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REVIEW

Socio-economic impacts and responses of the fishing industry and fishery managers to changes in small pelagic fish distribution and abundance

Felipe J. Quezada-Escalona · Desiree Tommasi · Isaac C. Kaplan · Pierre-Yves Hernvann · Timothy H. Frawley · Dorleta Garcia · Leire Ibaibarriaga · Sonia Sánchez-Maroño · Carryn de Moor · Jennifer Beckensteiner · Amy M. Schueller · Diana Feijó · Domenico Ciorciaro · Hiroyuki Kurota · Ricardo Oliveros-Ramos · Robert P. Wildermuth · Ray Mroch · Laura Wise · Matthew R. Baker · Cecilie Hansen · Sidi Ahmed Hemed · Timothée Brochier · Stephen M. Stohs · Concepcion Enciso-Enciso · Nis S. Jacobsen

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Abstract Small Pelagic Fish (SPF) exhibit large fluctuations in abundance and distribution in response to environmental variability. To maintain the resilience of fishing communities and develop effective and equitable climate adaptation strategies, improved understanding of how the fishing industry responds to spatio-temporal shifts within and across SPF populations is of critical importance. In this paper, we examine the responses of the fishing industry and resource managers to shifts in SPF availability worldwide and identify the resulting socioeconomic impacts. Leveraging SPF case studies from around the globe, we synthesize and compare the social-ecological linkages and feedbacks mediating how SPF fisheries respond to changes in marine ecosystem structure and function associated with (1) spatial shifts in species distribution and habitat availability, (2) 'boom

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F. J. Quezada-Escalona (✉) · D. Tommasi · T. H. Frawley
Fisheries Collaborative Program, Institute of Marine Sciences', University of California, Santa Cruz, Santa Cruz, CA, USA
e-mail: fequezad@ucsc.edu

F. J. Quezada-Escalona
Departmento de Economía, Universidad de Concepción, Concepción, Chile

D. Tommasi · T. H. Frawley · R. P. Wildermuth · S. M. Stohs
Fisheries Resources Division, Southwest Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, La Jolla, CA, USA

I. C. Kaplan
Conservation Biology Division, Northwest Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, Seattle, WA, USA

P.-Y. Hernvann
DECOD (Ecosystem Dynamics and Sustainability), IFREMER, INRAE, Institut Agro, Nantes, France

D. Garcia · L. Ibaibarriaga · S. Sánchez-Maroño
Marine Research, AZTI, Basque Research and Technology Alliance (BRTA), Sukarrieta, Bizkaia, Spain

C. de Moor
Marine Resource Assessment and Management (MARAM) Group, University of Cape Town, Rondebosch 7701, South Africa

J. Beckensteiner
Institut de Recherche pour le Développement, UMR ENTROPIE (IRD, University of La Réunion, CNRS, University of New Caledonia Ifremer), c/o IUEM, Plouzané, France

and bust' population dynamics, or (3) changes in fish size and quality. Our case studies illustrate multiple paths towards the resilience of small pelagic fisheries and the fishing industry dependent upon them while emphasizing the need for increased coordination and cooperation across sectors and scales as climate change progresses. Drawing from the lessons offered by historical responses, as environmental variability increases, efforts to increase the flexibility and dynamism of SPF harvest portfolios and management strategies, licensing regimes, and international catch and allocation agreements may be required to ensure resource sustainability and human well-being.

Keywords Climate change · Small pelagic species · Fisheries · Socio-ecological systems · Communities' adaptive responses

Introduction

Small Pelagic Fish (SPF) are critical for global food security (Robinson et al. 2022a) and make up 25% of the world's total fish catch (Hilborn et al. 2022). By volume, SPF comprise some of the largest and most productive fisheries worldwide, including both large-scale, industrial fishing fleets whose "reduction fisheries" (i.e., when fisheries catch is reduced to fish meal or fish oil) fuel the global aquaculture industry, and small-scale fisheries that provide fish for direct consumption to local markets and households and are considered a key source of

A. M. Schueller
Sustainable Fisheries Division, Southeast Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, Beaufort, NC, USA

D. Feijó
IPMA - Portuguese Institute of Ocean and Atmosphere, IPMA Matosinhos, Av. General Norton de Matos, 4, 4450-208 Matosinhos, Portugal

D. Feijó
UVigo, Universidade de Vigo, Edificio Filomena Dato, Oficina 46, Campus Universitario Vigo, 36310 Vigo, Pontevedra, Spain

D. Ciorciaro
Department of Science and Technology (DiST), Marine Ecology Laboratory, Parthenope University of Naples, Centro Direzionale—Isola C4, 80143 Naples, Italy

H. Kurota
Fisheries Resources Institute, Japan Fisheries Research and Education Agency, Nagasaki 851-2213, Japan

R. Oliveros-Ramos · T. Brochier
Institut de Recherche pour le Développement, UMR MARBEC (IRD Univ Montpellier, CNRS, Ifremer), Montpellier, France

R. Mroch
Fisheries Statistics Division, Southeast Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, Beaufort, NC, USA

L. Wise
IPMA - Portuguese Institute of Ocean and Atmosphere, IPMA Algés, Av. Alfredo Magalhães Ramalho, 6, 1495-165 Algés, Portugal

M. R. Baker
School of Aquatic and Fishery Sciences, University of Washington, 1122 NE Boat St, Seattle, WA 98105, USA

M. R. Baker
Resource Assessment and Conservation Engineering Division, Alaska Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, Seattle, WA, USA

C. Hansen
Institute of Marine Research, 5817 Bergen, Norway

S. A. Hemed
Institut Mauritanien de Recherches Océanographiques et des Pêches (IMROP), BP 22, Nouadhibou (Cansado), Mauritania

T. Brochier
Sorbonne Université, SU, Institut de Recherche pour le Développement, IRD, UMMISCO, F-93143 Bondy, France

Present Address:
T. Brochier
IRD, MARBEC, Av. Jean Monnet, CS30171, 34203 Sète Cedex, France

C. Enciso-Enciso
IMIPAS -Instituto Mexicano de Investigación en Pesca y Acuacultura Sustentables, Carretera Tijuana-Ensenada Km 97.5 Parque Industrial Fondeport, C.P. 22760 Ensenada, Baja California, Mexico

N. S. Jacobsen
National Institute of Aquatic Resources, Technical University of Denmark, Kemitorvet 1, 2800 Lyngby, Denmark

affordable and essential micronutrients for low and middle income countries (Robinson et al. 2022a). SPF biomass is highly variable across space and time due in part to the strong sensitivity of their dynamics to environmental variability (Peck et al. In Review, 2021; Chavez et al. 2003; McClatchie et al. 2017). Given their critical ecological role in transferring energy from the planktonic food web to higher trophic levels, changes in SPF availability and abundances impacts both directed SPF fisheries and other dependent predators, including commercially important higher trophic level finfish and endangered, threatened, and protected species such as turtles, mammals and seabirds.

Managers of SPF fisheries must negotiate volatile and cyclical population dynamics linked with environmental variability while balancing trade-offs between large-scale directed catch of SPF and their role in (1) supporting regional marine ecosystems as a forage base and (2) providing direct benefits to coastal communities as a source of livelihoods and nutrition. These fisheries have traditionally been managed using Maximum Sustainable Yield (MSY), Optimal Yield (OY), and other related principles rooted in classical bioeconomic theory. However, as the rate of global environmental change accelerates, fisheries scholars and practitioners seeking to manage for both ecological sustainability and human well-being have been compelled to consider SPF and other fisheries as complex and adaptive social-ecological systems (SES). Indeed, it is increasingly recognized that managing for MSY alone may constrain the contributions of fisheries to nutrition (Robinson et al. 2022b), employment (Bavinck et al. 2024), and human well-being (Giron-Nava et al. 2021). Those applying an SES framework to fisheries (Cinner et al. 2018; Mason et al. 2022) argue that system-level outcomes are a product of the interactions and feedbacks between ecological, socioeconomic, and governance dimensions, and that managing for resilience (i.e., the capacity of a system to absorb disturbance while retaining its core attributes and capacity to regenerate) may require moving beyond broad-scale single-species management paradigms (Walker et al. 2004; Wilson 2006; Frawley et al. 2021).

Climate change is already affecting the ocean and coastal ecosystems and the services they provide (IPCC 2021, 2022). At the current rate of greenhouse gas emissions, these changes are projected to impact fish distribution and productivity, including those of SPF (Cheung et al. 2015; Schickele et al. 2021; Koenigstein et al. 2022), sometimes with consequences for marine predators and ecosystems (Hilborn et al. 2017; Free et al. 2021; Guibourd de Luzinais et al. 2023; Liu et al. 2025) as well as resource dependent fishing communities (Smith et al. 2021; Payne et al. 2021; Mason et al. 2022) and households (Green et al. 2021). Improved understanding of how the fishing industry—which includes harvesters (individuals actively involved in harvesting fish), processors and dealers – responds to spatio-temporal shifts in SPF availability is paramount to developing adaptation strategies capable of buffering against climate shocks and stressors.

In this paper, we explore the adaptive response of the SPF fishing industry and management structures to shifts in resource abundance and spatial distribution by comparing case studies of SPF fisheries, and the unique local and/or regional context with which they are associated, from around the globe. Specifically, we discuss case studies for North-West Africa, South Africa, Japan, North East Atlantic macro-region, the Bay of Biscay, Portuguese Iberian waters, Southern Tyrrhenian Sea in Italy, U.S. West Coast, U.S. East Coast, Gulf of Mexico, Mexico Northwest Coast, and Peru. We allocate case studies into three different groups showcasing the coupled socio-ecological responses to (i) shifting stock distributions, (ii) the boom and bust dynamics of SPF, and (iii) changes in fish size and quality. This effort was initiated at the "Evaluating Inter-Sectoral Tradeoffs and Community-Level Response to Spatio-Temporal Changes in Forage Distribution and Abundance" workshop convened on November 7, 2022, as part of the PICES/ICES Small Pelagic Fish (SPF) Symposium on "New Frontiers in SPF Science and Sustainable Management" held in Lisbon, Portugal, which brought together 29 participants from across the globe.

While as yet undescribed unifying patterns and processes may exist, it is also likely that many responses are context-dependent, based on differences in local regulations, industry structures, market institutions, and social norms (OECD 2011). Indeed, even within the same set of institutions and regulations, harvesters and vessels might have heterogeneous responses to similar drivers depending on their individual preferences and technological characteristics (Zhang and Smith 2011; Quezada et al. 2023a). In conducting our comparative case study analysis, we identify the dynamics and operations of the main SPF fisheries globally, shocks that have occurred over time and their impacts on fishing communities, and the common issues and challenges faced by both industry and managers worldwide due to climate-driven changes. By learning from historical patterns of responses to variability, we infer potential opportunities or barriers to climate adaptation and identify attributes of socio-ecological systems that can foster resilience. Though our case studies focus on SPF, they are relevant to other global fisheries resilience frameworks (Cinner et al. 2018; Mason et al. 2022) that emphasize socio-economic and governance responses that hinge upon available assets, flexibility, organization, learning, and agency (Steins et al. 2023). The case studies illustrate adaptation (and barriers to it) at the scale of individual harvesters, nations, and international commerce and governance, and support the assertion that economic factors that explain harvesters, processors and dealer' behavior—especially the ones that depend on external factors beside the biological characteristics of the species or the environment, such as market prices, closures, and cost—must be considered when anticipating climate change impacts on fisheries globally (Haynie and Pfeiffer 2012).

Small pelagic fisheries around the world

Average annual catches reported by FAO FishStatJ (FAO 2020) show that South America is the most prominent global region for SPF landings (Fig. 1),

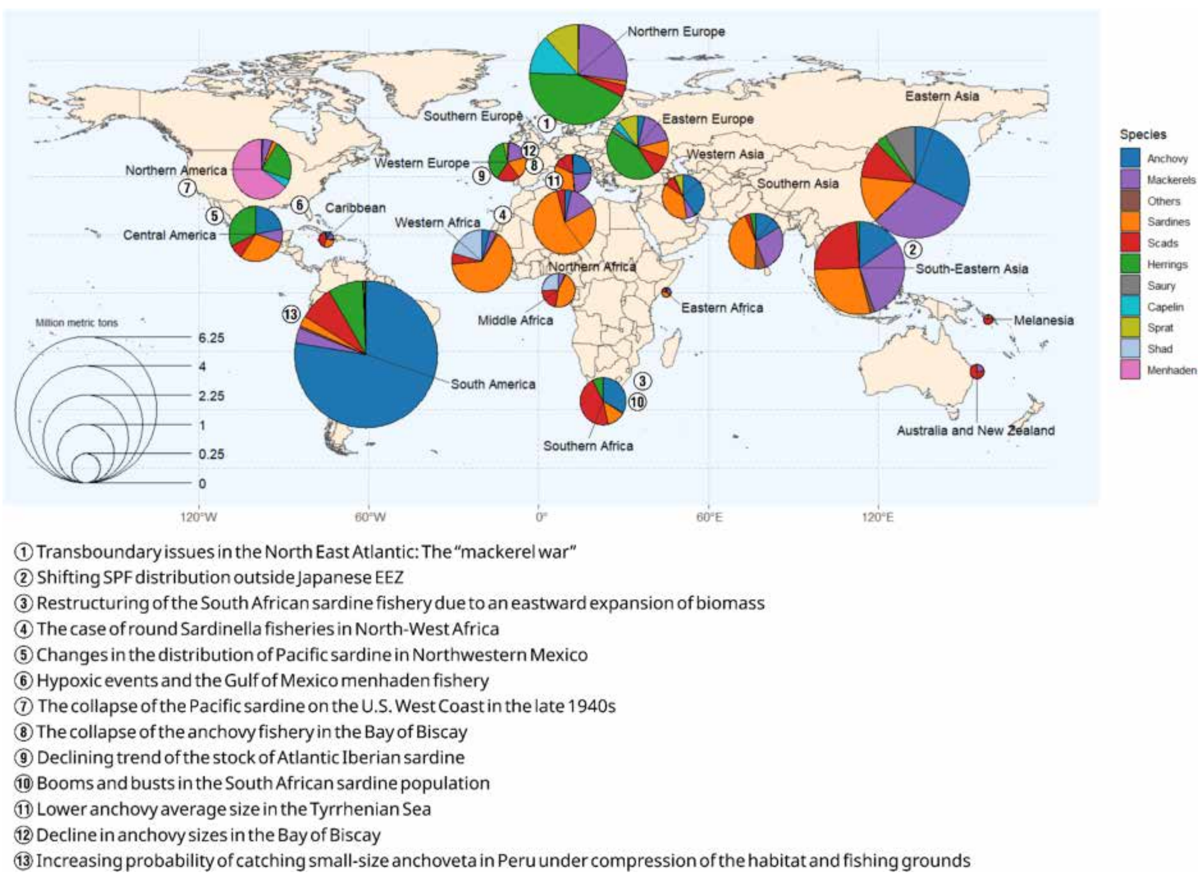

Fig. 1 Average annual catches (2010–2020) of forage fish by region and taxonomic group (Million metric tons). Each number within a white circle corresponds to a particular case study. The number is linked to the first column in Table 2. Data: FAO FishStatJ

with more than six million tons on average in annual catches. Global catches are driven mostly by landings of Peruvian anchoveta (*Engraulis ringens*). Other important species in terms of catches are mackerel (*Scomber scombrus*) and herring (*Clupea harengus*) in Northern and Eastern Europe, sardinella (*Sardinella aurita* and *Sardinella maderensis*) in Northern and West Africa, and mackerel and scad (*Scomber japonicus*, *Scomber australasicus* and *Trachurus japonicus*) in Eastern and South-Eastern Asia.

