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A systemic approach to analyzing post-collapse adaptations in the Bay of Biscay anchovy fishery

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Abstract :

The Bay of Biscay anchovy fishery system has undergone important transformations following a closure from 2005 to 2010. Through a multidisciplinary and systemic approach, combining analyses of fisheries and market data with interviews with key stakeholders, we analyze adaptive responses of the main system components in France and Spain, considering how the fishing sector and fishery management institutions have adapted to changes. Focusing on the question “what has been lost and gained following the collapse?”, we find that while the anchovy stock has recovered, the fishery system has not returned to its pre-collapse status with important socio-economic features having been lost. We highlight the need for holistic consideration of multiple system components and diverse stakeholders’ perspectives. The perceived losses and gains from the anchovy fishery collapse and aftermath are found to vary across the players in the fishery system, depending as well on the management objectives and scales being considered. Such retrospective analysis can serve as a basis for understanding the long-term responses to social-ecological changes in fisheries, and identifying the role of governance mechanisms in supporting adaptations that maintain sustainable fishery systems in the face of future potential shocks.

Keywords : Fishery social-ecological systems, systemic approach, dynamic adaptation, Bay of Biscay anchovy, moratorium impacts

1. Introduction

Fundamental concerns in natural resource governance today include adaptation to large-scale ecological, economic and/or politically driven changes (Holling 1973; Folke 2016). Indeed, marine ecosystems and fisheries face a number of anthropogenic challenges related to population growth, globalization, coastal multi-use conflicts, increased seafood demand, marine pollution, biodiversity loss and climate change (Halpern et al. 2008; Allison et al. 2009; Jouffray et al. 2020, FAO 2022). They are also increasingly subjected to sudden large-scale shocks, jeopardizing their sustainability, as illustrated by the collapse of fish stocks (e.g., the North Atlantic cod stock, Charles 1997, the Atlanto-Scandian herring stock, Hannesson 2022), impacts of Brexit (e.g., Dépalle et al. 2020) or consequences of the COVID-19 pandemic (e.g., Carpenter et al. 2023). This has led to growing calls for increasing the resilience of fishing industries, fishery-dependent communities and fisheries management systems to change (Charles 2001; Grafton et al. 2022), although the extent to which this can be operationalized in fisheries remains a key challenge (Grafton et al. 2019).

A typical question when a fishery faces a resource collapse is: "what has been lost or gained following the shock?". We propose an operational approach to the evaluation of fishery system changes which accounts for most important system components, following the integrated approach for analyzing fishery systems developed by Charles (2001, 2023) – analogous to Elinor Ostrom's Framework (Ostrom 2009) but specific to fisheries. Both of these Social-Ecological Systems (SES, Berkes et al. 2002) approaches link biophysical and human social elements because changes in ecological systems affect fishing-dependent societies in complex ways (and vice-versa) and this interaction affects overall governance (Charles 2023). It is then necessary to include as many fishery system components as possible to understand the two-way flow and suggest appropriate management measures and policies to support the two-way flow (Charles 2005, 2023). Besides, changes and adaptations assessment that include traditional knowledge from connected system components can help understand and address complex change's associated risks (Simpson et al. 2021). Indeed, dialoguing with different stakeholders helps identify the different key system components to include to answer the research question, based on an adequate definition of system boundaries.

Fishery systems can be subjected to events that completely change them, with no turning back (Nuttall 2012; Brattland et al. 2019). While long-term spatial distribution and abundance of marine resources resulting from climate-induced changes have been widely studied (Cheung et al. 2010; Pinsky et al. 2013), human responses to any major change have been considered less often, or only partially (Beckensteiner et al. 2023). Only a few empirical studies (e.g., Mason et al. 2021; Ojea et al. 2021; Villasante et al. 2022) considered the different fishery system components together. For example, Stoll et al. (2015) highlighted the need to examine diversification of the seafood distribution systems and the geography of resilience, which has direct implications for the social-ecological resilience of fisheries. In marine ecology, food web analyses consider many species and trophic levels, flows between them and their interactions as a whole (e.g., Ecopath with Ecosim approaches, Christensen et al. 2014), yet the full potential capability of such analyses to incorporate human adaptations to ecosystem changes is still largely underdeveloped. A similar systemic approach must be conducted in fisheries systems where the interactions need to be broadened and scaled up. For example, Mason et al. (2021) provided a holistic typology of attributes contributing to fishery system resilience, to be integrated across scales and sectors. Indeed, they identified 13 ecological attributes (e.g., population abundance, age structure), 15 socio-economic attributes (e.g., wealth and reserves, economic diversity, market access) and 10 governance attributes (e.g., responsive and participatory governance structure), noting that many of them do not function independently but emerge from or are influenced by other attributes. They furthermore stressed the need for empirical case studies, which could elucidate the relative importance and applicability of resilience attributes and could reveal additional attributes, relationships among them as well as how they could be measured. We believe using a systemic approach is then the best avenue to explore a fishery system dynamics and adjustment to changes.

Answering the research question "what has been lost or gained following a shock?" through a systemic approach implies several sequential steps, including defining for whom and according to which norms system performance should be assessed. Indeed, these are key normative sub-questions that must be resolved for an operational resilience evaluation to be carried out. First, clear ecological, social, economic and/or political objectives for the different stakeholders must be identified, leading to the selection of system components to consider. Second, the desirable states for each component must also be defined, considering the perspectives of multiple stakeholders. Only with this identification of key components and desirable states can the analysis of the system behavior and responses to change be effectively carried out, to assess the extent to which it is resilient. In carrying out such analysis, a key challenge pertains to the availability of empirical information that the assessment can rely on.

We investigate how fishing communities and industries on the one hand, and fishery management institutions and science processes, on the other, have responded and adapted to a large social-ecological shock: the collapse of the Bay of Biscay European anchovy (*Engraulis encrasicolus*) stock in ICES, International Council for the Exploration of the Sea, Subarea 27.8, which entailed a closure of the fishery from 2005 to 2010. This stock was traditionally exploited by Spanish purse seiners and since the mid-1980s by French pelagic trawlers and purse seiners too. Landings are mainly sold on the Spanish market for fresh and canned anchovies. The anchovy fishery has been richly described and several studies have looked at various aspects of this crisis. For example, Vermard et al. (2008) modeled the French fleet behaviors, Mulazzani et al. (2013) combined an Institutional Analysis and Development framework with bioeconomic theory to investigate shared stock governance, and Sánchez et al. (2019) discussed the challenges associated with the management strategy evaluation process. While highly informative, none of these studies have attempted to undertake a long-term evaluation perspective, simultaneously considering the different components of the system. We focus on the analysis of drivers, processes and their outcomes at the system level, i.e., including the fishing activities, communities, governance, postharvest and market perspectives in France and in Spain over the 2000s-2020s period (with some references to the 1960s). Combining data analysis with interviews, we examine how the fishery adapted to the moratorium and triggered transformations, and highlight obstacles and barriers to adaptation and opportunities that have arisen during this crisis. This in turn allows us to answer the question of what was lost and what was gained in the fishery system after the shock.

2. Methods

2.1 A Systemic approach to a shock adaptation in the Bay of Biscay anchovy fishery

A systemic approach makes it possible to link changes observed in the different components of the system and allows for the exploration of changes, including aspects (e.g., practices, norms and values) that have disappeared and/or reorganized - this is crucial when studying resilience. To achieve this, we consider the responses to the moratorium of several components of the anchovy fishery system: the anchovy stock, the activities of fishers, the processing sector and markets, the scientific advisory and stock assessment process and the management system (Table 1, expressed using Charles's Framework).

For each of these components, we investigate the key changes undergone during and after the crisis, the opportunities which stakeholders were presented with and obstacles to adaptation encountered. First, we reconstructed a historical perspective of the pre-collapse events. Second, we described the responses of the fishery system.

Table 1 | The anchovy fishery system components analyzed, with associated quantitative metrics or qualitative attributes, using Charles's Framework.

Anchovy fishery system components	Charles's Framework	Metric(s) or attribute(s)
The anchovy stock	Natural System	Stock biomass, its composition and size
The scientific advice in management decision-making	Fishery Knowledge	ICES advices vs TAC vs catch
The fishers, fleet behaviors and fishing communities	Human System	Catch, fishing effort and vessel numbers
The processing sector, buyers and markets	Human System	Prices and trade flows
Fishery management	Governance System	Fishery calendar and participation

For each system component, we identified quantitative metrics or qualitative attributes with the desirable state according to the perspective of the main stakeholders impacted. This included, e.g. stock biomass from the anchovy's perspective, activity and catch from the perspective of the different fleets, trade volumes and prices from the perspective of fish processors, timing of and level of participation in management actions from the perspective of policy makers. Finally, we discussed the performance of the whole fishery system considering the components together and for several reference periods (synthesis results in Table 2).

2.2 Perception survey and interviews with key stakeholders

We collected testimonies from stakeholders who experienced the anchovy crisis during 2005-2010 in the Bay of Biscay (French and Spanish stakeholders, Steins et al. 2022) and/or who played a key role during this crisis. Key stakeholders included impacted fishers, fishers' representatives and producer organizations, fishmongers and processors, managers and scientists. A purposeful snowball sampling process (Johnson 2014) was used to identify respondents for the perception survey. We developed online questionnaires and carried out in-person interviews with semi-structured questions. The former was intended for informants who lacked time to meet. The content of the questionnaire was structured in two parts related to 1) major changes in all of the fishery system components considered and 2) the actors' responses at different time periods (see the Supplementary Method for the detailed description of the questions).

In total, 39 stakeholders were interviewed (14 completed the online survey), with 10 from Spain and 29 from France (See the Supplementary Method for the sampling validation). Of these, 11 informants considered themselves as industry representatives, 15 were fishers, 6 were both fishers and industry representatives, 4 were scientists, 1 was an administration representative, 1 was a fishmonger, and 1 an auction market director. Among fishers, we interviewed 13 purse seiners' and 8 pelagic trawlers' captains. Citations reported in the manuscript (in italics) from French and Spanish stakeholders have been translated into English by the authors. Stakeholders are identified by the following code: "F." or "S." for French or Spanish followed by the letter corresponding to their categories, PT for pelagic trawler, PS for purse seiner, R for representative, S for scientists, F for fishmonger, and # specified their anonymous respondent number.

2.3 Analysis of system level responses combining mixed data

Useful insights on changes in the fishery system and "hidden data" were gathered from the grey literature comprising public administrative reports (e.g., Official Journal of the European Commission), the European Commission's Scientific, Technical and Economic Committee for Fisheries (STECF) technical reports, ICES working groups reports and South-Western Waters Regional Advisory Council (SWW RAC) reports (See Supplementary Method for additional grey literature search methodology). We also interviewed both retired and active key scientific experts working on this fishery to collect their knowledge about its history and their perceptions of its management and how this evolved over the study period.

The observations made by the survey respondents were also complemented with system-level quantitative analyses using both fishery and trade data that were available to the research team for the following components of the system: market, landings and patterns in the spatio-temporal activity of the fleets. French fisheries data were extracted from the Ifremer Système d'Informations Halieutiques[1] and contain annual landings per target species for vessels dependent on anchovy (dependency defined as having fished at least 10 metric tons of anchovy once from 2000 to 2021 or annual anchovy value was equal to 10% of total landings value for this vessel, Daurès et al. 2009). Similar data for the Spanish fleets were not available for the present study. We derived prices from total annual anchovy landings and values from official fisheries data from France (SIH), from Galicia (Ministry of Agriculture, Fisheries and Food[2]) and from the Basque country government[3].

International anchovy trade data were extracted from the Eurostat's Comext database[4] referencing annual trade values and quantities of anchovy by EU Member State country and the (EU Member State or not) partner country, with products categorized according to the FranceAgrimer nomenclature (i.e., fresh, prepared or preserved, frozen, or dried-salted). As 95% of French landings are sold on the Basque market and processed in Spain (Pita et al. 2014), we focused the analysis on anchovy imports by Spain. A Fisher price index was calculated to analyze changes in the prices of imported fresh anchovy by Spain over the 2001-2020 period (See Supplementary Method for the definition and equation of the index).

3. Results

3.1 The road to collapse

The European anchovy is a short-lived small pelagic fish (usually not exceeding the age of 3-4 years and a length of 20 cm in the fishery catches) reaching maturity during its first year and subject to high and variable natural mortality (Taboada and Anadón 2016). The anchovy stock in ICES Subarea 27.8 (Bay of Biscay, Figure 1) was exploited from the 1940s mainly by the Spanish fleet in spring in Divisions 8.c and 8.b with a peak harvest in 1965 (Figure 2). Fishing anchovy with pelagic trawl is forbidden by Spanish legislation, after a proposal by the *Federación Nacional de Cofradías de Pescadores* (i.e., coastal fishers guilds), implying that the Spanish fleet targeting anchovy is composed of only purse-

[1] http://sih.ifremer.fr
[2] https://www.mapa.gob.es/es/estadistica/temas/estadisticas-pesqueras/default.aspx
[3] https://www.euskadi.eus/estadistica/precios-evolucion-de-la-campana-de-anchoa-y-bonito/web01-a2estadi/es/
[4] https://ec.europa.eu/eurostat

seiners (about 600 vessels in the 1960s, 23 meters long on average; Uriarte et al. 1996 ; Del Valle et al. 2001). Starting from the 1970s, the anchovy fishing areas contracted along the Spanish coast, from West to East (Junquera 1984), and both the catches and the number of Spanish purse seiners declined (to about 300 vessels in the 1980s; Uriarte and Astudillo 1987). This decrease in vessel number was part of the Spanish plan for the structuring of fisheries by following the EU Common Fisheries Policy (CFP) (*Planes de Orientación Plurianual* attached to the *Política de Estructuras Pesqueras;* Uriarte et al. 1996; Astorkiza et al. 1998). In the 2000s, the Spanish fleet was located mainly in Galicia (49%) and the Basque Country (31%); the remaining vessels were distributed between Asturias (13%) and Cantabria (7%) (Garza-Gil et al. 2011).

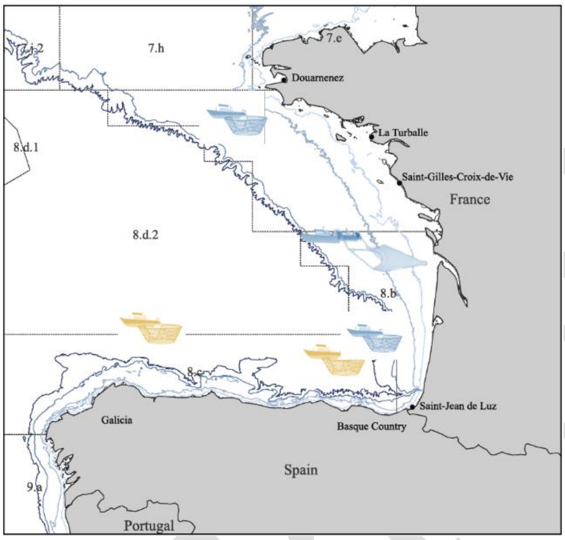

Figure 1 | The Bay of Biscay ICES divisions 8.a, 8.b and 8.c. The main French pelagic trawler and purse seiner fleets are represented in blue, while the main Spanish purse seiner fleets are represented in yellow. ICES spatial datasets are freely available for download from: https://gis.ices.dk and the EMODnet bathymetric contours (50, 100, 200, 1000 m) are available as a WFS service from EMODnet Bathymetry (Service URL is: https://ows.emodnet-bathymetry.eu/wfs).

