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REVIEW

# Issues of ecosystem-based management of forage fisheries in “open” non-stationary ecosystems: the example of the sardine fishery in the Gulf of California

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**Abstract** The Gulf of California system presents major challenges to the still developing frameworks for ecosystem-based management (*EBM*). It is very much an *open system* and is intermittently subject to important influxes of migratory visitors, including large pelagic predatory fishes and small pelagic forage fishes. These migrants include the more tropical species from the coastal ecosystems to the south and perhaps subtropical sardines and anchovies from the California Current upwelling system. In addition to the multi-annual ENSO-scale and what may seem to be rather erratic episodes of major population incursions, the Gulf presents nonstationary, transient aspects on a variety of longer time scales. Moreover, the removal of top predators by commercial and sport fisheries has introduced trends that must be affecting the entire ecosystem, and certainly the forage fishes that are their major prey base. In addition to size limits, fishing seasons, area closures and license limitations, the fishery is managed by an ad hoc adaptive management system, in which the fishing season can be shortened or additional areas closed to fishing if pre-season exploratory fishing surveys indicate a shortage of small pelagic fishes on the fishing grounds. Whether this system is likely to be sustainable in the long term is difficult to determine, given the potential for rapid changes in the system because of environmental changes and/or feedbacks within the food web. Thus it appears that innovative management frameworks, among other things utilizing the comparative method, may be required in order to determine defensible tradeoffs between precaution and resource utilization.

**Keywords** Ecology · Management · Environment · Clupeoid fishes · Radical variability · Transient responses · Stock assessment · ENSO

## Introduction

### Toward ecosystem-based management (EBM) for forage fisheries

Fisheries management has traditionally used regulations such as catch quotas, effort limitations, gear

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restrictions and time/area closures to control fishing mortality, in the belief that there is some optimal level of fishing mortality that will maximize the long term average yield without jeopardizing the sustainability of the fishery. Management benchmarks such as optimal fishing mortality rates and biomass levels, as well as the current status of the population relative to those benchmarks, are calculated within a stock assessment framework that makes mathematical assumptions of strong density dependence and system stationarity, mainly because these assumptions make the resulting predictive models amenable to parameterization with data that can practicably be obtained. But recently, a continuing sequence of unexpected fishery collapses, in many notable cases involving stocks of small pelagic *forage fishes*, has called the basic reliability of these approaches into question, even as the ever lengthening time series of available data exposes significant fallacies in the fundamental assumptions on which they are built (Freon et al. 2005; MacCall 2009).

The concept of ecosystem based management of fisheries (EBM, also called EAF for ecosystem approach to fishing), which has emerged in the past decade largely as a critique of conventional fisheries science and management, calls for a more nuanced understanding of non-stationarities, spatial patterns and dynamics, ecosystem-level processes and feedbacks, and the potential unintended consequences of fisheries removals. According to Pikitch et al. (2004), EBM of fisheries should (1) avoid degradation of ecosystems; (2) minimize the risk of irreversible change to natural assemblages of species and ecosystem processes; (3) obtain and maintain long-term socioeconomic benefits without compromising the ecosystem; and (4) generate knowledge of ecosystem processes sufficient to understand the likely consequences of human actions.

In addition to the usual imperatives of EBM, such as minimizing habitat damage and bycatch of threatened species, an effective EBM system for forage fish would require an understanding of the potential impact of removals of biomass of the forage fish on other components of the food web, either plankton that may be released from predation, or predators such as piscivorous fish, sea birds and mammals that may be forced to change their distribution or switch prey species and could suffer loss of productivity if their forage fish food source is depleted. The EBM system would also need to incorporate an understanding of the mechanisms controlling rapid, radical variations in abundance, distribution and productivity of forage fish populations, and of the relative complexity of the ecosystem interactions and feedbacks these variations may set in motion.

The extreme variability that characterizes small pelagic fish recruitment implies that traditional fishery management measures such as total allowable catch (TAC) quotas based on estimates of long term average yield from stock assessment may not be effective in preventing episodes of serious overfishing. In some small pelagic fisheries, regime specific harvest rates, allowing the fishery to take a larger fraction of the population in more productive regimes, could potentially be effective (Polovina 2005). However, the character of such “regimes”, as well as their duration, is currently confidently definable only after the fact. Katsukawa and Matsuda (2003) suggested requiring a multispecies small pelagic fishery to target only the species that are more abundant each year, to remove pressure from species undergoing a period of low productivity. This approach is complicated by the tendency for less abundant forage fish species to school together with more abundant species (Bakun and Cury 1999) and thus to be equally vulnerable, in a per unit biomass sense, to the same fishing operations. If they could be effectively employed, such management measures might improve long term average yields from some small pelagic fisheries, but they probably cannot eliminate the risk of stock collapse during times of particularly unfavorable environmental conditions. Thus, an effective EBM system for forage fish should be precautionary and as robust as possible with respect to potential uncertainties.

## Complex adaptive systems

Marine ecosystems are prime examples of complex adaptive systems (Levin 1998, 1999). They are dynamically nonlinear (Hsieh et al. 2005) and possibilities for self-enhancing nonlinear feedback loops clearly exist (Bakun and Weeks 2006). Perhaps the most fundamental feedback loop may be what Bakun and Weeks called the “*P2P*” (signifying “prey to predator”) *loop* in which the forage fishes impact their potential predators by eating their eggs and larvae.

They offer the analogy of the potential difficulty of maintaining stability in a terrestrial African veldt ecosystem if antelopes and zebras, were themselves voracious carnivores that relentlessly hunted and consumed young lions, leopards and cheetahs that when they were adults would be preying on them. A clue to the unexpected durability of recent collapses of formerly massive stocks of fishes such as cod, in spite of each female spawning literally millions of eggs, might be the subsequent increases of the small pelagic forage fishes which, while being the favored prey of the cod, are particularly adept at filtering cod eggs from the water column as favored food items (Bakun and Weeks 2006; Hjermann et al. 2004).

But forage fish themselves, for which such a *P2P feedback loop* explanation may not be easy to envision, have been susceptible to similar puzzling durability in their stock collapses. For example, both the massive California and Japanese sardine populations literally disappeared entirely from their ecosystems for two full decades before initiating their more recent rebounds, from which the Japanese stock has already experienced a second abrupt collapse. Meanwhile, the Peruvian anchoveta has been battered repeatedly by massive unrestrained fishing, has exhibited multiple significant declines, but has generally rebounded relatively rapidly. Moreover, the intervening periods of lowered anchoveta abundance tended to be significantly counteracted by increases in other forage fish species, such as sardines and the young age classes of jack mackerel. In contrast, the initial collapse of the formerly enormous Southeast Atlantic sardine population operating in the marine ecosystem off Namibia has never recovered to more than 10% of its former magnitude, nor has it been significantly replaced by comparably abundant populations of alternative forage fish species.

To the extent that nonlinear feedbacks (such as *P2P* and others proposed by Bakun and Weeks 2006) are realized, conventional modeling efforts cannot be expected to encompass the full range of possible outcomes and so must fail to be reliably predictive of the very types of radical consequences that may be most important to avoid. However, the dynamic nonlinearities that clearly exist in marine ecosystems (Hsieh et al. 2005), while preventing precise prediction of outcomes of actions taken, evidently do not normally produce utterly chaotic ecosystem responses. Rather, strong regularities such as apparent ocean basin-scale synchronies and rather consistent patterns of species alternations (Bakun 1996, 2005b; Chavez et al. 2003), suggest the action of important regulating and stabilizing mechanisms. As will be discussed in the sections to follow, these must be quite different from the simple density-dependent *carrying capacity*-type arguments that are reflected in the formulation of the classical fisheries management models, even when fisheries models are augmented with nuances such as environmentally-driven recruitment time series.