To better understand the institutional and operational context that the SPF fishery faces in different parts of the world, we summarize the operations of each case study region in Table 1. For a more detailed overview of landings, biomass, and price trends, and other relevant descriptions of the fishery operation, see the Supplementary Material.

Climate-driven impacts on SPF and responses of the fishing industry and managers

In this section, we present case studies in three different groups to showcase different drivers of the response of SPF fisheries to spatio-temporal changes in forage distribution, abundance, and size or quality. For each case study, we analyze the responses or adaptation strategies that the fishing industry implemented and the management challenges that government agencies faced under these scenarios. A summary of each case study presented in this section is presented in Table 2.

Challenges to the industry from shifting stock distribution

Climate change is expected to drive shifts in the spatial distribution of marine species (Pecl et al. 2017), exposing fishing communities to climate change risk as target species availability over fishing grounds is altered (Rogers et al. 2019). When changes in spatial distribution lead to mismatches between species availability and supply of quota, conflicts can arise. Such conflicts can be exacerbated when species cross management boundaries (e.g., between states or countries), as exemplified by the North East Atlantic mackerel case study.

Transboundary issues in the North East Atlantic: the "mackerel war"

The northwest expansion of North East Atlantic (NEA) mackerel (*Scomber scombrus*) into Icelandic and Greenlandic waters during the summer feeding season since 2007 motivated a conflict between the European Union, Faroe Islands, Greenland, Iceland, and Norway, and with the United Kingdom (UK) since Brexit (Gray 2021). The conflict began in 2009 when Iceland and the Faroe Islands decided unilaterally to increase their Total Allowable Catch (TAC) quota share and broke the TAC allocation agreement between member states of the North East Atlantic Fisheries Commission (NEAFC) (Gray 2021). At the beginning of the conflict, Iceland, Greenland, and the Faroe Islands argued that NEA mackerel had changed its distribution permanently, giving them the right to increase their quota share, while the European Union and Norway argued that the change might not be permanent. According to Olafsdottir et al. (2019), the northward movement of NEA mackerel was motivated by an increase in stock abundance and sea temperature that led to a northward expansion of the distribution range.

The resulting significant mismatches between stock distribution and historical TAC quota share could lead to continued future conflict as climate change progresses. Under the United Nations Convention for the Law of the Sea (Tseng and Ou 2010), Coastal States have the right to exploit the fish resources that appear in their exclusive economic zone (EEZ). Additionally, mackerel is the stock with the highest quota transfer from the EU to the UK derived from the EU-UK negotiations (Popescu and Scholaert 2022). The impact of this transfer on the small pelagic fishing fleets will depend on the country. For instance, fleets from Ireland, Netherlands, Germany, and France (in this order) are expected to be the most affected (Popescu and Scholaert 2022). Changes in spatial distribution are likely to happen in the future, necessitating realignment of quota shares with stock density, fisheries needs, and historical shares. Unfortunately, since 2010, there are no internationally agreed quotas, and the different parties set their quotas unilaterally, leading to fishing above the scientific advice (ICES 2023).

Table 1 Summary table of operations for each case study region

Subsection	Region	Species	Vessel types/gear	Current management	End product
A.1 Africa					
A.1.1	North-West Africa	Round sardinella (*Sardinella aurita*), Madeiran Sardinella (*Sardinella maderensis*), Atlantic chub mackerel (*Scomber colias*), European anchovy (*Engraulis encrasicolus*), bonga shad (*Ethmalosa fimbriata*), horse mackerels (*Caranx rhonchus* and *Trachurus trecae*), European sardine (*Sardina pilchardus*), silver scabbard (*Trichiurus lepturus*), and Atlantic horse mackerel (*Trachurus trachurus*)	Artisanal fishing, Inshore fishing/Purse seine and deep-sea fishing/Trawler fishing	Total Allowable Catch (TAC), MSY management targets	Animal feed (63%; fish meal and fish oil) and human consumption
A.1.2	South Africa	Sardine (*Sardinops sagax*), Cape horse mackerel (*Trachurus capensis*), European anchovy, red-eye round herring (*Etrumeus whiteheadi*)	Purse seine	Limited access, TACs based on Management Strategy Evaluation (MSE) tested management procedure; Total Allowable Bycatches and Precautionary Upper Catch Limits	Fishmeal and oil. Sardine canned or frozen for human consumption, bait or pet food
A.2. Asia					
A.2.1	Japan	Japanese sardine (*Sardinops melanostictus*), Pacific chub mackerel (*Scomber japonicus*), spotted mackerel (*Scomber australasicus*), Japanese jack mackerel (*Trachurus japonicus*), Japanese anchovy (*Engraulis japonicus*), red-eye round herring (*Etrumeus teres*), and Pacific saury (*Cololabis saira*)	Purse seiners (70%), set nets (30%)	TACs, MSY management targets	Human consumption, animal feed, fish meal, fish oil
A.3 Europe					

Table 1 (continued)

Subsection	Region	Species	Vessel types/gear	Current management	End product
A.3.1.1	North East Atlantic macro-region	Atlantic mackerel (*Scomber scombrus*), Atlantic horse mackerel, blue whiting (*Micromesistius poutassou*), herring (*Clupea harengus*), sandeel (*Ammodytes spp*)	Pelagic trawl, purse seine	TACs, MSY management targets, management plan (blue whiting), protection measures of some spawning components (herring)	Human consumption, fish meal/oil
A.3.1.2	Bay of Biscay	European anchovy, European sardine, Atlantic mackerel, Atlantic horse mackerel	Purse seiners, Trawlers	TAC and quotas allocated among countries and fleets, management plan (anchovy), size limits. Use of early recruitment indicators (anchovy)	Human consumption, fish meal, bait for tuna
A.3.1.3	Portuguese Iberian waters	European sardine, Atlantic chub mackerel, Atlantic horse mackerel, European anchovy	Purse seiners	TACs for anchovy, horse mackerel. Sardine quota management between Portugal and Spain, size limit, limited entry, closed areas	Human consumption, fish meal (some part of chub mackerel to feed tuna) and bait for black scabbardfish (*Aphanopus carbo*)
A.3.2	Southern Tyrrhenian Sea, Italy	European anchovy, European sardine, round sardinella	Purse seiners, small-scale driftnet (Menaide)	Size limit (9 cm) for anchovy only	Bait for larger pelagics, human consumption
A.4 North America					
A.4.1	U.S. West Coast	Pacific sardine (*Sardinops sagax*), Northern anchovy (*Engraulis mordax*), Pacific chub mackerel, Pacific jack mackerel (*Trachurus symmetricus*)	Purse seine, lampara net	TACs, limited entry, closures	Bait, human consumption, reduction (historically)
A.4.2	U.S. East Coast and Gulf of Mexico	Gulf menhaden (*Brevoortia patronus*), Atlantic menhaden (*Brevoortia tyrannus*)	Purse seine, pound nets	TACs for Atlantic menhaden, closed areas for reduction fleet, cap on harvest in some areas	Fishmeal, fish oil and bait

Table 1 (continued)

Subsection	Region	Species	Vessel types/gear	Current management	End product
A.4.3	Mexico Northwest Coast	Pacific sardine (*Sardinops sagax*), thread herring (*Opisthonema spp.*), Pacific anchoveta (*Cetengralus mysticetes*), Pacific chub mackerel, Northern anchovy, red-eye round herring (*Etrumeus teres*), leather jackets (*Oligoplites spp.*)	Purse seine	Size limit, limited entry, closed areas/seasons	Fishmeal (85%)
A.5 South America					
A.5.1	Peru	Anchoveta (*Engraulis ringens*), Pacific sardine	Purse seine	TAC and quota management using an individual transferable catch share system. Fishing ban within five nautical miles (nm) from the coast. Fishing closures during main reproductive periods	Fishmeal, small amounts for human consumption

Shifting SPF distribution outside Japanese EEZ

In the Pacific Ocean, SPFs, including Japanese sardine (*Sardinops melanostictus*), Pacific chub mackerel (*Scomber japonicus*), Japanese jack mackerel (*Trachurus japonicus*), Japanese anchovy (*Engraulis japonicus*), and Pacific saury (*Cololabis saira*), were initially caught mainly by Japan in the Japanese EEZ. Since the 2000s, however, catches outside the Japanese EEZ, including on the high seas and inside the Russian EEZ, have increased to the point where the total catch of China and Russia is now comparable to the Japanese catch. Managing saury, chub mackerel, and sardine on the high seas is currently being discussed at the North Pacific Fisheries Commission (NPFC), established in 2015. For saury, stock assessments and a TAC were first agreed upon in 2021, but this has not yet been achieved for the other species. The increase in catches outside of the Japanese EEZ is thought to be due to offshore shifts in the distribution associated with oceanographic changes (for saury; Kuroda and Yokouchi 2017) and an expansion in the distribution associated with increased abundance (for sardine; Furuichi et al. 2023).

By contrast, there is no regional fisheries management organization (RFMO) that controls regional fisheries in the East China Sea and the Sea of Japan, where SPF have been caught by China, South Korea, and Japan. In addition to countries fishing within their own unique EEZ, fishing operations in areas where EEZs overlap are currently based on an agreement between two countries, but excluding the other (i.e., between Japan and South Korea, Japan and China, and China and South Korea). China is estimated to land the largest SPF catch in this area (FAO 2020), but publicly available fishery information is limited. Cooperation among surrounding countries would be necessary for more accurate stock assessment and effective fishery management.

Restructuring of the South African sardine fishery due to an eastward expansion of biomass

The South African sardine (*Sardinops sagax*) fishery initially operated out of West Coast harbors only, with the first processing plant being opened in Lamberts Bay in 1947 (Jarre et al. 2013) and up to 17 canneries and processing factories located on the

Table 2 Summary table of main impacts on each case study region

Case number	Region	Detail	Socio-economics impact	Fishing industry's response	Management response
Challenges to the industry from shifting stock spatial distribution					
1	North East Atlantic	North West expansion of North East Atlantic mackerel into Icelandic and Greenlandic waters since 2007	Uneven distribution of the rents, mismatch between historical TAC allocation and stock distribution. Conflict between participant countries	N/A	Broke allocation agreement; some increased their TACs
2	Japan	Catches outside Japan EEZ have increased due to shifts in distribution	Conflict between participant countries	N/A	Transboundary TAC was implemented for saury, but not for other species. Countries operating or managing independently, or through bilateral agreement, despite having three or more countries involved
3	South Africa	Eastward expansion of the South African sardine	Closure of West Coast factories. Fleet reduction in historical West Coast ports	Increase in fishing effort further east. New canneries in the south have opened, and new right holders in the south	Spatial management measures (e.g. restricting catches off the West Coast)
4	North-West Africa	Change in distribution and stock of sardinella due to overfishing and potentially due to future climate variability	Potential closure of fishmeal factories	N/A	Gear restrictions, fishmeal processing restrictions, and requirement to set aside catch for freezing
5	Mexico Northwest Coast	Predicted decrease in habitat suitability due to climate change	Potential conflict with the small-scale sector and a potential disruption of the Gulf of California-based network of collaborative stakeholders	Follow the species, increasing fishing effort in zones where changes will be lower. Potential substitution to other species, but limited by market conditions	Management Plan for Small Pelagics: fleet zoning, active management through a Catch Control Rule

Table 2 (continued)

Case number	Region	Detail	Socio-economics impact	Fishing industry's response	Management response
6	U.S. East Coast and Gulf of Mexico	Hypoxia affects the distribution of Gulf menhaden	Potential higher cost of fishing as hypoxia pushes the boats further from their home ports. Potential increase in catchability as fish would accumulate in one place, thus reducing the cost of fishing	Shift in fishing dynamics, where efforts have moved closer to shore and westward, but further from home ports	N/A
Response to shocks driven by the boom and bust dynamics of SPF					
7	U.S. West Coast	The collapse of the sardine fishery in the late 1940s due to overexploitation and unfavorable environmental conditions	Negative impact on harvester and processing workers. Not all participants had the option to diversify, selling their equipment and vessels	Switching to Dungeness crab, rockfish, albacore, salmon, or groundfish. Vessels unable to switch gear focused on anchovy, squid, Pacific chub mackerel, and tuna	Closures in late 1960. Limited Entry and catch limits when the fishery reopened in the 1980s. Closure in 2015
8	The Bay of Biscay	Anchovy stock collapsed due to changes in environmental conditions, poor management leading to overexploitation, and successive recruitment failures	Loss of the market for the French operators. Compensation for losses of not being able to harvest anchovy. Imports from new regions	Decrease in fishing effort by both Spanish and French fleets. Some harvesters exited the fishery. Switching to other species	Closure of the fishery and the design of a management plan, which includes a TAC based on harvest control rules based on science and early recruitment indicators
9	Portuguese Iberian Waters	Declining trend of the Atlantic Iberian sardine stock due to low recruitment levels	Increased operational costs, social and economic impacts on fisheries and their communities	Vessels moving far from their port, or diversifying their fishing portfolio	Annual catch limits and daily catch limits. Restriction on catching juveniles. Seasonal closures. No take areas established, and real-time closure could be enforced
10	South Africa	Booms and bust dynamics in the South African sardine population	During bust periods, there has been an increase in imports of frozen products, increasing risk of pathogens. Also, closure of factories and local downscaling of the small pelagic fleet	Switching target species to anchovy. During boom periods, there was a redistribution of vessels to take advantage of TAC increase	Implementation of Management Procedures with a 'two-tier' system

Table 2 (continued)

Case number	Region	Detail	Socio-economics impact	Fishing industry's response	Management response
Changes in fish size and quality					
11	Tyrrhenian Sea, Italy	Decline in the profitability of small-scale SPF fleet due to competition with bigger vessels and imports, together with the lower size of anchovy catch	Small-scale vessels have exited the fishery, reducing the size of the fleet	Due to low prices, vessels have to stay close to ports to avoid incurring in high risk and fuel consumption, not allowing them to explore distant areas for larger size individuals. Agreement with tuna vessels to stop catching large-size SPF, helps to avoid losses in the small-scale sector	N/A
12	Bay of Biscay	Decline in anchovy sizes in the Bay of Biscay	Lower market price for anchovy. Loss of the market for the French operators. Changes in fishing cost due to travel	Displacement of fishing effort, switch fishing effort to other species	N/A
13	Peru	Heatwaves and El Niño reduce accessibility and increase the probability of catching small anchovies	Reduced profitability and economic losses due to anticipated closure of the fishing season	N/A	Implementation of temporary spatial fishing closures to protect small anchovies. Application of the juvenile TAC

West Coast by 1968 (M.D. Copeland, SAPIA, pers. comm). However, the boom in total abundance at the turn of the century (c.f. Sect. "Booms and busts in the South African sardine population") and almost simultaneous eastward expansion in biomass prompted an increase in fishing effort further east. Before 2005, more than 90% of the landings were taken, on average, off the West Coast. However, between 2005 and 2008, when TACs remained relatively high, though decreasing rapidly with the sharp decline in biomass, an average of 60% of the landings were taken off the South Coast. This eastward expansion was supported by some infrastructure development, including establishing a new cannery in Mossel Bay on the South Coast in 2007. Before this, most of the directed sardine catch off the South Coast was trucked back to West Coast processing plants at a substantial cost (van der Lingen 2021). Between 2006 and 2020, 27% of individuals or companies with a right to the sardine fishery, known as right-holders, operated out of South Coast harbors (J. Coetzee, pers. comm).

