CLIMATE CHANGE AND SMALL PELAGIC FISH

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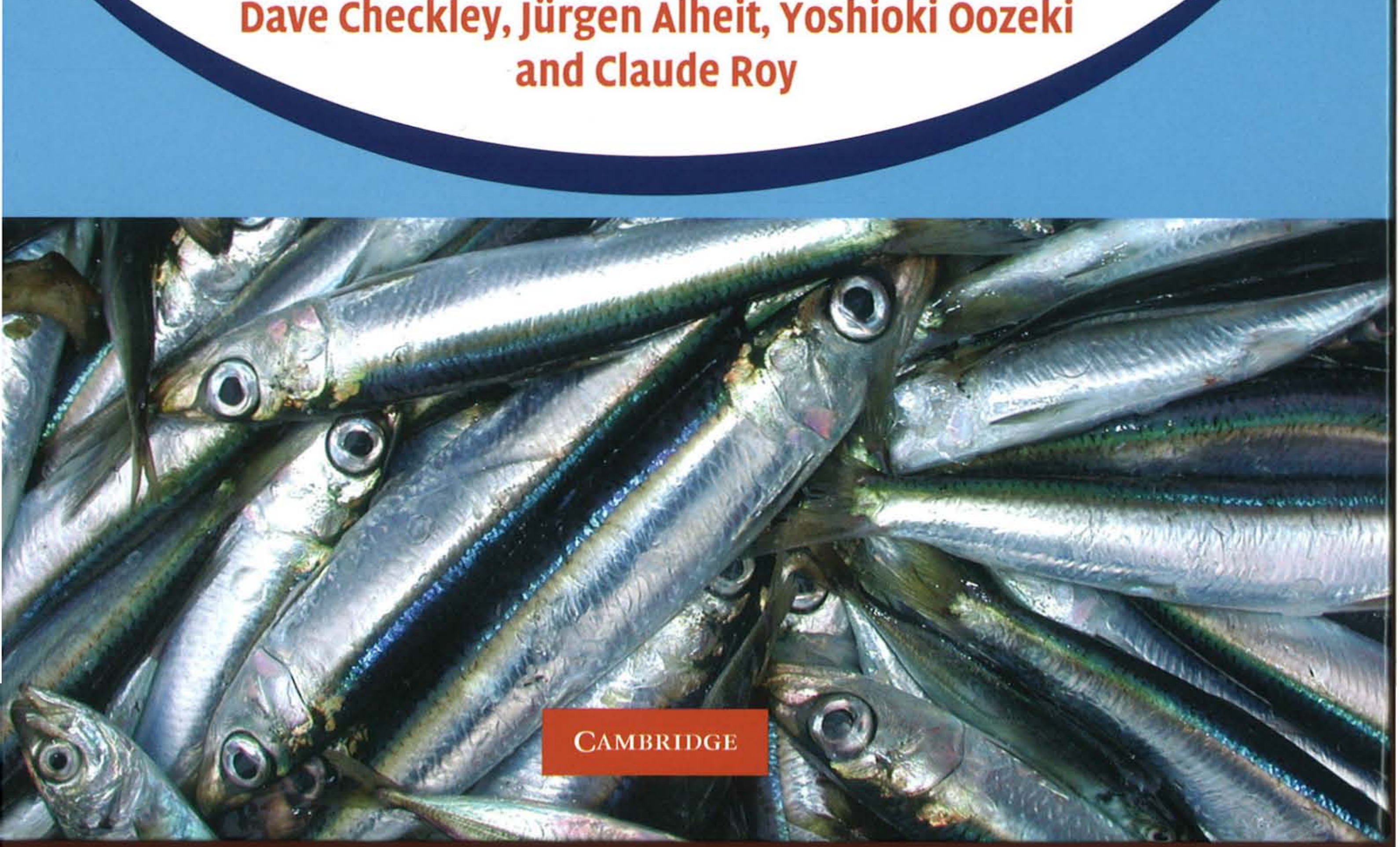