## The ecological role of forage fishes

In most large marine ecosystems (*LME*s) of the world, the biological communities exhibit a striking "*wasp waist*" configuration of their trophic structures (Rice 1995; Bakun 1996, 2006a; Cury et al. 2000). That is, they typically contain (1) a very large number of species at the lower (e.g., planktonic) trophic levels, (2) a large number of species (e.g., predatory fishes, large coelenterates, seabirds, marine mammals, etc.) that, as adults at least, feed near the apex of the foodweb, and (3) a crucial intermediate trophic level, occupied by small, plankton-feeding pelagic *forage fishes*, that is typically dominated by only one, or at most several, species. In such cases, the trophic energy of the system must flow upward from a highly diverse lower-trophic-level complex of species through a very narrow, constricted "chokepoint" in order to become accessible to the highly diverse upper-trophic-level complex of species that depends on it.

For example, the fish biomass of the world's major temperate eastern ocean boundary upwelling systems, as well as the western boundary of the North Pacific, tends to be dominated by a single species of sardine (of the genera *Sardinops* or *Sardina*) and a single species of anchovy (genus *Engraulis*) that have historically tended to alternate in dominance on multi-annual time scales. In other cases, a single anchovy species (e.g., *Engraulis anchoita* in the Falkand/Malvinas Current of eastern South America), or a single menhaden species (e.g., *Brevoortia tyrannus* in the Gulf Stream region off the eastern U.S.) may prevail. Tropical analogs of these temperate ocean ecosystems tend to be dominated by analogous tropical species such as sardinellas (*Sardinella* spp.), anchoviellas (*Anchoviella* spp.) and thread herrings (*Opisthonema* spp.). Other *wasp waist* examples are herring (*Clupea* *harengus. C. pallasii*), sprat (*Sprattus* spp.), capelin (*Mallotus villosus*) or sandeels (*Ammodytes* spp.) of boreal shelf ecosystems. In the Southern Ocean, Antarctic krill (*Euphausia superba*) may represent an invertebrate analog. During high abundance phases, the dominant *wasp waist* species by itself often constitutes the major portion of the total animal biomass of its entire regional ecosystem.

Accordingly, this massive population of *wasp waist* forage fish performs a crucial role in the overall function of its entire ecosystem. Modeling studies (Rice 1995) have confirmed that variations in its abundance and productivity regulate variability in the overall trophic dynamics of these ecosystems. Typically these populations of small pelagic planktivores experience wide inter-annual variability in reproductive success. Because of their short life spans, this results in extreme variability in their population sizes that has major effects on the trophic levels above, which depend on the *wasp-waist* populations as their major food source, and also on the trophic levels below which are fed upon by the *wasp waist* populations. Thus the major control on the productivity of the entire complex of species in these ecosystems may be neither "bottom up" nor "top down" but rather "both up and down from the middle" (Rice 1995; Bakun 1996; Cury et al. 2000; Arreguín-Sanchez et al. 2002).

Another key aspect is that the *wasp-waist* level is the lowest trophic level that is mobile, in the sense that it can expand, contract, or relocate its area of operation according to its own internal dynamical and behavioral responses, which may or may not be keyed to environmental changes (Bakun 2005a, 2006a). A prime example is the well-documented range contraction of the California sardine population after its initial collapse (Fig. 1). Such movements in geographical distribution have the potential to massively alter patterns of population productivities and trophic flow structures in the areas involved.

Accordingly, the proper management of fishery exploitation of these *wasp-waist* forage fishes may be critical for the preservation of the integrity of the total species complex and of the trophic functioning of the overall regional marine ecosystem. As mentioned earlier, conventional fisheries management has experienced notable failures in recent decades, and there is a resulting widespread consensus for a need for more holistic EBM (Pikitch et al. 2004), particularly since demand for forage-fish-based animal and aquaculture feeds is undergoing an explosive growth phase that is expected to continue into the foreseeable future. However, while the drive for EBM is expected to be the single most important influence on development of future assessment and management policies, no EBM approach has yet been applied to any exploited forage fish population in the world (Barange et al. 2009).

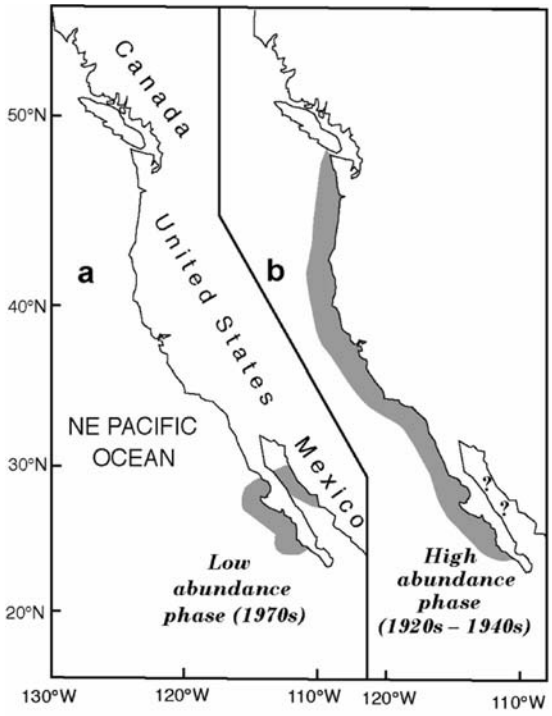

**Fig. 1** Changes in distributional extent between high and low abundance phases of sardines (*Sardinops sagax caeruleus*) in the NE Pacific (redrawn from Bakun 2005b)

In this paper, we examine the potential issues involved in terms of a particular regional exploited forage fish population, the sardine (*Sardinops sagax caeruleus*) population of the Gulf of California. This particular ecosystem appears to well represent some key unresolved issues (notably those associated with *nonstationarity* and *system openness*) in EBM of forage fish resources. It also well represents characteristic economic, social and political issues, being an important economic driver for a rapidly developing regional economy. Moreover, the fish stock on which it is based constitutes an important food base for higher trophic level fishes and other charismatic megafauna (García-Rodríguez and Aurioles-Gamboa 2004) that directly underlie additional key economic drivers (eco-tourism, sport fishing, diving, etc.). The Gulf ecosystem itself, for which the sardines and other small pelagics fulfill the *wasp waist* function, currently still represents a priceless remaining "jewel" of the earth's natural biological heritage, incorporating some of the most pristine natural ecological complexes left on earth, including more than 776 species of macro-invertebrates and 77 species of fish found nowhere else on our planet (Lluch-Cota et al. 2007). Large portions of the total world's populations of a number of marine bird species breed within the Gulf. There are 36 species of marine mammals occurring here, one (the vaquita *Phocoena sinus*, a critically endangered small porpoise) being found nowhere else. In terms of terrestrial biodiversity, the 922 islands within the Gulf if California host 90 species of endemic plants and animals, including 60 endemic reptile species (Lluch-Cota et al. 2007).

**Fig. 2** Bathymetry of the Gulf of California (redrawn from Lluch-Cota et al. 2007)

## The Gulf of California

### The physical and climatic contexts[1]

The Gulf of California is the eastern Pacific Ocean's only inland sea. Geologically, it is among the youngest peripheral seas in all the world's oceans, its mouth having opened as little as 4 million years ago (Oskin and Stock 2003). It is long and narrow, being 1,130 km long and 80–209 km wide and is divided into a series of large deep basins and trenches that deepen to the south (Fig. 2). Maximum depth at the mouth is greater than 3,000 m. The pronounced depth of the southern half of the Gulf, unusual for such a semi-enclosed sea, provides an opportunity for large populations of unexploited small vertically-migrating mesopelagic fishes (e.g., *Benthosema panamense*, *Triphoturus mexicanus* and *Diogenichthys laternatus*), which appear to provide an alternative to small pelagic forage fish for predators such as jumbo squid (*Dosidicus gigas*).