The very low biomass levels for sardine off the West Coast, following a prolonged period of poor recruitment, together with research indicating that the sardine population consists of multiple components rather than a single homogeneous stock and additionally having the majority of surveyed biomass distributed off the South Coast in 17 out of 23 years since 1999, has resulted in spatial management measures (c.f. Section A.1.2, Supplementary Material) restricting catches off the West Coast since 2014. These were initially non-binding, and given that right-holders operating from West Coast harbors prefer to catch closer to their home port to reduce costs, 70% of the 2014–2018 landings were from the West Coast. More restrictive spatial management measures in recent years have, however, resulted in, on average, more than 60% of the landings being taken off the South Coast between 2019 and 2023.

There was also an abrupt eastward shift in the adult biomass of European anchovies (*Engraulis encrasicolus*) in 1996 (Roy et al. 2007), with most biomass being surveyed off the South Coast for the following two decades. However, unlike for sardines, this shift in distribution did not substantially affect the distribution of landings along the coast as the fishery primarily targets the recruits during their southward migration along the West Coast.

The case of round Sardinella fisheries in North-West Africa

Over the past few decades, fishing effort in Mauritania has considerably increased. Prior to 2012, most SPF exploitation for fishmeal was conducted offshore by foreign industrial boats. In the event of a drop in catches, these boats left the area to seek better fishing grounds, since they could redeploy at a global scale. Although the stock was generally overexploited, this might have acted as a self-regulation of the local SPF fishing effort, and the fishery did not collapse during that period. After 2012, the development of fishmeal factories along the North-West African coast increased significantly, with 40 factories in Mauritania alone, closely aligned with the local abundance of SPF species (Thiao and Bunting 2022). These factories were established to allow the exploitation of small pelagics beyond the local needs in terms of human food consumption (very small); in particular, it was assumed that a large unexploited small pelagic population existed in the coastal waters of Mauritania (Corten et al. 2017).

The expansion of fishmeal factories in Mauritania since 2012 had a noticeable effect on the distribution and intensity of fishing efforts (Corten et al. 2017). The increased demand from these factories led to intensified overfishing in coastal areas, where catchability—the proportion of the stock caught by one unit of fishing effort—by artisanal purse seine is very high, exerting intense pressure on local stocks. By 2019, significant depletion of SPF stocks was observed in Senegal and Gambia (Brochier et al. 2023). Furthermore, round sardinella (*Sardinella aurita*) landings in Mauritania dropped dramatically after 2021, suggesting a collapse in the stock, and other species now seem under the same threat (Braham et al. 2024a). As Mauritania enacts stricter fishing regulations—such as the removal of active gear from shallow waters (< 20 m), the prohibition of fishmeal processing of certain species, the requirement to set aside a proportion of the catch for freezing, and more rigorous fishmeal certification standards—the fishing industry has been forced to reduce their landings. In contrast, Senegal and Gambia, with fewer restrictions on fishmeal processing, continue to experience intense fishing pressure, further exacerbating the risks of collapse in their fish stocks (Braham et al. 2024b).

How climate change will affect the marine southern Canary upwelling system and the habitat of round sardinella remains uncertain (Sylla et al. 2019). Changes in current strength and direction and in fish habitat parameters may impact the distribution of round sardinella. Observations between 1988 and 2015 have already documented a northward shift in SPF species, including round sardinella (Sarre et al. 2024). It is expected that SPF stocks will decline in areas with high capital investment, such as Mauritania, mainly due to fishing pressure and potentially under the effect of future climate variability. This could leave significant fishing capacity underutilized, leading to job losses previously supported by fishmeal factories. However, models predict that a substantial portion of round sardinella will remain within the Mauritanian EEZ, with seasonal migrations northward or southward (Brochier et al. 2018; Lopez-Parages et al. 2018).

Changes in the distribution of Pacific sardine in Northwestern Mexico

Physical and biological processes across the Gulf of California are uniquely sensitive to interannual oceanographic variability (Lavín and Marinone 2003; Lluch-Cota et al. 2007; Frawley et al. 2019). Recent literature asserts that significant changes in the distribution and biology of Pacific sardine (*Sardinops sagax*) are expected as climate change progresses, with suitable habitat in the Gulf of California expected to decrease by as much as 95% (Petatán-Ramírez et al. 2019). Historically, during cold water years, Pacific sardines tend to dominate alongside Pacific chub mackerel, as their range expands southward toward the mouth of the Gulf of California (Nevárez-Martínez et al. 2001). By contrast, during warm water phases with reduced primary productivity (i.e., El Niño events), which coincide with a low local abundance of Pacific sardine, broad harvest portfolios, and increases in the abundance of tropical species offer the opportunity for substitution (Martínez-Zavala et al. 2015; Arreguín-Sánchez et al. 2017). For instance, thread herring (*Opisthomnema* spp.) and Pacific anchoveta (*Cetengralus mysticetes*) may be targeted as substitutes — the relative abundance of thread herring and other species may increase (Arvizu-Martinez 1987) when the sardine distribution is restricted to the northern Gulf of California—while smaller quantities of Pacific chub mackerel, Northern anchovy (*Engraulis mordax*), red-eye round herring (*Etrumeus teres*) and leather jackets (*Oligoplites* spp.) are also landed.

However, under current market conditions, the catch value of these alternative species is substantially less. Thus, following recent trends, as harvesters migrate to follow shifting sardine distributions under such scenarios, fishing effort is expected to intensify across the West Coast of Baja California, where changes are anticipated to be less pronounced (Saldívar-Lucio et al. 2013). Potential risks associated with such dynamics may include additional and/or increasing conflict with the small-scale sector and a disruption of the Gulf of California-based network of collaborative stakeholders previously associated with sustainability certification and management success (Ojeda-Ruiz et al. 2022).

A management plan is in place to establish policies that encompass research lines, administrative provisions, regulations, and mechanisms for the responsible management of fisheries (DOF 2023). This management plan includes two categories of management: active and passive, with active management explicitly adjusting harvest control rules to prevent overexploitation, and passive management applying more generic or simpler rules. The general objectives of both categories of management are: to evaluate biomass and recruitment, conserve yield and economic benefit, reduce the impacts of environmental interactions, promote economic benefits for society and ensure the quality of fishery products. To achieve full utilization, indicators of overexploitation, overfishing, and optimal yield (Catch Control Rule) in the SPF fishery were explicitly defined, as well as management actions that must be adopted when reaching or exceeding reference points for each indicator. It is expected that, with these tools, including fleet zoning, the impact of climate change on the distribution of SPF can be mitigated.

Hypoxic events and the Gulf of Mexico menhaden fishery

The most significant hypoxia event in the United States and the entire western Atlantic Ocean (Rabalais and Turner 2001) happens annually in the northern Gulf of Mexico due to Mississippi River discharge, which drives high levels of nutrient loading, increased primary production in surface waters, and (after sinking and decay) subsequent depletion of oxygen in the lower water column. These events overlap in time and space with the Gulf menhaden (*Brevoortia patronus*) population and fishery, the second-largest fishery by volume in the United States (Langseth et al. 2014). Langseth et al. (2014) found shifts in the fishing fleet with shifts in the size and distribution of the Gulf of Mexico hypoxic event; in particular, the fishery moved closer to shore and westward during hypoxic events, further from their home ports than they would normally be in years with less hypoxia. Due to higher travel costs, the cost of fishing is expected to increase during a hypoxic event. However, during a hypoxic event, the fish are also expected to aggregate near the edges of the hypoxic waters, allowing for larger catches per unit of effort (increased catchability) (Langseth et al. 2014), which may reduce fishing costs. Therefore, the actual economic impact of a hypoxic event is uncertain.

In terms of management, as hypoxic events become more recurrent, and taking into consideration that the size and duration of hypoxia events is hypothesized to increase with climate change, the probability of giving potentially inaccurate advice regarding catch limits and sustainability would increase t (Langseth et al. 2014, 2016). Catchability is typically estimated as a constant value within stock assessments (Wilberg et al. 2009); therefore, with environmentally driven (e.g., hypoxia driven) fleet dynamics, the catchability could be estimated with a bias. Then, the overall fishing mortality rate would also be estimated with a bias, and the resultant catch advice could be more risk-prone than intended.

Shocks driven by boom and bust dynamics

Forage fish populations exemplify boom and bust cyclical dynamics driven by environmental sensitivity, high natural mortality, autocorrelation in recruitment, and short timeframes between recruitment and spawning (Szuwalski et al. 2019), even in the absence of fishing (Schwartzlose et al. 1999). Fishery closures have been implemented globally to reduce fishing effort and decrease the risk of species collapse. In the case of SPF fisheries, closures are generally implemented during an environmentally driven bust cycle. Closures might be effective (e.g., the anchovy stock was considered rebuilt in the Bay of Biscay after a five-year fishery closure when two consecutive years of successful recruitment occurred (Uriarte et al. 2023)). However, their application might bring several consequences to the socio-economic system as harvesters (and processors) might be forced to switch species or even exit fishing (e.g., because of decommissioning schemes or loss of the market). Historical responses to SPF boom and bust cycles and associated regulatory interventions allow us to assess the historical adaptive capacity to boom-bust dynamics of different fishing communities and evaluate what factors would increase their resilience in the future. For instance, we can observe harvesters' alternative sources of livelihood or how they design their portfolio strategies. Moreover, we can observe how the industry reacted in terms of investment or divestment in response to prolonged booms and busts in SPF fisheries. In this section, we present case studies highlighting the socio-economic consequences of booms and busts in SPF dynamics, starting with one of the earliest in modern recorded history, the collapse of the Pacific sardine on the U.S. West Coast in the late 1940s.

The collapse of the Pacific sardine on the U.S. West Coast in the late 1940s

The sardine stock off the West Coast of the U.S. undergoes boom and bust dynamics in the absence of fishing (Baumgartner et al. 1992), but overfishing can exacerbate busts (Essington et al. 2015). In its heyday, the fishery was initially largely unregulated, except for laws in California limiting the use of whole fish for reduction (Uber and MacCall 1990). It collapsed in the late 1940s due to a combination of overexploitation and unfavorable environmental conditions and was eventually closed in the late 1960s (Zwolinski and Demer 2012). It reopened in the late 1980s but was closed again in 2015 as the biomass fell below a 150,000 mt cutoff specified in the harvest control rule (PFMC 2020). In the early sardine fishery, most sardines were used for canning and reduction, and the collapse impacted harvesters and many fish processing workers (Uber and MacCall 1990). Some vessels and processing plants diversified by switching to Dungeness crab (*Metacarcinus magister*), rockfish (*Sebastes* spp.), albacore (*Thunnus alalunga*), salmon (*Oncorhynchus* spp.), and, particularly in the Pacific

Northwest, to the nascent groundfish fishery (Uber and MacCall 1990; Herrick et al. 2006). Those unable to switch gears focused on Northern anchovy, market squid (*Doryteuthis opalescens*), Pacific chub mackerel, and yellowfin (*Thunnus albacares*) and bluefin (*Thunnus orientalis*) tuna (Uber and MacCall 1990; Herrick et al. 2006). As the anchovy biomass increased in the late 1960s, the anchovy fishery increased in importance and was largely harvested for reduction until the 1980s (Bergen and Jacobson 2001). However, not all fishery participants could diversify, and many vessels, canning equipment, processing equipment, and reduction machinery were sold and transferred to other nascent SPF fisheries, such as the ones in Peru and Chile (Uber and MacCall 1990).

When the sardine fishery reopened in the late 1980s, managers were careful to prevent overcapitalization and set up both limited entry (i.e., limiting the number of vessels operating) and catch limits. Catch limits for sardine are modified in response to sea surface temperature to reduce harvesting during periods of supposedly low stock productivity (Kuriyama et al. 2024; PFMC 2024). It is hoped that the current collapse will not be as prolonged as the first since the fishery was closed as soon as biomass fell under a specified cutoff, unlike in the 1940s when fishing pressure on the remaining sardine stock continued into the 1960s (Radovich 1982). Furthermore, since today's fishery is smaller and less labor-intensive, as there is no large-scale canning or reduction capacity left on the U.S. West Coast, the socio-economic impacts of the 2015 closure were less harsh. Sardine vessels also still participate in multiple fisheries, and most were able to switch to other target species, such as Dungeness crab or market squid, rather than exiting the fishery (Quezada et al. 2023a). Some of them have switched to anchovy, as abundance has been high. However, unlike in the 1960s, harvesters have a low market incentive to target anchovy as there is no reduction capacity, negatively affecting the market for this fishery. Processors nowadays also have other species to fall back on in years of no sardine quota, such as market squid, groundfish, and shrimp.

The collapse of the anchovy fishery in the Bay of Biscay

In the Bay of Biscay, the fishery of anchovy (*Engraulis encrasicolus*), one of the main targets of the French and Spanish fleets, was closed from 2005 to 2009. The stock collapsed due to its extremely low abundance resulting from a combination of changes in environmental conditions (Taboada and Anadón 2016), successive recruitment failures in the early 2000s (Borja et al. 2008; Bueno-Pardo et al. 2019), and suboptimal management leading to high exploitation—e.g., a fixed TAC set to 33,000 tons for about twenty years, despite scientists' recommendations to reduce it (del Valle et al. 2001; Uriarte et al. 2023). As a consequence of the collapse of anchovy, the European Commission initiated the development of a long-term management plan in 2007 (CEC 2007) to prevent another fishery collapse in the future. The fishery was reopened in 2010 after the recovery of the anchovy stock, and the management plan has been revised several times since (Sánchez et al. 2019; Uriarte et al. 2023). As mentioned in section A.3.1.2 (Supplementary Material), the current management plan includes a TAC based on harvest control rules, early recruitment indicators and technical measures.