CAMBRIDGE

15 Synthesis and perspective

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Summary

The Small Pelagic Fish and Climate Change (SPACC) program was created to facilitate research on the dynamics of populations of small pelagic fish, including anchovy and sardine. These populations exhibit large variations in size, extent, and production on the scale of decades. At times, anchovy and sardine alternate in abundance. Collectively, small pelagic fish often occupy a central role in the food web they occur in, often described as a wasp-waist ecosystem. Humans are an integral part of those ecosystems. Variability of populations of small pelagic fish is believed to be due primarily to variations in climate and fishing, but the mechanisms of these relations remain unknown in most cases. It is also uncertain whether these ecosystems alternate between states, e.g. regimes, and whether inherent variability may limit our ability to predict their future states. The fisheries for populations of small pelagic fish are increasingly global in nature. While the global catch of small pelagic fish constitutes approximately one-quarter of the world fish catch and has been relatively constant during the past several decades, the catch of individual taxa and stocks varies much more. The management of these fisheries will be challenged by increasing demand for human consumption and mariculture in light of their finite and variable production, importance within the ecosystem, and unprecedented climate change, and will depend on both science and governance. We recommend continued, global research on climate change effects on small pelagic fish, and its periodic assessment for use by decision makers.

Introduction

This chapter is a partial synthesis of ideas in prior chapters. A general objective of the SPACC program has been to describe and understand the dynamics of populations of small pelagic fish (SPF) in the context of climate variability and change. The ultimate objective has been to contribute to the process of improving the global management of SPF populations, including research into areas identified as gaps in current knowledge and understanding of small pelagic fish dynamics.

Scientific uncertainty and inadequate, or inappropriate, governance, in addition to natural variability of fish stocks, have hampered successful management of SPF stocks, as manifest by collapses of the California sardine in the 1950s, the Peruvian anchoveta and Namibian sardine in the 1970s, and the Japanese sardine in 1990s (this volume, Chapters 3 and 9). Scientific uncertainty includes uncertainty inherent in an ecosystem and our imprecise knowledge and understanding of that system and how it functions, as well as uncertainty of estimating stock levels. Uncertainty also arises because ecosystems are complex and dynamic, and subject to long-term change as well as chaotic and chance events. Limits exist in our ability to predict the future state of SPF populations and ecosystems due, for example, to inadequate knowledge and the inherent variability of future climate states and fish population responses to these, including their ability to adapt to a changing environment by developing new strategies. What are our limits? To what extent can we achieve a mechanistic understanding that allows prediction, with uncertainties and perhaps including a range of scenarios, as opposed to relying on the statistical properties of the past behavior of a population or ecosystem?

While there is consensus among practitioners on many issues, it remains lacking on others. This does not necessarily indicate conflicting views but, rather, that process variability leads to different interpretations in certain situations. Thus, we are still unable to present a conceptual, let alone analytical or quantitative, model of the dynamics of

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populations of SPF capable of supporting their sustainable management. However, we do have substantial converging views, e.g. that common features are shared by the same taxon, such as anchovy or sardine, in different regions, that these taxa differ significantly from one another across regions, and that important forces on SPF include climate change and fishing. SPACC has used the comparative approach to draw broad lessons and acknowledges the need for, and value of, interdisciplinary work, given the nature of the systems it studies – e.g. climate and ocean physics, chemistry, biology, mathematical and bioeconomic modeling, and social sciences. Temporal and spatial scales, and their interactions, must be considered.

Below, we comment on our scientific understanding of the dynamics of SPF, including their populations and ecosystems, and fisheries, management, and social sciences, including economics. We discuss gaps in our current knowledge and understanding of SPF dynamics and requirements for the future. Finally, we recommend ways to achieve these requirements.

Science

Populations of small, pelagic fish, and their fisheries, fluctuate greatly on time scales of decades. Why does this occur and with what effects?