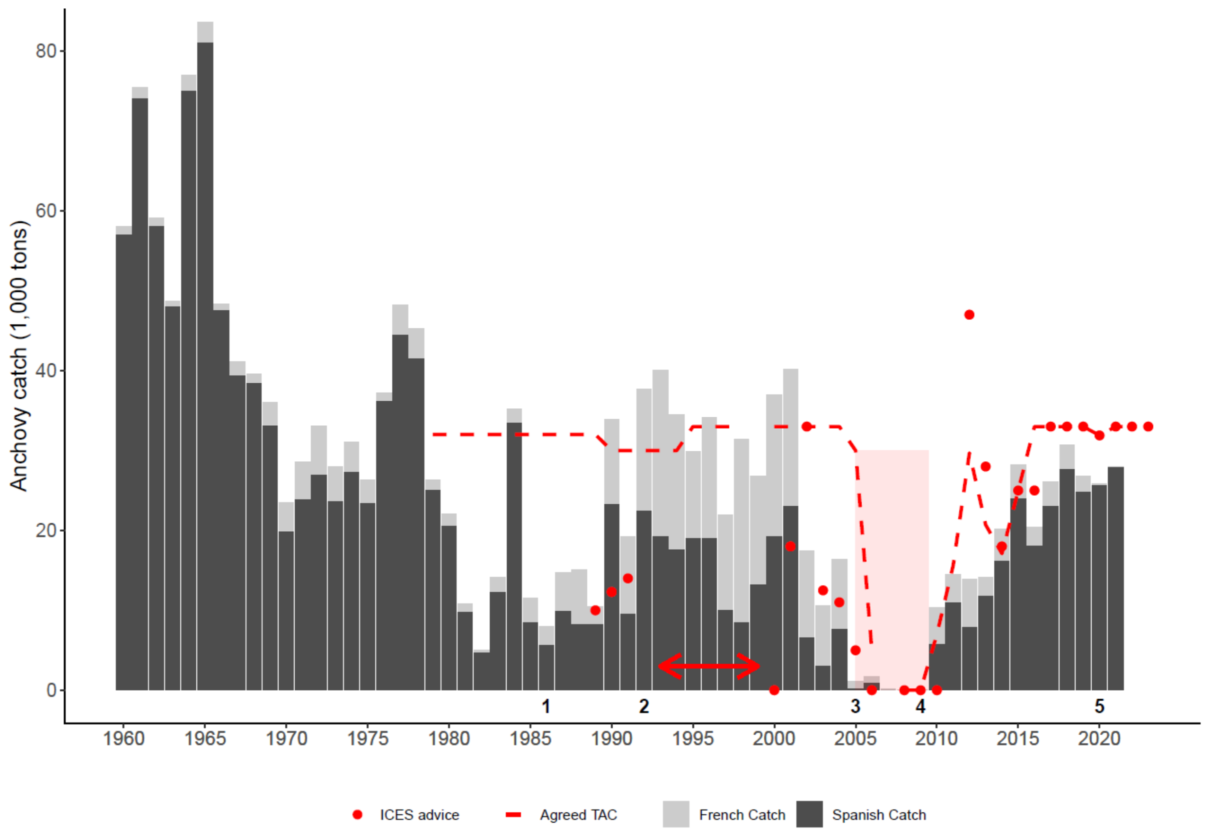

Figure 2 | Historical catches (1960-2021) of anchovy in the Bay of Biscay by Spanish (dark grey) and French (light grey) fleets and major events in this international fishery: ***1***. Spain EU accession, ***2***. Agreement of Arcachon, ***3***. Anchovy fishing ban from June 2005 to 2010 (red rectangle), ***4.*** Bilbao agreement, ***5***. Getaria agreement. Red dot dashed line indicates EU agreed TAC, red dots specify ICES advised TAC, the red arrow represents the period during which the ICES advisory group recommended a closed area and to diminish fishing mortality on juveniles. In 2012, the ICES catch advice was particularly important following a high stock recruitment year. Catch data for 2022 and 2023 were not yet available at the time of writing this article (Source: ICES WGHANSA 2020).

In the 1980s, a pelagic pair trawler fleet developed in France in response to a great demand of fresh products, particularly from the Spanish market (Fournet 1980, Prouzet et al. 1996), and 160 French vessels were authorized to fish anchovy as their main activity between March 1st and June 30th (Official Journal of the European Communities -OJEC- from 11/15/1985). With mid-water trawlers (mean length of 17 meters, working in pairs), French fishers were able to catch non-aggregated or deeper anchovy almost all year long, while Spanish purse-seiners could only catch anchovy aggregated in schools in the surface layer (depending on the net height) and in particular in spring on spawning aggregations (for a description of anchovy distribution and its life cycle, see Uriarte et al. 1996 and Taboada and Anadón 2016). Although most catches were reported in spring in coastal spawning grounds in Division 8.b (Uriarte et al. 1996), there was also a market in fall for the French industry to exploit bigger anchovies (i.e., ~15 cm and ~25g corresponding to 30-40 individuals per kilogram) that had migrated after spawning northward along the coast and across the mouth of Loire river into Division 8.a. French pelagic trawlers could operate in Division 8.b in spring but operated mostly in Division 8.a in fall. The French fleet also included some purse seiners (15 meters long on average, taking about 8% of the French catches in 1994; Prouzet et al. 1996) operating mainly in spring in 8.b, and in the North of the Bay in fall. 95% of French landings were sold on the Basque market and processed in Spain (Pita et al. 2014).

Since the entry of Spain in the European Union in 1986 (Figure 2, event 1), anchovy was managed primarily by means of a precautionary Total Allowable Catch (TAC). This was set at 33,000 tons for about twenty years, independently of ICES advice (see dashed line in Figure 2). According to historical reported catch and the relative stability principle endorsed in the CFP, 90% of the TAC was initially allocated to Spanish fishers while 10% was allocated to French fishers (Art. 161 of accession Act, OJEC from 11/15/1985). This allocation key was determined from the average catches in the 1970s, when the number of Spanish vessels targeting anchovy was between 500 and 600 and the pelagic trawler fleet had not yet developed (Astorkiza et al. 1998). The activity of the fleets was not conditioned by this allocation of fishing possibilities: since 1985, Spanish catches did not reach their quota, while French catches exceeded theirs.

A bilateral agreement between France and Spain (the so-called agreement of Arcachon, 1992; Figure 2, event 2) allowed France to have access to a higher proportion of the anchovy quota transferred from Spain in exchange for hake and anglerfish quota transferred from France (See Figure S1). For example, in 1994, 720 tons of northern hake and 500 tons of anglerfish were swapped against 6,400 tons of uncaught anchovy (Astorkiza et al. 1998). This quota transfer led to a more balanced share of the TAC, around 50% for both countries. Spanish vessels that fished hake more intensively were from Galicia while those who targeted anchovy were from the Basque country. After the swaps, Basque purse-seiners felt the deal was not optimal for them:

> "*Finally, a part of the anchovy caught by the Basques were exchanged to the profit of the Galician who could fish hake*" F. S #36,
>
> "*Basque fishers always received less hake than the Galician ones and ended up very angry against the quota swaps system*" F.R #35.

The agreement of Arcachon also guaranteed exclusivity for the purse-seiners to fish during the spring months at the start of the fishing season, to the exclusion of French pelagic trawlers (See Figure 3 for fishing calendar changes) during this period. Serious conflicts arose between the two main fleets related to the coexistence of the different fishing gears (Valle et al. 2001).

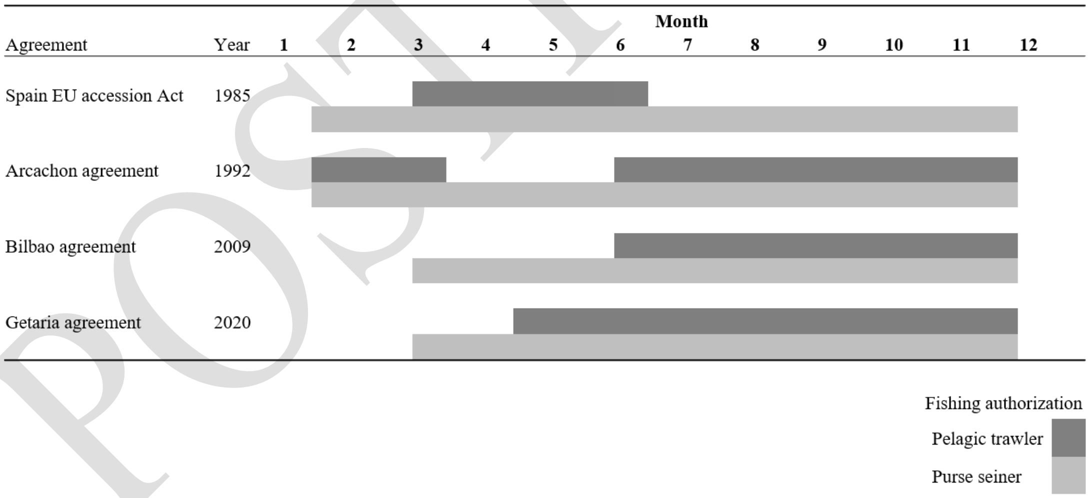

Figure 3 | Conceptual diagram of fishing authorization calendar for the anchovy fishery in the Bay of Biscay according to the fishing gear: French pelagic trawler (dark grey) and all purse-seiner (light grey).

The anchovy catches in the Bay of Biscay (8.a and 8.b) declined from almost 85,000 tons in the mid-60s to less than 4,500 tons in 1982 after two subsequent drastic declines. Following a similar pattern already reported for other species under the CFP (Carpenter et al. 2016), TACs started to be exceeded with the development of the pelagic trawler fleet in France. Although setting TACs above those advised by the ICES does not necessarily mean that stocks are being overfished, ICES advised to reduce the TAC for the anchovy to 10,000 tons in 1989. Further, the scientists advised to reduce fishing mortality on juveniles from 1993 to 1999, as well as to close a fishing area with high abundance of 1-year anchovy off the mouth of the river Gironde (Figure 1, and see section 3.2.b). But the TAC was kept between 30,000 and 33,000 tons, unchanged despite historically low levels of catches. This illustrates an apparent mismatch at the time between the general scientific advice which tried to significantly reduce the fishing mortality and political decisions regarding management which demonstrated a certain inertia regarding TAC modification (Da Rocha et al. 2012; Carpenter et al. 2016).

By the late 1990s, the anchovy stock experienced large inter-annual fluctuations in abundance driven by recruitment variability. Recruitment was low from 2001, and 2005 was classified as a recruitment failure year (JRCS 2008; Figure 4). Several non-exclusive hypotheses have been proposed to explain low recruitment such as a positive East-Atlantic oscillation index (low spring upwelling values with relatively high turbulences, Borja et al. 2008), summer gales affecting larval survival or variation in larval drifts (Allain et al., 2001; 2003), and changes in phytoplankton phenology or in larval drift (Taboada and Anadón 2016). However, forecasting recruitment based on environmental conditions still remains a challenge and Spain has put in place a recruit survey at sea (Boyra et al. 2013), which also has limitations. Yet, environmental fluctuations and recruitment variability alone barely explain the anchovy collapse, which also relates to the impact of elevated fishing pressure (Taboada and Anadon 2016; Bueno-Pardo et al., 2020). While the stock had started to decline from 2000 onwards, it collapsed by 2005 due to its extremely poor condition, with a combination of successive recruitment failures, and non-optimal management facing excessive exploitation **(**Boëns et al. 2023). In response, a fishing moratorium was established from July 2005 to 2010 (although the fishery was opened a couple of weeks during the first half in 2006; Figure 2, event 3).

3.2 Fishery system responses after the collapse

3.2.a The anchovy stock

Since the early 2010s, a rebound of the anchovy stock has been observed, with growing biomasses observed everywhere in the Bay of Biscay after the moratorium (Figure 4A). However, the composition of this stock is different. First, the average fish size for all age-classes is becoming smaller (Figure 4B). The underlying causes are challenging to establish but are probably a mixture of density-dependence because of high population biomass after the stock rebuilt, selective mortality on large individuals because of high fishing pressure before the collapse and changing trophic conditions with increasing sea water temperature (Doray et al. 2018; Véron et al. 2020; Boëns et al. 2021; Chust et al. 2022). Also, our perception survey pointed out similar phenomenon:

> "*the fishery can come back, it's just a question of size, if anchovies are small, it's probably because there are too many of them*" F.PT #31.

The decline in size may go along with a decrease in body condition and fat content as observed in the sardine stock of the Bay of Biscay and in the anchovy stock of the Mediterranean Sea (Van Beveren et al. 2014; Véron et al. 2020; Bertrand et al. 2022). As fish quality is fundamental for the canning industry, this change in size strongly affects the marketing value of the anchovy.

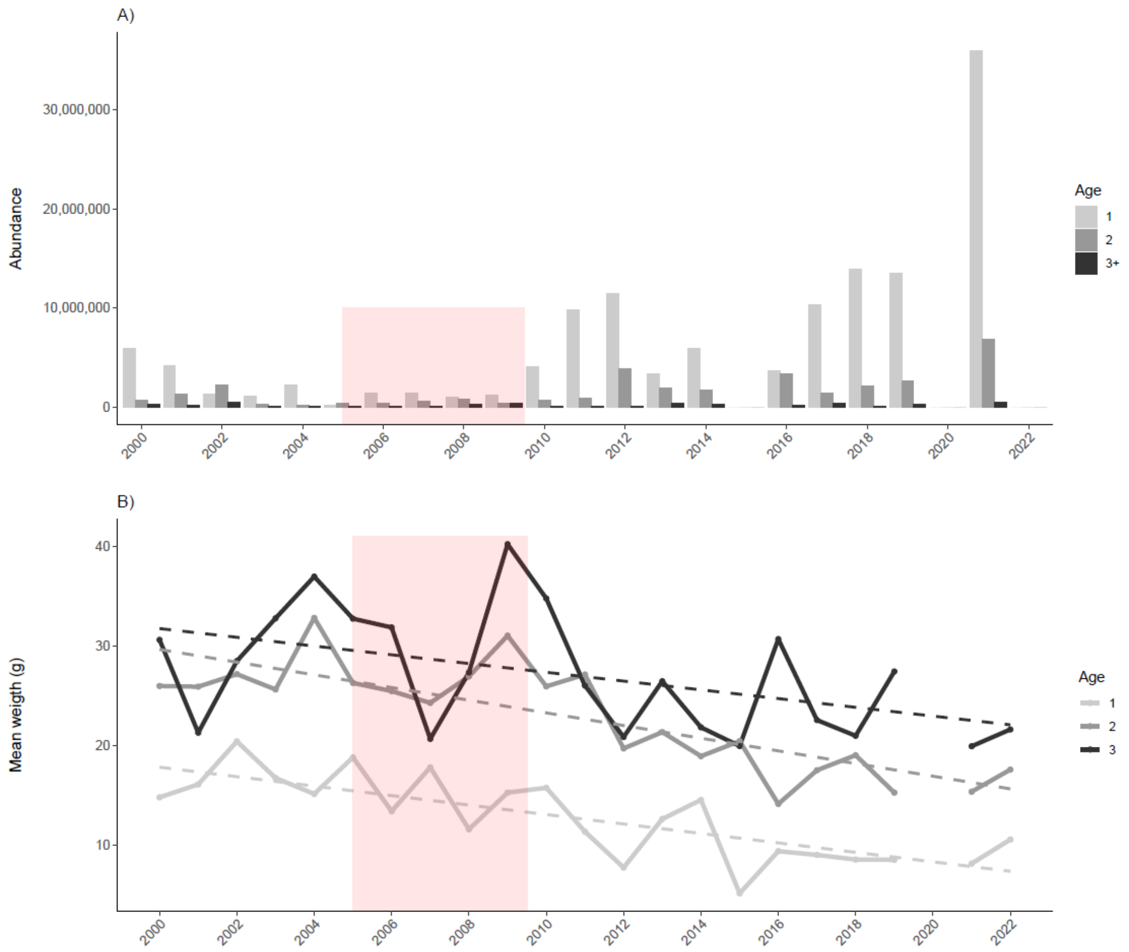

Figure 4 | Mean weight-at-age (A) and number-at-age (B) of anchovy estimated during the PELGAS survey in the Bay of Biscay in springtime. Red rectangles represent the moratorium period. Abundance for 2015 is omitted due to a potential overestimation on the recruitment resulting in huge age1-class. There is no data for 2020 since the survey could not be carried out due to the Covid-19 disruption (Sources: Ifremer Pelgas 2022 and Doray et al. 2022).