Even though the anchovy stock recovered, the socio-economic system did not return to its pre-collapse status (Beckensteiner et al. 2024). The consequences of the moratorium have been a decrease in the fishing effort mainly due to the decline of the French pelagic trawler fleet (− 70%), a reduction in the Spanish fleet (−20%), less competition between French and Spanish pelagic trawler and purse seiners fleets, and a displacement of fishing effort increasing pressure on other species, such as sea bass (*Dicentrarchus labrax*), mackerels (*Scomber scombrus* and *Trachurus trachurus*) and bluefin tuna (*Thunnus thynnus*) (Daurès et al. 2009; Andrés and Prellezo 2012; Beckensteiner et al. 2024). Additionally, once the fishery was reopened, the anchovy prices did not rebound to pre-closure market prices, probably related to a lower demand in the canning industry for local anchovy, which had increased imports from other regions during the closure (Pita et al. 2014; Uriarte et al. 2023). The fishery in both countries received financial public compensation to make up for the losses of being unable to harvest anchovy. In Saint-Gilles-Croix-de-Vie, the second most important French port of pelagic trawlers, most vessels were scrapped under national decommissioning schemes—most of the time, this coincided with ship-owners reaching their retirement age. In Galicia, Spain, a temporary conversion was often observed into the construction industry, but with professionals returning to the fishery once the stock had recovered in the 2010s (Beckensteiner et al. 2024). While there was also a reduction in the Spanish purse seiner fleet, the consequences depended on the fleet segment (Andrés and Prellezo 2012; Beckensteiner et al. 2024); overall, there were fewer scrapped boats than in France.

Declining trend of the stock of Atlantic Iberian sardine

Before 2012, the Atlantic Iberian sardine (*Sardine pilchardus*) stock faced significant challenges and concerns regarding its abundance and sustainability. The declining trend of the stock raised alarm among fisheries scientists and managers, primarily due to low levels of recruitment observed since 2004 and a subsequent decrease in biomass. The inability of the stock to adequately replenish itself was a cause for action and prompted the implementation of improved management strategies, as mentioned in section A.3.1.3 (Supplementary Material).

To address these concerns, a multiannual management plan was introduced, with common measures agreed upon by Portugal and Spain for the period between 2012 and 2026, with subsequent updates (DGRM 2012, 2018, 2021). This plan aimed to ensure the conservation and recovery of the sardine stock. Several key measures were established as part of the plan. Firstly, an annual catch limit was set for sardines, ensuring that fishing effort remained within sustainable levels. Due to the significant reduction of the sardine annual quota, this period was called the “sardine ban” period. Additionally, daily catch limits based on the overall length range were implemented, with strict restrictions on capturing juvenile sardines. A complete prohibition on sardine landings for a specific period, usually a minimum of three consecutive months, was imposed to protect the spawning periods and allow for stock recovery. The fishing season for sardines was adjusted based on the stock’s status, typically commencing on May 1st each year and generally ending in the last quarter of the year. To safeguard highly sensitive sardine recruitment areas, "no take areas" were established, and real-time closures could be enforced when the percentage of juvenile sardines in catches exceeded 30%, as reported by fishing observers or skippers.

The decline of the sardine stock and the implementation of stricter regulations have forced harvesters in Portugal to adapt their fishing practices. They have been compelled to move far away from their home ports along the Portuguese coast in search of alternative fishing grounds or to target different species to maintain their revenue and support sustainability efforts (Feijó et al. 2022). Fishing efforts have been directed towards multiple species rather than solely targeting sardines, involving three to four SPF species. Regarding the canned fish industry, they had to adapt its production in terms of location and timing, leading to an increase in imports of sardines from other areas.

The active involvement of fisheries managers in developing and implementing these measures demonstrates their commitment to balancing the economic benefits of the sardine fishery with the long-term sustainability of the stock. By controlling fishing effort, setting catch limits, establishing fishing seasons, and protecting vital spawning areas, managers aim to ensure the health and abundance of the Atlantic Iberian sardine stock. However, fleet displacement has increased operational costs and social and economic impacts on harvesters and their communities depending on various factors, such as the availability of alternative species, market demand, and the effectiveness of conservation measures.

Booms and busts in the South African sardine population

A boom in sardine landings in the late 1950s and early 1960s occurred relatively soon after the purse seine fishery targeting sardine and Cape horse mackerel (*Trachurus capensis*) in South African waters began. In response to the rapid drop in sardine landings once the boom passed, the industry adapted and diversified to additionally target European anchovy.

In more recent years, adaptation measures implemented by the industry to navigate the low sardine TAC years have included importing frozen sardines to keep factories operational and staff employed, and continue to meet local demand. However, such measures are not risk-free. For example, pathogens to which native sardines are naive could be introduced through frozen imports (van der Lingen 2021).

Adaptation management measures to navigate and take advantage of the boom periods without increasing the risk of unintended resource depletion have included Management Procedures with a ‘two-tier’ system, whereby the normal constraints on the maximum extent of interannual TAC reduction are modified when TACs rise above a specified threshold (Moor et al. 2011). Some fishing companies were able to respond to take advantage of the short-term increase in TACs at the turn of the century by chartering additional vessels from Namibia that were available at that time.

While the rapid expansion in the small pelagic fishery in the 1940s-50 s produced much-needed employment, with an influx of workers to the West Coast, the reduction in TACs in the early 2000s resulted in the closure of two West Coast factories and, in particular, the downscaling of the small pelagic fleet in Lambert’s Bay (Jarre et al. 2013). Exacerbated by the eastward expansion of the biomass and fishing effort, with right holders now operating out of South Coast harbors (c.f. Sect. "Restructuring of the South African sardine fishery due to an eastward expansion of biomass"), by 2024, only six canneries and factories were operating off the West Coast (M.D. Copeland, SAPFIA, pers. comm).

The South African small pelagic fishery has been identified as vulnerable to climate change (e.g., Cochrane et al. 2020). Climate change, such as changes in sea surface temperature, which are hypothesized to impact upwelling and primary productivity, could cause substantial changes in SPF abundances (van der Lingen 2021). Harmful algal blooms (HABs) have also had substantially negative impacts on the sardine population, with substantial reductions in the body condition of sardine within HAB areas, and catches off the South Coast (van der Lingen 2021). Poor body condition is hypothesised to negatively impact spawning success and subsequent recruitment as successful reproduction is dependent on stored energy (see van der Lingen (2021) for more details). In addition to importing frozen sardines, further diversification by expanding the fishery for round herring (Etrumeus whiteheadi), which is currently estimated to be underexploited, is a means to potentially help the industry weather rapid and substantial changes in SPF abundances. Utilization of mesopelagic fish was also previously attempted with some success, but is not currently targeted as further experimentation is required to ensure a continuously profitable operation. Opening new markets, particularly for the processing of anchovy for human consumption and bait and the canning of round herring for human consumption, with associated infrastructure development, have been suggested as further adaptation measures to address climate-induced changes in resource abundances (van der Lingen 2021).

Changes in fish size and quality

Together with shifting spatial distribution and boom-bust cycles, climate variability can also affect the size and quality of SPF individuals. Increases in temperature or changing forage composition can affect nutrient content and metabolism, resulting in shifts in size-at-age, declines in body condition, and compromised fish health (Audzijonyte et al. 2020; Alfonso et al. 2021; Lindmark et al. 2022). These changes in fish size and tissue quality affect marketability and product value in addition to stock productivity. Although there has been extensive focus on the effects of fishing pressure on changes in size-at-age of certain fish stocks (Hixon et al. 2013), here we focus our case studies on exogenous events causing changes in fish size and quality and the resultant impacts on related fisheries and markets.

Lower anchovy average size in the Tyrrhenian Sea

In Southern Italy (Tyrrhenian Sea; Geographical Sub Area (GSA) 10), the SPF fleet has decreased since 2017. This has been associated with a sharp decline in total landings in the last decade (FEAMP—ISSPA 2023). As abundance has not been a significant problem for this fishery, the decline in the fleet and landings is thus primarily attributed to a decline in the profitability of the SPF fishery.

One of the reasons that profitability has declined is because the average size of European anchovy individuals has been generally lower in recent years. The GSA10 fishery exploited mainly age-1 individuals from 2011–2016 (Maiorano et al. 2019). Basilone et al. (2017) highlighted a lower length at age-1 for anchovies in the Tyrrhenian Sea compared to those observed in the Strait of Sicily (GSA16), linking such differences to habitat conditions. The evidence of differences in trophic webs in the two ecosystems (GSA10 and GSA16) corroborated this hypothesis (Rumolo et al. 2016). Moreover, competition with other fleets has amplified the lower profitability observed in GSA10. For instance, small vessels that exclusively land SPF were affected by market competition by bigger vessels targeting tuna-like species that sporadically landed larger quantities of bigger-size anchovy. Since 2022, the latter fleet segment stopped catching SPF in light of an agreement among fisheries associations to assist the economic losses of the small-scale sector. Additionally, imported fish from the Adriatic Sea (GSA17) have also impacted market prices negatively due to an increased supply composed mostly of small-size SPF—the Adriatic Sea fleet mainly caught SPF with midwater trawls, which is associated with smaller-size catch.

The current conditions in GSA10 have obligated the purse seine harvesters to stay close to the landing ports to minimize risks and fuel consumption as well as to achieve a lower but secure price rather than improve the fish size by exploring more distant fishing areas (Tsitsika and Maravelias 2008).

Decline in anchovy sizes in the Bay of Biscay

In the Bay of Biscay, several studies have corroborated a decrease in individual size and body condition for the European anchovy (Chust et al. 2022; Menu et al. 2023; Boëns et al. 2023; Taboada et al. 2024). This led to difficulty in finding large individuals for processing industries, especially for French fleets (Doray et al. 2022), and to a westward movement of the Spanish fleets targeting the stock, implying an increase in fuel costs for the Basque fleets (whose base port is located in the northeastern part of the Cantabrian Sea) and a reduction of these costs for the rest of the Spanish fleets (Aldanondo et al. 2023). This change in size and weight, along with other market factors, has strongly affected the marketing value of the anchovy (Andrés and Prellezo 2012; Pita et al. 2014; García-del-Hoyo et al. 2023), with a 30% reduction of anchovy first sale prices between 2013 and 2022 (Aldanondo et al. 2023). Furthermore, before the closure (see Sect. "The collapse of the anchovy fishery in the Bay of Biscay"), 50% of fresh anchovy imports by Spain originated from France, while during the moratorium, when the production collapsed, imports of fresh anchovy from Italy and preserved anchovy from Morocco and Peru increased (García-del-Hoyo et al. 2023; Beckensteiner et al. 2024). Now, even though the anchovy stock recovered, French fresh anchovy imports to Spain have almost disappeared, only contributing to 5% of fresh anchovy imports in 2021, to the benefit of Portuguese fresh anchovies. The correlation between the decrease in the individual size of anchovy in the Bay of Biscay and the competition from new sources of imports has entailed a structural change in the conditions for market access for the products of the French fishing industry, facing lower prices than expected. This structural change is all the more profound as the decrease in individual size and body condition is also observed in sardine, the other emblematic small pelagic fish exploited in the Bay of Biscay (Véron et al. 2020; Menu et al. 2023; Boëns et al. 2023).

Increasing probability of catching small-size anchoveta in Peru under compression of the habitat and fishing grounds

Under normal conditions smaller anchovetas are distributed closer to the coast than larger individuals (Moron et al. 2019; Castillo et al. 2022). The first 5 nautical miles (nm) are closed to the industrial fisheries so the fishery targets mostly the distribution area of the larger anchovetas (Oliveros-Ramos et al. 2021). However, under warm conditions and especially El Niño and other heatwaves, the smaller anchovetas move even closer to the coast, while the larger anchovetas also move inshore and deeper (Bertrand et al. 2004; Espinoza-Morriberón et al. 2022; Díaz et al. 2024). Following these changes in the distribution, the fishery ground reduces and becomes more coastal too (Joo et al. 2014). There is an overall reduction in the accessibility of the anchoveta to the fishery, and an increased probability of juvenile by-catch (Cuadros Caballero et al. 2024). On top of that, during warming events, there's a higher juvenile mortality that could lead to a recruitment failure (Díaz et al. 2024). For these reasons, the anchoveta assessment needed to include a clear and explicit recognition of the environmental uncertainty and its impact on the population (Oliveros-Ramos et al. 2021).

Anchoveta is managed with a regime of two fishing seasons per year, starting around April and October. The fishing season normally starts with an "exploratory fishing" aimed to update information about the spatial distribution of anchoveta and the zones with a higher probability of juvenile by-catch. During the season, intense 24/7 fisheries monitoring, with nearly 100% coverage, allows near real-time management actions like temporal spatial closures to protect juvenile fish. More recently, this has also allowed the monitoring of a "juvenile TAC" that can lead to the end of the fishing season even if the global TAC is not reached (Oliveros-Ramos et al. 2021).

However, during the 2020s, an increased frequency of El Niño-like heatwaves that have impacted the fishing process has been observed. A regime shift in the average TAC can be detected around 2014, with lower TACs after 2014 and an increased frequency of seasons where the TAC is not fully landed due to unfavorable environmental conditions, particularly during the last decade. In particular, 2022 and 2023 have not had a normal fishing season, including a complete moratoria in the first season of 2023 (Bouchon 2024).

These distribution shifts in depth and distance to the coast have been very disruptive to the fishing process, impacting the fishery and its management. There is a need for new fishing technologies and strategies, in particular to reduce the juvenile by-catch under the more frequent overlap with the adult population. Besides the biological consequences of targeting juvenile anchovies, there is also an economic one regarding the yield of the fishery, given the lower proportion of fatty acids in the smaller anchovies.

Discussion and conclusions

In this article, we have presented 13 case studies from 11 regions/countries. The description of the fisheries in each region/country emphasizes the importance of SPF for the fishing industry and local economy (Supplementary Material). For instance, SPF is South Africa's largest fishery in terms of landings mass, while in Portugal it is the largest in terms of economic value and historical significance. In Japan, it accounts for almost half of the total fisheries catches in the country.

To identify common policies, responses, and impacts of the changes in fish distribution and variability, size, and quality, we categorize responses and impacts from each case study following Table 2 and then summarize them by group in Fig. 2. Based on this, we discuss potential opportunities or barriers to climate adaptation and identify attributes of socio-ecological systems that can foster resilience.

Socio-economic impacts

During bust periods or when the size and quality of the fish decreased, markets where the fishing industry sold their fish were lost, and profitability was reduced (Fig. 2). Vessels and processors impacted by closures or size reductions might have trouble re-entering the supply line once a fishery rebounds (e.g., Bay of Biscay anchovy, Sect. "Decline in anchovy sizes in the Bay of Biscay") as global sourcing of similar or lower-quality products (as noted by Beckensteiner et al., (2024)) increases competition within a traditional or local market. In the case of Tyrrhenian anchovy, the shift in SPF size and associated reduced prices was absorbed and ultimately reinforced by the market.