The combined results of analysis of the paleontological records, formed before intensive fishing, and more recent records, collected during fishing, indicate that populations of small pelagic fish have always fluctuated (this volume, Chapter 4). While year-to-year management does not require full understanding of the cause of these fluctuations, long-term management and investment planning would certainly benefit from a model capable of predicting the long-term dynamics of these populations with and without fishing, or as a combined outcome of the interacting drivers of fishing and the environment. Given that SPF are frequently the dominant forage fish in many, if not all, of the systems in which they occur (Cury *et al*., 2000), it is plausible that large variations in non-fishing mortality (e.g. the coefficient of natural mortality, M, units y^{-1}) are due to natural top predators or diseases. However, it often seems more likely that the cause of natural fluctuations in population size is from below, either directly by physical forcing (e.g. temperature, Takasuka *et al*., 2007), indirectly through the food web (e.g. van der Lingen *et al*., 2006; Rykaczewski and Checkley, 2008), or through a combination of such processes, e.g. "Bakun's triad" (Bakun, 1998). Our inability to predict the dynamics of SPF using traditional, density dependent models is consistent with the importance of extrinsic forcing of their dynamics (Mullon *et al*., 2009). An alternative to bottom-up and top-down forcing is the interaction between populations of SPF, e.g. competition for food or predation on early stages by one another (e.g. this volume, Chapter 7). These forces are not mutually exclusive and likely act in concert.

An associated question is whether such forcing and population responses vary continuously or non-linearly between alternative states, or regimes, and whether such changes are reversible? Often time series of population abundance or catch exhibit a hysteresis. Thus, historical populations with fishing often amass biomass gradually until achieving maximal abundance, then decline precipitously (Mullon *et al*., 2005). Whether this reflects intrinsic population or ecosystem properties or a response to fishing is unknown, due in part to low temporal resolution and imprecision of most paleontological records. A case is the Peruvian anchoveta, *Engraulis ringens* (R. Guevara-Carrasco, unpublished data). The highest recruitment of this species observed in the last two decades was during normal or mildly warm years rather than in cold years. In recent years, anchoveta larvae have been observed in more saline and warmer, subtropical waters. This is contrary to historic records, and consistent with the unexpected appearance of recruits offshore in some years. Thus, the Peruvian system does not seem to have returned to the same state that existed prior to the collapse of the anchoveta fishery in the early 1970s.

Populations of anchovy and sardine (*Sardinops* spp.) are sometimes viewed as alternating in size and/or "replacing" one another (Kawasaki, 1983). Alternation implies direct interaction (e.g. competition or predation), different responses to the same stimulus or co-occurring stimuli, and/or separate responses to simultaneous changes of their respective habitats. Thus, larvae of anchovy and sardine off Japan differ in their temperature for optimal growth (Takasuka *et al*., 2007). Within the Pacific basin, SPACC systems exhibited these alternations in the last century. However, studies of the paleontological and historical records do not support a strict alternation of populations (this volume, Chapter 4; Fréon *et al*., 2003). The explanation for the discrepancy between paleontological and recent records might be due to the different lengths of these two types of time series (1000s of years vs. ~ 100 years) and/or the effect of fishing, which has been shown to affect the response of fished populations to climate variability (e.g. Ottersen *et al*., 2004, 2006; Planque *et al*., in press). Strong fishing pressure may affect the alternation by increasing the abruptness of population decreases and thus enlarge the duration of the period when one taxon conspicuously dominates the system. Without fishing, this period may be shorter and thus not be noticed in the paleontological record because of its limited resolution (this volume, Chapter 4). Moreover, most SPACC regions have one dominant taxon whose peak abundance, or catch, exceeds that of other species. Anchovy and sardine are similar within their respective taxa but are different from one another (e.g. for the Benguela Current, this volume, Chapter 7). Thus, as the environment varies, it is plausible that sardine and anchovy respond independently and differently, i.e. they "march to the beat of different drummers." This is consistent with their differing properties of population production (Jacobson *et al.*, 2001), with sardine varying more gradually and over a larger time scale than anchovy, and with specific space occupation strategies (Barange *et al.,* 2005). Such major differences at this taxonomic level are also consistent with the shallow genetic histories of these species (Grant and Bowen, 1998; Lecomte *et al.*, 2004). That is, genetic lineages of anchovy and sardine are long (10^7 y) and distinct, while the populations of each have been established only relatively recently (10^4 y) and in similar habitats for each taxon, with sardine in more oceanic regions and anchovy in more coastal, productive regions (this volume, Chapter 3); these patterns vary with population size and exceptions exist (e.g. Barange *et al.*, 1999). The time series of abundance, both paleontological (several thousand years) and historical (to hundreds of years), are consistent with a conceptual model in which populations fluctuate due to extrinsic (climate, fishing, prey, and predation) rather than intrinsic (population size) factors. This, in turn, is consistent with the observed variation of sardine and anchovy being in or out of phase and with similar wavelengths of the "pseudocycles" of the two groups of species. It also allows for apparent global synchrony within or between anchovy and sardine stocks from different oceans, which does not necessarily reflect a global response to a common forcing (Fréon *et al.*, 2003).