Furthermore, in 2021 the biomass is mostly composed of age-1 anchovy (Figure 4A), with observations of small anchovies mixing with larger ones in biomass pools, making the sorting challenging, time consuming and costly for fishers:

> "*During the scientific campaign, we have seen some large individuals, but they were all mixed up with juveniles – it was not worth to go fish for anchovy this year"* F.PT #29.

Before the moratorium, the anchovy price justified the sorting costs even if it meant producing a lot of discards:

> "*Since the price of anchovies has decreased* [section 3.2.d] *and attitudes towards discards have changed, it is no longer profitable for pelagic trawlers to catch 4 tons of anchovies to only keep 400 kg of large individuals*" F.S #37.

In addition, the large anchovies that are demanded by the processors (i.e., 40 individuals/kg, corresponding to ~25g and ~15.5 cm long anchovies) are becoming difficult to find, especially by the French fishers, who are constrained to fish in the second half of the year:

> "*Today, anchovies are too small, we would like to open the anchovy season earlier so that we can find bigger anchovy for the Spanish market"* F.R #13,
>
> "*Today, it's useless to fish anchovies because the little there is, it is already fished by purse seiners and the Spanish market is then already saturated*" F.PT #27,

"*changing the fishing calendar is the last hope for the French pelagic trawlers"* F.S #37.

In summary, while stock abundance would usually be considered a key performance metric to measure stock recovery, our survey shows that we also need to consider the condition of fish and fish size distribution, as these are important characteristics for the fishery, in terms of both fishing operations and fish prices. Thus, despite restored biological abundance, the anchovy biomass in the Bay of Biscay has not recovered the characteristics that made its harvesting economically viable before the collapse.

Both the collapse itself and the subsequent changes in the characteristics of the anchovy stock have had ecological impacts as well. Small pelagic fishes play a pivotal role in marine food webs because of their intermediate trophic position, high abundance and energy content (Palomera et al. 2007). Higher anchovy biomass and smaller individual fish length have contrasting consequences, affecting perhaps more the spatial availability of food to predators than the total amount available. Anchovy is one of several small pelagic species in the Bay of Biscay where sardine and mackerel contribute to most to the total small pelagic biomass and where anchovy accounts for 10% only (Doray et al., 2021). Therefore, the total energy available to higher trophic levels in the ecosystem is probably not so much dependent on the variation in the anchovy population. But individual fish size has decreased both in anchovy and sardine (Doray et al., 2018; Boens et al., 2023), and this may affect their spatial distribution and thus the spatial availability to predators as well as their population dynamics. There are spatial distribution impacts as well (Petitgas et al., 2014), notably the occupation of coastal habitats (smaller fish are more coastal) and over larger areas on the plateau (a larger biomass occupies larger areas), with off-shore shelf-break habitats being less occupied (in particular for sardine: Petitgas et al., 2020). Further, given that growth in small pelagic species depends on available zooplankton, which has decreased in size in recent years (Grandremy et al., 2023), fishing-induced selective pressure (Boens et al., 2023) causes cascading effects in the ecosystem by affecting population biomass and the growth pattern, which may reinforce the effect of environmental conditions and climate change.

3.2.b The role of scientific advice in management decision-making

With respect to scientific advisory processes, while inertia in management decision-making had been observed before the moratorium (the Harvest Control Rule -HCR- was fixed), the fishery has evolved towards a more effective science-based management. The TAC was initially based on a precautionary approach where the spawning-stock biomass (SSB) should not be below a biomass limit (B_{lim}). Despite the fact that the first ICES stock assessment was carried out in 1995-96, a fixed TAC was set to 33,000 tons for about twenty years before the collapse of the resource (Figure 2, see the gap between the red dashed line and dots):

"*TACs and quotas were implemented according to negotiations with no scientific basis*" S.R #1.
Further, a particular area off the Gironde estuary was identified as essential for recruitment (Vaz et al. 2002) and spatial closures in addition to TAC reduction have been explored (Figure 2, red arrow; ICES 2005) but the advice for a spatial closure was not retained by ICES nor adopted by the EU.

In this shared stock fishery, research surveys, evaluation methods and recommendations from French and Spanish scientists are critical to TAC recommendations. The timing of the TAC recommendation is decisive but is susceptible of creating inequalities among countries' fleets due to the marked seasonality in the fishery (Sanchez et al. 2019). Our survey showed diverging views between French and Spanish scientists existed in the early 2000s:

"*In science there is also politics […] where everyone defends their own method*".

There are now three fishery-independent annual surveys that monitor the population. Two are carried out in spring since 1987 on the spawning stock and estimate the adult population-at-age: the daily egg production method (i.e., BIOMAN carried out by AZTI) and an acoustic survey (i.e., PELGAS carried out by IFREMER) (Massé et al. 2016; Santos et al. 2018; Doray et al. 2021). These surveys provide population estimates by the middle of the year but cannot be used to project recruitment in the following year, an important parameter when advising for TAC in the next year. Since 2003, there has been a third survey carried out in fall by Spanish scientists, an acoustic survey (i.e., JUVENA) that estimates the juvenile abundance (Boyra et al. 2013). This survey was implemented to forecast the strength of the recruitment in the following year. In France, the effort has been on increasing the reliability of the spring acoustic survey by developing a collaboration at sea with fishers. Since 2009, a professional pelagic trawler pair has accompanied the French survey PELGAS (i.e., PELGAS PRO; Massé et al. 2016). Also, sentinel surveys have been implemented, which consist of surveying several sites according to fisher's local knowledge and collecting biological sampling. Such a collaboration has led to a better understanding of the stock assessment objectives and processes by the industry and the establishment of a more trustful relationship with the scientists:

> *"We discuss much more today with scientists; it is important that there are good relationships between fishers and scientists but not all fishers will tell you the same thing*", F.PT #29.

The fishery was reopened in 2010 and the moratorium triggered a change in the management scheme with the development of a long-term management plan and TAC set according to HCRs. From 2010 to 2014, the TAC was established for the period between July 1st and June 30th the following year, based on the current year spring surveys and assessment. This plan was based on a precautionary approach with a B_{lim} set to 21,000 tons. The management plan was revised in 2014: there were important changes in the assessment methodology with the inclusion of a recruitment index from JUVENA (Boyra et al. 2013; Sánchez et al. 2019; Uriarte et al. 2023) allowing a change in the management calendar from July-June to January-December. The STECF noted that changing the management period to January–December reduced the biological risks of the stock falling below B_{lim} and reduced the probability of fishery closure. The information on recruits entering the population in the management year reduced the probability of fishery closure by ~25%, and led to a small increase in the quantity and stability of catches (~15%), compared with the management period from July–June. Since 2015, the precautionary HCR upon which ICES advice is based sets the TAC to zero if the SSB is below the lower trigger and to 33,000 tons if the SSB is above the upper trigger (STECF 2014):

$$TAC_{y+1} = \begin{cases} 0 & if\ \widehat{SSB}_{y+1} \leq 24000 \\ -2600 + 0.40 \cdot \widehat{SSB}_{y+1} & if\ 24000 < \widehat{SSB}_{y+1} \leq 89000 \\ 33000 & if\ \widehat{SSB}_{y+1} > 89000 \end{cases}$$

With the set-up of HCRs after the moratorium, the adopted TACs align henceforth with ICES advices and are set up dependently of the stock status with less negotiations between interested parties (Figure 2, red dots and dashed red line:

> "*An exploitation rule was agreed upon that serves to set TACs and quotas in a scientific manner, without any interference from political decisions*" S.R #1.

3.2.c The fishers, fleet behaviors and fishing communities

An overall reduction in the number of vessels targeting anchovy was observed in the three fleets with regional variability (Figure 5). The strongest negative impact was for the French pelagic trawlers with a decrease of about 70% of the fleet according to stakeholder's perceptions. The combination of the change in the biological resource with a loss of market access is perceived as the main causes of the downfall, leading (sometimes) to scrapping vessels, with the assistance in some cases of emergency Community measures (Council Regulation EC No. 2370/2002). The Basque purse seiner fleet also reduced its size by 40 % from 2001 to 2009 (Andres and Uriarte 2012).

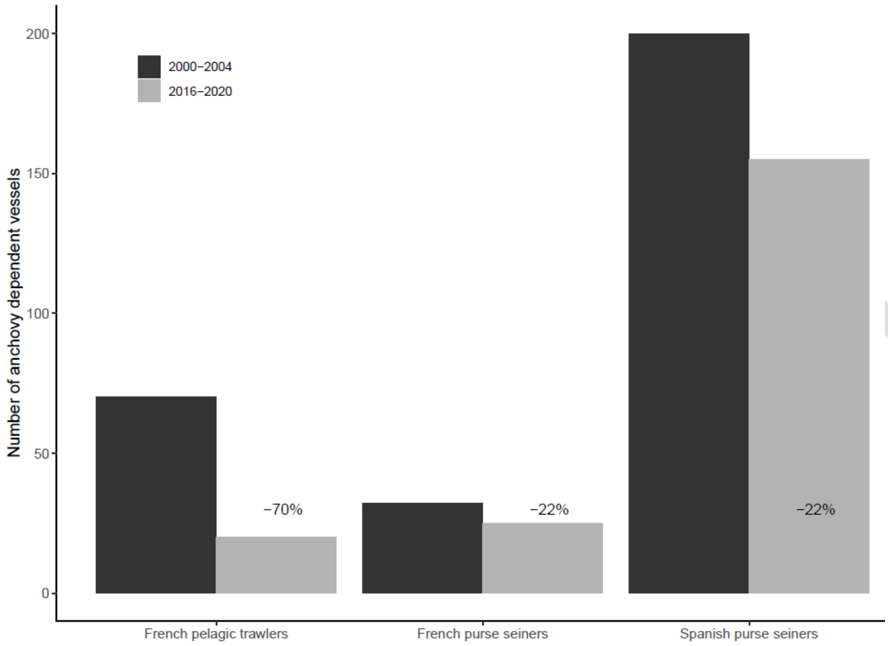

Figure 5 | Evolution of the French pelagic trawler and purse seiner fleets and Spanish purse seiner fleet according to our perceptions survey and official data in the early 2000 and mid-2010.

Total French fishing effort of pelagic trawlers and purse seiners targeting anchovy have considerably diminished in the last two decades (Figure 6). Three stages in the dynamics of this effort change can be identified, that can be explained by different drivers. The upper branch of the trajectories - *Collapse* (2000-2004) - is driven by anchovy biology, the left branch - *Closure* (2005-2009) by the politics of managing the fishery, and the lower branch - *Recovery* (2010-2019) by the economic drivers affecting fishing behavior. This phases diagram which captures in a single figure different stages in the dynamic of the fishery (as can be done in bioeconomic analyses such as the classic Clark and Munro 1975 diagram), clearly reveals the mixed system components' dynamics and adjustments to changes. Indeed, fishing effort remained relatively stable at a high level before the crisis (2000-2004) while, on the other hand, the SSB was rapidly decreasing. This was likely due to the fact that, while the apparent productivity of effort in volume had been decreasing, this was likely compensated by a price effect. Second, the system collapsed, leading to the adoption of the moratorium (2005-2009). Third, while the anchovy biomass rebuilt following this moratorium, even reaching higher SSB levels in 2015-2018 than in 2000, fishing effort did not return to pre-collapse levels, but remained at much lower levels than pre-collapse, for both fleets. This was likely due to changes in the characteristics of the resource and associated market effects, as well as in the structure of European trade for anchovy products (see section 3.2.d).

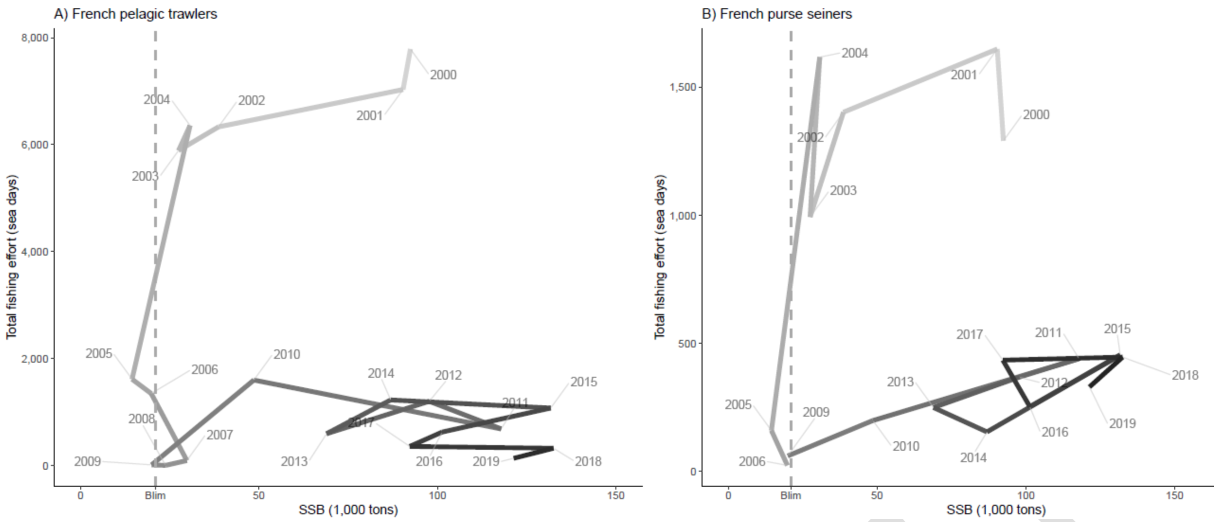

Figure 6 | Annual total fishing effort (in annual number of days at sea with 1 sea day corresponding to a 12-hours fishing trip) for anchovy-dependent French pelagic trawlers (A) and French purse seiners (B) and estimated spawning-stock biomass (SSB in tons) (Sources: Ifremer Système d'Informations Halieutiques SIH and ICES WGHANSA 2020).