Conflicts and rent redistribution were only observed when a shift in distribution occurred (Fig. 2). As we saw in the North East Atlantic mackerel case study, under transboundary management, allocation agreements can bring uneven distribution of rents and can cause tension, particularly when a quota is not increasing, and countries losing out may expect side payments (Miller and Munro 2004). As demonstrated in the Mexico and South African case studies, distribution shifts within domestic waters can also potentially lead to serious socio-economic impacts and similar tensions between domestic quota holders.

Capital reduction seems a likely path in all the scenarios studied (Fig. 2). For instance, the eastward expansion of the South African sardine brought a reduction of the capacity in the West Coast ports, while the collapse of the U.S. West Coast sardine fishery in the late 1940s forced harvesters to sell their equipment and vessels, with a reduction in shore-based infrastructure (Uber and MacCall 1990). Small-scale vessels in the Tyrrhenian Sea have exited the fishery due to lower sizes observed for anchovy.

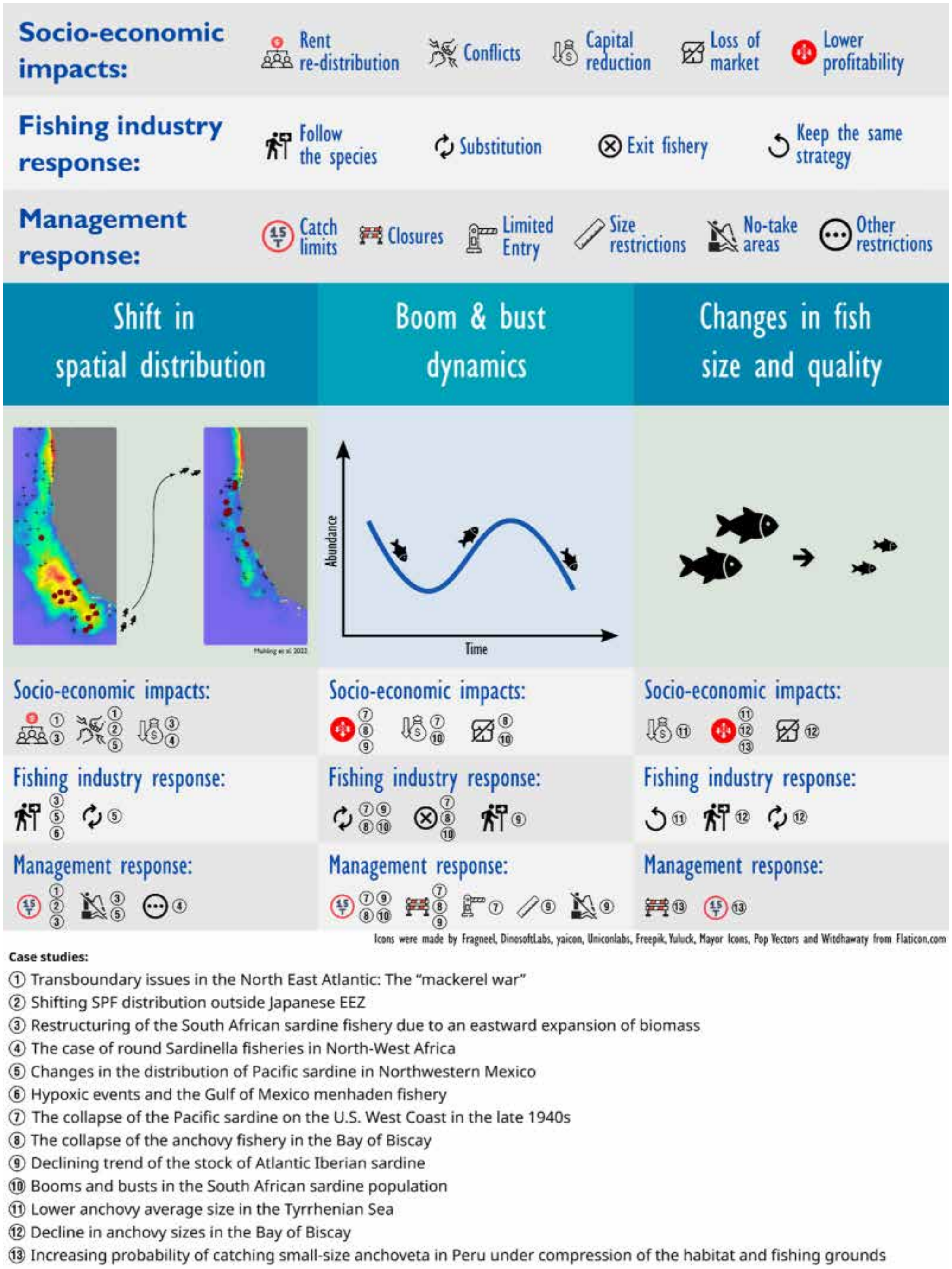

Fig. 2 Summary of responses and impacts to changes in fish dynamics, size, and quality. Case studies corresponding to each of these responses and impacts are given by the circled numbers, corresponding to the same numbers used in Fig. 1

Fishing industry's responses

An intuitive harvester's response to a shift in stock distribution, would be to follow the fish, which is observed in three of our six case studies under this scenario (Fig. 2). However, this might not always be the case as harvesters' adaptive responses may be constrained, even when stock spatial shifts are primarily within national boundaries. 'Following the fish' may not be a viable option for SPF harvesters with limited options for delivering catch to port-based processors, for instance, given costs and concerns about spoilage. As we observed in the South African case study, before 2007, due to a shift in spatial distribution, the directed sardine catch off the South Coast was trucked back to the West Coast at a substantial cost (van der Lingen 2021). South African harvesters were able to sustain the sardine fishery as new canneries were established on the South Coast in 2017. However, without this investment, 'following the fish' would not have been a sustainable option. Quezada et al. (2023b) found that U.S. West Coast purse seiners reported limiting operations within 30–90 km of home ports. As discussed below, this may mean that SPF vessels are more likely to 'adapt in place' via switching species than to 'adapt on the move' (sensu Samhouri et al. 2024). Vessels with greater flexibility—such as access to other species – may adjust their operations through portfolio diversification, while vessels constrained by capital or a lack of suitable alternative species may be more inclined to pursue their target species as it moves.

Under boom and bust dynamics, harvesters respond differently than they do to shifts in species distribution. 'Bust' conditions in one area may force fleets to move long distances to find (relative) 'boom' conditions elsewhere. We observe this in the case of the Iberian sardines in Portugal, where harvesters moved far away from their home ports along the Portuguese coast to find new fishing grounds. Nevertheless, this response is not as common as exiting the fishery or switching species, as we only observe it in this particular case study within the boom and bust dynamics group. As we saw in the U.S. West Coast case study, modern sardine vessels often participate in multiple fisheries, and processors have other species to rely on during years with no sardine quota, such as market squid, groundfish, and shrimp. Under boom and bust dynamics, harvesters' response will differ substantially in response to both the severity of the collapse and the management response. For instance, in the case of the Atlantic Iberian sardine, even though a low level of recruitment was observed in 2004 and biomass subsequently decreased, the implementation of improved management strategies likely reduced the severity of the collapse and allowed harvesters to continue fishing for sardines, albeit in different fishing grounds. Meanwhile, the severe collapse of the Pacific sardine on the U.S. West Coast in the late 1940s was exacerbated by weak management that permitted overexploitation, and forced part of the industry to exit the fishery and sell their capital to other SPF fisheries. Additionally, the duration of the shock matters: other literature suggests that fisheries may be resilient to short-term "pulse" events (Swinea and Fodrie 2021), but more vulnerable to "press" (i.e., persistent) events such as climate change.

No adaptation strategy (i.e. maintaining the same strategy) was only observed in our case studies when there was a change in fish size or quality, specifically in the case of the SPF fleet in the Tyrrhenian Sea. Lower but secure prices for European anchovies in the Tyrrhenian Sea have deterred harvesters from exploring other areas for larger-sized anchovies or other species, staying in their historical fishing grounds. The risk involved in exploring further fishing grounds in terms of safety and income uncertainty is a clear barrier for this fishery to adapt to a shift in fish size and quality.

The case studies presented in this paper support the assertion that fishing behavior not only depends on fish availability but also on social, economic, and regulatory variables (Selden et al. 2019). For instance, in Japan, harvesters/processors have preferred a more profitable species, such as Pacific chub mackerel (Makino 2011, 2018; Yatsu 2019), than a species that is abundant but not economically appealing (e.g., Japanese anchovy). A similar case happens in the U.S. West Coast, where a healthy Northern anchovy stock has been observed but was not targeted as the price was low compared to other SPF. Therefore, access to infrastructure, market demand, and costs associated with fishing operations will constrain or facilitate adaptation to climate change (Haynie and Pfeiffer 2012; Selden et al. 2019; Beckensteiner et al. 2023).

Management responses

Our evaluation of the case studies indicated that management responses to the boom and bust dynamics were the most diverse, including all identified potential management actions (Fig. 2). Some of these measures reflect relatively static frameworks that define the fishery (e.g., limited entry, no-take areas), but others can be enacted and retracted on shorter timeframes (e.g., catch limits, size limits, closures). Size limits and closures seem to be popular management tools to promote the recovery of a fishery during a bust cycle, or when the average size of the individuals in the population has decreased. It is important to be cautious when advocating for total closures, as such moratoriums may have unintended economic consequences. While total closures are generally more effective for species recovery, as they allow depleted stocks to rebound, it remains unclear whether a complete shutdown is superior to reducing fishing effort to lower, sustainable levels. Beckensteiner et al. (2024) advocate for maintaining a minimum quota during periods of low abundance, rather than entirely closing the fishery, to strike a balance between conservation and economic stability. A reduction in effort can preserve critical market opportunities, helping to maintain both the vessel and onshore fishing capital during these challenging periods.

As demonstrated above, in the boom and bust case studies in the U.S. West Coast and Bay of Biscay, as well as observed in the Japanese SPF fishery (Makino 2011, 2018; Yatsu 2019), these cyclical dynamics could encourage overcapitalization through investment in fishing vessels, gear, and infrastructure during boom periods that remain or come online after transition to a bust phase. To avoid this situation, a limited entry permit was implemented for the U.S. West Coast Coastal Pelagic Species (CPS) fishery, and a long-term management plan that includes a maximum threshold for the TAC was implemented for both U.S. West Coast CPS fishery and the Bay of Biscay anchovy fishery. This maximum TAC level was defined to provide TAC stability at high stock levels, on the basis of fleet capacity evolution (based not only on the number of vessels but also on the stationary availability of the resource) and the market absorption capacity. Moreover, in the Bay of Biscay anchovy fishery, the inclusion of a maximum TAC level in the Harvest Control Rule (HCR) reduced the biological risks and maximized the economic performance of the fleet, supporting the stakeholders' preference for a capped harvest strategy (Uriarte et al. 2023). In contrast, the two-tier Management Procedure implemented in South Africa allows larger annual changes in the TAC but only when the TAC is high.

The use of catch limits is a common approach across our case studies, most of which focus on regions with larger-scale vessels and substantial government investment in fisheries monitoring and enforcement. The effectiveness of this tool to reduce overfishing and to deal with climate-driven changes in species abundance and distribution, would depend on the degree to which it can be monitored—for SPF, the most effective monitoring programmes are based on fishery-independent surveys (Barange et al. 2009)—and enforced. In developing countries, enforcing a TAC might be costly, and illegal fishing (e.g., unreported fishing) might be a relevant problem for the sustainability of the resource (Oyanedel et al. 2018). In North-West Africa, a RFMO produces yearly catch limit recommendations, but these are generally not taken into account by managers and largely overlooked. In Mauritania, more attention is paid to spatial planning (e.g., limiting access to coastal/nursery areas), fish processing regulation (e.g., the prohibition of fishmeal processing of certain species and a requirement to set aside a proportion of the catch for freezing), or the use of certification standards (Braham et al. 2024b).

Timeframe of the shocks and the resist-accept-direct framework

Fishing industry and management responses in our case studies can be understood in the context of the Resist-Accept-Direct framework of Smith et al. (2022), considering also the timeframe of the shocks related to SPF distribution, abundance, and size or quality. The Resist-Accept-Direct framework describes a continuum of responses to system change: "resisting transformation by working to maintain or restore …historical or current conditions; accepting transformation by allowing … the system to change unimpeded; or directing transformation by actively shaping change…" (Smith et al. 2022). In many cases, we see long term evidence of species shifts, consistent with the "press" nature of climate changes.

In contrast, within our case studies, SPF abundance typically continued to oscillate, with booms following busts (e.g., U.S. West Coast sardine and Bay of Biscay anchovy recovery), consistent with "pulse" events, but at scales of a decade or more. The timeframes associated with declines in fish size or quality are less clear; in our case studies for Peru and the Tyrrhenian Sea, the shocks appear related to temporary habitat and oceanographic events, but globally we expect long-term declines in fish size under warming waters (Atkinson 1994). Therefore, the case studies mostly summarize long-term shocks, to which the fishing industry and managers exhibited substantial "Direct" actions aimed at "actively shaping change" in the fishery structure (Smith et al. 2022). Examples of such "Direct" actions include shifts in fishing ports and rights within South Africa, and new levels of diversification of some of the French pelagic fleets in the Bay of Biscay (Fig. 3). Managers also have taken "Direct" actions, for instance via formation of RFMOs in the Pacific, and developing more robust harvest rules for Bay of Biscay anchovy (Fig. 3). Though we did see examples of the less proactive "Resist" strategies, aimed at only maintaining status quo, or "Accept" strategies that allowed deterioration of historical benefits, many SPF fisheries exhibited more proactive responses to long-term changes in conditions.

Paths for resilience

With climate change, we can expect allocation challenges for SPF to increase (Baudron et al. 2020). Our case studies demonstrate that long-term stock shifts away from historical landings ports with associated infrastructure, processing plants, and established networks of stakeholders will pose challenges for dependent communities. Projections of shifts in distributions can warn managers of potential risks, and precautionary responses can be devised. Increased flexibility in international agreements, with side payments as an essential component, has been proposed as a potential strategy to build resilience (Miller and Munro 2004). Adaptive reallocation schemes have also been proposed (Bell et al. 2020). The North East Atlantic mackerel case also showed how a lack of agreement on the science regarding the permanence of the distribution change added to the political tension. This stresses the importance of cooperation in establishing a common, solid scientific understanding of observed changes before allocation redistribution discussions can arise. For instance, the Japanese case study demonstrated how establishing RFMOs can reduce potential conflicts by facilitating international cooperation and data sharing across member countries. This is an essential precursor to accurate assessments and effective management of transboundary populations (Aguero and Gonzalez 1996; Munro 2003).