Most of the northern Gulf is less than 200 m deep and experiences large-amplitude tidal effects, the tidal range reaching nearly 7 m near its inner end (Gutiérrez and González 1999). A zone in the vicinity of two large islands, Tiburón and Angel de la Guarda, situated somewhat north of the midpoint of the Gulf is dominated by strong tidal currents and resulting mixing of the water column. One of the great rivers of North America, the Colorado, flows into the Gulf at its upper (northern) end, but that inflow has steadily vanished over the past century as a result of steadily increasing impoundment to supply agricultural irrigation for much of the southwestern USA. The surrounding coastland areas are notably arid, with very little runoff entering from the western (peninsular) side. However, the eastern (continental) side receives significant runoff from continental mountain ranges of the inland interior.

As regards meteorology, winds in the Gulf tend to blow predominantly along its long axis. During the summer they are relatively weak, blowing predominantly from the southeast toward the northwest. However during the winter, winds blow predominantly from the opposite direction, from the head toward the mouth of the Gulf (from northwest to southeast). In the mid-Gulf and southern Gulf zones, the equatorward winds on the eastern side of Gulf continue through April at least (Marinone 2003). This leads to upwelling on the continental side that tends

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[1] Much of the information in this section comes rather directly from the recent multiple-authored review by Lluch-Cota et al. (2007); see references list, below.

to push surface water westward, to then converge and downwell as it approaches the peninsular coast. The southward current (Allen 1973) produced by the upwelling processes occurring at the eastern coast of the Gulf contributes to an anticyclonic (clockwise) circulation south of the big islands, which yields additional upwelling sources around the edges of the eddy (Bakun 2006b), as well as convergence toward the eddy center. Together, these processes yield a configuration called an *ocean triad*, because it comprises an appropriate sequence of *enrichment*, *concentration* and *retention* mechanisms (Bakun 1996, 2006b; Agostini and Bakun 2002) such that the area is a good nursery habitat for forage fish populations. A source of nutrient input (*enrichment*) of comparable importance is the intense tidal mixing that occurs in the vicinity of the big islands (Lluch-Cota et al. 2007). This contributes to the *enrichment* component of the winter *ocean triad* configuration, and in addition, continues to be a vigorous enrichment factor through the year.

Sardine spawning takes place mostly between fall and winter as upwelling extends along the eastern coast of the Gulf (Cisneros-Mata et al. 1995), thereby inserting larvae into the favorable winter–spring triad circulation. One result is the observed accumulation of late larvae and juveniles on the western side of the Gulf during the summer.

The mouth of the Gulf stands directly in the path of polewardly-propagating geophysical waves (Allen 1975) associated with the El Niño episodes that break out intermittently in the equatorial Pacific. During El Niño years, these waves propagate into the Gulf along the continental coast deepening the subsurface thermocline and nutricline and causing a northward flow tendency near the coast. These processes act to suppress the cooling and enrichment effects of the local wind-induced upwelling that occurs during winter in the spawning ground along the eastern coastal boundary of the Gulf. This implied suppression of the productive ocean triad system suggests that sardine reproductive success might tend to decline during annual El Niño episodes, although cooling and enrichment generated by the continuing tidal mixing in the zone near the big islands evidently allows a degree of successful reproduction to continue even under El Niño conditions.

In any case, catches of adult sardines have tended to decline during El Niño years (e.g., 1991/1992 and 1997/1998, Fig. 3). This effect on adults may be due to the action of higher temperatures in diminishing or even suspending the annual southward migration of the sardine within the Gulf, thereby reducing catches in the customary fishing zone of the central Gulf (Lluch-Belda et al. 1986; Huato-Soberanis and Lluch-Belda 1987). This effect on adults could also feed back to poor reproductive success in El Niño years by preventing reproduction in what normally would constitute the most favorable reproductive habitat (Lluch-Cota 2000).

## The sardine fishery in the Gulf of California

The Pacific sardine is the dominant species (50–80% of total landings) in a multispecies purse seine fishery that operates from ports in the central and Southern Gulf of California, from November through July (Nevárez-Martínez et al. 1999). Sardines and other small pelagic fishes are also caught in relatively small numbers near the mouth of the Gulf for use as bait by vessels targeting tuna (Rodríguez-Sánchez et al.

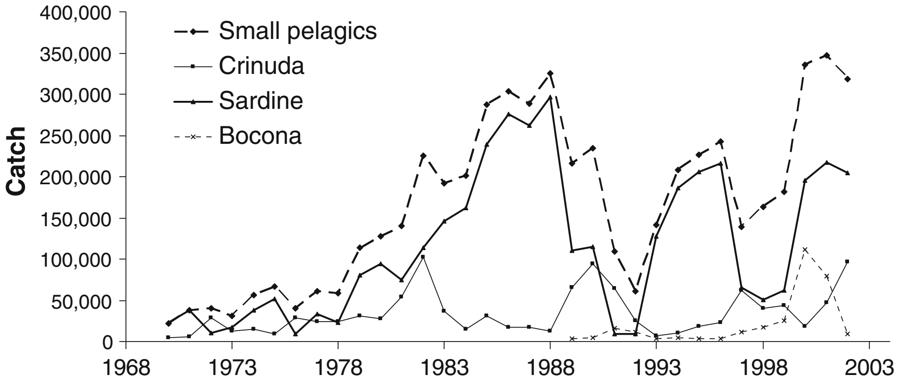

**Fig. 3** Annual landings of sardines (tonnes) and other small pelagic fishes in the Gulf of California, redrawn from Lluch-Cota et al. (2007) ["Crinuda": *Opisthonema libertate*, "Bocona": *Cetengraulis mysticetus*]

2003), and there is a developing fishery to supply sardines as feed for tuna farming operations (Dorry et al. 2008). In the directed fishery, about 85% of the total catch is used for reduction to fishmeal, mostly for animal feeds. Sardines are also packed in cans for sale to domestic and foreign markets. During years of poor sardine abundance, its low catches are compensated to some degree by increases of other small pelagic fishes such as the tropical thread herring *Opisthonema libertate* (Lluch-Belda et al. 1989) and, starting in the early 1990s, the tropical anchovy *Cetengraulis mysticetus* (Fig. 3). For this reason, the reduction industry is not as strongly affected by low abundance periods as the canning industry, in which there has historically been a clear preference for sardines (Lluch-Cota et al. 2007).

The fishery for small pelagic fish in the Gulf began in the 1970s, and landings increased to a peak in 1988–1989 of nearly 300,000 tons (Fig. 3), whereupon the fishery collapsed abruptly to less than one-third of that amount the following year. This collapse caused the loss of 3,000 jobs and about half of the fleet and processing plants. (Lluch-Cota et al. 1999). Landings have been highly variable since then, and tropical species of forage fish have become more prevalent in the catch (Fig. 3).

The sardine fishery has been regulated and managed by the federal government of Mexico since 1993 under Norma Oficial Mexicana (NOM) 003-PESC-1993. The NOM recognizes that the abundance of sardine and other small pelagic species fluctuates with environmental conditions but can also be influenced by fishing. The NOM specifies a minimum size limit of 150 mm in length for sardines, regulates fishing gear and fleet capacity, and requires that the fishery be closed in times and areas where the majority of sardines are spawning but does not include total allowable catch (TAC) quotas (NOM 003-PESC-1993). The development of a NOM is a collaborative effort between federal authorities and fishermen organizations and other NGOs, with final approval by Congress (Hernandez and Kempton 2003). The fishery does not yet have a formal fishery management plan, although one is currently being developed as required by the 2007 Ley General De Pesca y Acuacultura Sustentables (Nueva Ley DOF 24-07-2007). Since 1993, the Centro Regional de Investigación Pesquera (CRIP) in Sonora, a branch of the Instituto Nacional de Pesca (INP), has conducted a pre-season exploratory fishing survey in the fishing grounds, in cooperation with the fishing industry, in order to forecast expected catches for the year. If the abundance of fish on the grounds is low, the INP and the industry can agree to more extensive time and area closures.