In terms of fleet adaptation strategies, specific changes were observed according to gear, location and ports (Figure 7 and Figure S2). Beyond changes in the number of boats (Figure 5), fishing activity has also been transformed (e.g., season, targeted species, gear), especially for French purse seiners for which total effort targeting anchovy remained low after the crisis, as most vessels switched main target species.

The main two ports for French pelagic trawlers dependent on anchovy, La Turballe and Saint-Gilles-Croix-de-Vie, demonstrated completely different adaptation trajectories. In La Turballe, fishers mentioned trying new gear such as bottom trawl to target new fish and diversify their species portfolio (e.g., squids, sardines, European hake, seabass, albacore, Figure 7A, and Shannon diversity index's average of 1.69 in La Turballe compared to 1.32 in Saint-Gilles-Croix-de-Vie over the period 2010-2019, Figure S3):

> "*There were many boats from La Turballe that started using bottom trawls, and this is what saved the fleet here, unlike in St. Gilles where they did not try out*" F.PT #31,
> "*The only good thing about this crisis is that we were too monospecific; we learned from our mistakes and now we try to target multiple species*" F.PT #29.

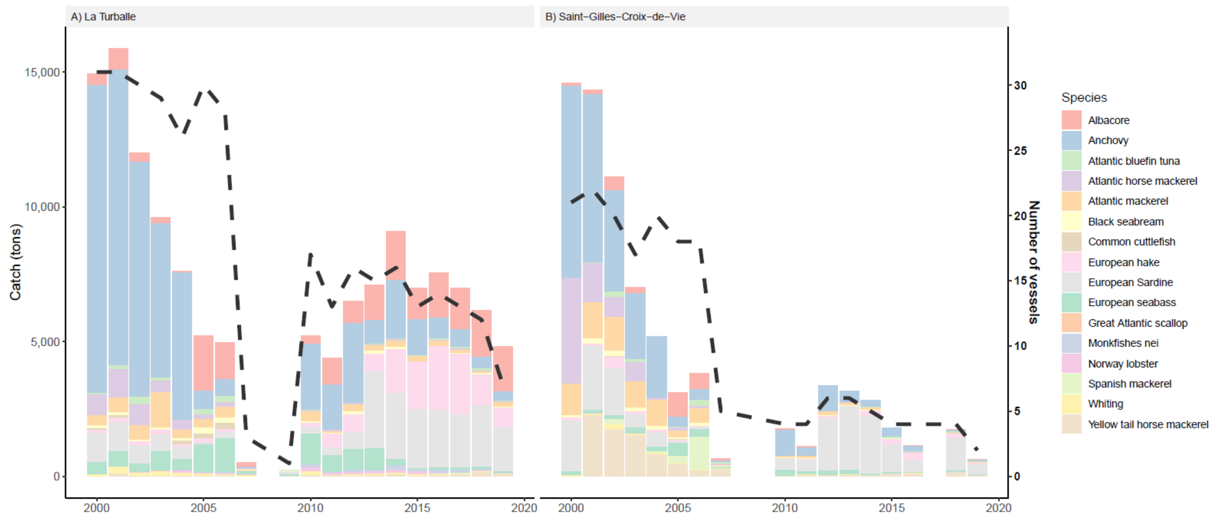

Figure 7 | Annual total catch (tons) of species for anchovy-dependent French vessels of two of the main harbors on the Atlantic coast of France and corresponding number of pelagic trawlers (dashed line). See Figure S2 for the adaptation strategies for the six other main French ports (Source: Ifremer SIH).

In Saint-Gilles-Croix-de-Vie (Figure 7B), the second most important French port of pelagic trawlers, most vessels were scrapped thanks to national decommissioning schemes – most of the time, this coincided with ship-owners reaching their retirement age. Some fishers mentioned that most barriers to their adaptation were related to how the calculation of the track record of catch, on which quota allocations across vessels is based in the French management system (Bellanger et al. 2016), was still based on the years 2001-2003. This was seen to block some from reallocating their activity to alternative fisheries:

> *"The calculation of track records [supporting quota allocation] completely blocked our fleet and are a barrier to enter any fishery"* F.R #12.

In the Saint-Jean de Luz area, South of France (Figure S2), the anchovy collapse came on top of a succession of events that had negatively impacted the fleet. Indeed, fishers had already lost their anchovy fishing rights in the 1990s, with most boats sold in Brittany in the early 2000s:

> "*For us, the anchovy crisis started in 1995 […] when anchovy started to be fished all year long with the development of pelagic trawlers, instead of only in spring as it was traditionally*" F.PS #21, and,
> "*The moratorium was the last straw for us; after losing our anchovy fishing rights from 90%, in the 1990s, to 3% within a decade because of the calculation of the track record of catch, we then lost the fresh markets*" F.R #10.

The purse seiner fleet located in Douarnenez, Brittany (Figure S2) grew (in particular via the sale of vessels sold from the Saint-Jean de Luz area) and intensified their effort on sardine with ensuing pressure on a stock which has also been impacted by environmental change in recent years:

> "*During the anchovy crisis, the price of sardine increased, there was a real opportunity for the development of this fishery in Brittany"* F.R. #13, although "*purse seiners are now 90-100% dependent on sardine*" F.PT #30.

In Galicia (Spain), one of the most important regions for the anchovy fishery in the country, behaviors were different. A temporary shift occurred to the construction industry, but with professionals coming back in the fishery once the stock had recovered, in the 2010s:

> "*This moment also coincided with the construction sector boom, and part of the local crew preferred to change to a profession economically more secure, less risky […] then over the years, they went back to fishing anchovy, influenced by the decline of work in the construction industry. This was also because the anchovy fishery became lucrative again*" S.PS #6.

Some fishers changed target species (e.g. mackerel), changed to hook-and-line fishing, especially for bonito, and/or adapted their fishing areas:

> "*During the moratorium, small Galician purse seiners felt the increased (displaced) fishing effort from larger purse seiners in their fishing area (IX) very much"* S.PS #8.

In the Basque country, fishers mostly switched target species, for mackerel and Bluefin tuna in particular. A gradual change in vessel performance and size (higher average gross tonnage by vessel) has been perceived over the last three decades (Andres and Uriarte 2012):

> "*The Basque vessels have evolved considerably, with new electronic tools and larger nets becoming more performant; their capacity has tripled*" F.PS #23.

While there was also a reduction in the Spanish purse seiner fleet, it seems that there were fewer scrapped boats overall and Spanish fishing industries seem to have been more robust to changes:

> *"Anchovy fishing continues at present, and the economic activity is similar to that before the moratorium"* S.PS #6.

The responses led to perceived impacts on other species due to the displacement of fishing effort after the closure of the anchovy fishery. This was for example observed in France with pelagic trawlers, with their diversification strategies impacting especially sea bass (Daurès et al. 2009):

> "*Everyone was fishing in the same place at the same moment; at the anchovy closure, there was an important [fishing] effort displacement to sea bass*" F.R #13,

and from French purse seiners:

> "*I am not going to lie, we started to fish horse mackerel 365 days a year*" F.PS #24,

as well as in Spain:

> "*Sardine, horse mackerel and mackerel suffered from more fishing pressure. Everyone switched to mackerel; it was a disaster for the stock*" S.PS #8.

3.2.d The processing sector, buyers and markets

The Bay of Biscay anchovy used to be a valuable small pelagic resource with higher price per kilogram landed (about 2 €/kg) compared to other small pelagic fish around the world subject to reduction fisheries (fish oil and fishmeal; Pita et al. 2014). Market disruptions resulting from the stock collapse and the fishery moratorium are examined in Figures 8 and 9. Anchovy prices responded very dynamically to the fishery crisis. From 2000 to 2006 when anchovy supply decreased, prices rose consequently (over 300%, Figure 8). Exceptionally high prices were observed in 2006 in both countries (with an average at around 6 €/kg during the period 2005-2009). Indeed, the fishery reopened for a couple of weeks in 2006 and anchovy prices reached a historical maximum of 11.3 €/kg in the Basque country (Andres and Prellezo 2012) and was even reported being as high as 14 €/kg in France:

> "*The year we fished the less anchovy, the highest was our annual turnover*" F.PS #21.

After the crisis, the system shifted to a new regime; real prices came back to their levels of the early 2000s in France from 2010 to 2016, but continued falling in Spain, and remained lower than average after 2017 in both countries.

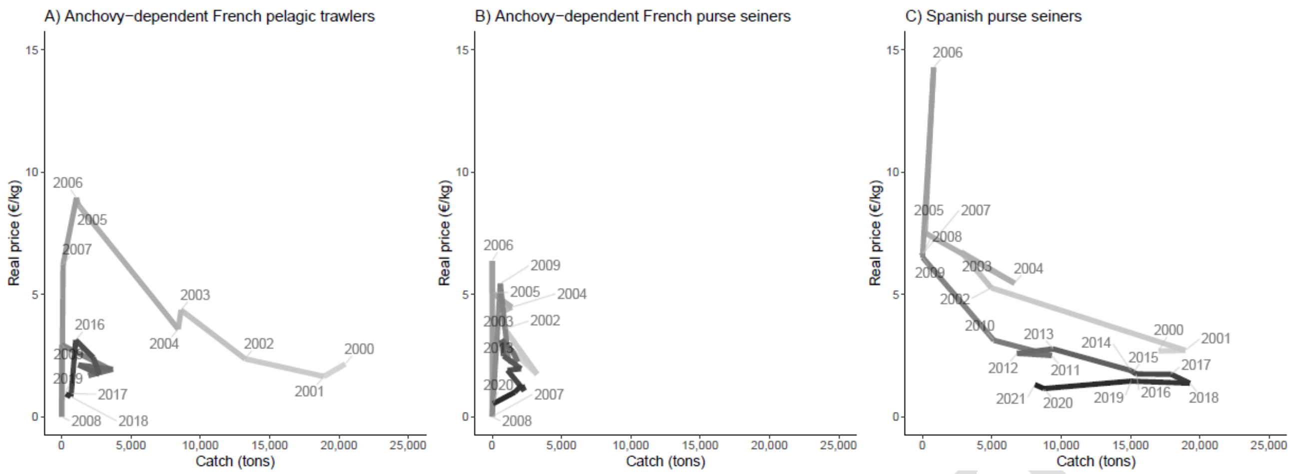

Figure 8 | Yearly adjusted prices (€/kg) vs landings (tons) for Bay of Biscay anchovy caught (A) by French pelagic trawlers, (B) French purse seiners, and (C) Spanish fleets. Prices are adjusted according to each country's FAOSTAT Consumer Price Food indices (https://www.fao.org/faostat/en/#data/CP) based on the year 2021. Quantity and value for French catch derived from Ifremer's SIH while the Spanish data (composed of Galician and Basque country data) come from the Ministry of Agriculture, Fisheries and Food[2] and from the Basque country government[3].

Despite the opening of canning industries in the Northern part of Spain, the majority of production used to go for fresh consumption in Spain, making this country the main importer of anchovies in Europe (Mulazzani et al. 2013). Figure 9 shows the annual quantity of fresh and prepared anchovies imported by Spain from the main countries of origin along price indices. Before the moratorium, France represented 50% of fresh anchovy imports by Spain, while during the moratorium, when French production collapsed, increased imports of fresh anchovy from Italy and preserved anchovy from Morocco and Peru were observed (Figure 9A). In the later part of the period, French fresh anchovy imports have almost disappeared (only contributing to 5% of fresh anchovy imports by Spain in 2021), to the benefit of Portuguese fresh anchovies. Respondents to our survey noted that the supply of the Spanish market switched to Portugal because Portuguese fleets are seen to use fishing gear that makes for higher quality product gear:

> "*the anchovy caught by French pelagic boats is of poorer quality, not suitable for canning, so that the buyers do not want it.* […] *If French fishers were using purse seiners then they could sell anchovies... like in Portugal, using purse seiners, they do sell anchovy to Spanish buyers*" S.PS #7.

The price index for fresh imported anchovies first increased during the reference period of 2000-2004 then decreased (Figure 9A), probably due to the new large supply of fresh Italian anchovies from the Adriatic Sea. The index rebounded in 2013, following the collapse of small pelagic fisheries in the Mediterranean Sea (Van Beveren et al. 2014), before diminishing again.

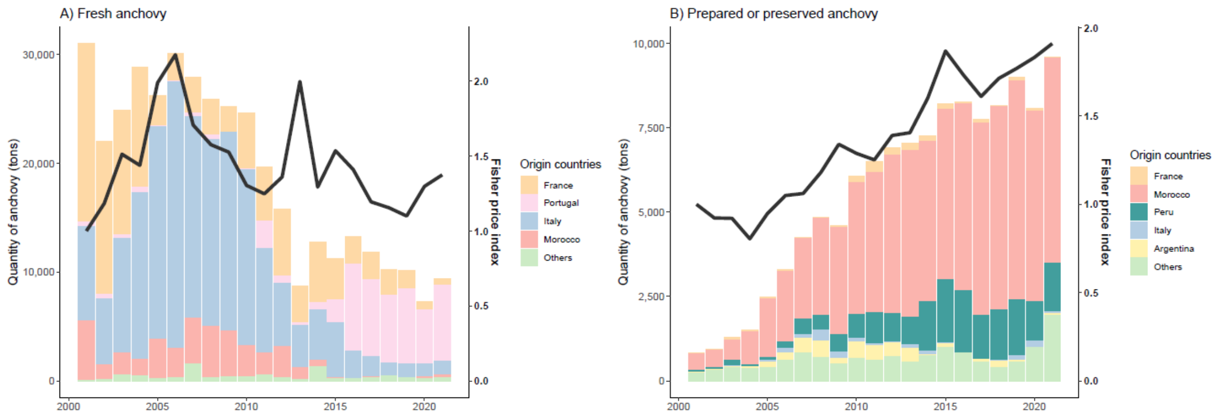

Figure 9 | Quantity (tons) of anchovies imported by Spain, by main country of origin, for fresh (A) and prepared or preserved (B) anchovy, with corresponding Fisher price indexes using 2001 as the reference year (thick black line). Note the different anchovy quantity scales between fresh and preserved products (Source: EU Comext).

Overall, imports of fresh products by Spain decreased over the period, while imports of preserved anchovies saw a marked increase, reaching 10,000 tons in 2021 (Figure 9B). Responses to our survey highlighted two phenomena that explain this increase in canned product imports. First, Spanish industries established long-term contracts with new import sources:

> "*Bay of Biscay anchovy was replaced by Mediterranean or South American anchovy, which are cheaper (1.20 €/kg) but of lower quality with lots of fish-bones. When the good quality anchovy came back in 2010, people didn't want it, they got used to the bad ones and were not willing to pay more*" S.PS #3, and
>
> "*During the crisis, processors had to work with South American anchovies, which are cheaper. Today, they have kept a foot in it, they are still importing from those sources and are engaged with long-term contracts to keep the low price*" F.PT #30.

