshore (pelagic) species, often very abundant in offshore waters during cool regimes/periods	Very important fishery off of Japan, elsewhere in North Pacific; presumably a potential large-scale target	Relatively important prey to albacore, sablefish, sharks, other HMS species (rarely found in predators shoreward of shelf break)	none

(continued on next page)

Table 2: Important Forage Species in the California Current LME (Cont.)

Common and species name	Relative abundance	Fisheries potential	Role in ecosystem	Managed
Silversides (Atherinospsidae; includes grunion, jacksmelt, topsmelt, perhaps 3-5 other rare spp.)	Moderately abundant in nearshore (but considerably less so than osmerids based on larval abundance data)	Historically commercial and recreational targets (up to ~ 1000 tons in 1940s), recent catches relatively modest. Fisheries typically nearshore	Very abundant in some nearshore areas, presumably important forage species in such areas, but rarely encountered in food habits data for key commercial species	none
Eulachon (*Thaleichthys pacificus*)	Anadromous, coastal, formerly fairly abundant, currently rare	Formerly of fairly high commercial/recreational importance (CCS landings in 1000s tons)	Common but not abundant prey item for wide range of predators	ESA
Other Osmerid smelts (Osmeridae; includes capelin, surf smelt, whitebait smelt, perhaps 3-5 other spp)	After the clupeids (and exclusive of mesopelagics), among the most abundant family of forage fish species in nearshore; typically less abundant offshore	Some species are of minor to modest commercial significance (surf smelt), or have been the target of major fisheries elsewhere (e.g., Atlantic capelin)	Preyed on by wide range of piscivores (seabirds, marine mammals, Pacific hake, sablefish, rockfish, salmon), but rarely comprise a large fraction of total prey.	none
Shortbelly rockfish (*Sebastes jordani*)	Likely the most abundant Sebastes spp. in Central and Southern California, exhibits low frequency (regime like) variability	Minor incidental landings, potential future fisheries target	Juvenile and adult life history stages are very important to salmon, many groundfish, seabirds and marine mammals.	Groundfish FMP
Sanddabs (*Citharichthys* spp), particularly Pacific (*C. sordidus*) and speckled (*C. stigmaeus*)	One of the more abundant soft-bottom groundfish, also found in water column, typically over shelf.	Substantial commercial and recreational catches (100s to 1000s tons)	Juvenile and adult life history stages are very important to many groundfish, particularly piscivorous flatfish; some seabirds and marine mammals.	Groundfish FMP
Pacific tomcod (*Microgadus proximus*)	Locally abundant in some nearshore habitats	Trace historical landings, little current fishery interest or potential	Relatively minor importance in most food habits studies.	none
Small croakers (*Sciaenidae*) e.g. white croaker and queenfish **	Fairly abundant, particularly in nearshore waters of the southern CCE	Some commercial and recreational landings (perhaps to 1000s tons)	Somewhat important for some nearshore species; larvae are very abundant in ichthyoplankton, suggesting relatively high abundance in some areas.	none
Invertebrates				
Euphausiids (krill), primarily *Euphausia pacifica* and *Thysanoessa spinifera*	Tremendously abundant throughout coastal and offshore waters, a hugely important component of the food web	Commercial targets in Antarctica, Japan, small fisheries off British Columbia and other locations; increasing commercial potential.	Key forage species for wide range of both juvenile and adult salmon, groundfish, squid, seabird and marine mammals	Fishing prohibited in CPS FMP
Market squid (*Doryteuthis opalescens*)	Nearshore and shelf distribution (adults relatively rare offshore)	Very important commercial target in CCS (up to, rarely over, 100,000 tons)	Key forage species for wide range of HMS, salmon, groundfish, seabird and marine mammals	CPS FMP (CA state)
Pelagic squids (such as boreal clubhook squid, neon flying squid and Humboldt squid)	Offshore distribution (most spp. rare inshore)	Important commercial target elsewhere in range	These and other squid are key prey for HMS species and marine mammals.	none

** Sciaenidae, excluding white sea bass (*Atractoscion nobilis*) and corbina (*Menticurrhus undulates*) but including small, schooling species such as queenfish (*Seriphus politus*), spotfin croaker (*Roncador stearnsii*), white croaker and potentially others (the latter three are probably the most abundant; note that white seabass is clearly a higher trophic level predator).

Source: PFMC Draft Pacific Fishery Ecosystem Plan, November 2011.

Conclusion

The health and biodiversity of the Monterey Bay National Marine Sanctuary depends, among other things, on abundant populations of forage species. Forage species literally feed and sustain our oceans; they are the lifeline for the sea. From whales to seabirds to tuna and salmon, forage species feed wildlife populations that we rely on and cherish for cultural, recreational and economic reasons.

The Monterey Bay National Marine Sanctuary Management Plan[158] is comprised of 23 action plans guiding MBNMS beginning in 2008. These action plans are grouped into four main management themes- Coastal Development, Ecosystem Protection, Water Quality and Wildlife Disturbance. The Ecosystem Protection theme addresses ecosystem-wide impacts to MBNMS marine resources, which laid the foundation for the Monterey Bay National Marine Sanctuary's involvement in the management of krill.

The purpose and policy of the National Marine Sanctuaries Act (NMSA) is to "Maintain for future generations the habitat, and ecological services, of the natural assemblage of living resources that inhabit [Sanctuaries]".[159] The NMSA conveys upon the Sanctuaries Program the duty to "improve the conservation, understanding, management and wise and sustainable use of resources". The process for NOAA's regulation of fishing in National Marine Sanctuaries is described in a detailed white paper and flowchart.[160]

In this review of forage species science and management off the U.S. West Coast, we identify several examples of how National Marine Sanctuaries, regional fishery managers, and state lawmakers have made important decisions and progress toward protecting forage species, particularly the state and federal prohibitions on commercial fishing for krill. We identify remaining challenges regarding explicitly accounting for the supportive value of forage species to other species and economic sectors when setting catch limits. While there is much progress to be made on the scientific side, there are opportunities to use recently available data and new ecosystem models to improve management. The diversity of viewpoints and representation on the Sanctuary Advisory Council makes the Sanctuary uniquely situated to participate in management decisions regarding forage species and ultimately help facilitate a more holistic, ecosystem-based approach.

From a scientific perspective, the focus of data collection needs to expand beyond assessing the populations of the forage species themselves, to their interactions with oceanographic conditions and predators. Currently, a wealth of existing data and analytical methods are available to address ecological factors relevant to the harvest strategy of forage species. Diet information, which indicates the existence and strength of predator-prey relationships, has been published by NOAA for several key west coast species found in the MBNMS.[161] In addition, food web models of the California Current have been published[162,163] providing the ability to qualitatively and quantitatively describe potential impacts of target species removals on other marine species and to evaluate food web resilience and biodiversity.

Forage species protection is a pillar of ecosystem-based management. To adequately protect the food web of the California Current marine ecosystem, significant attention to science and management is warranted to maintain an abundant, resilient supply of forage species. The Monterey Bay National Marine Sanctuary has an important role to play in this effort, particularly due to its geographic location as a key foraging hotspot within the California Current and its unique ecosystem protection mandates outlined in the National Marine Sanctuaries Act. Fishery managers are already familiar with managing under uncertainty; one challenge will be to extend these principles to a new framework that considers more than single species. Hopefully, this white paper can provide the Sanctuary with the background on the science and management of forage species so it can develop practical and tangible path toward contributing to this timely and important ecosystem protection issue.

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