The small pelagic fishery of the Gulf of California is currently being assessed for potential certification as a sustainable fishery under the Marine Stewardship Council.

## EBM for the Gulf of California sardine fishery

The Gulf of California ecosystem has several characteristics that complicate fishery management and that should probably be taken into consideration in efforts to develop an effective system of EBM. The system is open in the sense that it is impacted by wider oceanographic conditions in the surrounding coast, and the movements of animals in response to these conditions. Also, in addition to the fact that the abundance of sardines and other small pelagic fishes varies dramatically at a number of time scales, the Gulf has undergone secular changes over time (non-stationarity) that impact the productivity of sardines. These factors must be taken into account when evaluating the sustainability of the small pelagic fishery. Trophic interactions and the importance of sardines as a source of food for predators should also be incorporated into any EBM system.

### System “Openness”

The marine ecosystem within the Gulf is very much an *open system*, having a direct open connection to the wider northeast Pacific Ocean. The mouth of the Gulf itself constitutes the major separation between the Pacific coastal ecosystem extending to the north along the Baja California peninsula, which is strongly affected by coastal upwelling and cool California Current flow, and the coastal ecosystem to the south which reflects a transition to the warmer, more tropical, less upwelling-affected zones to the south. The Gulf ecosystem is intermittently subject to important influxes of migratory visitors, including predators such as tunas, billfishes and jumbo squids, whose incursions may or may not be related to tracking of movements of preferred environmental conditions. There are also major exchanges of small pelagic forage fishes, certainly with the more tropical analog species (*Opisthonema* spp., *Cenengaulis mysticetus*, *Oligoplites* spp.) from the coastal ecosystems to the south, but also perhaps with temperate sardines and anchovies from the California Current upwelling system that extends northward from the Gulf mouth, which the Gulf habitat in many ways mimics. In addition to the multi-annual ENSO-scale and what may otherwise seem to be rather erratic major population incursion episodes, fishing pressure itself could conceivably be involved in inducing migrational episodes via mechanisms such as the one called *school-mix feedback* by Bakun (2005b).

The Pacific sardine fishery in the Gulf of California developed, following the collapse of the Ensenada sardine fishery on the Pacific side of the Baja California Peninsula, to harvest what appears to have been at that time a growing local sardine population within the Gulf itself (Schwartzlose et al. 1999). This was several decades after the initial major collapse of the major northern California Current population of the same species that in the first half of the twentieth century had supported one of the world's great fisheries. By the 1970s, this northern subpopulation of Pacific sardine was entirely unobserved in its previous habitat that had earlier stretched along the open Pacific coastline of North America from the northern part of Baja California all the way to southern Canada (Fig. 1a), and was widely considered to have become permanently extinct (Fig. 1b). Meanwhile, a very much smaller southern California Current subpopulation held on within a lightly exploited refuge on the Pacific side of the southern half of the peninsula of Baja California.

Sardines continued to dominate the catch of small pelagic fishes in the Gulf of California until a major collapse of the fishery occurred in 1990/1991 (Fig. 3). Suddenly, anchovies (*Engraulis mordax*) appeared in abundance, a fish that in the knowledge of the current inhabitants had never before existed there; it is also a fish that in many other temperate coastal ecosystems of the world has exhibited a pattern of intermittently replacing sardines. The first time an anchovy was ever reliably recorded in the Gulf was in 1986 (Hammann and Cisneros-Mata 1989), just as the earlier increasing trend in sardine population abundance had evidently reversed to an abrupt decreasing trend (Nevárez-Martínez et al. 1999). The anchovy population established itself and briefly augmented what remained of the Gulf small pelagic fishery (Lluch-Belda et al. 1992), while sardines nearly disappeared completely from the landings by the 1991/1992 fishing season. But the story did not finish there. In the face of this exploitation, the anchovy population declined quickly, with catches falling to zero in 1996/1997, while the sardine catches increased, supporting a catch of over two hundred thousand tons in 1996/1997 (Fig. 3), the same year that anchovies ultimately entirely disappeared from the catches. Sardine catches increased through 1996/1997, dropped off during the 1997/1998 El Niño (when the adult sardine resource evidently did not collapse but sardine schools were restricted to their usual distribution around the big islands and did not expand south to the customary fishing ground along the eastern coast of the gulf.), stayed low through 2000, and recovered in 2001 and have remained relatively high through the present (Fig. 3, Lluch-Cota et al. 2007).

A subsequent analysis of fish scale deposits in anaerobic sea floor sediments (Holmgren-Urba and Baumgartner 1993) has indicated that this was not the first time anchovies had made an incursion into the Gulf of California, but in fact they had entirely dominated the fish biomass in the Gulf for most of the nineteenth century. Earlier, it had been thought that the Baja California peninsula, extending far south into quite tropical waters, constituted an effective barrier to exchange of temperate sardine and anchovy populations between waters of the Gulf and those of the California Current on the other (Pacific Ocean) side of the peninsula. But recent analysis of catches of these species by the tuna fleet, which uses them as bait, have shown that both species regularly frequent waters well south of the southern extremity of the peninsula (Rodríguez-Sánchez et al. 2003), actually occurring as far south as the Islas Revillagigedo which are some 400 km to the southward of Cabo San Lucas, the southern tip of the Baja Peninsula. In addition, Holmgren-Urba and Baumgartner (1993), in comparing their paleo-sedimentary scale deposit time series for the Gulf to that produced by Soutar and Isaacs (1974) for a California Current site in the Santa Barbara Channel, found indications of migratory shifts between the two systems at multi-decadal periods. Significant amounts of anchovy larvae were again briefly observed in the Gulf during the highly anomalous conditions of the 1997/1998 El Niño, coinciding with near absence of sardine larvae (Sánchez-Velaso et al. 2000).

Jumbo squid may also migrate into the Gulf. These large, extremely mobile, voraciously-feeding invertebrates are the object of a very important fishery in the Gulf. During the extremely intense 1982–1983 El Niño, the jumbo squid virtually disappeared from the Gulf for a number of years well after the El Niño-associated anomalies had retreated and the Gulf had already returned to more "normal" conditions. Later, in 1989 jumbo squid again reappeared in the Gulf, and by 1993 the fishery resumed operations. Catch rapidly increased to 140,000 tons by 1997. Then, in conjunction with another extremely intense El Niño in 1997–1998, the jumbo squid population appears to once again have largely exited the Gulf, with almost no catches being recorded there. Meanwhile, high concentrations of jumbo squid were detected off the west coast of the peninsula (Lluch-Cota et al. 2007), operating in that separated but normally similar coastal upwelling ecosystem, but which, during El Niño conditions, is protected by the barrier of the Gulf entrance from the anomalously high ocean temperatures and poor primary productivity that permeate the interior of the Gulf system.

While some of the above hypothesized migratory movements remain controversial (some experts preferring a scenario of separate populations simply collapsing and rebuilding in place, with apparent synchronies, etc., being coincidence or driven by the same large-scale climatic episodes) they do represent plausible reasons to question the "closed" local system autonomy that is often assumed in the classical models and conventional management methodologies. It is hard to see how the large changes in the catches of anchovies and jumbo squid that have been observed over the last decade could be explained as reflecting population productivity within the Gulf alone. Whether or not sardines themselves migrate into and out of the Gulf of California, the migratory movement of their predators and potentially competing forage fishes could influence the mortality and growth rates of sardines, and their reproductive success. This additional source of variability could bias assessments of stock status and influence the potential sustainability of the fishery.