Questions exist in regard to climate and its effects on small pelagic fish that limit our ability to predict their dynamics. What is the cause of the physical variability that appears so important to SPF? While ENSO and modes of multidecadal variation have been described, climate forecasts over decades and regions lack necessary accuracy to be useful for decisions. What is the relationship between physical forcing by the climate and the response of SPF? Alheit *et al.* (this volume, Chapter 5) posit that a sequence of physical changes may occur, followed by a relatively rapid response of biological components of the ecosystem. Jacobson *et al.* (2001) show that the specific (per capita) growth rate of SPF populations responds rapidly to change of the environment and precedes a numerical response of the population. Thus, population size lags physical forcing. The differing behaviors of time series of physical (linear or stochastic) and biological (non-linear) variables relevant to climate and fisheries off California indicate that there may be inherent limitations to our ability to predict fish dynamics (Hseih *et al.*, 2005). Once again, we need a mechanistic understanding of how the interdecadal changes observed in physical variables are related to biology to be able to interpret, let alone predict, the dynamics of SPF in a changing environment. Progress towards a mechanistic understanding has been made in some systems, e.g. the Benguela (Roy *et al.*, 2007; this volume, Chapter 7), California (Rykaczewski and Checkley, 2008; this volume, Chapter 12), Humboldt (this volume, Chapter 5), and Kuroshio (Takasuka *et al.*, 2007) Currents. Some attempts at prediction were made by Fréon *et al.* (this volume, Chapter 14), based on present knowledge, but they remain conjectures.

Wasp-waist (Rice, 1995; Bakun, 1996) is often used to describe the ecosystems with SPACC populations. It connotes a large population or assemblage of SPF, usually dominated at any one time by a single species, which interacts strongly with its prey and predators. Wasp-waist implies that variation in the abundance of SPF is likely to have significant effects on the ecosystem at several levels. This, however, does not preclude bottom-up effects on SPF. Thus, in the Peruvian upwelling ecosystem, parallel changes observed in phytoplankton, zooplankton, and anchoveta abundances are consistent with bottom-up effects, though top-down effects cannot be ruled out (this volume, Chapter 5; Chavez *et al.*, 2008). It may be important to distinguish between individual populations of SPF and the sum of all populations, either regionally or globally. The global catch of all SPF was less variable than that of its component taxa; for 1950–2004, the coefficient of variation was 0.36 for global SPF landings, 0.65 for global anchovy landings, and 0.77 for combined, global sardine, sardinella, and pilchard landings (this volume, Chapter 10). This, in turn, is consistent with the hypothesis that the composition of an ecosystem may change in a relatively subtle manner, e.g. between states dominated by anchovy or sardine, but with little change in system structure and hence the overall flow of matter and energy (Cury and Shannon, 2004; Jarre *et al.*, 2006). This also implies a constant carrying capacity of the ecosystem which, conversely, is believed in some cases to vary over time (e.g. Jacobson *et al.*, 2005). Alternatively, the ecosystem may change in a dramatic fashion, e.g. between states when SPF are dominant in an ecosystem and when they are almost entirely absent, as is currently the situation in the northern Benguela (see this volume, Chapter 8), with drastic changes in system structure and function (van der Lingen *et al.*, 2006b). In the Peruvian upwelling ecosystem, the warm period of mid 1970s to mid 1980s, when sardine was abundant, had similar or higher total biomass of pelagic (sardine, jack mackerel, and mackerel) and demersal (hake and other demersal) taxa to when anchoveta was abundant; the ecosystem may have fundamentally changed (R. Guevera-Carrasco, unpublished data). Another factor to consider in this context is the potential impact of interactions and energy flows between SPF and mesopelagic fish. In the Kuroshio region, myctophids may be a dominant component of the ecosystem in terms of biomass

(Gjøsæter and Kawaguchi, 1980); this is now being investigated using acoustic surveys. The effects of removal by fishing, as opposed to the natural variation of SPF population size, on the ecosystem remain unknown. Shannon *et al.* (this volume, Chapter 8) show that fishing may alter the relative production of pelagic and benthic components of an ecosystem, and that fishing and environmental changes act synergistically to produce the ecosystem dynamics we observe. A certainty is that humans must now be considered an important part of the ecosystem and that overexploitation decreases resilience of systems to climate change (for review see this volume, Chapter 14). Further, the effects of humans on the ecosystem require consideration of issues such as the non-consumptive value of SPF, e.g. as forage for fish, marine mammals, and birds. SPF play a pivotal and crucial role in the ecosystems in which they are found.