In a changing and uncertain environment, with impacts on resource quality, difficulties for industry planning are expected to increase, increasing investment risk in the fishing industry. Fishing fleets relying on SPF of a particular size or quality are highly restricted in their ability to adapt to these changes. Often, these fleets cannot change their fishing grounds due to established no-take areas in nearshore habitats (e.g., Peruvian anchoveta) and limits on distance from home port imposed by costs and fast spoiling times of their catch. Some potential

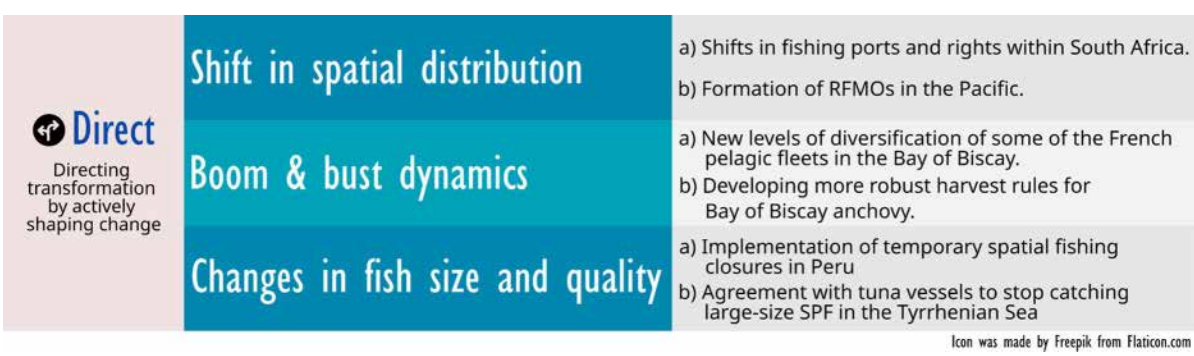

Fig. 3 Examples of "Direct" actions taken by the fishing industry and managers to system change by case study groups

solutions may partially relieve, if not solve, issues related to changing SPF size and quality. Coordination among fleet sectors to enforce size restrictions may mitigate impacts on highly vulnerable fisheries. In the case of Tyrrhenian anchovy, agreements between anchovy and tuna fisheries reduced competition for the remaining larger fish (Sect. "Lower anchovy average size in the Tyrrhenian Sea"). However, when broader ecosystem shifts lead to changes in size and quality, size limits will likely be insufficient. Dynamic spatial management (i.e., time-area closures) may increase catch per unit effort for vessels remaining in the fishery (e.g., Peruvian anchoveta, Sect. "Increasing probability of catching small-size anchoveta in Peru under compression of the habitat and fishing grounds"). In some cases, it may be possible to forecast in-season distribution of high-quality SPF using short-term species distribution models tuned for body condition of the catch, increasing consistency in catch quality for canning or reduction (e.g., Asche et al. 2014; Gücü et al. 2018; Bolin et al. 2021). Ultimately, when changes in SPF body condition are a result of system-wide, climate-driven forces rather than fishery-induced truncation of size structure, fisheries and managers should be prepared to face the resulting long-term demographic, trophic, and ecosystem transitions related to these changes (Levangie et al. 2022; Friedland et al. 2023).

Specialization might seem profitable in the short run, but in the case of boom and bust dynamics, it can cause negative impacts due to overcapitalization (Ward et al. 2018; Maltby et al. 2023; Schwoerer et al. 2023). Inherent natural cycles of boom and bust may be worsened by incentives that encourage fleet expansion during the prosperous phase of population growth cycles. This expansion aims to capitalize on the increasing fishing opportunities resulting from the growth of target populations. Delayed investment completion in fleet expansion, known as time-to-build effects, can prolong fleet growth even after the population has stabilized or started to decline. This can lead to surplus capacity in the fleet when fishing opportunities diminish, resulting in stranded capital. Without management measures to control fleet expansion during boom phases, there is a risk of the fleet growing to a size that leads to overfishing. In the U.S. West Coast, this time-to-build effect likely aggravated the decline of the sardine fishery in the mid-twentieth century, extending its economic repercussions beyond the fleet to affect supporting fishing industries in Monterey, California. Governance dimensions (Mason et al. 2022), such as limited entry permit systems, may be helpful to curtail pro-cyclical fleet expansion and prevent overfishing during boom periods, enhancing the resilience of the whole socio-ecological system. However, these practices could be combined with policies that foster species diversification to reduce overcapitalization and income risk during future climate events (Anderson et al. 2017; Fisher et al. 2021; Frawley et al. 2021). Alternatively, managers could allow the temporary use of vessels from other countries to allow the industry to take advantage of a short-term boom period without increasing the risk of overcapitalization, as occurred in South Africa at the turn of the century (see, for example, Sect. "Booms and busts in the South African sardine population"). Employing portfolio fishing strategies can mitigate adverse economic effects for fishery participants susceptible to boom-bust cycles and related fishing communities, increasing harvesters' resilience (Oken et al. 2021; Kroetz et al. 2022). Mason et al. (2022) identified this socioeconomic flexibility as a resilience attribute, even though it may require additional assets, such as gear or permits for new SPF. Diversification has allowed, for instance, the Portuguese SPF fleet to adopt seasonal switching or 'sequential targeting' between target species to reduce the impact of stock fluctuations. SPF research should focus on how to improve resilience within and between ecological and socio-economic SPF subsystems. For this, it is critical to evaluate the optimal design of policies that allow harvesters flexibility to adapt but, at the same time, take into consideration sustainable harvest goals. Limited to no regulation of access to a fishery (e.g., open-access) could result in "maladaptation," whereas well-designed adaptive management could enhance fisheries outcomes (Beckensteiner et al. 2023). Fishery practitioners often understand flexibility as a key aspect of adaptive capacity, for instance as demonstrated in a recent study in the U.S. (Golden et al. 2023, 2024). Fishery managers must ask: How can flexibility be enhanced given limited entry and other management constraints? Is there a policy design that encourages the adoption of a more diverse portfolio? How do markets function to limit diversification even when permits are flexible?

In the quest for improving resilience, managers have to take into consideration that adaptation attempts by harvesters, managers, and processors may have unintended consequences (Beckensteiner et al. 2023) or may fail in some ways while strengthening resilience in other respects. For instance, Feijó et al. (2022) describe the social consequences of the displacements and targeting shifts as harvesters coped with the decline in Portuguese sardine (i.e., economic solutions with social costs). Similarly, Ojeda-Ruiz et al. (2022) detail a loss of certain knowledge networks and types of cooperation as the Mexican fleet shifted operations from the Gulf of California toward the Pacific. Unintended consequences may also arise in terms of market access, for instance, in the case of French vessels in the Bay of Biscay that suffered the anchovy moratorium and then experienced reverberations in terms of loss of markets to Peruvian and Moroccan anchovy. The interaction between Norwegian Spring Spawning (NSS) herring fisheries and Barents Sea capelin is a good example of unintended responses to changes in target species for fisheries. Following the decline in NSS herring from the 1950s until the stock collapsed in the late 1960s (Nakken 1998), the fishery was allowed to shift to the Barents Sea capelin. Little was known about the stock size before 1970, and the maximum catch peaked in the mid-1970s with nearly three million tons. A stock collapse in capelin became evident in the mid-1980s, with a stock reduction of close to 95% (Gjøsæter 1998). The first known collapse of the Barents Sea capelin had severe ecosystem effects on top predators, as other forage species were simultaneously low (Johannesen et al. 2012). The collapse and ecosystem effects eventually led to a change in how the Barents Sea capelin fishery is managed, including taking into account the predation level caused by the Northeast Atlantic cod stock and not letting the spawning stock fall below 200,000 tons (Gjøsæter et al. 2015).

Our case studies suggest that the fishing industry and resource managers have demonstrated substantial ability to adapt to past SPF shocks, and that they will continue to do so under climate change, despite the possibilities of unintended consequences and faltering steps. However, a notable constraint is the slower pace at which managers respond and adapt. This delay can lead to losses over time due to their lagging responses (Beckensteiner et al. 2023). Local responses will continue to be shaped by local adaptive capacity – assets, flexibility, organization, agency, and learning (Cinner et al. 2018; Mason et al. 2022). Adaptation occurs due to the biological situations discussed here (boom-bust dynamics, distribution shifts, and size or quality shifts), but also due to new situations, such as the effects of the Covid-19 epidemic on fishing operations (Smith et al. 2020), increase fuel prices (Bastardie et al. 2022), or toxins such as domoic acid that accumulate in some SPF during marine heatwaves (McCabe et al. 2016), which are expected to increase under warming conditions (Frölicher et al. 2018).

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Data availability No datasets were generated or analysed during the current study.

Declarations

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References

Aguero M, Gonzalez E (1996) Managing transboundary stocks of small pelagic fish. The World Bank

Aldanondo N, Cotano U, Ibaibarriaga L, et al (2023) SIZANE. Bloque III: Conocimiento. Elaborado por AZTI para el Ministerio de Agricultura y Pesca, Alimentación y Medio Ambiente, Secretaría General de Pesca, dirección General de Pesca Sostenible bajo el Plan Nacional de Recuperación, Transformación y Resiliencia del Gobierno de España. Componente 3. AZTI

Alfonso S, Gesto M, Sadoul B (2021) Temperature increase and its effects on fish stress physiology in the context of global warming. J Fish Biol 98:1496–1508. https://doi.org/10.1111/jfb.14599

Anderson SC, Ward EJ, Shelton AO et al (2017) Benefits and risks of diversification for individual fishers. Proc Natl Acad Sci U S A 114:10797–10802. https://doi.org/10.1073/pnas.1702506114

Andrés M, Prellezo R (2012) Measuring the adaptability of fleet segments to a fishing ban: the case of the Bay of Biscay anchovy fishery. Aquat Living Resour 25:205–214. https://doi.org/10.1051/alr/2012018

Arreguín-Sánchez F, del Monte-Luna P, Zetina-Rejón MJ, Albáñez-Lucero MO (2017) The Gulf of California large marine ecosystem: fisheries and other natural resources. Environ Dev 22:71–77. https://doi.org/10.1016/j.envdev.2017.03.002

Arvizu-Martinez J (1987) Fisheries activities in the Gulf of California, Mexico. CalCOFI Rep 28:32–36

Asche F, Chen Y, Smith MD (2014) Economic incentives to target species and fish size: prices and fine-scale product attributes in Norwegian fisheries. ICES J Mar Sci 72:733–740. https://doi.org/10.1093/icesjms/fsu208

Atkinson D (1994) Temperature and organism size–a biological law for ectotherms. Adv Ecol Res 25:1–58

Audzijonyte A, Richards SA, Stuart-Smith RD et al (2020) Fish body sizes change with temperature but not all species shrink with warming. Nat Ecol Evol 4:809–814. https://doi.org/10.1038/s41559-020-1171-0

Barange M, Bernal M, Cercole MC et al (2009) Current trends in the assessment and management of stocks. In: Checkley D, Alheit J, Oozeki Y, Roy C (eds) Climate change and small pelagic fish. Cambridge University Press, Cambridge, pp 191–255

Basilone G, Mangano S, Pulizzi M et al (2017) European anchovy (Engraulis encrasicolus) age structure and growth rate in two contrasted areas of the Mediterranean Sea: the paradox of faster growth in oligotrophic seas. Mediterr Mar Sci 18:504–516. https://doi.org/10.12681/mms.2059

Bastardie F, Feary DA, Brunel T et al (2022) Ten lessons on the resilience of the EU common fisheries policy towards climate change and fuel efficiency–a call for adaptive, flexible and well-informed fisheries management. Front Mar Sci. https://doi.org/10.3389/fmars.2022.947150

Baudron AR, Brunel T, Blanchet M-A et al (2020) Changing fish distributions challenge the effective management of European fisheries. Ecography 43:494–505. https://doi.org/10.1111/ecog.04864

Baumgartner T, Soutar A, Ferreira V (1992) Reconstruction of the history of Pacific sardine and Northern anchovy populations over the past two mllenia from sediments of the Santa Barbara Basin, California. CalCOFI Rep

Bavinck M, Scholtens J, Fabinyi M (2024) Maximum sustainable employment: adding to the beacons of wild fisheries governance. Fish Fish. https://doi.org/10.1111/faf.12829

Beckensteiner J, Boschetti F, Thébaud O (2023) Adaptive fisheries responses may lead to climate maladaptation in the absence of access regulations. npj Ocean Sustain 2:1–5. https://doi.org/10.1038/s44183-023-00010-0

Beckensteiner J, Villasante S, Charles A et al (2024) A systemic approach to analyzing post-collapse adaptations in the Bay of Biscay anchovy fishery. Can J Fish Aquat Sci. https://doi.org/10.1139/cjfas-2023-0087

Bell RJ, Odell J, Kirchner G, Lomonico S (2020) Actions to promote and achieve climate-ready fisheries: summary of current practice. Mar Coast Fish 12:166–190. https://doi.org/10.1002/mcf2.10112

Bergen DR, Jacobson LD (2001) Northern anchovy. In: Leet WS, Dewees CM, Klingbeil R, Larson EJ (eds) California's living marine resources: a status report 2001. Univ. Calif. Agricul. Nat. Res., pp 303–305

Bertrand A, Segura M, Gutiérrez M, Vásquez L (2004) From small-scale habitat loopholes to decadal cycles: a habitat-based hypothesis explaining fluctuation in pelagic fish populations off Peru. Fish Fish 5:296–316. https://doi.org/10.1111/j.1467-2679.2004.00165.x

Boëns A, Ernande B, Petitgas P, Lebigre C (2023) Different mechanisms underpin the decline in growth of anchovies and sardines of the Bay of Biscay. Evol Appl 16:1393–1411. https://doi.org/10.1111/eva.13564

Bolin JA, Schoeman DS, Evans KJ et al (2021) Achieving sustainable and climate-resilient fisheries requires marine ecosystem forecasts to include fish condition. Fish Fish 22:1067–1084. https://doi.org/10.1111/faf.12569

Borja A, Fontán A, Sáenz J, Valencia V (2008) Climate, oceanography, and recruitment: the case of the Bay of Biscay anchovy (Engraulis encrasicolus). Fish Oceanogr 17:477–493. https://doi.org/10.1111/j.1365-2419.2008.00494.x

Bouchon M (2024) El Niño 2023–2024 y su impacto en los recursos pelágicos del mar peruano. In: El Niño 2023–2024: efectos y proyecciones en el mar peruano y sus recursos vivos. Libro de resúmenes

Braham C-B, Ahmed-Jeyid M, Bensbai J et al (2024a) Overexploitation of round sardinella may lead to the collapse of flat sardinella: what lessons can be drawn for shared stocks. Fish Res 269:106873. https://doi.org/10.1016/j.fishres.2023.106873

Braham C-B, Gascoigne J, Montero-Castaño C, Godard C (2024b) The role of certification standards in supporting improved fisheries management for small pelagics in mauritania: an example to follow in the North West African zone? Mar Policy 161:106054. https://doi.org/10.1016/j.marpol.2024.106054

Brochier T, Auger PA, Pecquerie L, Machu E, Capet X, Thiaw M, Mbaye BC et al (2018) Complex small pelagic fish population patterns arising from individual behavioral responses to their environment. Prog Oceanogr 164:12–27