## Nonstationarity

Small pelagic populations are generally variable and subject to periods of low and high abundance, and this is certainly true of Gulf of California sardines. In addition, it appears that the physical–biological system of the Gulf of California may, in a number of respects, conform poorly to the standard assumption of stationarity that provides the rationale for parameterizing conventional models and procedures based on historical time series of data and for establishing rigidly fixed benchmarks and triggers for management actions.

While the relative geological youth of the Gulf of California basin is probably not a significant factor, the nearly total cutoff of Colorado River inflow during the twentieth century is almost certainly relevant, undoubtedly having triggered sequences of transient population responses that are still in the process of unfolding. For example, the evidence for domination of the "*wasp waist*" of the Gulf ecosystem by anchovies during the nineteenth century, and its apparent total absence in the later twentieth century before its brief, rather ethereal reappearance in the 1990s that coincided with the initial sardine collapse, has been discussed in the previous section. Anchovies throughout the world exhibit a generally higher degree of affinity for estuarine-affected habitats than do sardines, perhaps reflective of their much coarser gillraker structures that they employ as food filtering apparatus. While not capable of filtering as small a size of food particles as can sardines, anchovies may be less likely to experience clogging of these structures a result of terrestrial sediment material and other particulate matter characterizing estuarine situations. Note that free flow of water through gill structures is critical also for respiration in these fishes. Thus a question arises as to whether it may have been the cutoff of Colorado River inflow that shifted the advantage at the *wasp waist* of the Gulf ecosystem from anchovies to sardines.

The major physical and biological anomalies affecting the Gulf in association with El Niño events are also certainly initiating transients in the biological/trophic system that play out on a variety of time scales. Moreover, there seems to a relevant longer, not yet totally understood *Pacific regime shift* time scale (~20–60 years), (Chavez et al. 2003; Bakun 2005b) that appears to be more or less linked to variations in the Pacific ocean–atmosphere–climate system that themselves may or may not have cyclic elements (Overland et al. 2009).

Finally, the history of fishing in the region could potentially be causing evolutionary changes in both the small pelagic fishes and their predators. The small pelagic fishery is managed with minimum size limits, so that fishing mortality is higher on large individuals. Harvest, and particularly size selective harvest, has been shown to cause reductions in age and size at maturity and other changes in life history characteristics (Jørgensen et al. 2007). In the lab these heritable changes in growth rates and size at maturity can occur in as little as four generations (Conover and Munch 2002). Such evolutionary changes in life history traits are one possible explanation for the fact that exploited fish populations are often more variable than unexploited ones (Anderson et al. 2008).

Like system openness, non-stationarity can potentially invalidate the stock assessment models used to design fishery management strategies for sardines. In particular, a level of harvest that would be sustainable in one decade may not be sustainable in the next, so that a long term management strategy should be able to adapt to changing conditions.

## Stock assessment and status of the sardine population

Unlike many industrial fisheries, management of the small pelagic fishery in the Gulf of California is not based on fisheries reference points calculated through fisheries stock assessment. However, the available stock assessments can be used as a source of information about the productivity of the stock and its ability to sustain fishing pressure, keeping in mind the caveats about system openness, non-stationarity and variability outlined above.

The sardine population has been the subject of several stock assessments in the late 1990s, including a virtual population analysis (VPA) covering the period 1972–1990 (Cisneros-Mata et al. 1995; Nevárez-Martínez et al. 1999), which was later updated through 1997 (Nevárez-Martínez 2000), and a statistical catch at age model used for bioeconomic scenario monitoring (de Anda-Montañez and Seijo 1999). Both the highest catch ever recorded (1988/1989) and the subsequent collapse (1991/1992) occurred during this assessed period. The increasing catch between 1983 and 1989 corresponded to an increase in effort with a resulting increase in fishing mortality rate (de Anda-Montañez and Seijo 1999; Nevárez-Martínez 2000). The collapse in 1991/1992 was apparently caused by a combination of several years of low recruitment and severe overfishing (de Anda-Montañez and Seijo 1999). When recruitment started to increase in the late 1990s, apparently because of good environmental conditions, biomass increased with a 1 year time lag (Nevárez-Martínez 2000), as would be expected for a fast growing species like sardines. However, the increase in adult biomass was less than would be expected from the large numbers of juveniles observed in surveys during the late 1990s (Instituto Nacional de la Pesca 2006).

These assessment models appeared to be able to match the observed catch trends fairly well, which is perhaps surprising given that they make the classical stationarity assumptions. Allowance for the fact that environmental factors impact recruitment is included in the models (Nevárez-Martínez 2000; de Anda-Montañez and Seijo 1999), but potential trends in life history characteristics and natural mortality rates are not included. Thus, management benchmarks (e.g., Maximum Sustainable Yield, Instituto Nacional de la Pesca 2006) calculated from these models should be treated with caution.

There is a growing consensus that small pelagic fisheries, because they are short lived, highly dynamic, spatially complex, and influenced by environmental factors and trophic dynamics, cannot be managed based on classical stock assessment techniques. Rather, within-season management measures should be based on direct fishery independent surveys of population abundance and recruitment, such as ichthyoplankton sampling and acoustic methods (Barange et al. 2009). Pre-season experimental fishing surveys of small pelagic catch rates on the fishing grounds are routinely made as part of the management process overseen by the Federal Government of Mexico. Management decisions are made on the basis of these data at quarterly meetings (Instituto Nacional de la Pesca 2006). Size limits, limits on total boat numbers per area, and seasonal areal closures are used as management tools. For example, the western side of the Gulf where juveniles accumulate in the summer season is currently closed to fishing during part of the summer.

In principle, this adaptive management system based on fishery independent surveys is an appropriate method to manage a small pelagic fishery because it allows managers to react quickly to changes in population abundance. However, this system can be expected to work reliably (even in the absence of unexpected shifts in ecosystem configuration) only if time and area closures are sufficiently extensive to constrain or even reduce fishing mortality during periods of low recruitment. If the closures are only used to protect young fish or spawning fish, they may not be sufficient during times of unfavorable oceanographic conditions (de Anda-Martínez and Seijo 1999). The high variability in catches is probably an unavoidable consequence of the dynamic nature of the system (de Anda-Martinez and Seijo 1999). Consequently, economic disruptions such as plants closing and boats entering and leaving the fishery are likely to be a continuing feature of this fishery.

The sustainability of the fishery for sardines will also depend on the dynamics of other small pelagic fish that are caught in the purse seine fishery. Although sardines dominated this fishery in the 1970s and 1980s, thread herring and tropical anchovies have become more important in recent years (Fig. 3). It is unclear whether the increased abundance of these other species in the Gulf releases sardines from fishing pressure or provides an equally beneficial alternative food source for birds and mammals, or whether these species may compete with sardines for food.

## Ecosystem role of sardines in the Gulf of California

As a key wasp-waist component of the food web in the Gulf of California, it is expected that changes in the abundance of sardines will influence the abundance of predators such as marine mammals and sea birds, as well as of lower trophic level organisms that either feed upon them or are fed upon by them. Sardines, with their relatively fine gillrakers, are able to feed on phytoplankton as well as zooplankton (van der Lingen 1994). For example, López-Martínez et al. (1999) found 13 genera of phytoplankton and 41 genera of zooplankton in the stomachs of sardines from the central Gulf of California, and that Pacific sardines consumed a wider range of particle sizes than did Northern anchovy or thread herring.