Fisheries

Most SPF stocks are commercially exploited, and many are assessed and managed on the basis of scientific understanding (with some glaring exceptions; this volume, Chapter 9). How can we distinguish between the effects of climate change and fishing on those stocks and their ecosystems, and of what value is this to management?

Fisheries on SPF are local, but the industry is increasingly global. From the physical forcing, with hypothesized teleconnections, to economics, including global trade, a fishery in one region is affected by multiple activities worldwide. This is perhaps most evident in the increasing demand for anchovy and sardine products for mariculture. The early, and large, fisheries for small pelagics were almost entirely for human consumption, especially canning, or agrifeed, e.g. fish meal and oil for poultry and swine. The use of SPF to feed fish, poultry, and swine has grown relative to its use for human consumption and, in particular, an increasing fraction of the world catch of SPF is used for mariculture. It is predicted that, by 2010, 50% of the fish meal and 80% of the fish oil will be used in global mariculture (Delgado *et al.*, 2003). Both are global commodities, the average fish meal ton traveling over 10 000 miles between producer and consumer, and increasingly in demand by mariculture in developing regions such as China (Delgado *et al.*, 2003). Much of the sardine harvested off California is frozen in blocks and shipped to Australia to feed bluefin tuna captured from the wild, "grown out" in pens, harvested, and exported to global markets. In addition, fish meal and oil can be partially substituted for the animal food markets by vegetable proteins (e.g. soybean, corn). The balance between these products is currently under threat by the increased production of biofuels; these displace agrifeed vegetable crops which, in turn, affects the demand for and price of SPF. As the world's population grows, these demands, as well as the direct use by humans, will only increase. SPF stocks will thus be managed under increasing global demand and a limited, variable supply.

This difficult management situation is likely to be aggravated by the issue of bycatches and discards, which are already frequent in SPF due to the implementation of quotas by species and size limitations. SPF tend to shoal by size but different species are frequently found within the same school or in neighboring schools and, as a result, are caught together. Mixed fish schools are more frequent in situations of low abundance of at least one of the two species, for reasons that are still debated (Bakun and Cury, 1999; Fréon and Dagorn, 2000; this volume, Chapter 13). Under a scenario of a decrease in production due to the interaction of heavier exploitation and increased variability in abundance, due to climate change, bycatches and discards of SPF are likely to increase, promoting a negative feedback on the abundance of these species.

Another issue is the effect of climate change on the catchability of SPF. Anchovy off Peru and sardine off California are confined to nearshore waters during El Niño, increasing their availability to fisheries (this volume, Chapter 3, and the entire book). Fishing gears directed to massive capture of SPF take advantage of the highly gregarious behavior of these species, which are found in dense schools, themselves regrouped in clusters. Furthermore, the purse seine (the fishing gear by far the most used to catch SPF) only captures schools located sufficiently close to the surface. Therefore, SPF catchability largely depends on the level of aggregation and distance of fish from the surface. How climate change will affect catchability is difficult to predict, but it is likely that in areas where the depth of the thermocline and/or the oxycline will decrease (increase), fish schools will be distributed in a thinner (wider) upper layer and therefore more (less) vulnerable to purse seiners. Similarly, lower (higher) plankton concentration is expected to decrease (increase) school size.