Second, Spanish industries delocalized their production activities, particularly in Morocco:

> "*80% of the anchovy (the largest anchovy, <30 ind./kg) remains in the factories of the Basque Country and Cantabria; the rest of the anchovy (the smallest anchovy, >45 ind./kg) goes to Morocco*" S.PS #5, and
>
> "*Small processing plants had to close, bigger ones were relocated in Morocco because labor cost is five times cheaper there*" S.F #34.

It is important to note that in the international trade data, imported anchovy are not necessarily the same species as the European anchovy (*Engraulis encrasicolus*) but are composed of anchovy products belonging to the same family (*Engraulidae*). According to respondents, South American products are Peruvian anchovy (or anchoveta, *Engraulis rigens*) and can end up in anchovy cans mixed up with local products to keep the Bay of Biscay label. The quality of this product is different according to a fisher:

> "*There are several species of anchovies in the world but it is the European species that, according to experts, has the most quality and fat content*" F. S #37,

although the consumer does not necessarily see the difference:

> "*The consumer adapts. Who knows enough about anchovies to differentiate between Peruvian, Moroccan and Bay of Biscay anchovies?*" S.F #34.

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 French fishers.

3.2.e Fishery management

Some aspects of the governance of the anchovy fishery seem to have been strengthened by the crisis, with the implementation of a series of adaptations over the last two decades. First, the fishing authorization calendar for the pelagic trawler and purse seiner fleets was revised multiple times (Figure 3) to adjust to the recovery and understanding of the population dynamics of the Bay of Biscay anchovy. The Spanish and French fleets now mainly carry out seasonal fisheries, in spring and fall respectively, with less in-season competition among fleets compared to the 1980s and 1990s when the pelagic trawlers and the purse seiners operated both in spring and fall.

Second, it was the first time in French fisheries governance that the administration implemented temporary fishing interruptions with financial compensation. Between 2007 and 2008, a budget of 3,5 million euros was allocated towards 126 French vessels constrained to stop their activity for at least fifteen (and up to forty-five) consecutive days. The compensation allocated to fishers (ca. 15 million euros) was based on the number of days of stoppage, the total catch value for all species combined during the 2000-2004 period, the number of months of activity during 2000-2004 and the number of months of stoppage of the vessel. While some interviewees noted that the payments arrived quite late compared to the economic impacts of the moratorium, the administration emphasized it was an emergency measure allowed by the EU CFP and that they had to ensure a certain reliability, developing calculations rules from scratch but guaranteeing that fishers would receive the aid as quickly as possible and that no one was left behind:

> "*Temporary stoppage subsidies were interesting for the wages of the sailors but not for the owners; everybody received the same amount whether they were in debt or not. It was particularly hard on new entrants in the fishery"* F.PT #30.

Also, there was no financial compensation for the ports, the fish buyers and the canning industries, although these claimed to also be severely impacted:

> "*There was no financial support for the auction market*" F.action market #19, and
> "*There was absolutely no administrative and financial support for the fishmonger sector despite some promises*" S.#34.

As previously described (section 3.2.b), the decision-processes evolved to a more adaptive management of the fishery by setting a management plan. The TAC is now set after the recruit survey and is not fixed but a function of the estimated population biomass. The management plan also limits competition between fleets with a rule to share the TAC between fleets and countries, which also depends on population biomass. The quota for French pelagic trawlers increases with population biomass and is null when the biomass is below a set threshold (Uriarte et al. 2023). The interactive collaboration between fishers, scientists and managers and the formation of the South Western Waters Regional Advisory Councils (SWW RAC 2008) allowed better inclusion of stakeholder's preferences for the selection of the HCRs, technical measures and development of the long-term management plan, therefore appearing as a successful participatory process in EU fishery management (Uriarte et al. 2023). Since the reopening of the fishery, the adopted TACs align with ICES advice. This convergence is probably helped by the fact that the anchovy stock biomass is high, above historical levels, and the fishing pressure is reduced. At these high biomass levels, the differences between Spanish and French scientific evaluations associated with differences in assessment protocols have minor consequences. Because the biomass levels are high and the competition between fleets is reduced with a smaller Spanish fleet and an almost non-existent French fleet, the tradeoffs considered in the science-based management process are limited.

While fisheries management has been improved (no more overlap of the fishing calendar between fleets, better alignment between TAC levels, population biomass and ICES advice, creation of the RAC), the adopted TACs have not been binding in recent years (Figure 2). Indeed, effort and catches are apparently only restricted by economic factors. The downfall of the French pelagic trawlers and the loss of the market for the French operators have led to decreased incentives to harvest and reduced pressure on the stock, independently of the management framework. In this context, one would expect less conflicts around the TAC levels definitions, which is not necessarily related to improved management.

3.3 Perceptions about the moratorium

We asked all interviewees for their perceptions about the fishery moratorium, and if they believed it was the right management decision to take (Table S1). We found an important variability of perceptions among actors, origins, and professions. About one-third of all respondents agreed with the closure. Interviewees who agreed with the moratorium usually highlighted how it was necessary for resource recovery:

> "*It was necessary because they [pelagic fleets] were fishing in spawning areas. Now, the anchovy has recovered*" S.PS #5, and
>
> "*It was a necessary closure which has served as a lesson for the management approach*" F.R #17.

This necessity was perceived mainly by purse seiners and/or Spanish actors. Interviewees who disagreed with the moratorium stressed the socio-economic impacts that it caused:

> "*We lost the market, then we lost the boats and in the end, the crews*" F.PS #24, "*The moratorium was an urgency, although the market was sacrificed*" F.PS #21, and "*There are three pillars: economy, social, and environment but we can see today they only think about the environment, the two other pillars are only included from time to time when they think about them*" F.R #11.

Most of these respondents advocated for a minimal quota to maintain markets when a stock collapses, instead of a complete closure, to limit such negative impacts:

> "*They should have maintained a small quota to better understand the resource trends and restart the market more easily; Fishers lost their bearings*" F.R #13.

3.4 Synthesis: Responses of fishery system components

We synthesized the adaptive responses of fishery system components according to several quantitative and qualitative metrics, considering different dimensions relating to the performance of the system, and several reference periods (Table 2). Taking the period '2000-2004' as the reference period, seven metrics out of twenty-one, especially related to the biological resource component (e.g., anchovy abundance) or to the science-based management (e.g., gap between TAC and ICES advice), displayed improvements over time. Indeed, the anchovy stock biomass has recovered to maximal historical levels today. However, overall, the fishery system has not returned to its pre-collapse status. For the other fishery system components, a degradation seems to be observed for all dimensions, although results differ according to the metrics, the reference periods, the actors and the country considered.

Results can be nuanced for each component. For example, 'abundance' is often identified as a key performance metric to measure recovery of the stock, but the analysis shows that a high biomass is not enough for the recovery of this system: the condition of fish (size and fat content) and its catchability (mix) also need to be considered in relation to the sustainability of marketing possibilities.

The management decision to close the fishery in order to preserve the fish resource has generated radical long-term changes in the fleets, the sector and international markets. For the fishery, the consequences of the moratorium have been a decrease in the fishing effort mainly due to the downfall of the pelagic trawler fleet, less competition between fleets and a management scheme that is more precautionary. Other repercussions include altered price formation dynamics and lower prices than expected, as well as a loss of market access for French operators. Spanish fishing companies, on the other hand, seem to have been more resilient to changes, with improved total catch and a fleet still composed of over 150 vessels (compared to 40 vessels in France). The country may have benefitted from the new management scheme put in place when the fishery reopened. Besides, Spanish buyers quickly found alternative suppliers, which led to a complete restructuring of the marketing system. While this restructuration was to the detriment of French fishers, this has likely benefited other economic actors, in other countries (such as Morocco and Italy). The canning industry could appear as one of the winners from this crisis, as it seems to have better adapted to the lack of local anchovy, finding substitutes from other locations (Mulazzani et al. 2013).

Nevertheless, these results are moot if we change the period of reference and zoom out to the '1960s-1980s' period. Then, the total Spanish landings were almost twice those today, with three times the number of vessels, and only about thirty French purse seiners. With the advent of pelagic trawlers, the anchovy stock was heavily exploited, twice a year, in spring (at the south-eastern corner of the Bay of Biscay, Divisions 8.c and 8.b, Figure 1) and late summer and autumn (northwestward areas of the Bay of Biscay, Division 8.a). It is likely that before this development in the 1980s, a de facto harvesting pause implying a temporary reserve effect may have benefited the stock during the autumn period. Nowadays, with the loss of the market for the French operators, this area may have become a reserve from fishing again.

Furthermore, the spatial distribution of anchovy at spawning time in May is dependent on population biomass, as well as on fish length, with larger areas occupied by higher biomass and a more coastal distribution of smaller individuals (MacCall 1990, Petitgas et al. 2014). In the future, these distribution change projections will be even more important under the RCP8.5 climate change scenario due to an expected higher egg production (Erauskin-Extramiana et al. 2019). Finding large anchovies that are not mixed with smaller individuals or with sardines, and not too far from coastal fishing zones, might become even harder for fishers.

Table 2 | Synthesis of fishery system components' response metrics (means) for different reference periods. Colors represent the improvement (green), reduction (red) or status quo (yellow, <10% of change), and shades represent the magnitude of the change (lighter colors for a 10-50% change and darker colors for a >50% change). The evaluation is taken from the perspective of the subject considered (A for anchovies, FF for French fishers, SF for Spanish fishers, FO for French operators and SO for Spanish operators). *In 2012, the ICES catch advice was particularly important following a high stock recruitment year; we included in parenthesis the mean calculated without the data from this year.

System components	Metric or Attribute (mean)	Subject	1960-1980	2000-2004	2010-2015	2016-2020	Last year of data		Sources
Biological resource	Total SSB (tons)	A	-	55 903	91 937	124 373	**174 428**	*2020*	ICES evaluation data
	Abundance	A	-	4 149 869	7 457 181	10 380 299	**43 269 901**	*2021*	Pelgas
	Adult anchovy weight (g)	A	-	28.77	23.61	20.95	**19.59**	*2021*	Pelgas
	Adult anchovy (%)	A	-	28.90	23.43	23.92	**16.85**	*2021*	Pelgas
	Big anchovy (%)	A	-	6.28	2.92	1.99	**1.05**	*2021*	Pelgas
Fishing behavior	Total French catch (tons)	FF	2 575	12 445	4 138	2 158	**64**	*2021*	ICES evaluation data
	French fishing effort (sea days)	FF	42 165	8 069	1 372	582	**14**	*2020*	SIH
	French vessels	FF	-	100	80	50	**40**	*2022*	Prouzet et al. 1996 + interviews
	Total Spanish catch (tons)	SF	35	11 877	12 744	23 817	**27 917**	*2021*	ICES evaluation data
	Spanish vessels	SF	600	200	200	155	**155**	*2020*	Prouzet et al. 1996 + interviews
Market and trades	French anchovy price (€/kg)	FO	-	2.85	2.03	1.26	**0.53**	*2020*	SIH
	Share of French imports of fresh anchovy (%)	FO	-	0.50	0.33	0.17	**0.05**	*2021*	Comext
	Spanish anchovy price (€/kg)	SO	-	4.57	2.44	1.46	**1.31**	*2021*	Governmental Statistics
	Fresh anchovy imports price Index	SO	-	1.28	1.46	1.23	**1.37**	*2021*	Comext
	Total fresh imports (tons)	SO	-	26 708	13 643	10 539	**9 384.69**	*2021*	Comext
	Total canned imports (tons)	FO	-	1 148	7 003	8 253	**9 605.91**	*2021*	Comext
Science	Gap TAC vs Total Catch (tons)	A	-	-8 679	-2 302	-6 803	**-5 019**	*2021*	ICES evaluation data
	Gap TAC vs Advice (tons)	A	-	18 100	5,680*	1 600	**0**	*2022*	ICES evaluation data (*2,775)
Management	Purse seiner fishing interruptions (month)	A	-	1.5	3	3	**3**	*2022*	Management plan
	Pelagic trawlers interruptions (month)	A	-	4	6	4.5	**4.5**	*2022*	Management plan
	Inclusive management	A						*2022*	Key experts' knowledge

4. Discussion

Examining stakeholder perceptions to identify key dimensions and desirable states, in relation to post-collapse transformations and adaptations, provides multiple perspectives on what such desirable states might be. Indeed, there may not be only one defined system state towards which one may aspire (Pimm et al. 2019), and the question thus becomes that of performance at which scale, for whom and from which point of view.

Assessing performance requires clear ecological, social, economic and/or political objectives, for the different stakeholders and system components, but in many instances, their definition remains vague. As part of these unavoidable normative decisions, choices are needed of the indicators or metrics used, as well as the reference period which should be considered. Here we chose to adopt the perspectives that were put forward by the stakeholders interviewed in our survey, to decide on the dimensions, as well as the metrics and scales at which to consider them, and the reference states with which to compare more recently observed situations.

Thus, in answering the overall question "what have we lost or gained after the collapse?", we observe that some important features of the fishery system have been lost, but how this is perceived varies among stakeholders. Our analysis also shows that if economic and social criteria are to be considered in fisheries management, the cascading effects on the supply chain also need to be considered, in addition to the responses of the biological resources and fishing fleets. This highlights the challenges associated with resilience evaluation, which usually refers to restoring a certain performance of a system (Grafton et al. 2019). Yet, the way in which system performance can be defined, its desirable states, are often not discussed in analyses which largely focus on the mechanistic processes enabling a system to resist, change and/or bounce back to previous states.

An important part of the diagnosis depends on the availability and accessibility of data regarding system components. In the Bay of Biscay anchovy case, over the study period, scientific and governance efforts have largely focused on fisheries catch and effort surveys, biological evaluations and choices of management measures. However, when we study the transformations of a fishery system, we need to broaden the scope and incorporate multiple system components as well as the multiple interactions that drive system dynamics (Ostrom 2009). Yet, finding metrics or performance indicators for all system components and reference periods can prove a challenge, especially in looking across countries and may require combining data sources and data types. Indeed, in this case study, we identified a need for better data to assess flows up and down the supply chain (i.e., the connections from landings to processors and markets) as well as social transformations occurring in the industry (e.g., changes in working conditions and labor in both the catching and the processing sectors).

Particularly noticeable was the lack of data for useful comparisons between France and Spain, to provide context for the perceptions we recorded relating to socio-economic changes (e.g., industry profits, jobs created or lost, changes in activities, changes in crew composition, generational replacement issues). Some of this data is currently assembled by the European Commission Joint Research Centre but is aggregated by country and fleet segment and currently lacks detailed geographical segmentation by regional, provincial or local administrative units (Natale et al. 2013). This is an area currently under development.

Further research and information on linkages between the catching sector, value chain structure and consumer preferences could be also beneficial for a better simultaneous understanding of system component transformations after a shock (Roheim et al. 2018; Thébaud et al. 2023). New initiatives within ICES, including the Strategic Initiative on Human Dimensions[5] and the new Working Groups on Economics and on Social Indicators, will improve the integration of social and economic sciences in integrated ecosystem assessments, identifying and reporting data gaps that point to priorities for data collection. Brooks et al. (2015) developed indicators providing benchmarks over the life of a management plan which could identify trends in social and economic effects that could be compared to objective levels identified in the management of a fishery. This illustrates that it is possible to explicitly incorporate social objectives into decision-making processes, which would assist in assessing the resilience of fisheries systems to changes.