Sardines are an important component of the diet of many commercially and ecologically important fish species in the Gulf of California, including striped marlin (*Tetrapturus audax*, Abitia-Cárdenas 1992), sciaenids, scombrids and carangids (Arreguin-Sanchez et al. 2002). For migratory large pelagic fishes (such as sailfish *Istiophorus platypterus*; Arizmendi-Rodríguez 2004), blue marlin (*Makaira mazara*; Abitia-Cárdenas 1992), and dolphinfish (*Corhyfaena hippurus*; Tripp-Valdez 2005), scalloped hammerhead shark (*Sphyrna lewini* Torres-Rojas et al. 2006), and teutophague cetaceans (Salvadeo 2008), entering the gulf in summer, giant squid is the most important prey. Sardine is a minor component of the diet of the commercially important giant squid, for which mictophids *Benthosema panamense*, *Triphoturus mexicanus* and *Diogenichthys laternatus* represent the major diet component (Markaida and Sosa-Nishizaki 2003; Markaida 2006). Whether sardine abundance influences the abundance of any of these mesopelagic fish species is unknown. It is also possible that decreases in abundance of predators such as tunas and billfishes due to fishing could influence the population dynamics of sardines and other forage fish. For example, yellowfin tuna in the eastern Pacific is currently estimated to be at 36% of its unexploited population (IATTC 2008). The other tunas and the billfishes are less depleted, but the large removals of predator biomass in the region are likely to have impacts throughout the food web.

Sardines and other small pelagic fishes are prey for brown pelicans (*Pelecanus occidentalis*; Jiménez-Castro 1988), blue-footed (*Sula nebouxii*; Castillo-Guerrero 2003) and brown boobies (*S. leucogaster*; Mellink et al. 2001; Suazo-Guillén and Mellink 2004), which have their largest breeding colonies in the Gulf of California, as well as Heermann's gulls (*Larus heermanni*) and elegant terns (*Sterna elegans*), both of which are quasi-endemic with more than 90% of their breeding populations in the Gulf. The diet and breeding success of these birds is dependent on sardine abundance, so much so that Velarde et al. (2004) could predict both catch per unit effort (CPUE) and total catch of sardines in the fisheries of the Central Gulf with models that included the proportion of sardines in the diet of elegant terns and the breeding success of Heerman's gulls at a breeding colony in the same region. Velarde et al. (2004) proposed using these predictions to inform management of the fishery.

For some cetaceans, small pelagic fishes are the major diet component, particularly for the small odontocetes (*Delphinus* sp.), the most abundant cetaceans in the Gulf (Salvadeo 2008), and *Balaenoptera edeni* (Urbán and Flores 1996). Other odontocetes feed mostly on giant squid (pilot *Globicephala macrorhynchus* and sperm *Physeter macrocephalus* whales, Jaquet and Gendron 2002), or zooplankton (blue whale, *Balaenoptera musculus*).

Distributions of many of the species that prey on sardines are quite variable from 1 year to the next. For example, Bryde's whale (*Balaenoptera edeni*), common dolphin (*Delphinus delphis*), blue-footed booby and brown booby were more abundant in the Canal de Ballenas in the Central Gulf of California during the 1983 El Niño than in subsequent years (Tershy et al. 1991), which the authors attributed to the fact the this area has high productivity irrespective of the ENSO cycle and might therefore serve as a refuge from adverse conditions.

Sardines are an important component of California sea lion (*Zalophus californianus*) diets at places and seasons when sardines are abundant, such as near Angel de la Guarda and Isla Tiburon in the summer (García-Rodríguez and Aurioles-Gamboa 2004). There is some evidence of correlation between sardine abundance and sea lion pup counts, implying the possibility of bottom up control of sea lion populations (Lluch-Cota et al. 2007). Because sea lions are dependant on the availability and quality of food that they can find within range of their rookeries, changes in sardine distribution can have a profound effect on their production. The California sea lions in the Gulf of California are genetically distinct from the population off the coast of the USA (Maldonado et al. 1995). The population has declined by 20% over the last 20 years (Szteren et al. 2006) with 8 of the 13 colonies showing a declining trend, including all but one of the colonies in the Central Gulf. On the other hand, a recent population viability assessment (PVA, Gonzalez-Suarez et al. 2006) found that the population was likely to be increasing, although this result depended on the assumptions made about movements between breeding colonies, with greater isolation of breeding colonies increasing vulnerability.

Finally, the small pelagic fishery could directly impact populations of other species through bycatch. Purse seine fisheries for small pelagic fishes tend to have very low levels of bycatch of other fish and invertebrate species (Kelleher 2005). Vessels have been observed discarding some of their catch of sardines when the fish are too small, or the haul is too large to fit in the hold of the vessel, and there is also a small amount of bycatch of giant squid and triggerfish (Balistidae, Instituto Nacional de la Pesca 2006). Although no observer data exist from the Gulf of California fishery, bycatch of fishes is not expected to be significant. No data are available on interactions between the small pelagic fishery and protected species of mammals and sea birds, but there is some concern that California pelicans and common dolphins may be caught (Dorry et al. 2008). The sardine fishery does not overlap with the range of the endangered vaquita (*Phocoena sinus*), which is found only in the Northern Gulf (Rojas-Bracho et al. 2006).

## Sustainability in the long term

The previous section discussed the potential for sustainable EBM of sardines in the Gulf of California, given our understanding of the dynamics of the system at present. To develop a management system that is sustainable in the long term it is necessary to evaluate the potential that the ecosystem will change drastically, and perhaps irreversibly, due to climate change or feedbacks within the food web. One basis for forecasting potential outcomes in the Gulf system is to look at what has happened in comparable systems throughout the world.

### Comparative eco-dynamics

The proximity of the upwelling system in the Gulf of California to a rather more temperate upwelling system (the California Current system that stretches far northward along the outer Pacific coast) resembles quite similar dual-system configurations situated off the west coasts of South America and southern Africa that feature nearly identical *wasp-waist* species complexes (Bakun 1996).

The Humboldt Current LME contains two quasi-autonomous upwelling systems, a more temperate one located off central and northern Peru that features strong upwelling occurring year round but with peak upwelling intensity during austral winter, and a more seasonal upwelling system extending along the coast of Chile, peaking in intensity during austral spring or summer. The Benguela Current LME of the SW Atlantic is made up of the Northern Benguela upwelling system off Namibia and southern Angola, and the Southern Benguela upwelling system off the nation of South Africa. Upwelling in the northern Benguela system continues throughout the year, peaking in intensity in austral winter, while in the southern Benguela it is much more seasonal, peaking in austral spring and summer. Exchanges of sardine and anchovy stock components between the Peruvian and Chilean systems are obvious during El Niño episodes. Similar exchanges between the two Benguela systems are likely, but have not been so obvious. Strong dynamic similarities of these three "doublet" system configurations extend to include rather precisely congruent patterns of seasonalities of the upwelling processes.

However, beneath the striking patterns of similarity lie enormous differences in fishery productivity and evident system resilience. The Peruvian upwelling system is the undisputed world's champion producer of exploited fish biomass. For example, in the late 1960s, the single country, Peru, exploiting a single fish species, the anchoveta (*Engraulis ringens*), routinely landed more fishery tonnage than the combined total of all the other fished species, both marine and freshwater, landed by all the other countries of North and South America combined. In seeming paradox, the Humboldt system appears to be less productive in terms of primary productivity than the Benguela systems. In fact, a recent study by Carr (2001) indicates that it may be only half as productive as the Benguela system. Nonetheless, the Benguela system produces less than one-twentieth the tonnage of fish routinely harvested from the Humboldt system. Moreover, while the Peruvian system has apparently managed to absorb all the blows that a massive, largely unregulated fishing industry could deliver, massive fishing by mobile fleets in the 1970s produced a collapse of the northern Benguela sardine stock and evidently switched that stock to a low productivity mode from which it has not recovered to this day.

Bakun and Weeks (2008) concluded that this "miracle of Peru" might be understood as a combination of two factors. The first is the advantageous low-latitude situation of Peru that combines strong upwelling-based nutrient enrichment with low wind-induced turbulence generation and relatively extended mean "residence times" within the favorable upwelling-conditioned near-coastal habitat. The second involves the rather novel inference that El Niño events, which are widely considered the to be the bane of the Peruvian marine ecosystem, may in reality be a unique boon in that the cyclic "resetting" of the system by temporarily destructive El Niño perturbations serves to interrupt malignant growth of adverse self-amplifying feedback loops (Bakun and Weeks 2006) within the nonlinear biological dynamics of the ecosystem.