Brochier T, Braham CB, Thiaw M, Brehmer P (2023) Raréfaction des sardinelles rondes en Afrique du Nord-Ouest : comment éviter l'effondrement. http://theconversation.com/rarefaction-des-sardinelles-rondes-en-afrique-du-nord-ouest-comment-eviter-leffondrement-211881

Bueno-Pardo J, Petitgas P, Kay S, Huret M (2019) Integration of bioenergetics in an individual-based model to hindcast anchovy dynamics in the Bay of Biscay. ICES J Mar Sci 77:655–667. https://doi.org/10.1093/icesjms/fsz239

Castillo PR, Peña C, Grados D et al (2022) Characteristics of anchoveta (*Engraulis ringens*) schools in the optimum zone and the physiological stress zone of its distribution between 2011 and 2021. Fish Oceanogr 31:510–523. https://doi.org/10.1111/fog.12601

CEC (2007) Non-paper of the EC on Long long-term management for anchovy in Bay of Biscay. 8 pp

Chavez FP, Ryan J, Lluch-Cota SE, Miguel Niquen C (2003) From anchovies to sardines and back: multidecadal change in the Pacific Ocean. Science 299:217–221. https://doi.org/10.1126/science.1075880

Cheung WWL, Brodeur RD, Okey TA, Pauly D (2015) Projecting future changes in distributions of pelagic fish species of Northeast Pacific shelf seas. Prog Oceanogr 130:19–31. https://doi.org/10.1016/j.pocean.2014.09.003

Chust G, González M, Fontán A et al (2022) Climate regime shifts and biodiversity redistribution in the Bay of Biscay. Sci Total Environ 803:149622. https://doi.org/10.1016/j.scitotenv.2021.149622

Cinner JE, Adger WN, Allison EH et al (2018) Building adaptive capacity to climate change in tropical coastal communities. Nat Clim Chang 8:117–123. https://doi.org/10.1038/s41558-017-0065-x

Cochrane KL, Ortega-Cisneros K, Iitembu JA et al (2020) Application of a general methodology to understand vulnerability and adaptability of the fisheries for small pelagic species in the Benguela countries: Angola, Namibia and South Africa. Afr J Mar Sci 42:473–493. https://doi.org/10.2989/1814232X.2020.1844798

Corten A, Braham C-B, Sadegh AS (2017) The development of a fishmeal industry in Mauritania and its impact on the regional stocks of sardinella and other small pelagics in Northwest Africa. Fish Res 186:328–336. https://doi.org/10.1016/j.fishres.2016.10.009

Cuadros Caballero GR, Castillo PR, La Cruz L et al (2024) Variabilidad de la anchoveta (Engraulis ringens) entre febrero y junio en la zona restringida a la pesca industrial en el inicio la primera temporada de pesca del 2022. Bol Invest Mar Cost 53:145–166. https://doi.org/10.25268/bimc.invemar.2024.53.1.1246

Daurès F, Rochet M-J, Van Iseghem S, Trenkel VM (2009) Fishing fleet typology, economic dependence, and species landing profiles of the French fleets in the Bay of Biscay, 2000–2006. Aquat Living Resour 22:535–547. https://doi.org/10.1051/alr/2009031

de Moor CL, Butterworth DS, De Oliveira JAA (2011) Is the management procedure approach equipped to handle short-lived pelagic species with their boom and bust dynamics? The case of the South African fishery for sardine and anchovy. ICES J Mar Sci 68:2075–2085. https://doi.org/10.1093/icesjms/fsr165

del Valle I, Astorkiza I, Astorkiza K (2001) Is the current regulation of the viii division European anchovy optimal? Environ Resour Econ 19:53–72. https://doi.org/10.1023/A:1011127610739

DGRM (2012) Plano de Gestão para a pesca da sardinha (2012–2015). Direcção-Geral dos Recursos Naturais, Segurança e Serviços Marítimos, Lisboa, Portugal

DGRM (2018) Multiannual management and recovery plan for the Iberian Sardine (2018-2023). Lisboa, Portugal

DGRM (2021) Multiannual management plan for the Iberian Sardine (2021–2026). Lisboa, Portugal

Díaz E, Marin P, Quispe E, et al (2024) Impactos de El Niño 2023–2024 sobre la dinámica poblacional de la anchoveta peruana. In: El Niño 2023–2024: efectos y proyecciones en el mar peruano y sus recursos vivos. Libro de resúmenes

DOF (2023) ACUERDO por el que se da a conocer el Plan de Manejo Pesquero para la Pesquería de Pelágicos Menores (sardinas, anchovetas, macarela y afines) del noroeste de México. Diario Oficial de la Federación

Doray M, Herrmann B, Simier M (2022) Economic and operational impacts of the spatial distribution shifts in fish stocks: Insights from the Bay of Biscay. Fish Res 249

Espinoza-Morriberón D, Echevin V, Colas F et al (2022) Diferencias entre los impactos en la costa peruana de los eventos ENOS cálidos y El Niño Costero 2017. Bol Inst Mar Perú 36:329–348. https://doi.org/10.53554/boletin.v36i2.341

Essington TE, Moriarty PE, Froehlich HE et al (2015) Fishing amplifies forage fish population collapses. Proc Natl Acad Sci U S A 112:6648–6652. https://doi.org/10.1073/pnas.1422020112

FAO (2020) FishStatJ - software for fishery and aquaculture statistical time series

FEAMP – ISSPA (2023) PO EMFF Campania 2014/2020: Innovazione, sviluppo e sostenibilità nel settore della pesca e dell'acquacoltura per la Regione Campania

Feijó D, Rocha A, Dias A, et al (2022) Purse-seine fishery in Portugal: no sardine, no future?

Fisher MC, Moore SK, Jardine SL et al (2021) Climate shock effects and mediation in fisheries. Proc Natl Acad Sci U S A. https://doi.org/10.1073/pnas.2014379117

Frawley TH, Crowder LB, Broad K (2019) Heterogeneous perceptions of social-ecological change among small-scale fishermen in the central Gulf of California: implications for adaptive response. Front Mar Sci. https://doi.org/10.3389/fmars.2019.00078

Frawley TH, Muhling BA, Brodie S et al (2021) Changes to the structure and function of an albacore fishery reveal shifting social-ecological realities for Pacific Northwest fishermen. Fish Fish 22:280–297. https://doi.org/10.1111/faf.12519

Free CM, Jensen OP, Hilborn R (2021) Evaluating impacts of forage fish abundance on marine predators. Conserv Biol 35:1540–1551. https://doi.org/10.1111/cobi.13709

Friedland KD, Ganley LC, Dimarchopoulou D et al (2023) Change in body size in a rapidly warming marine ecosystem: consequences of tropicalization. Sci Total Environ 903:166117. https://doi.org/10.1016/j.scitotenv.2023.166117

Frölicher TL, Fischer EM, Gruber N (2018) Marine heatwaves under global warming. Nature 560:360–364. https://doi.org/10.1038/s41586-018-0383-9
Furuichi S, Yukami R, Kamimura Y, et al (2023) Stock assessment and evaluation for the Pacific stock of Japanese sardine (fiscal year 2022). Marine fisheries stock assessment and evaluation for Japanese waters. Japan Fisheries Agency and Japan Fisheries Research and Education Agency, Tokyo
García-del-Hoyo JJ, Jiménez-Toribio R, Castilla-Espino D (2023) Price volatility transmission in the value chain of fresh anchovies in Spain. Fish Res 260:106606. https://doi.org/10.1016/j.fishres.2022.106606
Giron-Nava A, Lam VWY, Aburto-Oropeza O et al (2021) Sustainable fisheries are essential but not enough to ensure well-being for the world's fishers. Fish Fish 22:812–821. https://doi.org/10.1111/faf.12552
Gjøsæter H (1998) The population biology and exploitation of capelin (Mallotus villosus) in the barents sea. Sarsia 83:453–496. https://doi.org/10.1080/00364827.1998.10420445
Gjøsæter H, Bogstad B, Tjelmeland S, Subbey S (2015) A retrospective evaluation of the Barents Sea capelin management advice. Mar Biol Res 11:135–143. https://doi.org/10.1080/17451000.2014.928414
Golden AS, Baskett ML, Holland D et al (2023) Climate adaptation depends on rebalancing flexibility and rigidity in US fisheries management. ICES J Mar Sci 81:252–259. https://doi.org/10.1093/icesjms/fsad189
Golden AS, Levine A, Baskett ML et al (2024) Enhancing the adaptive capacity of fisheries to climate change: Bridging academic theory and management practice through practitioner interviews. Mar Policy 168:106321. https://doi.org/10.1016/j.marpol.2024.106321
Gray T (2021) Normative theory of international relations and the "mackerel war"in the North East Atlantic. Mar Policy 131:104620
Green KM, Selgrath JC, Frawley TH et al (2021) How adaptive capacity shapes the adapt, react, cope response to climate impacts: insights from small-scale fisheries. Clim Change 164:15. https://doi.org/10.1007/s10584-021-02965-w
Gücü AC, Genç Y, Başçınar NS et al (2018) Inter and intra annual variation in body condition of the Black Sea anchovy, Engraulis encrasicolus ponticus—Potential causes and consequences. Fish Res 205:21–31. https://doi.org/10.1016/j.fishres.2018.03.015
Guibourd de Luzinais V, du Pontavice H, Reygondeau G et al (2023) Trophic amplification: a model intercomparison of climate driven changes in marine food webs. PLoS One 18:e0287570. https://doi.org/10.1371/journal.pone.0287570
Haynie AC, Pfeiffer L (2012) Why economics matters for understanding the effects of climate change on fisheries. ICES J Mar Sci 69:1160–1167. https://doi.org/10.1093/icesjms/fss021
Herrick S, Hill K, Christian R (2006) Climate change and the economics of the world's fisheries: examples of small pelagic stocks. In: Hannesson R, Barange M, Herrick SF (eds) An optimal harvest policy for the recently renewed United States Pacific sardine fishery. Edward Elgar Publishing, Glasgow
Hilborn R, Amoroso RO, Bogazzi E et al (2017) When does fishing forage species affect their predators? Fish Res 191:211–221. https://doi.org/10.1016/j.fishres.2017.01.008
Hilborn R, Buratti CC, Díaz Acuña E et al (2022) Recent trends in abundance and fishing pressure of agency-assessed small pelagic fish stocks. Fish Fish 23:1313–1331. https://doi.org/10.1111/faf.12690
Hixon MA, Johnson DW, Sogard SM (2013) BOFFFFs: on the importance of conserving old-growth age structure in fishery populations. ICES J Mar Sci 71:2171–2185. https://doi.org/10.1093/icesjms/fst200
ICES (2023) Mackerel (Scomber scombrus) in subareas 1–8 and 14 and division 9.a (the Northeast Atlantic and adjacent waters). Report of the ICES Advisory Committee
IPCC (2021) Climate change 2021: the physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA
IPCC (2022) Climate change 2022: impacts, adaptation, and vulnerability. Contribution of working group II to the sixth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, UK and New York, NY, USA
Jarre A, Ragaller S, Hutchings L (2013) Long-term, ecosystem-scale changes in the southern benguela marine pelagic social-ecological system: interaction of natural and human drivers. Ecol Soc. https://doi.org/10.5751/ES-05917-180455
Johannesen E, Ingvaldsen RB, Bogstad B et al (2012) Changes in Barents Sea ecosystem state, 1970–2009: climate fluctuations, human impact, and trophic interactions. ICES J Mar Sci 69:880–889. https://doi.org/10.1093/icesjms/fss046
Joo R, Bertrand A, Bouchon M et al (2014) Ecosystem scenarios shape fishermen spatial behavior. The case of the Peruvian anchovy fishery in the Northern Humboldt current system. Prog Oceanogr 128:60–73. https://doi.org/10.1016/j.pocean.2014.08.009
Koenigstein S, Jacox MG, Pozo Buil M et al (2022) Population projections of Pacific sardine driven by ocean warming and changing food availability in the California current. ICES J Mar Sci 79:2510–2523. https://doi.org/10.1093/icesjms/fsac191
Kroetz K, Nøstbakken L, Quaas M (2022) The future of wild-caught fisheries: expanding the scope of management. Rev Environ Econ Policy 16:241–261. https://doi.org/10.1086/721097
Kuriyama PT, Allen Akselrud C, Zwolinski JP, Hill KT (2024) Assessment of the Pacific sardine resource (*Sardinops sagax*) in 2024 for U.S. management in 2024–2025. U.S. Department of Commerce, NOAA
Kuroda H, Yokouchi K (2017) Interdecadal decrease in potential fishing areas for Pacific saury off the southeastern coast of Hokkaido, Japan. Fish Oceanogr 26:439–454. https://doi.org/10.1111/fog.12207

Langseth BJ, Purcell KM, Craig JK et al (2014) Effect of changes in dissolved oxygen concentrations on the spatial dynamics of the gulf menhaden fishery in the northern gulf of Mexico. Mar Coast Fish 6:223–234. https://doi.org/10.1080/19425120.2014.949017

Langseth BJ, Schueller AM, Shertzer KW et al (2016) Management implications of temporally and spatially varying catchability for the Gulf of Mexico menhaden fishery. Fish Res 181:186–197. https://doi.org/10.1016/j.fishres.2016.04.013

Lavín MF, Marinone SG (2003) An overview of the physical oceanography of the Gulf of California. In: Velasco Fuentes OU, Sheinbaum J, Ochoa J (eds) Nonlinear processes in geophysical fluid dynamics: a tribute to the scientific work of Pedro Ripa. Springer, Netherlands, Dordrecht, pp 173–204

Levangie PEL, Blanchfield PJ, Hutchings JA (2022) The influence of ocean warming on the natural mortality of marine fishes. Environ Biol Fishes 105:1447–1461. https://doi.org/10.1007/s10641-021-01161-0

Lindmark M, Audzijonyte A, Blanchard JL, Gårdmark A (2022) Temperature impacts on fish physiology and resource abundance lead to faster growth but smaller fish sizes and yields under warming. Glob Chang Biol 28:6239–6253. https://doi.org/10.1111/gcb.16341

Lopez-Parages J, de Fonseca MR, Brochier T, Auger PA, Zanchettin D, Rubino A, Gaetan C, Keenlyside N (2018) A promising effect of El Niño on sardinella distribution along the northwest African coast: a potential source of seasonal predictability?[résumé]. In ICAWA: International Conference AWA. SRFC/CSRP; IRD. pp 126

van der Lingen CD (2021) Adapting to climate change in the South African small pelagic fishery. In: Bahri T, Vasconcellos M, Welch D, et al. (eds) Adaptive management of fisheries in response to climate change. Food and Agriculture Organization of the United Nations, Italy, p. 177

Liu OR, Kaplan IC, Hernvann P-Y et al (2025) Climate change influences via species distribution shifts and century-scale warming in an end-to-end California current ecosystem model. Glob Chang Biol 31:e70021. https://doi.org/10.1111/gcb.70021