To our knowledge, few studies have evaluated the social and economic outcomes of a moratorium considering the entire fishery system, including the processing industries and markets. The anchovy fishery system thus appears as an insightful example of the short- and long-term socioeconomic impacts that could emanate from a fishery closure. Indeed, fisheries management measures have focused on reducing fishing effort and rebuilding the stock biomass, but did not consider the market and processing industries, which have faced severe economic and social challenges. Further, in this fishery, the quality of the fish (size, fat content) is fundamental for the market but is not yet taken into account in scientific evaluations and TAC recommendations. Given their importance for the sustainability of the SES, one could argue that stock-based management advice should better account for both fish condition and socio-economic objectives.

Shifts in targeting by the fishing fleets was also important. Unable to pursue anchovy, French purse seiners turned to sardines, pelagic trawlers turned to albacore and sea bass, while Spanish purse seiners substituted anchovy essentially with mackerel and tuna. These other fisheries have been affected by the resulting fishing effort displacement, especially, sea bass (Daurès et al. 2009). Further coordination of the anchovy TAC setting with the development of long-term management plans for other pelagic fish, considering and anticipating the dynamics of these different components of the pelagic system, seem key to meet the objectives of ecosystem-based fisheries management.

While, in this case study, fishers responded to the crisis by diversifying their catch portfolio (at least the Spanish purse seiners and the French pelagic trawlers) and becoming more multi-species dependent, the opposite trend was seen in other fisheries such as in the Gulf of Maine (United States and Canada). Indeed, development of the lobster fishery there appeared as an opportunity emanating from the Atlantic cod fishery collapse, but created a lucrative monoculture that has reduced by almost 70% the economic diversity of the marine resources harvested (Charles 1997, Steneck et al. 2011). The lessons learned from the anchovy case study are that specialization makes for harder adjustments when a problem occurs with the key target species. This experience supports the call to shift fisheries management away from single species, and towards integrated social-ecological approaches that incorporate future potential transformations at the sectoral, coastal community and institutional levels.

5. Conclusion

In assessing the dynamics and adaptations of the anchovy fishery system, we show how a shock like the closure of the fishery creates not only diverse adaptive responses (e.g., different French and Spanish fishers' behaviors), but also triggers new connections (e.g., new countries feeding the Spanish market), opportunities (e.g., science-based management), transformations (e.g., the evolution of the canned market) and challenges (e.g., loss of the market for the French fishing industry). Our study has

[5] https://www.ices.dk/community/groups/Pages/SIHD.aspx

demonstrated that pursuit of the basic goal of preserving the fish resource within its biological limits has had long-lasting cascading effects in the fishing fleets, the sector and international markets.

Three key messages have arisen from this research. First, selection of suitable social and economic indicators can provide an important understanding of the systemic responses of a fishery system. Second, in governing fisheries, resilience may be an important objective for some components of the fishery system, while for other components, the focus may be on achieving strategic transformation. Third, setting strategic socio-economic objectives for the fishery system, and achieving their alignment with the management objectives set for the fisheries, seem indispensable to sustain resilient fishery systems and assess management performance within an integrated policy framework.

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Competing interests

The authors declare there are no competing interests.

Author contributions
Conceptualization: J.B., O.T., A.C.; Investigation, formal analysis and writing - original draft: J.B.; Data curation: J.B, C.L, S.V.; Writing - Review & editing: J.B., O.T., S.V., P.P., A.C.; Validation: P.P., S.V.; Funding acquisition: J.B.; Supervision: O.T., S.V., A.C.

Data availability
The data used in this research associated with individual vessel adaptation cannot be shared publicly because it is considered private and confidential information. Summary data not included with the article or associated supplementary materials will be shared upon reasonable request to the corresponding author.

References
Allain, G., Petitgas, P., and Lazure, P. 2001. The influence of mesoscale ocean processes on anchovy (Engraulis encrasicolus) recruitment in the Bay of Biscay estimated with a three-dimensional hydrodynamic mode. Fisheries Oceanography 10(2): 151–163. doi:10.1046/j.1365-2419.2001.00164.x.

Allison, E.H., Perry, A.L., Badjeck, M.-C., Adger, W.N., Brown, K., Conway, D., Halls, A.S., Pilling, G.M., Reynolds, J.D., Andrew, N.L., and Dulvy, N.K. 2009. Vulnerability of national economies to the impacts of climate change on fisheries. Fish and Fisheries **10**(2): 173–196. doi:10.1111/j.1467-2979.2008.00310.x.

Andrés, M., and 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**(3): 205–214. EDP Sciences. doi:10.1051/alr/2012018.

Astorkiza, K., del Valle, I., and Astorkiza, I. 1998. Fisheries Policy and the Cofradias in the Basque Country: The Case of Albacore and Anchovy. *In* Documento de trabajo 9809. Departamento de Economía: Universidad Pública de Navarra. p. 18. Available from https://dlc.dlib.indiana.edu/dlc/handle/10535/1718.

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

Bellanger, M., Macher, C., and Guyader, O. 2016. A new approach to determine the distributional effects of quota management in fisheries. Fisheries Research **181**: 116–126. doi:10.1016/j.fishres.2016.04.002.

Berkes, F., Colding, J., and Folke, C. (Editors). 2002. Navigating Social-Ecological Systems: Building Resilience for Complexity and Change. Cambridge University Press, Cambridge. doi:10.1017/CBO9780511541957.

Bertrand, M., Brosset, P., Soudant, P., and Lebigre, C. 2022. Spatial and ontogenetic variations in sardine feeding conditions in the Bay of Biscay through fatty acid composition. Marine Environmental Research **173**: 105514. doi:10.1016/j.marenvres.2021.105514.

Boëns, A., Ernande, B., Petitgas, P., and Lebigre, C. 2023. Different mechanisms underpin the decline in growth of anchovies and sardines of the Bay of Biscay. Evolutionary Applications 16(8): 1393–1411. doi:10.1111/eva.13564.

Boëns, A., Grellier, P., Lebigre, C., and Petitgas, P. 2021. Determinants of growth and selective mortality in anchovy and sardine in the Bay of Biscay. Fisheries Research **239**: 105947. doi:10.1016/j.fishres.2021.105947.

Borja, A., Fontán, A., Sáenz, J., and Valencia, V. 2008. Climate, oceanography, and recruitment: the case of the Bay of Biscay anchovy (*Engraulis encrasicolus*). Fisheries Oceanography **17**(6): 477–493. doi:10.1111/j.1365-2419.2008.00494.x.

Boyra, G., Martínez, U., Cotano, U., Santos, M., Irigoien, X., and Uriarte, A. 2013. Acoustic surveys for juvenile anchovy in the Bay of Biscay: abundance estimate as an indicator of the next year's recruitment and spatial distribution patterns. ICES Journal of Marine Science **70**(7): 1354–1368. doi:10.1093/icesjms/fst096.

Brattland, C., Eythórsson, E., Weines, J., and Sunnanå, K. 2019. Social–ecological timelines to explore human adaptation to coastal change. Ambio **48**(12): 1516–1529. doi: 10.1007/s13280-018-1129-5.

Brooks, K., Schirmer, J., Pascoe, S., Triantafillos, L., Jebreen, E., Cannard, T., and Dichmont, C.M. 2015. Selecting and assessing social objectives for Australian fisheries management. Marine Policy **53**: 111–122. doi:10.1016/j.marpol.2014.11.023.

Bueno-Pardo, J., Petitgas, P., Kay, S., and Huret, M. 2020. Integration of bioenergetics in an individual-based model to hindcast anchovy dynamics in the Bay of Biscay. ICES Journal of Marine Science 77(2): 655–667. doi:10.1093/icesjms/fsz239.

Carpenter, G., Carvalho, N., Guillen, J., Prellezo, R., Villasante, S., et al. 2023. The economic performance of the EU fishing fleet during the COVID-19 pandemic. Aquat. Living Resour. **36**: 2. EDP Sciences. doi:10.1051/alr/2022022.

Carpenter, G., Kleinjans, R., Villasante, S., and O'Leary, B.C. 2016. Landing the blame: The influence of EU Member States on quota setting. Marine Policy **64**: 9–15. doi:10.1016/j.marpol.2015.11.001.

Charles, A. 1997. Fisheries management in Atlantic Canada. Ocean & Coastal Management **35**(2): 101–119. doi:10.1016/S0964-5691(97)00028-8.

Charles, A. 2001. *Sustainable Fishery Systems*. Blackwell Science, Oxford UK.

Charles, A. 2005. The big picture: a “fishery system approach” links fishery management and biodiversity.

Charles, A. 2023 Sustainable Fishery Systems. 2nd Edition, Wiley-Blackwell (formerly Blackwell Science). Oxford UK. 672p.

Cheung, W.W.L., Lam, V.W.Y., Sarmiento, J.L., Kearney, K., Watson, R., Zeller, D., and Pauly, D. 2010. Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change. Global Change Biology **16**(1): 24–35. doi:10.1111/j.1365-2486.2009.01995.x.

Christensen, V., Coll, M., Steenbeek, J., Buszowski, J., Chagaris, D., and Walters, C.J. 2014. Representing Variable Habitat Quality in a Spatial Food Web Model. Ecosystems **17**(8): 1397–1412. doi:10.1007/s10021-014-9803-3.

Chust, G., González, M., Fontán, A., Revilla, M., Alvarez, P., Santos, M., Cotano, U., Chifflet, M., Borja, A., Muxika, I., Sagarminaga, Y., Caballero, A., de Santiago, I., Epelde, I., Liria, P., Ibaibarriaga, L., Garnier, R., Franco, J., Villarino, E., Irigoien, X., Fernandes-Salvador, J.A., Uriarte, A., Esteban, X., Orue-Echevarria, D., Figueira, T., and Uriarte, A. 2022. Climate regime shifts and biodiversity redistribution in the Bay of Biscay. Science of The Total Environment 803: 149622. doi:10.1016/j.scitotenv.2021.149622.

Clark, C.W. and Munro, G.R., 1975. The economics of fishing and modern capital theory: a simplified approach. Journal of environmental economics and management, 2(2), pp.92-106.

Da Rocha, J.-M., Cerviño, S., and Villasante, S. 2012. The Common Fisheries Policy: An enforcement problem. Marine Policy **36**(6): 1309–1314. doi:10.1016/j.marpol.2012.02.025.

Daurès, F., Rochet, M.-J., Iseghem, S.V., and Trenkel, V.M. 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**(4): 535–547. EDP Sciences. doi:10.1051/alr/2009031.

Dépalle, M., Thébaud, O., and Sanchirico, J.N. 2020. Accounting for Fleet Heterogeneity in Estimating the Impacts of Large-Scale Fishery Closures. Marine Resource Economics. The University of Chicago PressChicago, IL. doi:10.1086/710514.

Doray, M., Boyra, G., and Kooij, J. van der. 2021. ICES Survey Protocols – Manual for acoustic surveys coordinated under ICES Working Group on Acoustic and Egg Surveys for Small Pelagic Fish (WGACEGG). report, ICES Techniques in Marine Environmental Science (TIMES). doi:10.17895/ices.pub.7462.

Doray, M., Duhamel, E., Boiron-Leroy, A., Marchand, L., Bled--Defruit, G., and Petitgas, P. 2022. Mean length and weight at-age of anchovy and sardine estimated during the PELGAS survey in the Bay of Biscay in springtime. SEANOE. doi:10.17882/88357.

Doray, M., Petitgas, P., Huret, M., Duhamel, E., Romagnan, J.B., Authier, M., Dupuy, C., and Spitz, J. 2018. Monitoring small pelagic fish in the Bay of Biscay ecosystem, using indicators from an integrated survey. Progress in Oceanography **166**: 168–188. doi:10.1016/j.pocean.2017.12.004.

Erauskin-Extramiana, M., Alvarez, P., Arrizabalaga, H., Ibaibarriaga, L., Uriarte, A., Cotano, U., Santos, M., Ferrer, L., Cabré, A., Irigoien, X., and Chust, G. 2019. Historical trends and future distribution of anchovy spawning in the Bay of Biscay. Deep Sea Research Part II: Topical Studies in Oceanography **159**: 169–182. doi:10.1016/j.dsr2.2018.07.007.

FAO. 2022. The State of World Fisheries and Aquaculture 2022. Towards Blue Transformation. FAO, Rome. doi:10.4060/cb4474en.

Fernández-González, R., Pérez-Pérez, M., Nobre, A.L., and Garza-Gil, M.D. 2019. Evolution and Trends in a Spanish Fishery of Anchovies. Current Politics & Economics of Europe **30**(2): 285–308. Nova Science Publishers.

Folke, C. 2016. Resilience (Republished). E&S **21**(4): art44. doi:10.5751/ES-09088-210444.

Fournet, P. 1980. Le chalutage pélagique dans les eaux côtières du sud-ouest de la France. Norois **106**(1): 277–287. Persée - Portail des revues scientifiques en SHS. doi:10.3406/noroi.1980.3890.

Garza-Gil, M.D., Varela-Lafuente, M.M., Caballero-Miguez, G., and Álvarez-Díaz, M. 2011. Analysing the profitability of the Spanish fleet after the anchovy moratorium using bootstrap techniques. Ecological Economics **70**(6): 1154–1161. doi:10.1016/j.ecolecon.2011.01.008.

Grafton, R.Q., Doyen, L., Béné, C., Borgomeo, E., Brooks, K., et al. 2019. Realizing resilience for decision-making. Nat Sustain **2**(10): 907–913. Nature Publishing Group. doi:10.1038/s41893-019-0376-1.

Grafton, R.Q., Squires, D., and Steinshamn, S.I. 2022. Towards resilience-based management of marine capture fisheries. Economic Analysis and Policy. doi:10.1016/j.eap.2022.11.012.

Grandremy Nina, Romagnan Jean-Baptiste, Dupuy Christine, Doray Mathieu, Huret Martin, Petitgas Pierre (2023). Hydrology and small pelagic fish drive the spatio–temporal dynamics of springtime zooplankton assemblages over the Bay of Biscay continental shelf. Progress in Oceanography, 210. https://doi.org/10.1016/j.pocean.2022.102949.

Halpern, B.S., Walbridge, S., Selkoe, K.A., Kappel, C.V., Micheli, F., et al. 2008. A Global Map of Human Impact on Marine Ecosystems. Science **319**(5865): 948–952. doi: 10.1126/science.1149345.

Hannesson, R. 2022. Stock crash and recovery: The Norwegian spring spawning herring. Economic Analysis and Policy **74**: 45–58. doi:10.1016/j.eap.2022.01.007.

ICES WGHMSA 2005 report, ICES Working Group on Mackerel Horse Mackerel Sardine and Anchovy (WGMHSA). ICES CM 2005/ACFM:31, chapter 10.