Ecosystem-based management requires an understanding of the role of SPF in their respective ecosystems. To what degree are fluctuations in abundance natural, and thus presumed to be unavoidable, and to what degree are these due to human activity, including fishing and anthropogenic climate change? The paleontological record shows SPF stocks varied independent of fishing. The hysteresis in stock fluctuations may be due to fishing and, if so, perhaps minimized by decreasing fishing mortality (F, y^{-1}) when a decline is indicated. What are the trade-offs between harvesting small pelagic fish for immediate economic gain and leaving them in the water as forage for higher trophic levels, including predatory fish, squid, marine mammals, and seabirds? The biological, economic, and social consequences of these choices are complex, yet necessary to understand for wise, long-term management. If populations and ecosystems change among states that persist over time (~ regimes), are these changes reversible? For example, whether forced by physics, fishing, or both, is the shift of the Northern Benguela ecosystem from one dominated by small pelagics to one that appears to be dominated by gobies and jellyfish likely to persist, or will anchovy and sardine return to dominate (Boyer and Hampton, 2001)? Does fishing of a stock of SPF alter the resilience of the ecosystem of which it is a part? Decline in biodiversity appears to decrease resilience (Chapin *et al.*, 2000; Planque *et al.*, in press). Does exploitation of a stock have a similar effect? For example, the variation of SPF abundance is believed to have led to decreased abundance of their seabird predators off Peru (Jahncke *et al.*, 2004) and South Africa (Crawford *et al.*, 2006), yet it is unclear if declines in SPF abundance from fishing alter the resilience of the respective ecosystems to climate change and further fishing.

The time scales of change of the interacting elements of small pelagic fish and their fisheries merit consideration. The time scales of investment and capitalization (e.g. in vessels and processing plants) and fish stock fluctuations interact to exacerbate the effects of unfavorable environmental conditions and represent a threat for SPF stocks. This threat is enhanced when overcapacity is high, as in Peru, with the largest monospecific fishery in the world and where overcapacity surpasses 300% (Fréon *et al.*, 2008). On a longer time scale, fishing may alter the genetics of the fished stocks and thus their population dynamics and perhaps resilience to environmental change. Recent studies indicate that the life history characteristics of exploited populations of cod, herring, salmon, plaice, and other taxa have changed over time due to fishing (Jørgensen *et al.*, 2007, and references therein). The "shallow life histories" of SPF stocks worldwide indicate that these stocks may be particularly susceptible to forces such as fishing and climate change (Grant and Bowen, 1998; Lecomte *et al.*, 2004). In fact, small pelagic fish are the subject of the SPACC program due to this susceptibility (e.g. Box 5.1 in this volume, Chapter 5). Anchovy lifespan being shorter than sardine, the former species may be more prone to genetic adaptation in response to climate change and harvest pressure.

If one assumes that SPF stock size varies with the environment, sustainability of the catch of that stock may not be an appropriate goal. Rather, fisheries management must adapt to such variability, e.g. by allowing increased fishing pressure for a particular stock under an improving environment and *vice versa*. The challenge is to know, in real time, when the environment is improving or deteriorating. Fréon *et al.* (2005) proposed a two-level (short- and long-term) management strategy to cope with interannual and interdecadal variations in abundance of pelagic species. This would entail adjusting the quota at the interannual scale, and adjusting the nominal effort (number of boats) at the interdecadal scale. Other practitioners instead favor adjustments in harvest rates that reflect ecosystem productivity (see this volume, Chapter 9).

Two examples of management illustrate the combined importance of science and governance. The fishery for the Pacific sardine off California may be an example of science and governance resulting in successful management. Long-term variation of sardine productivity is incorporated in the harvest decision rule, allowing for a greater fraction of the assessed stock to be harvested in favorable than unfavorable ocean conditions (Hill *et al.*, 2006). The Magnuson Stevens Act (http://www.nmfs.noaa.gov/msa2007/index.html) created a governance structure that incorporates science in US fishery management. Conversely, the Bay of Biscay anchovy may have suffered from both scientific uncertainty and a lack of adequate governance, the consequence being the recent closure of the fishery. This situation is complicated, however, by the northward shift in distribution of anchovy into the North and Baltic Seas in recent decades, this being detrimental to anchovy in the Bay of Biscay, where the catches are regulated, but favorable to anchovy in the North and Baltic Seas, where they are not regulated (Beare *et al.*, 2004). Because governance decisions involve economic and social considerations in addition to scientific evidence, such considerations should be incorporated into management models of these fisheries. This reinforces our belief that humans are part of the ecosystem and that decisions affecting the ecosystem, and/or its stocks, must consider humans, as acknowledged in the current shift towards an ecosystem approach to fisheries management (cf. this volume, Chapter 11).