Lluch-Cota SE, Aragón-Noriega EA, Arreguín-Sánchez F et al (2007) The Gulf of California: review of ecosystem status and sustainability challenges. Prog Oceanogr 73:1–26. https://doi.org/10.1016/j.pocean.2007.01.013

Maiorano P, Sabatella RF, Marzocchi BM (2019) Annuario sullo stato delle risorse e sulle strutture produttive dei mari italiani

Makino M (2011) Fisheries management in Japan: its institutional features and case studies. Springer Science & Business Media, Dordrecht

Makino M (2018) Rebuilding and full utilization of alternating pelagic species around Japan: a social-ecological approach. In: Garcia SM, Ye Y, Charles A (eds) Rebuilding of marine fisheries Part 2: Case studies. FAO, Rome, pp 61–73

Maltby KM, Kerin S, Mills KE (2023) Barriers and enablers of climate adaptation in fisheries: insights from Northeast US fishing communities. Mar Policy 147:105331. https://doi.org/10.1016/j.marpol.2022.105331

Martínez-Zavala MA, Nevarez-Martinez MO, Gonzalez-Corona ME, et al (2015) Pesquería de pelagicos menores en el Golfo de California durante los oscuros 4 (enero) al 6 (marzo) de la temporada 2014/2015. Instituto Nacional de Pesca

Mason JG, Eurich JG, Lau JD et al (2022) Attributes of climate resilience in fisheries: from theory to practice. Fish Fish 23:522–544. https://doi.org/10.1111/faf.12630

McCabe RM, Hickey BM, Kudela RM et al (2016) An unprecedented coastwide toxic algal bloom linked to anomalous ocean conditions. Geophys Res Lett 43:10366–10376. https://doi.org/10.1002/2016GL070023

McClatchie S, Hendy IL, Thompson AR, Watson W (2017) Collapse and recovery of forage fish populations prior to commercial exploitation. Geophys Res Lett 44:1877–1885. https://doi.org/10.1002/2016gl071751

Menu C, Pecquerie L, Bacher C et al (2023) Testing the bottom-up hypothesis for the decline in size of anchovy and sardine across European waters through a bioenergetic modeling approach. Prog Oceanogr 210:102943. https://doi.org/10.1016/j.pocean.2022.102943

Miller KA, Munro GR (2004) Climate and Cooperation: a new perspective on the management of shared fish stocks. Mar Resour Econ 19:367–393. https://doi.org/10.1086/mre.19.3.42629440

Moron G, Galloso P, Gutierrez D, Torrejon-Magallanes J (2019) Temporal changes in mesoscale aggregations and spatial distribution scenarios of the Peruvian anchovy (Engraulis ringens). Deep Sea Res Part 2 Top Stud Oceanogr 159:75–83. https://doi.org/10.1016/j.dsr2.2018.11.009

Munro GR (2003) On the management of shared fish stocks. The management of shared fish stocks FAO Fisheries …

Nakken O (1998) Past, present and future exploitation and management of marine resources in the Barents Sea and adjacent areas. Fish Res 37:23–35. https://doi.org/10.1016/S0165-7836(98)00124-6

Nevárez-Martínez MO, Lluch-Belda D, Cisnerosata MA et al (2001) Distribution and abundance of the Pacific sardine (*Sardinops sagax*) in the Gulf of California and their relation with the environment. Prog Oceanogr 49:565–580. https://doi.org/10.1016/S0079-6611(01)00041-6

OECD (2011) The economics of adapting fisheries to climate change. Organization for economic co-operation and development (OECD), Paris Cedex, France

Ojeda-Ruiz MÁ, Petatán-Ramírez D, Guerrero-Izquierdo T, Salvadeo C (2022) Rapid vulnerability assessment of Pacific sardine (*Sardinops sagax*) fisheries facing climate change in Mexico. Prog Oceanogr 206:102826. https://doi.org/10.1016/j.pocean.2022.102826

Oken KL, Holland DS, Punt AE (2021) The effects of population synchrony, life history, and access constraints on benefits from fishing portfolios. Ecol Appl 31:e2307. https://doi.org/10.1002/eap.2307

Olafsdottir AH, Utne KR, Jacobsen JA et al (2019) Geographical expansion of Northeast Atlantic mackerel (Scomber scombrus) in the Nordic Seas from 2007 to 2016 was primarily driven by stock size and constrained by low temperatures. Deep Sea Res Part 2 Top Stud Oceanogr 159:152–168. https://doi.org/10.1016/j.dsr2.2018.05.023

Oliveros-Ramos R, Ñiquen M, Csirke J, Guevara-Carrasco R (2021) Management of the Peruvian Anchoveta (Engraulis ringens) fishery in the context of climate change. In: adaptive management of fisheries in response to climate change. FAO

Oyanedel R, Keim A, Castilla JC, Gelcich S (2018) Illegal fishing and territorial user rights in Chile. Conserv Biol 32:619–627. https://doi.org/10.1111/cobi.13048

Payne MR, Kudahl M, Engelhard GH et al (2021) Climate risk to European fisheries and coastal communities. Proc Natl Acad Sci U S A 118:e2018086118. https://doi.org/10.1073/pnas.2018086118

Peck MA, Alheit J, Bertrand A et al (2021) Small pelagic fish in the new millennium: a bottom-up view of global research effort. Prog Oceanogr 191:102494. https://doi.org/10.1016/j.pocean.2020.102494

Peck MA, Catalán IA, Rykaczewski RR, et al (In Review) Small pelagic fish: new frontiers in science and management. Mar Ecol Prog Ser

Pecl GT, Araújo MB, Bell JD et al (2017) Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being. Science. https://doi.org/10.1126/science.aai9214

Petatán-Ramírez D, Ojeda-Ruiz MÁ, Sánchez-Velasco L et al (2019) Potential changes in the distribution of suitable habitat for Pacific sardine (Sardinops sagax) under climate change scenarios. Deep Sea Res Part 2 Top Stud Oceanogr 169–170:104632. https://doi.org/10.1016/j.dsr2.2019.07.020

PFMC (2020) Status of the pacific coast coastal pelagic species fishery and recommended acceptable biological catches: Stock assessment and fishery evaluation for 2019

PFMC (2024) Coastal pelagic species management plan; as amended through amendment 21. Pacific Fishery Management Council

Pita C, Silva A, Prellezo R, Andrés M (2014) Socioeconomics and management. In: Ganias K (ed) Biology and ecology of sardines and anchovies. CRC Press, pp 348–379

Popescu I, Scholaert F (2022) Post-Brexit fishing quota changes: 2021. European Parliament

Quezada FJ, Tommasi D, Frawley T et al (2023) Catch as catch can: markets, availability, and fishery closures drive distinct responses among the U.S. West Coast Coastal Pelagic Species fleet segments. Can J Fish Aquat Sci. https://doi.org/10.1139/cjfas-2023-0094

Quezada FJ, Wildermuth R, Tommasi D, et al (2023b) Report From the future seas stakeholder engagement workshop, November 2022. NOAA Fisheries

Rabalais NN, Turner RE (2001) Hypoxia in the northern Gulf of Mexico: description, causes and change. Coastal and estuarine studies. American Geophysical Union, Washington, pp 1–36

Radovich J (1982) The collapse of the California sardine fishery. What have we learned 56–78

Robinson JPW, Mills DJ, Asiedu GA et al (2022a) Small pelagic fish supply abundant and affordable micronutrients to low- and middle-income countries. Nat Food 3:1075–1084. https://doi.org/10.1038/s43016-022-00643-3

Robinson JPW, Nash KL, Blanchard JL et al (2022b) Managing fisheries for maximum nutrient yield. Fish Fish 23:800–811. https://doi.org/10.1111/faf.12649

Rogers LA, Griffin R, Young T et al (2019) Shifting habitats expose fishing communities to risk under climate change. Nat Clim Chang 9:512–516. https://doi.org/10.1038/s41558-019-0503-z

Roy C, van der Lingen C, Coetzee JC, Lutjeharms JRE (2007) Abrupt environmental shift associated with changes in the distribution of Cape anchovy Engraulis encrasicolus spawners in the southern Benguela. Afr J Mar Sci 29:309–319

Rumolo P, Bonanno A, Barra M et al (2016) Spatial variations in feeding habits and trophic levels of two small pelagic fish species in the central Mediterranean Sea. Mar Environ Res 115:65–77. https://doi.org/10.1016/j.marenvres.2016.02.004

Saldívar-Lucio R, Salvadeo C, Lluch-Belda D, Villalobos H (2013) Proyecciones de la captura de sardina monterrey en la Costa Occidental de Baja California y el Golfo de California. In: Segundo Congreso Nacional de Investigación en Cambio Climático

Samhouri JF, Feist BE, Jacox M et al (2024) Stay or go? Geographic variation in risks due to climate change for fishing fleets that adapt in-place or adapt on-the-move. PLOS Climate 3:e0000285. https://doi.org/10.1371/journal.pclm.0000285

Sánchez S, Ibaibarriaga L, Uriarte A et al (2019) Challenges of management strategy evaluation for small pelagic fish: the Bay of Biscay anchovy case study. Mar Ecol Prog Ser 617–618:245–263. https://doi.org/10.3354/meps12602

Sarre A, Demarcq H, Keenlyside N et al (2024) Climate change impacts on small pelagic fish distribution in Northwest Africa: trends, shifts, and risk for food security. Sci Rep 14:12684. https://doi.org/10.1038/s41598-024-61734-8

Schickele A, Goberville E, Leroy B et al (2021) European small pelagic fish distribution under global change scenarios. Fish Fish 22:212–225. https://doi.org/10.1111/faf.12515

Schwartzlose RA, Alheit J, Bakun A et al (1999) Worldwide large-scale fluctuations of sardine and anchovy populations. S Afr J Mar Sci 21:289–347

Schwoerer T, Berry K, Dugan DG et al (2023) Fish or not fish—fisheries participation and harvest diversification under economic and ecological change. Mar Policy 157:105833. https://doi.org/10.1016/j.marpol.2023.105833

Selden RL, Thorson JT, Samhouri JF et al (2019) Coupled changes in biomass and distribution drive trends in availability of fish stocks to US West Coast ports. ICES J Mar Sci 77:188–199. https://doi.org/10.1093/icesjms/fsz211

Smith SL, Golden AS, Ramenzoni V et al (2020) Adaptation and resilience of commercial fishers in the Northeast United States during the early stages of the COVID-19 pandemic. PLoS One 15:e0243886. https://doi.org/10.1371/journal.pone.0243886

Smith JA, Muhling B, Sweeney J et al (2021) The potential impact of a shifting Pacific sardine distribution on U.S west coast landings. Fish Oceanogr 30:437–454. https://doi.org/10.1111/fog.12529

Smith SL, Cook S, Golden A et al (2022) Review of adaptations of U.S. Commercial Fisheries in response to the COVID-19 pandemic using the resist-accept-direct (RAD) framework. Fish Manag Ecol 29:439–455. https://doi.org/10.1111/fme.12567
Steins NA, Baker MR, Brooks K et al (2023) Co-creating knowledge with fishers: challenges and lessons for integrating fishers' knowledge contributions into marine science in well-developed scientific advisory systems. Front Mar Sci. https://doi.org/10.3389/fmars.2023.1338271
Swinea SH, Fodrie FJ (2021) Gulf fisheries supported resilience in the decade following unparalleled oiling. Ecosphere. https://doi.org/10.1002/ecs2.3801
Sylla A, Mignot J, Capet X, Gaye AT (2019) Weakening of the Senegalo-Mauritanian upwelling system under climate change. Clim Dyn 53:4447–4473. https://doi.org/10.1007/s00382-019-04797-y
Szuwalski CS, Britten GL, Licandeo R et al (2019) Global forage fish recruitment dynamics: a comparison of methods, time-variation, and reverse causality. Fish Res 214:56–64. https://doi.org/10.1016/j.fishres.2019.01.007
Taboada FG, Anadón R (2016) Determining the causes behind the collapse of a small pelagic fishery using Bayesian population modeling. Ecol Appl 26:886–898. https://doi.org/10.1890/15-0006
Taboada FG, Chust G, Santos Mocoroa M et al (2024) Shrinking body size of European anchovy in the Bay of Biscay. Glob Chang Biol 30:e17047. https://doi.org/10.1111/gcb.17047
Thiao D, Bunting SW (2022) Socio-economic and biological impacts of the fish-based feed industry for sub-Saharan Africa. FAO; WorldFish; University of Greenwich
Tseng H-S, Ou C-H (2010) The evolution and trend of the traditional fishing rights. Ocean Coast Manag 53:270–278. https://doi.org/10.1016/j.ocecoaman.2010.02.002
Tsitsika EV, Maravelias CD (2008) Fishing strategy choices of purse seines in the Mediterranean: implications for management. Fish Sci 74:19–27. https://doi.org/10.1111/j.1444-2906.2007.01492.x
Uber E, MacCall A (1990) The collapse of California's sardine fishery'. Climate Variability, Climate Change and Fisheries
Uriarte A, Ibaibarriaga L, Sánchez-Maroño S et al (2023) Lessons learnt on the management of short-lived fish from the Bay of Biscay anchovy case study: satisfying fishery needs and sustainability under recruitment uncertainty. Mar Policy 150:105512. https://doi.org/10.1016/j.marpol.2023.105512
Véron M, Duhamel E, Bertignac M et al (2020) Major changes in sardine growth and body condition in the Bay of Biscay between 2003 and 2016: temporal trends and drivers. Prog Oceanogr 182:102274. https://doi.org/10.1016/j.pocean.2020.102274
Walker B, Holling CS, Carpenter SR, Kinzig A (2004) Resilience, adaptability and transformability in social–ecological systems. Ecol Soc 9
Ward EJ, Anderson SC, Shelton AO et al (2018) Effects of increased specialization on revenue of Alaskan salmon fishers over four decades. J Appl Ecol 55:1082–1091. https://doi.org/10.1111/1365-2664.13058
Wilberg MJ, Thorson JT, Linton BC, Berkson J (2009) Incorporating time-varying catchability into population dynamic stock assessment models. Rev Fish Sci 18:7–24. https://doi.org/10.1080/10641260903294647
Wilson JA (2006) Matching social and ecological systems in complex ocean fisheries. Ecol Soc 11
Yatsu A (2019) Review of population dynamics and management of small pelagic fishes around the Japanese Archipelago. Fish Sci 85:611–639. https://doi.org/10.1007/s12562-019-01305-3
Zhang J, Smith MD (2011) Heterogeneous response to marine reserve formation: a sorting model approach. Environ Resour Econ 49:311–325. https://doi.org/10.1007/s10640-010-9434-x
Zwolinski JP, Demer DA (2012) A cold oceanographic regime with high exploitation rates in the Northeast Pacific forecasts a collapse of the sardine stock. Proc Natl Acad Sci U S A 109:4175–4180. https://doi.org/10.1073/pnas.1113806109

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