ICES WGHANSA 2020. ICES Working Group on Southern Horse Mackerel, Anchovy and Sardine (WGHANSA). ICES Scientific Reports. 2:41. 655 pp. http://doi.org/10.17895/ices.pub.5977

Jouffray, J.-B., Blasiak, R., Norström, A.V., Österblom, H., and Nyström, M. 2020. The Blue Acceleration: The Trajectory of Human Expansion into the Ocean. One Earth **2**(1): 43–54. doi: 10.1016/j.oneear.2019.12.016.

Junquera, S. 1984. Pêche de l'anchois (*Engraulis encrasicholus*) dans le golfe de Gascogne et sur le littoral atlantique de Galice depuis 1920. Variations quantitatives. Revue des Travaux de l'Institut des Pêches Maritimes **48**(3–4): 133–142. ISTPM.

Lazkano, I., Nøstbakken, L., and Prellezo, R. 2013. Past and Future Management of a Collapsed Fishery: The Bay of Biscay Anchovy. Natural Resource Modeling **26**(3): 281–304. doi: https://doi.org/10.1111/j.1939-7445.2012.00138.x.

MacCall, A.D. 1990. Dynamic geography of marine fish populations. Washington Sea Grant Program: Distributed by University of Washington Press, Seattle.

MAPAMA. 2022. Estadísticas Pesqueras, Available online at https://www.mapa.gob.es/es/estadistica/temas/estadisticas-pesqueras/default.aspx [Accessed October 2022].

Mason, J.G., Eurich, J.G., Lau, J.D., Battista, W., Free, C.M., et al. 2021. Attributes of climate resilience in fisheries: From theory to practice. Fish and Fisheries **23**(3): 522–544. doi:10.1111/faf.12630.

Massé, J., Sanchez, F., Delaunay, D., Robert, J.M., and Petitgas, P. 2016. A partnership between science and industry for a monitoring of anchovy & sardine in the Bay of Biscay: When fishermen are actors of science. Fisheries Research **178**: 26–38. doi:10.1016/j.fishres.2015.11.018.

Mulazzani, L., Curtin, R., Andrés, M., and Malorgio, G. 2013. Multilevel governance and management of shared stocks with integrated markets: The European anchovy case. Marine Policy **38**: 407–416. doi:10.1016/j.marpol.2012.06.020.

Natale, F., Carvalho, N., Harrop, M., Guillen, J., and Frangoudes, K. 2013. Identifying fisheries dependent communities in EU coastal areas. Marine Policy **42**: 245–252. doi:10.1016/j.marpol.2013.03.018.

Nuttall, M. 2012. Tipping points and the human world: living with change and thinking about the future. Ambio **41**(1): 96–105. doi:10.1007/s13280-011-0228-3.

Ojea, E., Fontán, E., Fuentes-Santos, I., and Bueno-Pardo, J. 2021. Assessing countries' social-ecological resilience to shifting marine commercial species. Sci Rep **11**(1): 22926. doi:10.1038/s41598-021-02328-6.

Ostrom, E. 2009. A General Framework for Analyzing Sustainability of Social-Ecological Systems. Science **325**(5939): 419–422. doi:10.1126/science.1172133.

Petitgas, P., Doray, M., Huret, M., Massé, J., and Woillez, M. 2014. Modelling the variability in fish spatial distributions over time with empirical orthogonal functions: anchovy in the Bay of Biscay. ICES Journal of Marine Science **71**(9): 2379–2389. doi:10.1093/icesjms/fsu111.

Petitgas, P., Renard, D., Desassis, N., Huret, M., Romagnan, J.-B., Doray, M., Woillez, M., and Rivoirard, J. 2020. Analysing Temporal Variability in Spatial Distributions Using Min–Max Autocorrelation Factors: Sardine Eggs in the Bay of Biscay. Math Geosci 52(3): 337–354. doi:10.1007/s11004-019-09845-1.

Pimm, S.L., Donohue, I., Montoya, J.M., and Loreau, M. 2019. Measuring resilience is essential to understand it. Nat Sustain **2**(10): 895–897. doi:10.1038/s41893-019-0399-7.

Pinsky, M.L., Worm, B., Fogarty, M.J., Sarmiento, J.L., and Levin, S.A. 2013. Marine taxa track local climate velocities. Science **341**(6151): 1239–1242.

Pita, C., Silva, A., Prellezo, R., Rocha, J., Andrés, M., and Uriarte, M. 2014. Socioeconomics and Management. In Ganias, C. (Ed.) Biology and Ecology of Sardines and Anchovies pp. 335–366, CRC Press. doi:10.1201/b16682-13.

Prouzet, P., D. Milly, N. Caill and C. Caboche. 1996. L'anchois du Golfe de Gascogne - Généralités et campagne de pêche en 1994. Rapport CNPM - IMA - IFREMER.

Roheim, C.A., Bush, S.R., Asche, F., Sanchirico, J.N., and Uchida, H. 2018. Evolution and future of the sustainable seafood market. Nat Sustain **1**(8): 392–398. Nature Publishing Group. doi: 10.1038/s41893-018-0115-z.

Sánchez, S., Ibaibarriaga, L., Uriarte, A., Prellezo, R., Andrés, M., Abaunza, P., Jardim, E., Lehuta, S., Pawlowski, L., and Roel, B. 2019. Challenges of management strategy evaluation for small pelagic fish: the Bay of Biscay anchovy case study. Marine Ecology Progress Series **617–618**: 245–263. doi:10.3354/meps12602.

Santos M., Uriarte, A., Boyra, G., Ibaibarriaga, L. 2018 Anchovy DEPM surveys 2003–2012 in the Bay of Biscay (Subarea 8): BIOMAN survey series. In: Massé J, Uriarte A, Angélico MM, Carrera P (eds) Pelagic survey series for sardine and anchovy in ICES Subareas 8 and 9 towards an ecosystem approach. ICES Cooperative Research Report 332. ICES, Copenhagen, p 85–102

Simpson, N.P., Mach, K.J., Constable, A., Hess, J., Hogarth, R., Howden, M., Lawrence, J., Lempert, R.J., Muccione, V., Mackey, B., New, M.G., O'Neill, B., Otto, F., Pörtner, H.-O., Reisinger, A., Roberts, D., Schmidt, D.N., Seneviratne, S., Strongin, S., van Aalst, M., Totin, E., and Trisos, C.H. 2021. A framework for complex climate change risk assessment. One Earth 4(4): 489–501. doi:10.1016/j.oneear.2021.03.005.

Steins, N.A., Mackinson, S., Mangi, S.C., Pastoors, M.A., Stephenson, et al. 2022. A will-o'-the wisp? On the utility of voluntary contributions of data and knowledge from the fishing industry to marine science. Frontiers in Marine Science **9**. Available from https://www.frontiersin.org/articles/10.3389/fmars.2022.954959.

Steneck, R.S., Hughes, T.P., Cinner, J.E., Adger, W.N., Arnold, S.N., Berkes, F., Boudreau, S.A., Brown, K., Folke, C., Gunderson, L., Olsson, P., Scheffer, M., Stephenson, E., Walker, B., Wilson, J., and Worm, B. 2011. Creation of a Gilded Trap by the High Economic Value of the Maine Lobster Fishery. Conservation Biology **25**(5): 904–912. doi:https://doi.org/10.1111/j.1523-1739.2011.01717.x.

Stoll, J.S., Pinto da Silva, P., Olson, J., and Benjamin, S. 2015. Expanding the 'geography' of resilience in fisheries by bringing focus to seafood distribution systems. Ocean & Coastal Management **116**: 185–192. doi:10.1016/j.ocecoaman.2015.07.019.

SWWRAC. 2008. Contribution du CCR Sud sur le document informel de la Commission Européenne pour un plan de gestion à long terme de la pêcherie d′ anchois du Golfe de Gascogne. 22 juillet 2008. Conseil Consultatif Régional pour les eaux occidentales australes.

Taboada, F.G., and Anadón, R. 2016. Determining the causes behind the collapse of a small pelagic fishery using Bayesian population modeling. Ecol Appl **26**(3): 886–898. doi:10.1890/15-0006.

Thébaud, O., Nielsen, J.R., Motova, A., Curtis, H., Bastardie, F., et al. 2023. Integrating economics into fisheries science and advice : progress, needs, and future opportunities. ICES Journal of Marine Science: 80(4): 647–663. doi:10.1093/icesjms/fsad005.

Uriarte, A., and Astudillo, A. 1987. The anchovy in the Bay of Biscay: new data and analysis of the fishery, 1974–1987. ICES CM 1987/H:20.

Uriarte, A., Ibaibarriaga, L., Sánchez-Maroño, S., Abaunza, P., Andrés, M., Duhamel, E., Jardim, E., Pawlowski, L., Prellezo, R., and Roel, B.A. 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. Marine Policy **150**: 105512. doi:10.1016/j.marpol.2023.105512.

Uriarte, A., Prouzet, P., and Villamor, B. 1996. Bay of Biscay and Ibero Atlantic anchovy populations and their fisheries. Sci Mar **60**: 237–255.

Valle, I.D., Astorkiza, I., and Astorkiza, K. 2001. Is the Current Regulation of the VIII Division European Anchovy Optimal? Environmental and Resource Economics **19**: 53–72.

Van Beveren, E., Bonhommeau, S., Fromentin, J.-M., Bigot, J.-L., Bourdeix, J.-H., Brosset, P., Roos, D., and Saraux, C. 2014. Rapid changes in growth, condition, size and age of small pelagic fish in the Mediterranean. Mar Biol **161**(8): 1809–1822. doi:10.1007/s00227-014-2463-1.

Vaz, S and Petitgas, P. 2002. Study of the Bay of Biscay anchovy population dynamics using spatialized age-specific matrix models. ICES CM 2002/O:07, 20p.

Vermard, Y., Marchal, P., Mahévas, S., and Thébaud, O. 2008. A dynamic model of the Bay of Biscay pelagic fleet simulating fishing trip choice: the response to the closure of the European anchovy (*Engraulis encrasicolus*) fishery in 2005. Can. J. Fish. Aquat. Sci. **65**(11): 2444–2453. doi: 10.1139/F08-147.

Véron, M., Duhamel, E., Bertignac, M., Pawlowski, L., and Huret, M. 2020. Major changes in sardine growth and body condition in the Bay of Biscay between 2003 and 2016: Temporal trends and drivers. Progress in Oceanography **182**: 102274. doi:10.1016/j.pocean.2020.102274.

Villasante, S., Macho, G., Silva, M.R.O., Lopes, P.F.M., Pita, P., Simón, A., Balsa, J.C.M., Olabarria, C., Vázquez, E., and Calvo, N. 2022. Resilience and Social Adaptation to Climate Change Impacts in Small-Scale Fisheries. Front. Mar. Sci. **9**: 802762. doi:10.3389/fmars.2022.802762.

Xunta de Galicia (2023) Informes estatísticos https://www.pescadegalicia.gal/estadisticas/ [Accessed October 2022].

Supplementary Material

Supplementary Method

1. Grey literature and key experts' knowledge

A systemic approach requires inspecting and collecting complementary information from different sources such as scientific literature, grey literature, expert knowledge and stakeholder observations (Adams et al. 2017). Useful insights on changes in the SES and "hidden data" were gathered from the grey literature comprising public administrative reports (e.g., Official Journal of the European Commission, *circulaires de la Direction des Pêches Maritimes et de l'Aquaculture, arrêtés du Journal Officiel de la République Française*), the European Commission's Scientific, Technical and Economic Committee for Fisheries (STECF) technical reports, ICES working groups reports and South-Western Waters Regional Advisory Council (SWW RAC) reports. Also considered were press articles from the 1990s to the 2020s identified from a keyword search using various combinations of the terms "Bay of Biscay", "anchovy", "collapse", "fishery", "crisis", "management", "closure" and "adaptation". We also interviewed retired and active key scientific experts of this fishery to collect their knowledge about its history and their perceptions about its management and how this evolved over the study period.

2. Perception survey and interviews with key stakeholders

We collected testimonies from stakeholders who experienced the anchovy crisis during 2005-2010 in the Bay of Biscay (French and Spanish stakeholders) and/or who played a key role during this crisis. Key stakeholders included impacted fishers, fishers' representatives and producer organizations, fishmongers and processors, managers and scientists. A purposeful snowball sampling process (Johnson 2014) was used to identify respondents for the perception survey. We asked each participant the names of at least three other potential participants before closing up the interview, starting with fishers' representatives and fishing organizations head.

We developed online questionnaires and carried out in-person interviews. The former was intended for informants who did not have much time (or will) to discuss with us and contained cross-cutting generic questions, common to all interviewees in order to compare their perceptions on global changes and transformations in the fishery SES. In-person interviews included semi-structured questions adapted for each of the stakeholder categories (e.g., fishers, processors, managers), open and conducive to discussion about their personal experiences, and their adaptation strategies. The content of the questionnaire protocol was structured in two parts related to 1) major changes in all of the SES components considered and 2) actors' responses at different time periods.

Relying on non-proportional quota sampling (Tashakkori et al. 2003), we interviewed those actors who played an active role in the anchovy fishery affected by the closure. In-person interviews with narrativebased methods and appropriate probes can be well-suited for exploring subjective and experiential topics. In total, 39 stakeholders were interviewed (14 completed the online survey), 10 from Spain and 29 from France. 11 informants considered themselves as industry representatives, 15 were fishers, 6 were both fishers and industry representatives, 4 were scientists, 1 was an administration representative, 1 was a fishmonger, and 1 an auction market director. Among fishers, we interviewed 13 purse seiners' and 8 pelagic trawlers' captains. This sample size was considered sufficient to identify the impacts of the anchovy closure since, when conducting in-depth semi-structured interviews, the number of new concepts and/or results associated with each additional interview generally tends to diminish after 20 interviews (Tashakkori et al. 2003; Villasante et al. 2016). We conducted fieldwork between June 2021 and September 2021. Interviews began with signing a consent form and confidentiality agreement along with a brief project description, both in writing and verbalized by the interviewer. The survey was reviewed by the CNRS process for approval of survey procedures. It was not examined by an ethics review committee as this was not deemed necessary given the nature of the information collected. All reported citations in the manuscript (in italics) from French and Spanish stakeholders have been translated in English by the authors. Stakeholders are identified by the following code: "F." or "S." for French or Spanish followed by the letter corresponding to their categories, PT for pelagic trawler, PS for purse seiner, R for representative, S for scientists, F for fishmonger, and # specified their identity anonymous number.

3. Analysis of system level responses using fisheries and international trade data

The observations made by the survey respondents were complemented with system-level quantitative analyses using both fishery and trade data that were available to the research team for describing for the following components of the system: market, landings and patterns in the spatio-temporal activity of the fleets.

French fisheries data were extracted from the Ifremer Système d'Informations Halieutiques (http://sih.ifremer.fr) and contain annual landings per target species for vessels dependent on anchovy (dependency defined as having fished at least 10 metric tons of anchovy once from 2000 to 2021 or annual anchovy value was equal to 10% of total landings value for this vessel). The data set includes landings value and effort (i.e., days at sea), technical information for each vessel (e.g., length, age, engine power, maritime district and port) and ownership information (i.e., owner or company name, age). Similar data for the Spanish fleets were not available at the time of the manuscript submission.