Future

We know that the Earth's climate is changing due to human activity and that the human population is growing (IPCC, 2007). How will these two processes affect stocks of SPF in the future? Although SPACC focuses on climate change effects, it is impossible to consider these in isolation from the increasing demand for SPF.

Throughout this book, the effects of climate variability on SPF have been discussed (e.g. see boxes in all chapters). Most of the issues concerning the effects of past climate change on SPF are relevant to our consideration of future climate change. However, future change due to human activity will be unprecedented, at least with regard to the time scales of our present knowledge (e.g. decades to millennia). Thus, the past behavior of SPACC populations may not represent their future behavior, due to changes in both the physical forcing and biological response. Global warming, due to enhanced atmospheric CO_2, will vary regionally and affect hydrology; ocean temperature, stratification, and currents; winds and the magnitude and frequency of events, such as cyclones and perhaps ENSO; and affect the phenology, or timing, of biological events, with potential effects on ecological interactions (e.g. match–mismatch). In addition, approximately half of the CO_2 introduced into the atmosphere will be sequestered in the ocean, altering its chemistry in ways that are only now being imagined and elucidated, and with equally unknown effects on its biota and ecology. Longitudinal shifts in species, e.g. the ongoing poleward shift in distributions of anchovy and sardine into the North Sea (Beare *et al.*, 2004), may affect management as well as have ecological implications. Recent progress in ocean observation techniques and high-resolution models of ocean dynamics (e.g. Guo *et al.*, 2003; Miyazawa *et al.*, 2004; this volume, Chapters 6 and 14) will allow us to test hypothetical mechanisms with the data for SPF and their physical and biological environment. A summary of expected climate change impacts on fish populations is provided in Barange and Perry (in press).

As the human population increases in size and expectations (e.g. quantity and quality of life), the demands on SPF, and other aspects of their ecosystems, will only grow. As discussed above, mariculture will require increasing amounts of SPF for feed, competing with the demand of SPF for human consumption and non-consumptive use (e.g. forage for species at higher trophic levels). The global dimension of these demands indicates the complexity of SPF dynamics and the potential for effects on such issues as food security (cf. Lobell *et al.*, 2008).

Ultimately, scientists must inform decision makers and, ideally, governance will use science to wisely manage resources. Because the future will include unprecedented climate change and demands, it is necessary, now more than ever, to achieve a mechanistic understanding of the dynamics of SPF.

Recommendations

SPACC has benefited from the global comparison of populations of and regions with small pelagic fish. Although each stock and region is unique, common properties exist. Among these are the recognition of the influence of a varying climate on populations, of consistency within and differences between anchovy and sardine, of the pivotal role these stocks occupy in their wasp-waist ecosystems, of the global nature of interactions involving SPF, and of the certainty of future change in climate and demand for SPF. While past studies have focused primarily on the highly productive upwelling regions, future studies will benefit from extending the synthetic approach to multiple systems at a global scale, including, for example, western boundary currents. We feel that these stocks and systems merit continued examination to achieve the best understanding with which to inform decision makers.

To facilitate future research on climate change and small pelagic fish, we recommend an international program like SPACC. This should use the comparative approach and involve scientists from a broad spectrum of disciplines, including climate, fisheries, oceanography and the social sciences. The research focus should include the ecosystem.

International assessments of the state of science in particular areas are effective means by which to inform decision makers. Examples include the Intergovernmental Panel on Climate Change (http://www.ipcc.ch/) and the International Assessment of Agricultural Science and Technology for Development (http://www.agassessment.org/). An assessment is a periodic, critical evaluation of the status of information on a subject for use by decision makers. It is achieved by amassing, evaluating, and synthesizing all the relevant, peer-reviewed literature to arrive at, in an open and transparent manner, a consensus statement relevant to policy. Risk and uncertainty are addressed. While we recognize the need of managers of fisheries for rapid and timely scientific advice, e.g. population assessments, economic evaluations, and near-term forecasts, we also recognize the need for a broad assessment of the science of SPF and climate. Hence, we recommend the periodic, international assessment of climate effects on small pelagic fish.

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