In the contrasting case of the Northern Benguela, Bakun and Weeks (2006) argue that this ecosystem has been shifted to, and durably trapped within, an "adverse" phase, ultimately due to massive overfishing by distant-water fleets in the 1970s, that initiated a sequence of adverse nonlinear feedback loops that finally led to a degraded system that no longer favors reproductive success to the degree that it had formerly. Among the suggested factors were: (1) destruction of migratory linkages that had earlier permitted synergistic use of specialized subregional segments of the regional habitat, (2) associated removal of grazing control, allowing burgeoning planktonic growth, (3) resulting explosive proliferation of rapid-responding, opportunistic zooplanktivores, (4) ultimate infestation of the fish reproductive habitats by the zooplanktivores, with extremely destructive predation on fish eggs and larvae as a consequence.

Being located on the eastern side of the Pacific and therefore similarly directly in the path of ocean-transmitted ENSO effects, the Gulf of California system may be more similar to the Peru system in its intermittent perturbation by El Niño-associated environmental anomalies. Indeed, the Gulf of California sardine fishery appears to have rebounded very quickly from its major collapse episode in its brief history. This might be grounds for a degree of cautious optimism. However, the Gulf of California ecosystem is quite dissimilar to Peru, and also to the northern Benguela, as regards the magnitude of its fishery production. On the other hand, to this date, damaging jellyfish infestations have not appeared to be a major problem in the Gulf of California (although there seems to be a sense that jellyfish may be increasing in abundance even in the face of a growing fishery on them in the Gulf). Thus, a long term EBM strategy for the Gulf should probably involve monitoring for increases in jellyfish or other signs that the system is moving toward a drastic change in configuration, similar to the Benguela example.

## Climate change: what might the future hold?

Climate change is likely to influence the Gulf of California and its fisheries through alteration of the upwelling system in the Gulf itself, and through changes in the ENSO (El Niño Southern Oscillation) process. One of the reasons that coastal upwelling tends to be a spring-summer phenomenon in the subtropics, and a more year-round phenomena in more near-equatorial regions such as Peru, is that a strong pressure gradient forms between a thermal low pressure cell that develops over the heated land surface and higher pressure existing over the more slowly warming waters of the ocean. This cross-shore pressure gradient supports an alongshore wind that drives an offshore-directed Ekman transport of the ocean surface layer which in turn, requires upwelling of subsurface waters to balance the surface water export.

Eastern sides of oceans are characterized by much drier atmospheres than western sides. Because the most important greenhouse gas in the earth's atmosphere is water vapor, eastern ocean boundary regions tend naturally to experience a much reduced greenhouse effect. Consequently, nighttime cooling by long wave radiation is rapid and efficient. This tends to relax the thermal low pressure cells that had built up over the coastal landmass during the day. But as atmospheric greenhouse gas content increases, nighttime radiative cooling is suppressed and the average rate of heating over the land is further enhanced relative to that over the ocean, causing intensification of the low pressure cells over the coastal interior. This generates a feedback sequence as the resulting pressure gradient increase is matched by a proportional wind increase, which correspondingly increases the intensity of the upwelling in a nonlinear manner (Trenberth et al. 1990) which, in concert with ocean surface cooling produced by the intensified upwelling, further enhances the land-sea temperature contrast, the associated cross-shore pressure gradient, the upwelling-favorable wind, and so on. Moreover an additional contributing set of feedback mechanisms involves greenhouse-associated effects on the vegetal land cover that may regulate the heating of the coastal landmass (Diffenbaugh et al. 2004). A variety of observational evidence indicates that this projected increase in upwelling intensity, intensified by climate change, may even now be in the process of unfolding in the major upwelling regions of the world (Bakun 1990, 1992; Shannon et al. 1992; Schwing and Mendelssohn 1997; Mendelssohn and Schwing 2002).

One would expect that climate change might act to intensify the low pressure over the Sonora coastlands along the eastern side of the Gulf, at least during the spring and summer heating seasons. This would favor upwelling intensification along the eastern side. But it would also tend to increase the monsoon effect of the thermal heating of the continental landmass to the north, which tends to induce southerly winds in the Gulf. Thus, it is not clear which effect would predominate, although one could guess that the summer monsoon effect would be strongest in the northern Gulf, while the upwelling-intensifying effect might act strongest in the mid- and southern Gulf.

On a much larger, Pacific-basin scale, growing evidence, modeling findings, and resulting scientific consensus (e.g., Vecchi et al. 2006; Vecchi and Soden 2007) predicts, as a result of continued buildup of greenhouse gases in the earth's atmosphere, relaxation of the Pacific trade wind system, which is a key dynamic "player' in the ENSO system that produces the most intense perturbations of conditions in the Gulf of California. Thus, the Pacific equatorial system, due to relaxation of the trade wind circulation, may become in some ways more chronically "El Niño"-like in its underlying mean background state. Accordingly, while long-term mean seasonal conditions may be expected to become more chronically El Niño-like, the El Niño-associated anomalies transmitted to the Gulf of California can be expected to be less intense. These El Niño-like conditions could be more favorable to more tropical species of forage fish, and less favorable to sardines.

How these competing effects might play out in the future is unclear. But it does seem abundantly clear that rapid unidirectional climate change caused by continued increasing releases of greenhouse gases must be considered yet an additional source of uncertainty and potential peril with respect to EBM of the fishery on small pelagic forage fish, as well as other fisheries and various other types of ecosystem values that may be linked to processes occurring at the *wasp waist* of the marine ecosystem in the Gulf of California.

## Discussion

In summary, small pelagic forage fish populations are well known for their extremely variable population dynamics. This variability may be a key element in their evolved ability to interrupt incessant growth of predation pressure. Fisheries management has not been effective in controlling the radical fluctuations of exploited populations of forage fish; in fact, harvested populations are generally more variable than unexploited ones (Hsieh et al. 2006; Brander 2005). This variability has economic consequences in that fishery yields tend to be variable and difficult to predict. The natural variability of forage fish populations, and their high productivity and fast growth rates, allow forage fish populations, after they have been depleted, to recover more rapidly than slower growing and more stable fish populations (Hutchings 2001). This implies that the risk of permanently harming a forage fish population (and consequently the surrounding ecosystem) through overfishing are lower than for other kinds of fish. But a worrying counter-example is the case of the Namibian sardine, where over-fishing in the 1970s seems to have durably transformed that ecosystem to a degraded state of reduced fishery productivity that has featured a major shift from dominance by sardines to dominance of the "*wasp waist*" trophic level by jellyfish and pelagic gobies (*Sufflogobius bibarbatus*). Unfortunately, the question of what causes a pelagic marine ecosystem to "cross the line" to such a state of durable degradation is currently unanswered.

Marine ecosystems may operate to more or less degree as complex *adaptive systems*, and under this awkward reality, approaches that are designed to identify the most likely outcome of actions or events may entirely miss the less likely, but highly radical, outcomes that may lurk hidden in the "tails" of the probability distributions; even if such a radical outcome may be less likely in any particular case, it may be potentially so critical that the need to avoid it may predominate in importance over any other issue. Examples of this nature might be calamitous system transitions to widespread anoxia (Weeks et al. 2004; Chan et al. 2007) or durable infestation with medusas or other jelly predators (Daskalov 2002; Dumont and Shiganova 2003; Lynam et al. 2006) that may preclude reproductive success of *wasp waist* forage fish species that are vital to maintenance of a diverse, productively-functioning ecosystem, but in particular, to controlling the mechanisms that may generate such transitions (Bakun and Weeks 2006, 2008; Richardson et al. 2009).