We derived prices from total annual anchovy landings and values from official fisheries data from France (SIH), from Galicia (Ministry of Agriculture, Fisheries and Food, https://www.mapa.gob.es/es/estadistica/temas/estadisticas-pesqueras/default.aspx) and from the Basque country (https://www.euskadi.eus/estadistica/precios-evolucion-de-la-campana-de-anchoa-y-bonito/web01-a2estadi/es/). These prices were adjusted according to the corresponding country FAOSTAT Consumer Price Food indices relative to 2021 (https://www.fao.org/faostat/en/#data/CP).

International anchovy trade data were extracted from the Eurostat's Comext database (https://ec.europa.eu/eurostat) referencing annual trade values and quantities of anchovy by EU Member State country (the declarant) and the partner country (EU Member State or not), with products categorized according to the FranceAgrimer nomenclature (i.e., fresh, prepared or preserved, frozen, or dried-salted). As 95% of French landings are sold on the Basque market and processed in Spain (Pita et al. 2014), we focused the analysis on anchovy imports by Spain. A Fisher price index was calculated to analyze changes in the prices of imported fresh anchovy by Spain over the 2001-2020 period, as follows (eq. 1):

$$F_{t/t0\,(price)} = \sqrt{\frac{\sum_i (p_{i,t} \times q_{i,0})}{\sum_i (p_{i,0} \times q_{i,0})} \times \frac{\sum_i (p_{i,t} \times q_{i,t})}{\sum_i (p_{i,0} \times q_{i,t})}} \times 100 \quad (1)$$

with $p_{i,t}$ the price of imported anchovy from country *i* at time *t*, $p_{i,0}$ the price at the base period 2001, $q_{i,t}$ the quantity of imported anchovy from country *i* at time *t*, and $q_{i,0}$ its quantity at the base period. The index was calculated for one of the main products, i.e., fresh anchovies since the evaluation of the index for prepared or preserved anchovies requires broader analyses of the international market dynamics involving external factors not considered in this paper.

Supplementary Figures and Tables

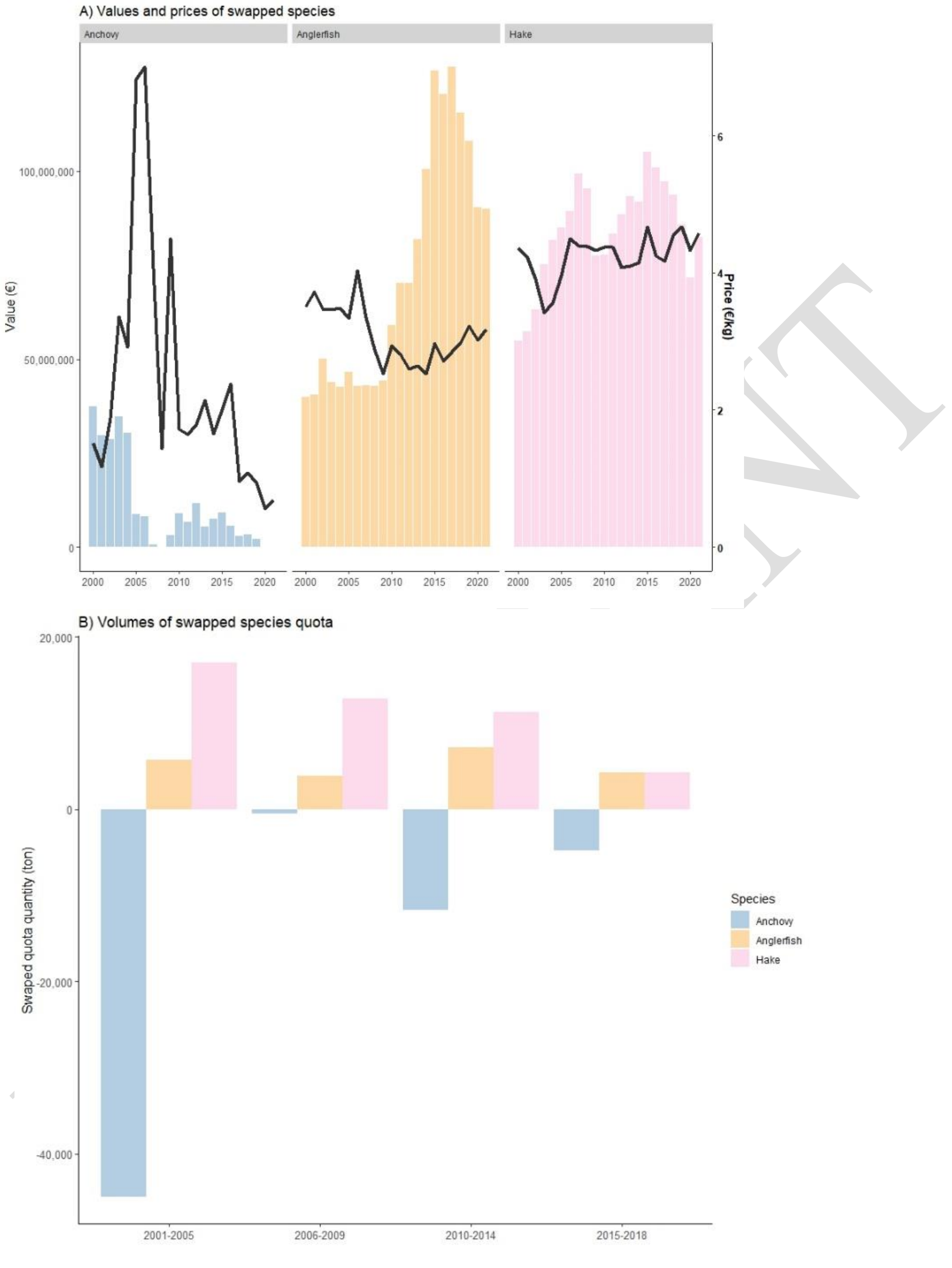

Figure S1 | Value, price (A) and volume of quota swaps (B) by species between France and Spain: anchovy quota was given by Spain to France while anglerfish and hake quotas were given by France. (Sources: Ifremer Système d'Informations Halieutiques SIH for catch values and prices, European Commission Directorate-general for maritime affairs and fisheries for quota swaps)

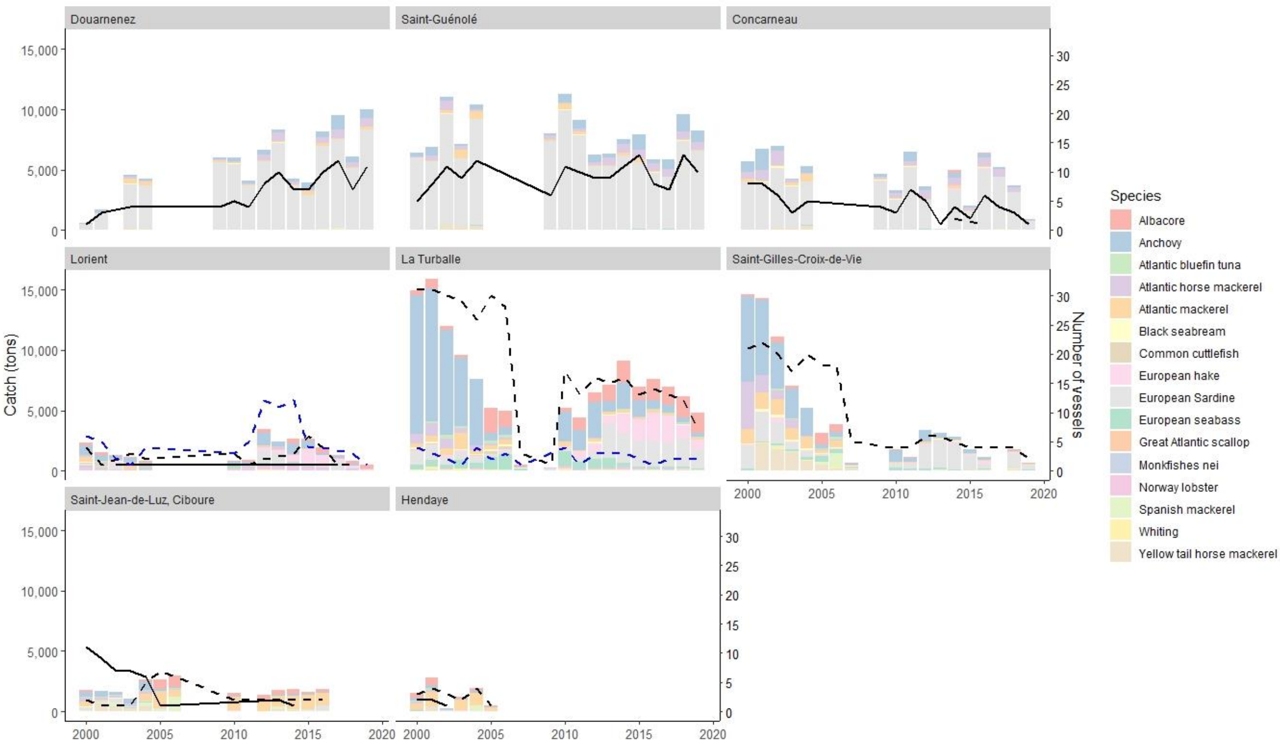

Figure S2 | Annual total catch of species for anchovy dependent French vessels for the eight main ports in Atlantic coast of France and corresponding number of purse seiners in solid line, pelagic trawlers in black dashed line and bottom trawlers in blue dashed line. (Sources: Ifremer SIH).

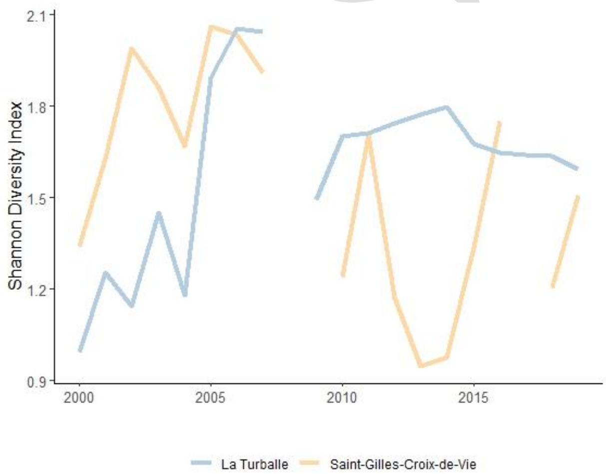

Figure S3 | Compositional diversity of the fisheries portfolio in terms of catch using the Shannon–Wiener index (H′), calculated as, $H'_t = -\sum_i^k p_{i,t}$ where $p_{i,t}$ is the proportional catch of the species i-th for the year t and k is the number of species in year t. (Sources: Ifremer SIH for catch landings).

Table S1 | Agreement with the fishery moratorium and perceptions of the interviewees about it

Country	Actor	YES	NO	Reason and/or comment
Spain	Representative	X		“There was no choice otherwise stock would have collapsed and more boats would have been scraped”
Spain	Representative		X	“More quota control could have been put in place before the collapse of the stock. Then there were fishing effort displacements on sardines and horse mackerel”
Spain	Purse seiner		X	“It was not an adequate management measure; it is better to reduce quotas earlier (or close the fishery in the North). The we observed effort displacement on sardine, horse mackerel and mackerel, with decreased incomes. It implies the loss of the market and international imports at lower prices”
Spain	Purse seiner		X	“We advocated for the reduction of quotas in order to be able to maintain the buyers and market trades. Closures of fisheries should be the last option. To help a fishery recover there are other alternatives, which avoid the complete closure of the fishery: lower quotas, monthly closures, reducing the number of boats per month (alternating boats), reducing the quotas per boat per day”
Spain	Purse seiner	X		“It was necessary because they were fishing in spawning areas. Now the anchovy had recovered. The relationships between French and Spanish have improved”
Spain	Purse seiner	X		“It was difficult but the right decision. We had small anchovies afterward but everything was very controlled and things got better”
Spain	Purse seiner	X		“There was no more anchovy, now the anchovy has recovered”
Spain	Purse seiner	X		“I am in favor of biological closures, they are good for the fisheries, but I am against TACs”
Spain	Purse seiner		X	“Mackerel fishery became a disaster, we advocated for the reduction of quotas and size limits”
Spain	Scientist	X		“It was for biological reasons: there was no more anchovy”
French	Representative		X	“Impact of the fishery was "secondary" related to other factors impacting the resource. A minimum exploitation could have been maintained with a minor impact on the duration and intensity of the renewal of the resource”
French	Representative		X	“No more anchovy fishery for the purse seiners because of the loss of the market; they should have reduced quota”
French	Representative		X	“Anchovy fishery hasn’t restarted since the closure. Temporal closures (9-10/12mo) could have maintained the activity. They should have maintained a small quota to better understand resource trends and restart market more easily. Fishers lost their bearings”
French	Representative		X	“Moratorium does not fix anything and involves more damages”
French	Representative	X		“It was a necessary closure which has served as a lesson for the management approach for seabass”
French	Representative		X	“Without any catch data, scientific models could not run correctly; European Commission should have put in place experimental fishery”
French	Purse seiner	X		“It was an urgency, but market was sacrificed”
French	Purse seiner	X		“It was more than necessary”
French	Purse seiner	X		“Because of the size limit, we were already limited by the anchovy fishery. But it had major negative impact on other fisheries”
French	Purse seiner		X	“We lost the market, then we lost the boats and the crew. We should help fishers with a minimum quota or temporary closures”
French	Purse seiner	NA		“I was not concerned by the moratorium - I had already switched to sea bream by that time”
French	Purse seiner	X		“There was no other choice. It was a need to stop the pelagic trawler fishery which is not considered as "fishing"”
French	Pelagic Trawler		X	“They pointed out the fishers but ignored pollution and global warming that impacted the resource as well”
French	Pelagic Trawler		X	“The Spanish don't care about anchovies because they have quotas for tuna. Not us, we only have the anchovy to live”
French	Pelagic Trawler		X	“The Spanish pushed for the closure. By closing every fishery, fishers end up on the same species creating clashes; Today everyone fish tuna, squid and cuttlefish”
French	Pelagic Trawler		X	“Scientific advices were considered, not industry's ones. We would have agreed with the moratorium if there were any solutions proposed to support fishers; the upkeep of a minimum quota, or days limit per week, would have allowed to maintain a turnover”

French	Pelagic Trawler		**X**	“We could have managed the fishery with a diminished quota set at 10,000 tons”
French	Pelagic Trawler		**X**	“I have just built my vessel by the time of the closure so I had important economic loans”
French	Pelagic Trawler		**X**	“We should have let the fishery opened because in any cases vessels would have been in debt and would have gone bankrupt”
French	Market		**X**	“It was an economic impact during the crisis years (decrease of turnover ~ 50%), but it was salutary for saving the resource. Maybe we could have done size limits restrictions”
French	Market		**X**	"We didn't really see the moratorium coming, it happened from one week to the next"
French	Administration		**X**	“It was the will of Spain to end up the pelagic trawling fishery. France completely opposed to the moratorium”
French	Scientist		**X**	
French	Scientist	**X**		“Recruitment was low since 2002. I was supporting the moratorium since then. There were no age-1 individuals in 2005, and no fish at all in 2007: no fish during the survey. Drastically reducing the fishery would not have change much of the outcomes since French only have 10% of TAC”
French	Scientist	**NA**		