Because no one system is so well understood that the probability of a transition to an unfavorable state can be confidently estimated, it will be necessary to look beyond one's particular local ecosystem in order to begin to discern such a probability distribution of a range of potential outcomes. The great evolutionary biologist, Ernst Mayr, has called the *comparative method* and the better known *experimental method* the "two great methods of science" (Mayr 1982). The comparative method is the method of choice when experimental controls are unavailable. Large marine ecosystems and large, mobile fish populations, are hardly amenable to experimental controls, and so the *comparative method* is the available alternative.

In such a case, it may be considered a high priority to assemble available experience and observations according to a well-founded comparative framework categorized as to ecosystem type and function. This would not only provide a basis for conceiving outcomes that may not have yet occurred in a system of interest, but would serve as a basis for convincing stakeholders of the importance of taking sufficient actions to guard against the worst of these, even if their likelihood may be undemonstrated in their local situation. Of course, the balance between precaution and use is always a value judgment. But it is also true, that politics works, not necessarily on the basis of proven facts, but on the basis of narratives. The extent that marine ecosystems may be preserved may depend significantly on the availability of such precautionary narratives.

The examination of the case of the sardine fishery in the Gulf of California has pointed to a number of potentially important elements of such narratives. System openness and nonstationarities have clearly emerged as important factors in interpreting available information. Effects of possible short-time-scale evolutionary adaptation appear to deserve attention. The details of the physical processes controlling ecosystem function are important. Successful management strategies for other small pelagic fisheries have been based on either the ability to forecast year class strength based on environmental conditions or (more commonly) on same-season estimates of abundance from surveys. These types of approaches, in contrast to classical stock assessment, allow management to adapt to the changing abundance of the target species (Barange et al. 2009).

The current management of the sardine fishery in the Gulf of California does appear already to include several essential EBM elements. For example, design of currently established areal fishery closures is evidently based on understanding of physical ecosystem processes and knowledge of life cycle processes and spatial habitat use by the fish stock. Most importantly, efforts are made to monitor, at least roughly, stock abundance prior to each fishing season. This may be sufficient to identify major problems before the situation may be further degraded by uninformed actions, provided that appropriate management actions are taken based on this information. The fact that the sardine catches continue to rebound in the face of an unrelenting level of fishing offers a plausible argument that this approach may have worked, at least so far. On the other hand, there is evidence, even for highly variable and productive forage fish species, that the lower a population falls during a stock collapse, the longer it will take to recover (Hutchings 2001). Reduced fishing mortality during the recovery phase may not be as effective at speeding recovery (Hutchings 2001), implying that it is better to reduce fishing during stock declines to speed subsequent recovery. Whether the ad hoc adaptive management strategy currently used for Gulf of California sardines reduces mortality sufficiently during periods of low stock productivity or whether management of the small pelagic fishery in the Gulf of California could be improved with more formal science-based harvest control rules cannot be known without an updated assessment that adequately accounts for the temporal and spatial complexity of the system.

The dynamics of the food web in the Gulf of California also merit further research, to determine whether the small pelagic fishery adversely impacts other species. The ecological importance of sardines and other small pelagic fishes as food for breeding populations of birds and mammals and potentially as grazers controlling phytoplankton growth underscore the importance of an ecosystem based approach to management of these fisheries. Considerable data exist on the diets of predators, so that it may be possible to develop a detailed trophic model for the pelagic ecosystem in the Gulf of California. Such an analysis, particularly if it was spatially explicit, would be useful for evaluating the ecosystem impacts of the small pelagic fishery.

Even if the fishery appears to be sustainable in the short term, a more elaborate system of ecosystem observations (to try to keep track of any potential expansion of zones of anoxia or of incipient increases of "jelly predators") may be warranted, given the potential importance of associated consequences. Effective arguments for the necessary resources to accomplish this may depend on availability of a well-founded, abundantly-exemplified, broadly-based interregional comparative framework, as argued earlier. Accordingly, assembly of such a framework would seem to be a high priority. Broadly-based international collaborative efforts, and willingness to share what might be considered proprietary information, would probably be vital in accomplishing it.

## Summary comments and opinions

In summary, it must be said that sustainable management of small pelagic fisheries in situations such as that of the sardine in the Gulf of California remains, at the present state of our science, somewhat of a "wing and a prayer" proposition. It appears probable that such resource populations would vary radically even in the absence of fishing.

In any ecosystem, the natural population increases of top predators must eventually be limited by "carrying capacity", i.e., limited ultimately by absence of sufficient food. In general terms, coastal upwelling ecosystems are the most productive type of ecosystem existing in the world's oceans, but they also tend to be the ones characterized by the most radical variability. Thus, when more or less inevitable starvation-related mortality of charismatic top predator fauna (e.g., seabirds, marine mammals, etc.) may occur in an upwelling situation, particularly one like the Gulf of California that is also subject to intense Pacific ENSO variability, it is likely to occur in rather massive, highly visible surges. But, however distressing, such episodes may be a necessary feature of such ecosystems (in much the same way that periodic forest fires have been found to be essential features of healthy forest ecosystems).

That being admitted, it is undeniable that modern industrial fisheries powered by fossil fuels ultimately have the capacity, if unchecked, to utterly devastate the structure and productivity of marine ecosystems, thereby depriving society of economic, cultural, and esthetic goods and services that we have come to accept as part of our natural patrimony. Therefore, we must require that these fisheries be managed as effectively as possible for the common good.

In the case of the Gulf of California sardine fishery, the management framework, based on in season estimation of abundance at the fishing grounds and biologically reasonable closed areas and seasons, seems to be adaptive. However, in the absence of a published fishery management plan and up-to-date stock assessments of the major species, it is difficult to tell whether the actual management measures that are taken every year are sufficient to sustain the resource and achieve the broader objectives of ecosystem based management. Management of this fishery currently employs basic but useful elements that can be implemented without enormously increased expenditures on detailed assessments of variabilities of both exploited and unexploited (e.g., jellyfish, mesopelagic fish, temporary migratory "visitors", marine mammals and birds etc.) components, i.e., those made by much richer, more technologically-endowed regions. On the other hand, it presently is not well documented as to how management measures (i.e., size and location of aerial closures) are determined. Moreover, production of updated formal stock assessments of major exploited components, etc., could yield an additional useful source of accessory information on the stocks themselves, as well as on ecosystem linkages and apparent consequences. In the Gulf of California case, the existence of alternate trophic pathways through the "*wasp waist*" (forage fish-dominated) "chokepoint" of the ecosystem, as well as the history of resilience of other ecosystems (e.g., Peru) similarly impacted by radical ENSO-related variability, may offer some degree of reassurance.

However, lurking always in the background is our lack of real understanding of the sort of radical shift that (as described in System "Openness") after an episode of extended heavy overfishing, left the Northern Benguela ecosystem in a durable state of seriously degraded fishery productivity. Avoiding this type of regrettable consequence must certainly be a first goal of management. But unfortunately, we don't have available a very good "road map" of the way to do it.

Clearly, our science as a whole is in need of improved technological and conceptual tools. Due to old assumptions as to the nature of the problems, it has become the pervasive custom to regionalize fisheries-related research, and thus to fund scientific development only in terms of value to a specific regional situation. This has left fisheries science largely without the resources to effectively address globally-pertinent generic issues that we are coming to recognize as recorded historical time series become longer and experiences, both positive and negative, multiply (other than via the favorable trend toward a growing number of international comparative symposia that at least allow sharing of regional information). Accordingly, we are forced to continue to rely on the old assumptions even as we are led by our experience to question them. This puts us in the uncomfortable position of being without definite answers to serious questions, often leaving the central questions as to appropriate tradeoffs between precaution and utilization to be issues more of conceptual beliefs, philosophy, and ethics, than of hard science.

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